

Proceedings of the International Conference on Innovation - driven Knowledge Economies and Transformation in the Global South

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Volume VI Measurement of the Knowledge Economy: Indicators, data requirements, different approaches and methodologies

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GLOBELICS | Gulati Institute of Finance and Taxation | Research and
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Preface / A word of welcome and thanks

It is a matter of great pride that the 20th-anniversary Globelics International Conference is being held in Thiruvananthapuram. This conference deliberates on an issue of much contemporary relevance – Innovation-driven Knowledge Economies and Transformation in the Global South, which is at the centre stage of development strategy both at the national and that of the government of Kerala. In 2006, when inclusive development was a major issue of global concern, Globelics conference was held in Trivandrum and deliberated on Innovation Systems for International Competitiveness and Shared Prosperity.

This Conference intends to bring together scholars across disciplines from over 50 countries to pool together experiences and expertise to reflect on varied issues involved in the process of transforming developing economies into sustainable, resilient, and inclusive innovation-driven knowledge economies.

In the conference, to be inaugurated by Shri Pinaryi Vijayan, the Hon'ble Chief Minister of Kerala, scholars of eminence will join as keynote speakers and panelists in plenary sessions and special sessions. The conference, organized in nine parallel tracks, will also have book presentations, excursions, and cultural events. As part of the conference, about 20 leading scholars from Globelics will visit different universities and colleges in Kerala to deliver lectures and interact with faculty and students, which is facilitated by Kerala Higher Education Council and Kerala Economic Association.

We welcome with great appreciation the Honourable Chief Minister Shri Pinarayi Vijayan and all the dignitaries who joined us for the inaugural address and eminent scholars delivering keynotes and addressing in different plenary sessions, special sessions, and parallel sessions. While the invisible hand of our honourable Chief Minister is there in all the important initiatives of GIFT, this program has been ably guided and steered by our Chairperson Shri K N Balagopal, Hon'ble Finance Minister of Kerala.

This important event is the outcome of the collective effort of all those involved, especially the Co-organising institutions: RIS, New Delhi, who inter alia managed the political clearance from the Ministry of External Affairs, IIM Bangalore, K DISC and the Digital University of Kerala. Our partnering institutions, ICSSR, Kerala State Higher Education Council, Centre for

Development Studies, Kerala Economic Association, and the Centre for Latin American Studies also have been helpful in organising this conference.

With much appreciation for all of you for being with us, we welcome you

K J Joseph
For the local organising Committee

About the 20th Anniversary Conference

The central theme of the 20th Anniversary Globelics International conference is Innovation-driven Knowledge Economies and Transformation in the Global South.

This conference intends to bring together scholars across disciplines from over 50 countries to pool together experiences and expertise to reflect on varied issues involved in the process of transforming developing economies into sustainable, resilient, and inclusive innovation-driven knowledge economies. Episodes of development in economic history highlight the successful experience of countries that have managed to harness Learning, Innovation and Competence-building Systems at the global, national, subnational and sectoral levels in order to transform their social and economic structures for achieving prosperity. In the current times, the constellation of innovations driven by rapid advances in digital technologies has given rise to a new technological revolution, commonly referred to as the fourth industrial revolution, or Industry 4.0, with profound impacts on all sectors of the economies and sections of societies. New and persisting developmental challenges have driven a renewed interest in different types of innovations that highlight their impact on society and the natural environment, such as inclusive innovation, responsible innovation, transformative innovation, grassroots innovation and Jugaad. At the core of all these approaches is how knowledge, both science-based and experience-based, is harnessed for addressing development challenges, the basic premise being “the knowledge divide is at the root of the development divide”

At the current juncture, wherein globalization is at the crossroads, the economies across the world, ravaged by the once-in-a-century pandemic and external shocks, consider strengthening the innovation system as a strategic approach towards building resilience. Evidently, there is an across-the-board drive among developing countries to transform their economies into innovation-driven knowledge economies. Such a transformation is often viewed as capable of building resilience by addressing many of the downsides of globalization-induced high growth, like excessive exploitation of exhaustible resources and accentuated divides within and between countries. Such

initiatives in India are manifested, among others, in Atal Innovation Mission (AIM), Digital India, Skill India, and Make in India and other concerted efforts to transform India into an innovation-driven knowledge economy. It is also in sync with the national agenda of harnessing Science, Technology, and Innovation (STI) to achieve sustainable development. The choice of the location of the conference is inspired by Kerala's strategy towards transforming the state into a knowledge economy, as explicitly stated in the budgets starting with 2020-2021 and the subsequent concerted efforts that followed. It is in this background that Globelics revisits India for the 20th Globelics International conference with the chosen central theme: 'Innovation-Driven Knowledge-Economies and Transformation in the Global South'.

The 20th Anniversary Globelics is also an occasion to celebrate the journey of Globelics from Brazil 2003 to India 2023 and its varied achievements. At the same time, it is also a forum for critically reflecting on our perspective and the approaches *inter alia* in terms of its achievements and limits. This is especially important at the current juncture wherein there is growing disenchantment with the development experience under globalisation on the one hand and the need on the other hand, for reimagining innovation systems in the COVID and Post COVID world towards building the much needed resilience in the South.

Globelics-India 2023 coincides with India's Presidency of G-20 that *inter alia* aims at influencing the development dynamics of Global South and it is an appropriate time for translating the insights of the conference with respect to strengthening Learning, Innovation and Competence-building Systems (LICS) into policy action. For the past two decades, we have observed an increasing influence of Global South in shaping the paradigms and trajectories of the global development agenda—sustainability, climate change, pandemic, and energy security issues—with India playing a key role; all being closely linked to the research domains of the Globelics.

World-leading scholars are set to give this year's keynote address on innovation and development. It is planned that the conference will be inaugurated by the Chief Minister of Kerala and there will be a special keynote on the conference theme along with a Globelics Lecture and Freeman Lecture. The conference will combine plenary sessions, presentations of research papers in parallel tracks, thematic panel sessions or special sessions, poster presentations, book presentation sessions, excursions, and cultural events.

Conference Tracks

While submissions on the central theme of the conference have been especially encouraged, submissions on all the issues conventionally deliberated in the Globelics international conferences are also included. Submissions have been organized around the following themes:

1. Science, technology, innovation: Theory and policy for a knowledge economy
2. Transformative innovation, responsible innovation and mission-oriented innovation
3. Knowledge-driven development of national, regional, local and sectoral innovation systems, including Agricultural innovation systems and rural development
4. Measurement of the knowledge economy: Indicators, data requirements, different approaches and methodologies
5. Skilling for the knowledge economy: Industry-academy interaction, Intellectual property rights, open innovation and development
6. Industry 4.0 and development: Digitalization and automatization, productivity and employment implications, gig economy and quality of employment
7. Economic and social upgrading for sustainable Catch-up: trade policies, FDI, value chains and innovation networks in a knowledge-driven economy
8. Innovation for inclusive development: Indigenous knowledge, Grassroot innovations, Jugaad, informal economy, micro and small enterprises
9. Entrepreneurship, employability and gender dimension in innovation and development
10. The green economy and financing innovation: Low carbon innovations, environmental technologies and renewable energy

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Measurement of innovation: Selection of indicators and (mis) use of scoreboards

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Abstract

The choice of indicators to measure innovation processes and assess performance is of vital significance. This paper argues that those economic theories give a more accurate, more reliable account of innovation activities that follow a broad approach of innovation, that is, consider all knowledge-intensive activities leading to new products (goods or services), processes, business models, as well as new organisational and managerial solutions, and thus take into account various types, forms and sources of knowledge exploited for innovation by all sorts of actors in all economic sectors. In contrast, the narrow approach to innovation focuses on the so-called high-tech goods and sectors. The broad approach is needed to collect data and other types of information, on which sound theories can be built and reliable and comprehensive analyses of innovation activities can be offered to decision-makers to underpin public policies and company strategies.

Analysts and policy-makers need to avoid the trap of paying too much attention to simplifying ranking exercises. Instead, it is of utmost importance to conduct detailed, thorough comparative analyses, identifying the reasons for a disappointing performance, as well as the sources of – opportunities for – balanced, and sustainable, socio-economic development.

Keywords: Mainstream economics; Evolutionary economics of innovation; Measurement of innovation; Composite indicators; Scoreboards, league tables

1. Introduction

In an ideal world, data are collected to characterise the state of a given system at a certain point in time, analyse its dynamics and assess its performance over time. By the same token, policies aimed at influencing a given system, can only be evaluated by drawing on appropriate indicators. Evaluation, in turn, assists policy learning and help designing more effective policies. Data collection for both empirical and policy analyses (conducted either for academic or practical purposes) need to be theoretically guided, based on meaningful definitions and a thorough understanding of relevant phenomena. From time to time, however, empirical observations necessitate the reconsideration of various building blocks of theories and point to new policy challenges or opportunities. Some of these new policy needs also raise theoretical questions. In sum, measurement, theory building and policy-making are closely interrelated, and thus social scientists need to consider all these elements in their interactions practically on all fields. Research, technological development and innovation (RTDI) activities and science, technology and innovation (STI) policies are no exception. This paper, therefore, assesses the relevance of two sets of widely used innovation indicators, that is, those that are used for compiling the Innovation Union Scoreboard and the Global Innovation Index. The main question is as follows: to what extent are these relevant from the point of view of assessing innovation performance, advancing theory development, and assisting policy formation?

Significant progress has been achieved in measuring RTDI activities since the 1960s (Gault (ed.), 2013; Gault, 2016; Grupp, 1998; Grupp and Schubert, 2010; Smith, 2005) with the intention to provide comparable data sets as a solid basis for assessing RTDI performance and thereby guiding policy-makers in devising appropriate policies¹ Although there have been widely used guidelines to collect data on R&D and innovation for decades – that is, the Frascati and Oslo Manuals (their most recent editions are OECD, 2015 and OECD/ Eurostat, 2018, respectively) –, it is not straightforward to find the most appropriate way to assess R&D and innovation performance. To start with, R&D is such a complex, multifaceted process that it cannot be sufficiently characterised by just two or three indicators, and that applies to innovation *a fortiori*. Hence, there is always a need to select a certain set of indicators to depict innovation activities, and especially to analyse and assess innovation performance. The choice of indicators is, therefore, an important decision reflecting the mindset of those decision-makers who have chosen them. These figures are ‘subjective’ in that respect, but as they are expressed in numbers, most people perceive indicators as being ‘objective’ by definition.

For this reason – besides several others – it is important to review how business innovation – henceforth innovation – is understood in particular models of innovations and how it is analysed by various schools of economics. (Sections 2

and 3) Based on this, two major measurement endeavours, namely the European Innovation Scoreboard and the Global Innovation Index are assessed in detail. (Sections 4 and 5) The paper argues that these indicators mainly capture the so-called S&T mode of innovation activities – that is, those based on R&D results – and thus eclipse innovations based on learning by doing, using and interacting (called DUI mode of innovation by Jensen et al., 2007). In other words, these indicators are mainly relevant for underpinning STI policies aimed at fostering the S&T (science and technology) mode of innovation at the expense of the DUI mode of innovation. Further, they are in line with the market failure rationale for STI policies, but far less relevant for the systems approach to innovation and the concomitant systemic failures policy rationale. Theoretical and policy implications are summarised in Section 6.

2. Linear, networked and interactive learning models of innovation

Besides Schumpeter, only a few economists had perceived innovation as a relevant research theme in the first half of the 20th century.² At that time, however, natural scientists, managers of firms' R&D labs, and policy advisors had formulated the first models of innovations – stressing the importance of scientific research –, and these ideas are still highly influential.³ Since the late 1950s, more and more economists have shown interest in studying innovation, leading to new models of innovation, as well as an explicit mention of innovation in various economics paradigms. The role of innovation in economic development, however, is analysed by various schools of economics in diametrically different ways.⁴ The underlying assumptions and key notions of these paradigms lead to diverse policy implications.

2.1 Linear models of innovation

The first models of innovation had been devised by natural scientists and practitioners before economists showed a serious interest in these issues.⁵ The idea that basic research is the main source of innovation had already been proposed at the beginning of the 20th century, gradually leading to what is known today as the science-push model of innovation, forcefully advocated by Bush (1945).

It is worth recalling some of the main building blocks of Bush's reasoning:

“We will not get ahead in international trade unless we offer new and more attractive and cheaper products. Where will these new products come from? How will we find ways to make better products at lower cost? The answer is clear. There must be a stream of new scientific knowledge to turn the wheels of private and public enterprise. There must be plenty of men and women trained in science and technology for upon them depend both the creation of new knowledge and its application to practical purposes. (...)

New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science.

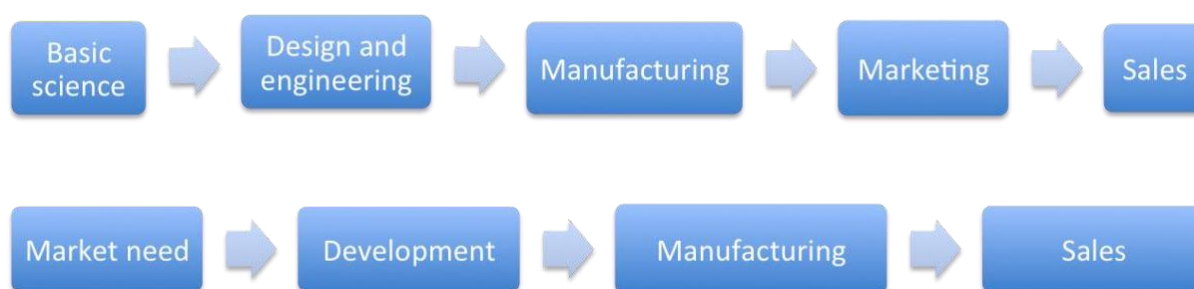
Today, it is truer than ever that basic research is the pacemaker of technological progress. In the nineteenth century, Yankee mechanical ingenuity, building largely upon the basic discoveries of European scientists, could greatly advance the technical arts. Now the situation is different.

A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill." (Bush, 1945: chapter 3)

By the second half of the 1960s the so-called market-pull model contested that reasoning, portraying demand as *the* driving force of innovation. Then a long-lasting and detailed discussion started to establish which of these two types of models is correct, that is, whether R&D results or market demand are the most important information sources of innovations.⁶

Both the science-push and the market-pull models portray innovation processes as linear ones. (Figure 1) In other words, these models assume that (a) there is an 'ideal type' of an innovation process, (b) there are distinct, clearly separable stages in this process, and (c) these stages follow each other in a certain, somewhat predetermined sequence. Their aim is to describe and characterise innovation processes. These models also identify causal links by pinpointing the starting stage and the order, in which the other ones succeed each other.

Figure 1: Linear models of innovation

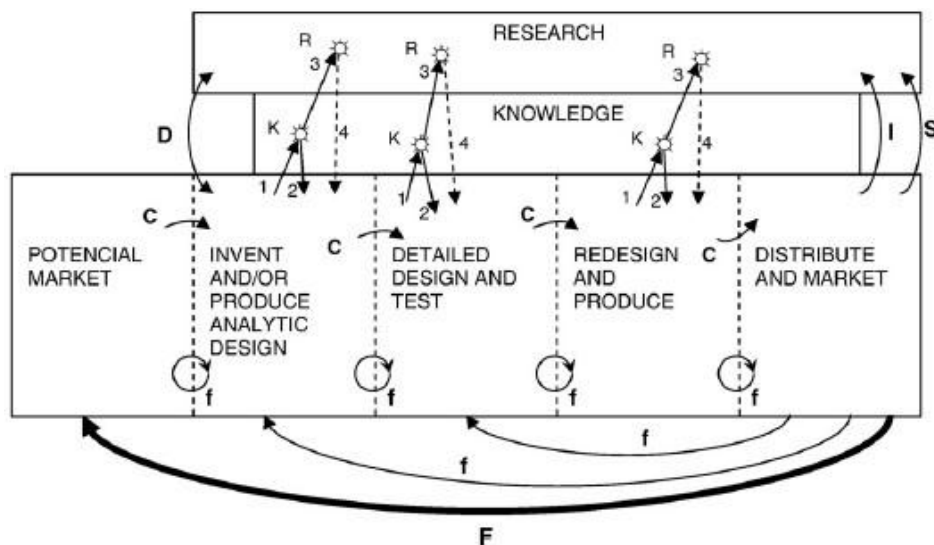


Source: Dodgson and Rothwell (eds) (1994), Figures 4.3 and 4.4 (p. 41)

1.1 Networked and interactive learning models of innovation

Kline and Rosenberg (1986) rejected the idea that an innovation process can be characterised by a clear sequence of activities (or stages). They suggested the chain-linked model of innovation, stressing the non-linear properties of innovation processes, the variety of information sources, as well as the importance of various feedback loops. (Figure 2)

Figure 2: The chain-linked model of innovation



Chain-linked model showing flow paths of information and cooperation.
 Symbols on arrows: **C** = central-chain-of-innovation; **f** = feedback loops; **F** = particularly important feedback.

K-R: Links through knowledge to research and return paths. If problems solved at node K, link 3 to R not activated. Return from research (link 4) is problematic - therefore dashed line.

D: Direct link to and from research from problems in invention and design.

I: Support of scientific research by instruments, machines, tools, and procedures of technology.

S: Support of research in sciences underlying product area to gain information directly and by monitoring outside work. The information obtained may apply anywhere along the chain.

Source: Kline and Rosenberg (1986)

Smith (2002a) went further in rejecting the main assumptions of the linear models of innovation. Indeed, in his bold claim he questions if an 'ideal type' of innovation process can be constituted at all. In his view it is not even a worthwhile effort to devise any model of innovation: "There is no single model of the innovation process: enterprises can differ very significantly in their approaches to innovation." (p. 102)

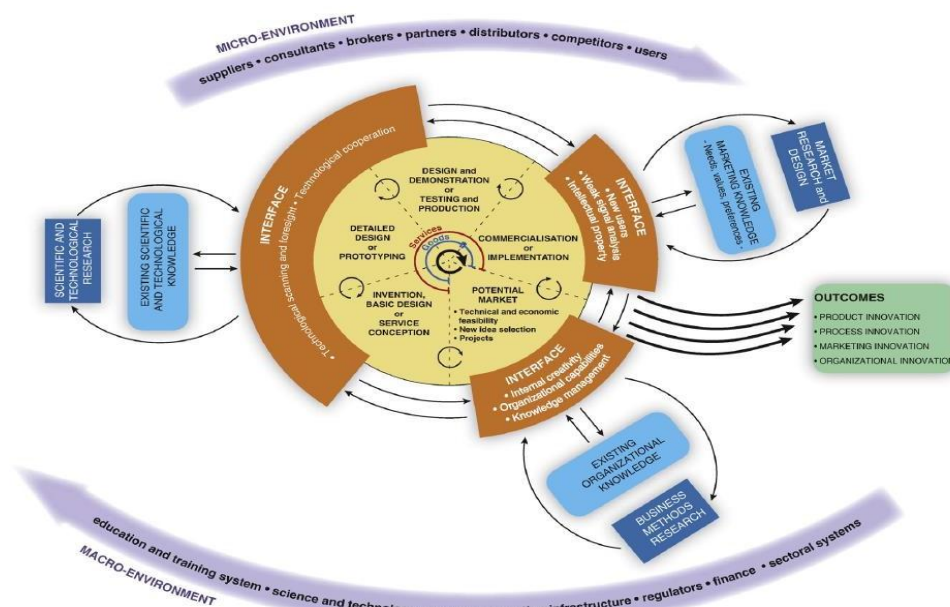
The networked model of innovation rests on this observation. Its recent, refined

version is called the multi-channel interactive learning model. (Caraça et al., 2009) (Figure 3) This model

“has representational purposes and not representative ones, i.e. it does not assume that all factors have to be in place for innovation to be realised and successful. Rather, it tries to provide a stylised representation of the main classes of variables, and their interrelationships, which are involved in the innovation process taking place in a wide array of industries. (...)”

Thus, the model is an analytical grid that describes and contextualises elements, but it also provides a set of flexible generalisations upon which to base our thinking when trying to explain the sources and stages of the innovation process. It points to the ubiquitous experience-based learning processes taking place within firms, as well as at the interfaces with users, suppliers and competitors.” (Caraça et al., 2009: 864–866; emphasis added – AH; footnotes are removed from the original).

Figure 3: The multi-channel interactive learning model of innovation



Source: Caraça et al. (2009)

Just as the notion of the national innovation system, it is a focussing device, a lens that helps thoroughly analysing a subject (Lundvall, 2007: 98–99). In other words, this model is not a model in a strict sense. Rather, it aims at identifying the major (potential) actors and highlighting their roles, activities, and interactions, and thus ways and channels of (co-)producing, disseminating and exploiting knowledge in innovation processes. The model is emphasising various sources, types and forms of knowledge, and hence not only the S&T mode of innovation can be analysed by using this lens. The importance of the

micro and macro environment is also stressed. Finally, as opposed to the linear models of innovation, this one does not aspire to describe or characterise a 'typical', 'schematic' innovation process.

3. Theoretical approaches to innovation

3.1 Classical economics: A strong emphasis on changes

Although classical economics cannot be regarded as a paradigm – in terms of having shared axioms, basic notions, research questions, methods, postulates or main theses – it can be safely generalised that major classical economists had put a strong emphasis on technological, organisational, institutional, and managerial changes as well as the opening up of new markets when analysing "*the Nature and Causes of the Wealth of Nations*", the "*Principles of Political Economy*", or "*the Principles of Political Economy and Taxation*" (Smith, 1776/1904; Mill, 1848/1909, and Ricardo, 1817/1821, respectively). More generally, these authors had paid attention to historical developments (long-term issues) and thus to the dynamic nature of the economy and considered it embedded in political and social structures.

Major representatives of this school shared an important intention: they were interested in explaining various types of changes, taking into account complex relationships, including the co-evolution of technologies (in a broad sense, that is, both products and processes), organisations, markets and various societal features – without using the term innovation. They also paid attention to the diversity of contexts, in which changes took place. Just to mention an obvious, and fundamental, difference among these scholars, the main concern for Marx was not (only) to explain socio-economic phenomena, but to change the socio-economic structures.⁷

To conclude this brief characterisation of classical economics from the angle of their approach to change processes, it is worth stressing that classical economists had not paid a particular attention to the allocation of scarce resources. Following Kaldor (1972), two functions of decentralised markets are identified by Dosi and Orsenigo (1988: 14): allocation of resources and transmission of impulses to change. To generalise, classical economists had inclined to focus on the latter one.

"Fundamental dynamic properties such as the relationship between expansion of markets, division of labour, and productivity growth in Smith, or the 'increasing organic composition of capital' in Marx, are examples of a class of propositions argued on the grounds of the *irreversible transformations* originated by processes of what we could call 'dynamic competition'. Moreover, their neglect of explicit microfoundations was justified on the grounds of what we may term a 'holistic' or 'macroinstitutional' assumption

about behaviour: it seemed obvious to them that, for example, given an opportunity, capitalists were ready to seize it, or that their ‘institutional’ function was to invest and accumulate the surplus.” (*ibid.*, emphasis in the original)

Yet, in that period measurement of change processes was not an issue, and thus no implications were derived as to what to be measured and how.

3.2 Neo-classical economics: Focus on static allocative efficiency

In contrast, *neo-classical economics* had a strictly defined, unifying theoretical framework. A fundamental postulate is that economic actors, who can be characterised by a representative agent, have perfect information, and thus can rationally calculate when making decisions. This school, in a sharp contrast with classical economics, essentially abandoned research questions concerned with dynamics, and instead focused on static allocative efficiency. Optimisation was the key issue for this paradigm, assuming homogenous products, diminishing returns to scale, technologies accessible to all producers at zero cost, perfectly informed economic, rational agents, perfect competition, and thus zero profit. Technological changes were treated as exogenous to the economic system, while other types of innovations were not considered at all. Hence, measurement of change processes was a non-issue for neo- classical economists.

3.3 Mainstream economics

Given the empirical findings and theoretical work on firm behaviour and the operation of markets, mainstream industrial economics and organisational theory has relaxed the most unrealistic assumptions, especially perfect information, deterministic environments, perfect competition, and constant or diminishing returns. Yet, “this literature has not addressed institutional issues, it has a very narrow concept of uncertainty, it has no adequate theory of the creation of technological knowledge and technological interdependence amongst firms, and it has no real analysis of the role of government.” (Smith, 2000: 75)

Mainstream economics considers R&D as a main source of innovation, and thus pays attention to measuring R&D-based technological innovations.

3.4 Evolutionary economics of innovation

Evolutionary economics of innovation rests on radically different postulates compared to mainstream economics.⁸ The latter assumes rational agents, who can optimise by calculating *risks* and taking appropriate actions, while the former stresses that “innovation involves a fundamental element of *uncertainty*, which is not simply the lack of all the relevant information about the

occurrence of known events, but more fundamentally, entails also (a) the existence of techno-economic problems whose solution procedures are unknown, and (b) the impossibility of precisely tracing consequences to actions". (Dosi, 1988a: 222 – emphasis added) Thus, *optimisation* is impossible on theoretical grounds.⁹

Availability of *information* (symmetry vs. asymmetry among agents in this respect) has been the central issue in mainstream economics until recently. Evolutionary economics, in contrast, has stressed since its beginnings that the success of firms depends on their accumulated *knowledge* – both codified and tacit –, *skills*, as well as *learning capabilities*. Information can be purchased (e.g. as a manual, blueprint, or licence), and hence can be accommodated in mainstream economics as a special good relatively easily and comfortably. Yet, knowledge – and *a fortiori*, the types of knowledge required for innovation, e.g. tacit knowledge, skills, and competence in pulling together and exploiting available pieces of information – cannot be bought and used instantaneously. A learning process cannot be spared if one is to acquire knowledge and skills, and it is not only time-consuming, but the costs of *trial and error* need to be incurred as well.¹⁰ Thus, the uncertain, cumulative and path- dependent nature of innovation is reinforced.

Cumulativeness, path-dependence and learning lead to *heterogeneity* among firms, as well as other organisations. On top of that, sectors also differ in terms of major properties and patterns of their innovation processes. (Castellacci, 2008b; Malerba, 2002; Pavitt, 1984; Peneder, 2010)

Innovators are not lonely champions of new ideas. While talented individuals may develop radically new, brilliant scientific or technological concepts, successful innovations require various types and forms of knowledge, rarely possessed by a single organisation. Close collaboration among firms, universities, public and private research organisations, and specialised service-providers is, therefore, a prerequisite for major innovations, and can take various forms, from informal communications to highly sophisticated R&D contracts, alliances, and joint ventures. (Freeman, 1991, 1994, 1995; Lundvall and Borrás, 1999; OECD, 2001; Smith, 2000, 2002b; Tidd et al., 1997) In other words, 'open innovation' is not a new phenomenon at all. (Mowery, 2009)

3.5 Policy rationales derived from contemporary economics paradigms

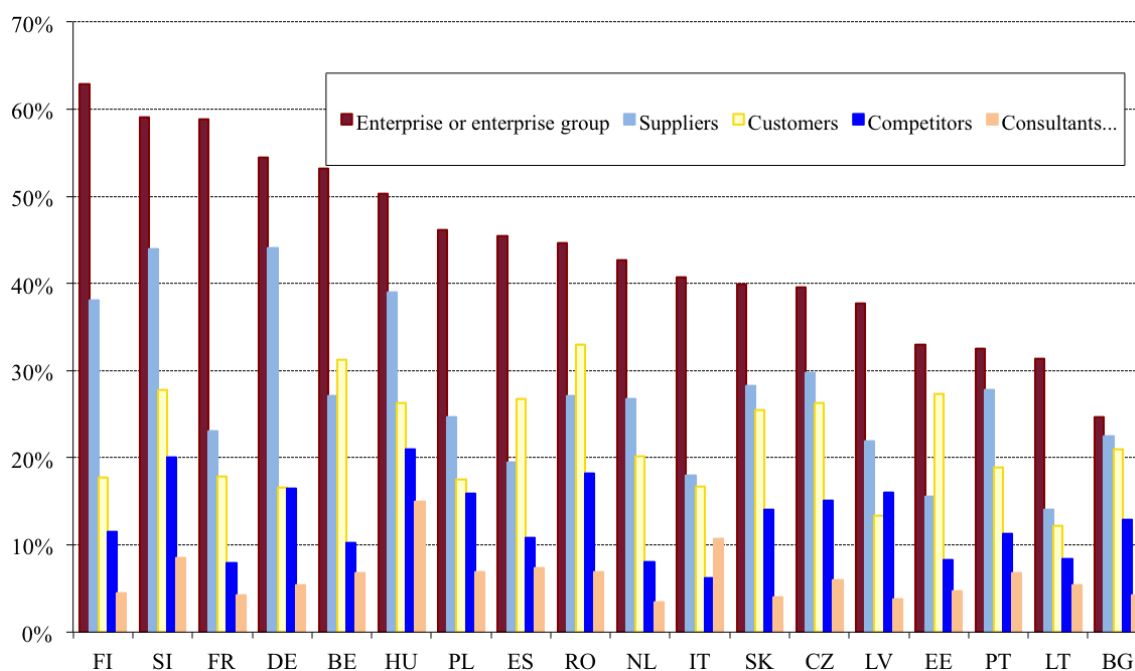
Different policy rationales can be drawn from competing schools of economic thought. Mainstream economics is primarily concerned with market failures: the unpredictability of knowledge outputs from inputs, the inappropriability of full economic benefits of private investment in knowledge creation, and the indivisibility in knowledge production lead to a 'suboptimal' level of business R&D efforts. Policy interventions, therefore, are justified if they aim at (a)

creating incentives to boost private R&D expenditures by ways of subsidies and protection of intellectual property rights, or (b) funding for public R&D activities.

Evolutionary economics of innovation investigates the role of knowledge creation and exploitation in economic processes; that is, it does not focus exclusively on R&D. This school considers various types and forms of knowledge, including practical or experience-based knowledge acquired via learning by doing, using and interacting. As these are *all* relevant to innovation, scientific knowledge is far from being the only type of knowledge required for a successful introduction of new products, processes or services, let alone non-technological innovations. R&D is undoubtedly among the vital sources of knowledge. Besides in-house R&D projects, however, results of other R&D projects are also widely utilised during the innovation process: extramural projects conducted in the same or other sectors, at public or private research establishments, home or abroad. More importantly, there are a number of other sources of knowledge, also essential for innovations, such as design, scaling up, testing, tooling-up, trouble-shooting, and other engineering activities, ideas from suppliers and users, inventors' concepts and practical experiments (Hirsch-Kreinsen et al. (eds), 2005; Klevorick et al., 1995; Lundvall (ed.), 1992; Lundvall and Borrás, 1999; Rosenberg, 1996, 1998; von Hippel, 1988), as well as collaboration among engineers, designers, artists, and other creative 'geeks'. Further, innovative firms also utilise knowledge embodied in advanced materials and other inputs, equipment, and software.

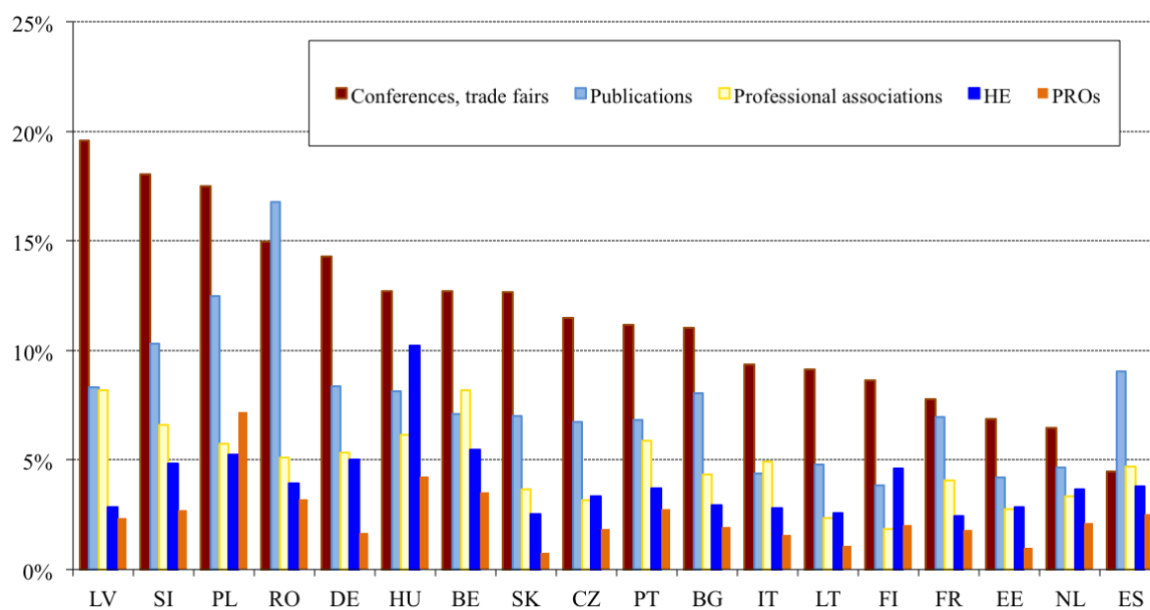
The Community Innovation Survey (CIS) defines its own set of categories as highly important sources of information for product and process innovation: the enterprise or the enterprise group; suppliers of equipment, materials, components or software; clients or customers; competitors or other enterprises from the same sector; consultants, commercial labs or private R&D institutes; universities or other higher education institutes; government or public research institutes; conferences, trade fairs, exhibitions; scientific journals and trade/technical publications; and professional and industry associations. All rounds of CIS clearly and consistently show that firms regard a wide variety of sources of information as highly important ones for innovation. Given space limits, data are only presented here for two periods, namely for 2006–2008, and 2014–2016, respectively, in Figures 4–7.¹¹

Figure 4: Highly important ‘business’ sources of information for product and process innovation, selected EU members, 2006–2008



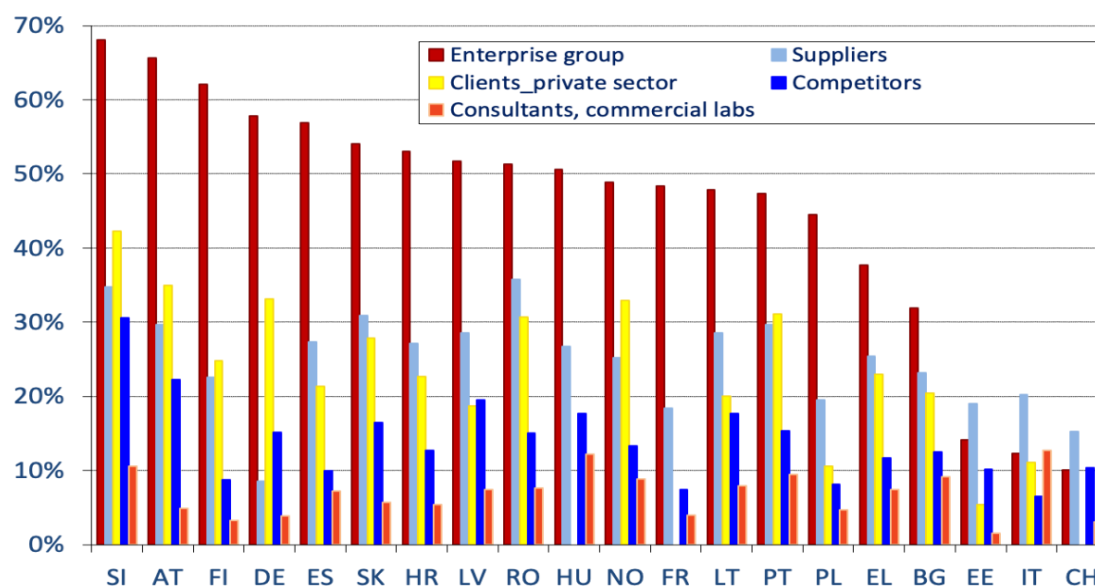
Source: Eurostat, CIS2008

Figure 5: Highly important ‘scientific’ sources of information for product and process innovation, selected EU members, 2006–2008



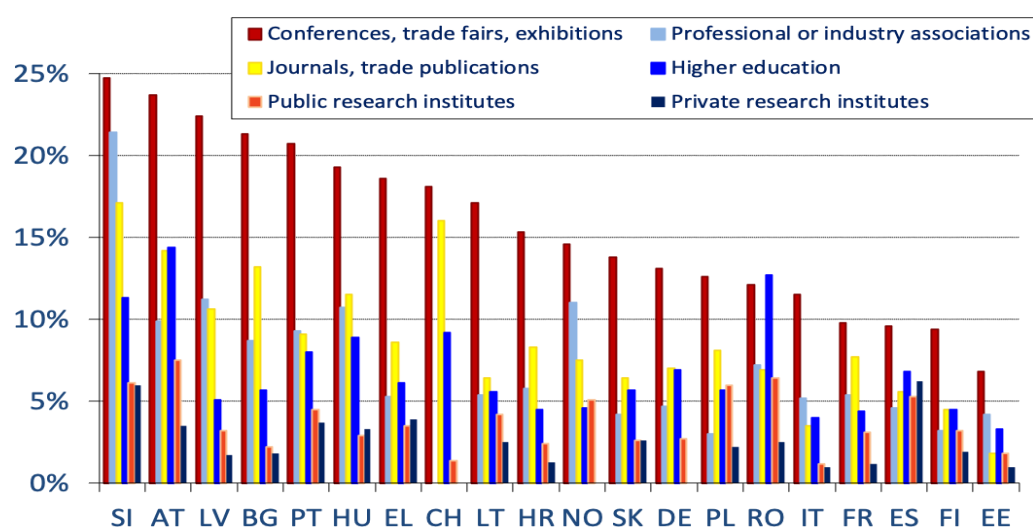
Source: Eurostat, CIS2008

Figure 6: Highly important ‘business’ sources of information for product and process innovation, selected EU members, 2014–2016



Source: Eurostat, CIS2016

Figure 7: Highly important ‘scientific’ sources of information for product and process innovation, selected EU members, 2014–2016



Source: Eurostat, CIS2016

From a different angle, CIS data also confirm that a much larger share of firms are engaged in innovation co-operation with business partners than with academic partners. (Figures 8–11) Of course, many of those business partners might have their own internal R&D units, these data still indicate rather strongly that besides codified knowledge, stemming from formalised R&D activities, several other types of knowledge, accumulated via learning by doing, using and interacting, are also of crucial importance. To put it simple, firms can and want to learn more frequently from each other than from academic partners.

Figure 8: Types of innovation co-operation partners, 2006–2008

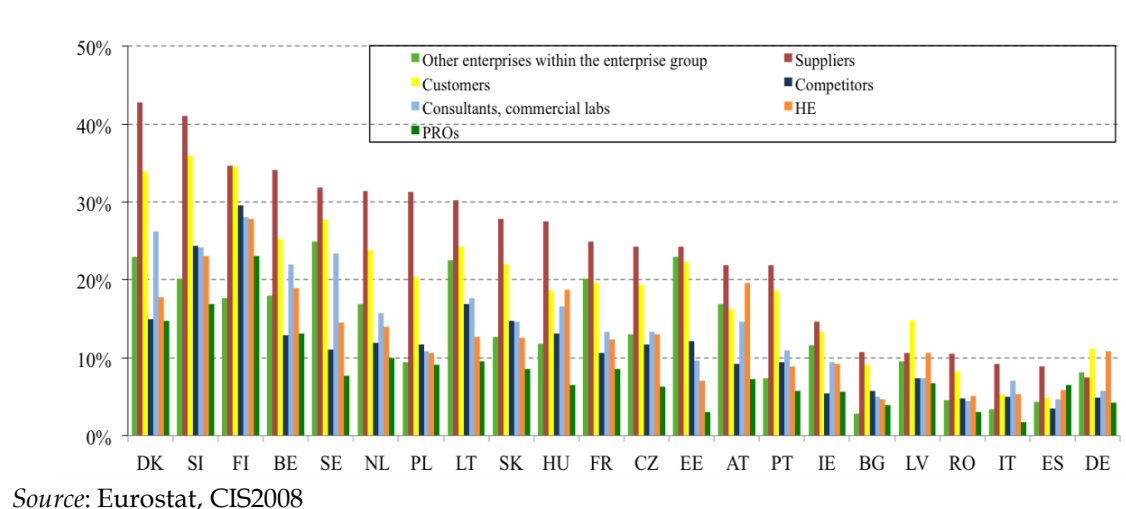


Figure 9: Most valuable methods of innovation co-operation, 2006–2008

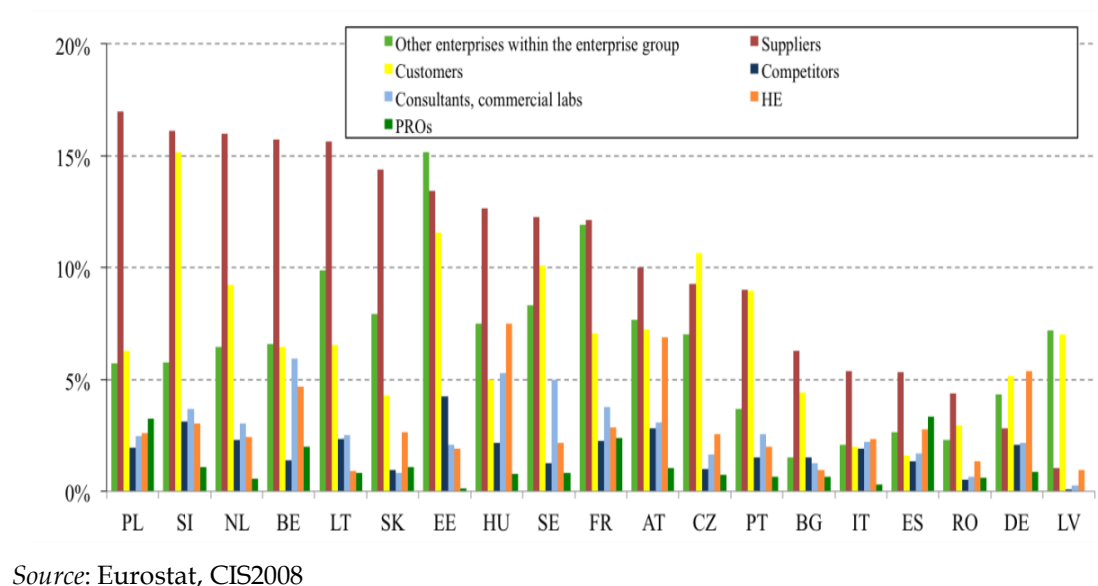
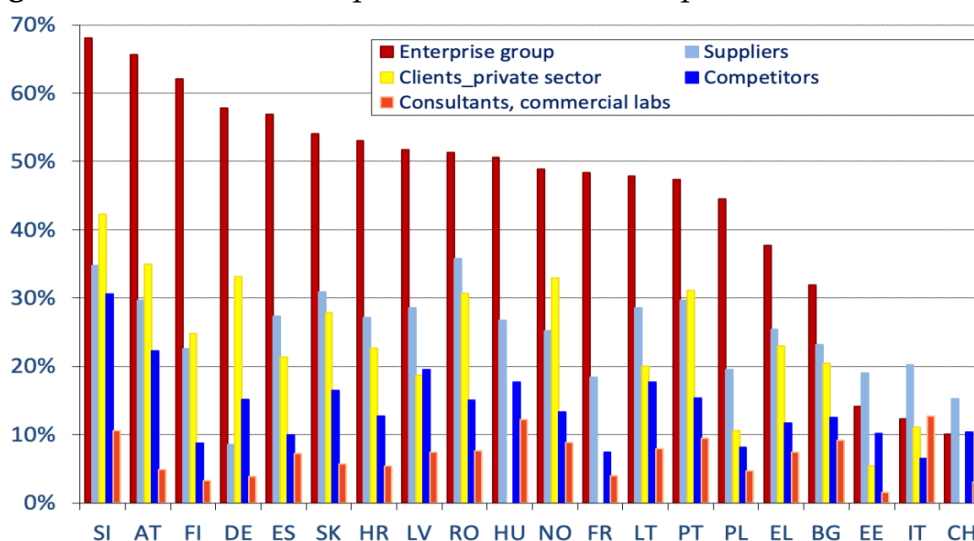
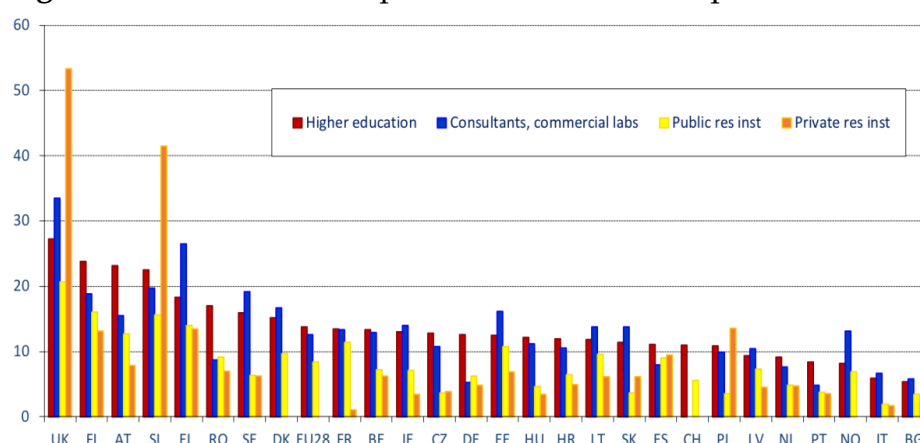


Figure 10: Innovation co-operation with business partners, 2014–2016¹²



Source: Eurostat, CIS2016

Figure 11: Innovation co-operation with scientific partners, 2014–2016 (%)



Source: Eurostat, CIS2016

The wide variety of knowledge drawn on in innovation processes is a crucial point to bear in mind as the OECD classification of industries only takes into account expenditures on formal R&D activities, carried out within the boundaries of a given sector.¹³ In other words, a number of highly successful, innovative firms, exploiting advanced knowledge created externally in distributed knowledge bases (Smith, 2002b) and internally by non-R&D processes, are classified as medium-low-tech or low-tech, just because their R&D expenditures are below the threshold set by the OECD.

Evolutionary economics has also noticed the *highly uneven speed of progress*, that is, performance improvement, in various fields, e.g., rather fast development in space exploration, drugs, medical imaging and telecommunications, on the one

hand, and hardly any change in improving education, on the other. One of the major reasons explaining these differences is that these fields have different underlying knowledge bases and the types of knowledge required for advancing progress can be developed at a different pace. (Nelson, 1977, 2011)

Without trying to capture all the major building blocks of this thorough analysis of learning processes, a few key features are highlighted here. First, this evolutionary account of learning stresses that „the ability to learn from variation, from experiments natural or deliberate” is a key to achieve progress. (Nelson, 2011: 684) Clearly, experimentation is a completely different ‘ballgame’ when the ‘subjects’ are human beings: ethical, societal and political considerations become vital (as opposed to a number of technological experiments, notwithstanding the significance of these issues in some of those fields). Second, progress is a rather vague notion; it should be translated (observed) as a better performance. Measuring performance, however, is far from being a trivial task, even when it comes to technological or economic performance (in a somewhat narrow sense). Progress can only be measured in an appropriate, context-specific way even in these realms. But to compare performance, and thus being able to learn (what directions of search seem to be promising, i.e., what efforts should be redoubled, and what doesn’t work, and thus should be abandoned) one needs a reliable yardstick: „the criteria for better performance must be clear and relatively stable, and competing practices must differ non-trivially in efficacy under those criteria. Further, the evidence of efficacy must be relatively sharp, and available in timely fashion.” (ibid: 684) That seems to be a tall order even for a relatively ‘simple’ technological innovation, let alone more far-reaching ones, e.g., the so-called generic purpose technologies.

In sum, evolutionary economics of innovation posits that the success of firms is largely determined by their abilities to exploit various types of knowledge, generated by both R&D and non-R&D activities. Knowledge generation and exploitation takes place in, and is fostered by, various forms of internal and external interactions. The quality and frequency of the latter is largely determined by the properties of a given innovation system, in which these interactions take place. STI policies, therefore, should aim at strengthening the respective innovation system and improving its performance by tackling *systemic failures* (Table 1) hampering the generation, diffusion, and utilisation of any type of knowledge required for successful innovation.¹⁴ (Edquist, 2011; Foray (ed.), 2009; Freeman, 1994; Lundvall and Borrás, 1999; OECD, 1998; Smith, 2000) From a different angle, *conscious, co-ordinated policy efforts are needed to promote knowledge-intensive activities in all sectors.*

Table 1: Types of systemic failures in innovation systems

<i>Evolutionary failures</i> • generation of technological opportunities • learning by firms (accumulation of capabilities) • lock-in in inferior technology (competence trap), trade-offs ◦ exploration vs. exploitation (current vs. future profits) ◦ variety generation vs. selection ◦ tight IPR vs. exploration of new approaches/ diverse competence base
<i>System failures (problems)</i> • missing or weak elements of the system ('nodes', actors) • missing, weak, or inappropriate connections among the actors • transition to a substantially different system (system dynamics)
<i>Policy failures</i> • weak learning (e.g., from previous practice, interactions with other actors, and good practices) • inflexibility in policy implementation • lack of understanding of sectoral characteristics • poor (or no) vision-building • ineffective co-ordination of policies

Source: Malerba (2009)

3.6 Implications for measuring innovation activities

As already mentioned, mainstream economics mainly considers R&D-based technological innovations and puts a considerable emphasis on protecting intellectual property rights. Therefore, following this paradigm, measurement should focus on R&D inputs and outputs, as well as on patenting activities (which can be regarded as a throughput of R&D efforts). These are the required types of information for validating and refining theories, on the one hand, and underpinning policy proposals, on the other.

This focus on technological innovations, however, leads to a sectoral bias: attention is paid to the so-called high-tech sectors, with the highest share of internal R&D intensity. From a different angle, knowledge content of actual activities of a given firm, as well as intra-sectoral differences are neglected. For example, a firm statistically belonging to a high-tech sector, but in practice performing activities with low knowledge intensity – for instance, assembling technologically advanced products developed by the central R&D unit of its parent company, based in another country, or by its buyer – is regarded similar to another firm in the same sector, but performing knowledge-intensive activities. This occurs rather frequently in numerous countries and sectors. Yet, this phenomenon is overlooked by those analysts who disregard these qualitative features, that is, mechanistically equate the knowledge content of goods with

knowledge intensity of activities and that of sectors. This oversight can easily lead to unsubstantiated theoretical observations and deceiving policy advice.

Evolutionary economics of economics, following a systems approach to innovation, in contrast posits that various types (both S&T and practical) and forms of knowledge (both codified and tacit) are needed for successful innovation activities. That requires interactions among the actors, as required types and pieces of knowledge are practically never possessed by a single actor. These interactions facilitate flow of knowledge, especially that of tacit knowledge, but codified one as well. Further, learning and competence building processes at all levels (individual, intra- and inter- organisational) are of crucial importance. As new knowledge is often co-produced by various actors, with different previous knowledge, experience and mindsets, interactions among these actors not only facilitate knowledge flows, but at least as importantly the production of new knowledge as well. For these reasons, evolutionary economics of innovation considers both R&D-based and non-R&D-based innovations, and hence does not suffer from a sectoral bias.

As for measurement, both technological and non-technological innovations should be covered, on the one hand, and both the S&T and DUI modes of innovations should be observed, on the other, for distilling valid theoretical conclusions and deriving reliable, relevant policy implications.

4. The european innovation scoreboard

This section first offers an overview of changing set of indicators used to compile of the various editions of the European Innovation Scoreboard. Then it recalls two other EC initiatives to rank the EU member states by their innovation activities.

4.1 Indicators in the various editions of the european innovation scoreboard

As shown in section 3, firms exploit various types of knowledge for their innovation activities. Applying this general observation to the Danish case, and relying on the DISKO survey, Jensen et al. (2007) made an elementary distinction between two modes of innovation: (a) one based on the production and use of codified scientific and technical knowledge (in brief, the S&T mode), and (b) another one relying on informal processes of learning and experience-based know-how (called DUI: learning by doing, using and interacting).

Following this distinction, the indicators used in the various editions of the Innovation Union Scoreboard¹⁵ are characterised below, using a rudimentary classification. An indicator can be relevant to reflect:

- only R&D-based innovations

- mainly R&D-based innovations
- only non-R&D-based innovations
- mainly non-R&D-based innovations
- both types of innovations.

This rudimentary classification reveals a bias towards R&D-based innovations in the first edition of the EIS: 10 indicators were only relevant for R&D-based innovations; 8 could be relevant for both types of innovations; and none focused on non-R&D-based innovations.¹⁶ (Table 2)

Table 2: The 2002 European Innovation Scoreboard indicators

	Relevance for R&D based innovation	Relevance for non-R&D based innovation
1 Human resources	X	
New S&E graduates (ISCED 5a and above) per 1000 population aged 20-29		
Population with tertiary education (% of 25-64 years age class)	b	b
Participation in life-long learning (% of 25-64 years age class)		
Employment in medium-high and high-tech manufacturing (% of total workforce)	X	
Employment in high-tech services (% of total workforce)	X	
2 Knowledge creation	X	
Public R&D expenditures (GERD - BERD) (% of GDP)		
Business expenditures on R&D (BERD) (% of GDP)	X	
EPO high-tech patent applications (per million population)	X	
USPTO high-tech patent applications (per million population)	X	
3 Transmission and application of knowledge	b	b
SMEs innovating in-house (% of manufacturing SMEs) b b		
SMEs involved in innovation co-operation (% of manufacturing)	b	b
Innovation expenditures (% of all turnover in manufacturing)	b	b
4 Innovation finance, output and markets	X	
High technology venture capital investment (% of GDP) X		
Capital raised on parallel markets plus by new		

	Relevance for R&D based innovation	Relevance for non-R&D based innovation
firms on main markets (% of GDP) ⁱ		
Sales of 'new to market' products (% of all turnover in manufacturing)	b	b
Home internet access (% of all households)	b	b
ICT expenditures (% of GDP)	b	b
Share of manufacturing value-added in high-tech	X	
Legend: X: only relevant b: relevant for both types Source: own compilation, drawing on the detailed definition of indicators, EC (2002). Notes: Public R&D expenditures do not equal to GERD – BERD; rather, it should be the sum of government-funded parts of BERD, GOVERD, and HERD Three indicators, namely EPO patent applications (per million population), Home internet access (per 100 population), and Inward FDI stock (% of GDP) were only used for candidate countries. i "Parallel stock exchanges focus on high technology sectors." (EC, 2002: 31)		

Jumping ahead, the 2021–2022 editions of the EIS used 32 indicators, grouped by 8 headings. (EC, 2021, 2022) Repeating the same exercise shows that the bias towards R&D-based innovations has been slightly eased: 11 of the most recent EIS indicators are *only* relevant for, and a further 7 *mainly* capture, R&D-based innovations; 12 could be relevant for both types of innovations; and a mere 2 focus on non-R&D-based innovations. (Table 3)

Table 3: The 2021-2022 European Innovation Scoreboard indicators

	Relevance for R&D- based innovation	Relevance for non-R&D-based innovation
Human resources		
New doctorate graduates (ISCED 6) per 1000 population aged 25-34	X	
Percentage population aged 30-34 having completed tertiary education	b	b
Lifelong learning	b	b
Attractive research systems		
International scientific co-publications per million population	X	
Scientific publications among the top 10% most cited publications worldwide	X	
as % of total scientific publications of the country		
Foreign doctorate students as a % of all doctorate students	X	

	Relevance for R&D- based innovation	Relevance for non-R&D-based innovation
Digitalisation		
Broadband penetration	b	b
Individuals with basic overall digital skills (% of population aged 16-74)	b	b
Finance and support		
R&D expenditure in the public sector as % of GDP	X	
Venture capital investment as % of GDP	x	
Direct gov't funding and gov't tax support for business R&D (% of GDP)	X	
Firm investments		
R&D expenditure in the business sector as % of GDP	X	
Non-R&D innovation expenditures as % of turnover		X
Innovation expenditures per person employed	b	b
Use of information technologies		
Enterprises providing ICT training for their personnel	x	
ICT specialists (as a percentage of total employment)	X	
Innovators		
SMEs introducing product innovations as % of SMEs	x	
SMEs introducing business process innovations as % of SMEs		X
Linkages		
Innovative SMEs collaborating with others as % of SMEs	b	b
Public-private co-publications per million population	X	
Job-to-job mobility of Human Resources in Science & Technology	X	
Intellectual assets		
PCT patents applications per billion GDP (in PP\$)	x	
Trademarks applications per billion GDP (in PP\$)	b	b
Designs applications per billion GDP (in PP\$)	b	b
Employment impacts		
Employment in knowledge-intensive activities as % of total employment	x	
Employment in innovative enterprises (% of total employment)	b	b
Economic effects		
Exports of medium and high-tech products (share of total product exports)	x	
Knowledge-intensive services exports as % total service exports	x	
Sales of new-to-market and new-to-firm innovations as % of turnover	b	b
Environmental sustainability		

	Relevance for R&D- based innovation	Relevance for non-R&D-based innovation
Resource productivity	b	b
Air emissions by fine particulate matter (PM2.5) in the manufacturing sector	b	b
Development of environment-related technologies (% of all technologies)	X	
Legend: X: only relevant x: mainly relevant b: relevant for both types Source: own compilation		

As already mentioned, a fairly detailed, partly technical, partly substantive discussion would be needed to refine this simple classification, especially concerning the following issues: to what extent upper secondary education, venture capital, employment in knowledge-intensive activities, and knowledge-intensive services exports are relevant indicators to capture non-R&D-based innovations; and to what extent non-R&D-based innovation activities are needed for successful R&D-based innovations?

To provide an overview of the evolution of the EIS and IUS indicators, results are summarised in Table 4. In sum, the bias towards R&D-based innovations has been rather persistent, although there has been some fluctuation.

While the number and definitions of indicators used to compile the various editions of EIS and IUS have changed to a non-negligible extent since 2002, these indicators consistently focus on measuring R&D activities (inputs and outputs) and R&D-based innovation activities. In other words, they can be relevant in settings characterised predominantly by the so-called S&T mode of innovation, but significantly less useful in other settings, characterised by other types of innovation activities. In other words, using the EIS or IUS indicators would not help establishing if a certain system is characterised by a low level of innovation activities altogether – or a low level of R&D- based innovation activities. Yet, that is a fairly important distinction both from an analytical and a practical (policy) point of view: these two systems (settings) are fundamentally different.

Several analysts and policy-makers tend to believe that (a) advanced economies can be sufficiently characterised by focussing on the S&T mode of innovation, and (b) less advanced economies should also attempt to change the sectoral composition of their economy by increasing the weight of the so-called high-tech (HT) sectors. These views, however, cannot be corroborated by empirical evidence.

Table 4: The evolution of the EIS and IUS indicators, 2002–2022

	2002	2003	2004	2005 - 2006	2007	2008	2009	2010 - 2013	2014 - 2016	2017 - 2020	2021 - 2022
Indicators reflecting											
only R&D-based innovations	10	9	9	8	7	8	8	10	10	8	11
mainly R&D-based innovations	-	3	3	5	5	4	4	4	4	6	7
both types	8	9	9	12	12	15	16	6	7	11	12
only non-R&D-based innovations	-	-	-	-	-	1	1	4	4	2	2
mainly non-R&D-based innovations	-	-	1	1	1	1	1	-	-	-	-
Number of indicators	18	21	22	26	25	29	30	24	25	27	32
<i>Source: own compilation</i>											

Any simple statistical analysis reveals that the so-called high-tech sectors – supposed to be drivers of economic development, due their intense S&T mode innovation activities – have a fairly low weight either in output or employment. Innovation studies have shown that technological innovations can hardly be introduced without organisational and managerial innovations. Moreover, the latter ones – together with marketing innovations – are vital for the success of the former ones.¹⁷ (Pavitt, 1999; Tidd et al., 1997) Further, those companies are the most successful ones, which consciously combine the ST and DUI modes of innovation. (Jensen et al., 2007)

Yet, the high-tech myth is so powerful that even those researchers who base their work on thorough analysis of facts are taken by surprise when the facts are at odds with the widespread obsession with high-tech. A telling example is Peneder's excellent study on the 'Austrian paradox':

"On the one hand, macroeconomic indicators on productivity, growth, employment and foreign direct investment indicate that overall performance is stable and highly competitive. On the other hand, an international comparison of industrial structures reveals a severe gap in the most technologically advanced branches of manufacturing, suggesting that Austria is having problems establishing a foothold in the dynamic markets of the future." (Peneder, 1999: 239).

In contrast, evolutionary economics of innovation claims that any firm – belonging to either a low- and medium-technology (LMT) or a HT sector – can become competitive in ‘the dynamic markets of the future’ if it is successful in combining its own, firm-specific innovative capabilities with ‘extra-mural’ knowledge available in distributed knowledge bases. In other words, Austrian policy-makers need not be concerned with the observed ‘paradox’ as long as they help Austrian firms sustain their learning capabilities, and thereby maintain their innovativeness. That would lead to good economic performance – irrespective of the share of LMT industries in the economy.

From a different angle, while the bulk of innovation activities in the LMT sectors are not based on intramural R&D efforts, these sectors also improve their performance by various types of innovations. These firms are usually engaged in the DUI mode of innovation, but they also draw on advanced S&T results available through the so-called distributed knowledge bases (Robertson and Smith, 2008; Smith, 2002a, 2002b), as well as advanced materials, production equipment, software and various other inputs (e.g. electronics components and sub-systems) supplied by HT industries. (Bender et al. (eds), 2005; Hirsch-Kreinsen et al. (eds), 2005; Hirsch-Kreinsen and Jacobson (eds), 2008; Hirsch-Kreinsen and Schwinge (eds) 2014; Jensen et al., 2007; Kaloudis et al., 2005; Mendonça, 2009; Sandven et al., 2005; von Tunzelmann and Acha, 2005) Thus, demand by the LMT sectors constitutes major market opportunities for HT firms, and also provides strong incentives – and ideas – for their RTDI activities. (Robertson et al., 2009)

It is worth recalling that the 2003 EIS report also stressed the importance of the LMT sectors, as well as the significance of their innovation activities:

„The EIS has been designed with a strong focus on innovation in high-tech sectors. Although these sectors are very important engines of technological innovation, they are only a relatively small part of the economy as measured in their contribution to GDP and total employment. The larger share of low and medium-tech sectors in the economy and the fact that these sectors are important users of new technologies merits a closer look at their innovation performance. This could help national policy makers with focusing their innovation strategies on existing strength and overcome areas of weakness.” (EC, 2003a: 20)

Since then, however, these ideas have been given less prominence. No doubt, it would be an interesting research question why this is the case, but this paper cannot address this issue. More recently, another EC document, namely the 2013 EU Competitiveness Report is sending ‘mixed’ messages on these issues. At certain points it reinforces these adverse effects:

„the EU has comparative advantages in most manufacturing sectors (15 out of 23) accounting for about three quarters of EU manufacturing output. (...) Of the 15 sectors with comparative advantages mentioned above, about two-thirds are in the low-tech and medium-low tech manufacturing groups. On a positive note though, even in those sectors EU competitiveness is based on high-end innovative products.” (EC, 2013b: 3–4, emphasis added – AH)

Is it a negative phenomenon, then, that around 10 EU LMT sectors are internationally competitive?!? Then a more balanced view is also offered:

“... the policy priority attached to key enabling technologies which lead to new materials and products in all manufacturing sectors has a strong potential to upgrade EU competitiveness not only in the high-tech sectors but also in the traditional industries.” (*ibid*: 5)

4.2 A league table of research and innovation performance of EU member states

The EC Directorate-General for Research and Innovation is publishing country profiles aimed at “providing policy makers and stakeholders with concise, holistic and comparative overviews of research and innovation (R&I) in individual countries.” (EC, 2013c: 2) The 2011 edition of this series identified nine groups of countries and then Hungary – together with the Czech Republic, Italy, Slovakia, and Slovenia – belonged to group 8, characterised by “medium-low knowledge capacity with an important industry base.” (EC, 2011b: 436)

A new feature in the 2013 edition was a synthesis table on member states’ research and innovation performance with some striking observations: Ireland had the highest level of knowledge-intensity, and Hungary came ninth, ahead of Germany, Austria and the EU average, for example, and just behind Denmark and Finland. Yet, Malta was ahead of Finland. (Table 5)

Table 5: Overview of research and innovation performance in the EU countries, 2010-2011

	R&D intensity (2011)	Excellence in S&T (2010)	Index of economic impact of innovation (2010-2011)	Knowledge-intensity of economy (2010)	HT & MT contribution to trade balance (2011)
Ireland	1.72	38.11	0.69	65.43	2.57
Luxembourg	Jan-43	19.84	0.589	64.75	-3.35
Sweden	Mar-37	77.2	0.652	64.6	2.02
United Kingdom	1.77	56.08	0.621	59.24	3.13
Belgium	2.04	59.92	0.599	58.88	2.37
France	2.25	48.24	0.628	57.01	4.65
Netherlands	2.04	78.86	0.565	56.22	1.68
Denmark	3.09	77.65	0.713	54.95	-2.77
Malta	0.73	17.53	0.35	54.45	0.92
Finland	3.78	62.91	0.698	52.17	1.69
Hungary	1.21	31.88	0.527	50.23	5.84
European Union	2.03	47.86	0.612	48.75	4.2
Estonia	2.38	25.85	0.45	46.48	-2.7
Slovenia	2.47	27.47	0.521	45.9	6.05
Germany	2.84	62.78	0.813	44.94	8.54
Cyprus	0.48	27.77	0.558	44.11	1.72
Austria	2.75	50.46	0.556	42.4	3.18
Portugal	1.5	26.45	0.387	41.04	-1.2
Czech Republic	1.84	29.9	0.497	39.58	3.82
Spain	1.33	36.63	0.53	36.76	3.05
Italy	1.25	43.12	0.556	35.43	4.96
Lithuania	0.92	13.92	0.223	35.28	-1.27
Latvia	0.7	11.49	0.248	34.38	-5.42
Greece	0.6	35.27	0.345	32.53	-5.69
Poland	0.77	20.47	0.313	31.78	0.88
Slovakia	0.68	17.73	0.479	31.64	4.35
Bulgaria	0.57	24.65	0.234	29.45	-4.78
Romania	0.48	17.84	0.384	28.35	0.38
Croatia	0.75	12.25	0.353	n.a.	2.98
Source: EC (2013c): 5					
Note: Countries are ranked by the composite index called “knowledge-intensity of economy”.					

The table was reproduced in the 2014 edition of the Innovation Union progress report (EC, 2014b: 19) with updated data. Ireland kept her top position, just a Hungary her rank of No. 11, still ahead of Germany and Austria, while Malta was overtaken by Finland.¹⁸ These implausible results certainly demand an explanation.

The ‘knowledge-intensity of the economy’ is defined as follows: “Eight compositional structural change indicators have been identified and organized into five dimensions:

- The R&D dimension measures the size of business R&D (as a % of GDP) and the size of the R&D services sector in the economy (...);
- The skills dimension measures changing skills and occupation in terms of the share of persons employed in knowledge intensive activities;
- The sectoral specialization dimension captures the relative share of knowledge intensive activities;
- The international specialization dimension captures the share of knowledge economy through technological (patents) and export specialization (revealed technological and competitive advantage);
- The internationalization dimension refers to the changing international competitiveness of a country in terms of attracting and diffusing foreign direct investment (inward and outward foreign direct investments).

(...) The five pillars have also been aggregated to a single composite indicator of structural change (...).” (EC, 2013c: 321–322)

Knowledge is understood in these reports in a narrow sense: only higher education and R&D activities are supposed to create it and thus all other types of knowledge are disregarded. The name of this indicator is, therefore, misleading. The inclusion of high-tech exports and foreign direct investment in this composite indicator explains the unexpectedly high ranking of Ireland and Hungary: in both countries (i) high-tech goods account for an extremely large share in exports (Table 6) and (ii) high-tech sectors are dominated by foreign-owned firms.

These ‘twinned’ characteristics warrant further remarks from the point of view of knowledge-intensity. The bulk of the exported high-tech goods are developed outside Ireland or Hungary;¹⁹ the main activity of most foreign subsidiaries is the assembly of high-tech goods by semi-skilled workers, and thus the local knowledge content is rather low. These features cannot be reflected in this indicator, and thus it does not necessarily express knowledge-intensity in the

case of countries with similar structural characteristics. Hence, it may only be used with a rather big pinch of salt to compare countries' performance or devise policy measures.

Table 6: Share of high-tech goods in industrial exports, 2001–2009 (%)

	2001	2005	2006	2007	2008	2009
Ireland	58.0	52.1	48.9	46.6	48.9	52.2
Hungary	28.3	31.7	30.8	29.9	30.6	35.5
Netherlands	29.6	30.1	28.7	27.4	25.2	29.1
United Kingdom	35.8	27.7	27.4	26.1	25.1	n.a.
France	25.2	22.8	23.7	22.5	23.0	n.a.
Finland	24.3	25.3	21.9	20.0	19.7	17.1
Slovak Republic	6.0	11.3	14.4	16.9	19.4	n.a.
Sweden	23.1	21.3	21.4	18.9	18.6	21.9
Czech Republic	11.8	15.0	16.8	17.5	17.9	18.8
Belgium	14.4	17.8	16.8	17.7	17.4	22.0
Germany	20.3	19.7	19.5	17.7	17.2	19.5
Denmark	19.6	20.1	18.1	17.3	15.6	17.9
Slovenia	10.8	10.7	11.5	11.6	13.0	15.0
Austria	15.4	13.3	12.9	12.8	12.4	14.0
Greece	8.7	12.9	11.5	10.7	11.8	14.8
Spain	10.2	11.1	10.6	10.3	10.1	11.3
Poland	6.5	6.3	7.4	8.1	9.8	n.a.
Italy	11.8	10.7	10.1	9.3	9.1	10.8
Estonia	25.5	21.5	16.4	9.5	8.9	8.0
Luxembourg	15.7	10.1	10.0	8.6	6.8	10.4
Portugal	11.3	11.5	11.4	n.a.	n.a.	n.a.

Source: own calculation based on OECD.Stat data n.a.: not available

In more detail, two major policy lessons can be drawn from this attempt. First, policies aimed at promoting innovation and hence competitiveness should consider the actual activities of firms, rather than the OECD classification of sectors. Four units of analysis should be distinguished: activities, products, firms and sectors. Firms belonging to the same statistical sector might possess quite different innovation, production, management, and marketing capabilities. Furthermore, they are unlikely to produce identical goods, in terms of e.g., skills and investment required, level of quality or market and profit opportunities. Finally, they perform different activities, especially regarding their knowledge-intensity. These dissimilarities are likely to be even more pronounced when we consider sectors, firms, products and activities across different countries. In short, policies that neglect the intra-sectoral diversity of firms cannot be effective.

Second, various types of foreign direct investment activities have different longer- term impacts on economic development. Globalisation either poses threats to, or offers opportunities for, economic development, depending on the capabilities and investment promotion policies of the host country. To use an elementary dichotomy of foreign direct investment, one type can be called '*foot-loose*'. These companies conduct activities with low level of local knowledge content, and thus pay low wages.

They are ready to leave at any time for cheaper locations.²⁰ The other types of investors, in contrast, are '*anchored*' into a national system of innovation and production: they perform knowledge-intensive activities, create higher-pay jobs, build close contacts with domestic R&D units and universities and develop a strong local supplier base.²¹ In brief, co-ordinated, mindful investment promotion, STI, human resource and regional development policies are required to embed foreign investors. In this way, skills can be upgraded, local suppliers' innovation capabilities can be improved to boost their competitiveness and intense, mutually beneficial business- academia collaboration can be nurtured. Otherwise, most of the investment 'sweeteners' are wasted if foreign firms only use a given region or country as a cheap, temporary production site.

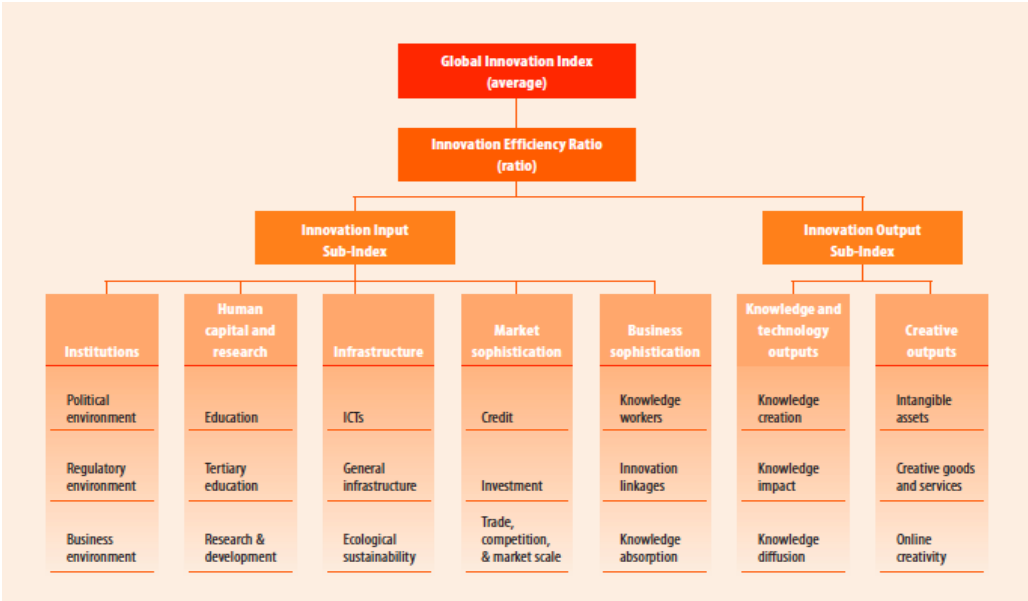
4.3 The EU 2020 innovation indicator

The European Commission introduced the so-called EU 2020 Innovation Indicator in October 2013 to measure progress in achieving the goals of the Europe 2020 Strategy and complement its former headline R&D intensity indicator. Yet, this new indicator is composed of four individual indicators from the EIS/ IUS: patent applications economic significance of knowledge-intensive sectors, trade performance of knowledge-intensive goods and services, and significance of fast-growing firms in innovative sectors. Thus, this apparently new composite indicator 'inherits' and further strengthens the bias of the EIS/ IUS towards the S&T mode innovation. (Janger et al., 2017)

5. The global innovation index

Compared to the IUS, the Global Innovation Index (GII) has a significantly broader coverage in two respects: it covers well over 100 countries, and considers 80 indicators, arranged in 7 "pillars". The seven pillars used in the 2016–2019 editions of the GII include: Institutions (7 indicators), Human capital and research (12), Infrastructure (10), Market sophistication (10), Business sophistication (15), Knowledge and technology outputs (14), and Creative outputs (13). The themes considered by each pillar are summarised in Figure 12.

Figure 12: Framework of the global innovation index 2016–2022



Source: Global Innovation Index editions in 2016–2019

To assess the relevance of these 80 indicators, and especially the ‘match’ between the themes (or headings) captured by the 7 pillars would require a fairly lengthy paper. In other words, the GII indicators are characterised in a somewhat simplified way here.²² It should be stressed that most elements are indices themselves, that is, not ‘stand-alone’ indicators. In other words, several methodological weaknesses are likely to remain hidden.

Pillar 1: Institutions

Pillar 1 is composed of 3 sub-pillars. The political environment sub-pillar incorporates two indices with the intention to reflect the following aspects: “perceptions of the likelihood that a government might be destabilized” and “the quality of public and civil services, policy formulation, and implementation”.

The second sub-pillar, called regulatory environment, is comprised of two indices to capture “perceptions on the ability of the government to formulate and implement cohesive policies that promote the development of the private sector and at evaluating the extent to which the rule of law prevails (in aspects such as contract enforcement, property rights, the police, and the courts)”. A third indicator is meant to evaluate “the cost of redundancy dismissal as the sum, in salary weeks, of the cost of advance notice requirements added to severance payments due when terminating a redundant worker”.

The third sub-pillar – business environment – is aimed at summarising three aspects directly affecting private entrepreneurial endeavours. It uses the World Bank indices “on the ease of starting a business; the ease of resolving insolvency

(based on the recovery rate recorded as the cents on the dollar recouped by creditors through reorganization, liquidation, or debt enforcement/foreclosure proceedings); and the ease of paying taxes". (Cornell University et al., 2016: 51–52)

Not all the above elements are institutions ("rules of the game"), and not all are directly related to innovation processes and performance. It can be argued, though, that the aspects (attempted to be) captured by these indices are relevant to characterise the political, regulatory and business environment for innovation. Among the important missing elements, one should mention legislation on competition,²³ as well as the entrepreneurial culture in a given country.

Pillar 2: Human capital and research

Pillar 2 is also comprised of 3 sub-pillars. Sub-pillar 2.1 is composed of several of indicators with the intention to capture achievements at the first two levels of education, namely elementary and secondary education. Education expenditure and school life expectancy are taken as "good proxies for coverage". Government expenditure per pupil at secondary level is meant to indicate "the level of priority given to secondary education by the state". The quality of education is measured via (a) PISA (OECD Programme for International Student Assessment) results indicating 15-year- old students' performances in reading, mathematics, and science, as well as (b) the pupil-teacher ratio.

Sub-pillar 2.2 on tertiary education is designed to measure coverage at this level of education. "(...) priority is given to the sectors traditionally associated with innovation (with a series on the percentage of tertiary graduates in science and engineering, manufacturing, and construction); and the inbound mobility of tertiary students, which plays a crucial role in the exchange of ideas and skills necessary for innovation."

Sub-pillar 2.3 on R&D is meant to capture the level and quality of R&D activities by using the number of researchers (FTE/ million of population), gross expenditures on R&D as percentage of GDP, the R&D expenditures of top global R&D spenders, and the quality of scientific and research organisations proxied by the average score of the top three universities in the QS World University Ranking as of 2015. "These indicators are not aimed at assessing the average level of all institutions within a particular economy." (Cornell University et al., 2016: 52)

Formal education is a crucial factor determining the quality of human capital, no doubt, but life-long learning and other, informal modes of learning are also important. Research is conducted outside universities, too, both by other publicly financed research organisations and businesses. Moreover, the quality of research conducted by these latter types of organisations is not necessarily

lower than that at universities. Moreover, university rankings themselves suffer from several major methodological weaknesses. Thus, *the name of this pillar is more 'ambitious' than its actual content.*

Pillar 3: Infrastructure

Three sub-pillars form the third pillar of infrastructure: information and communication technologies (ICT), general infrastructure, and ecological sustainability. Sub-pillar 3.1 on ICT is computed by using four indices developed by international organisations on ICT access, ICT use, on-line service by governments, and on-line participation of citizens. Sub-pillar 3.2 on general infrastructure is composed of “the average of electricity output in kWh per capita; a composite indicator on logistics performance; and gross capital formation, which consists of outlays on additions to the fixed assets and net inventories of the economy, including land improvements (fences, ditches, drains); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings”. Sub-pillar 3.3 on ecological sustainability is constructed by using three indicators: “GDP per unit of energy use (a measure of efficiency in the use of energy), the Environmental Performance Index of Yale and Columbia Universities, and the number of certificates of conformity with standard ISO 14001 on environmental management systems issued”. (Cornell University et al., 2016: 53)

Ecological sustainability is certainly an important issue, but it is difficult to grasp why it is part of the “Infrastructure” pillar, especially when it is measured by the above three components. These are more relevant to reflect those environmental challenges that require innovation efforts – or the outcome of previous eco-innovation efforts. In other words, *there is a certain mismatch between the name of this pillar and its actual content.*

Pillar 4: Market sophistication

The fourth pillar on market sophistication integrates three sub-pillars “structured around market conditions and the total level of transactions”. Sub-pillar 4.1 on credit intends to reflect “the ease of getting credit aimed at measuring the degree to which collateral and bankruptcy laws facilitate lending by protecting the rights of borrowers and lenders, as well as the rules and practices affecting the coverage, scope, and accessibility of credit information”. Transactions are measured by the total value of domestic credit to the private sector (as a percentage of GDP) as well as by the gross loan portfolio of microfinance institutions (as a percentage of GDP) with the intention to make the method applicable to emerging markets, too.

Sub-pillar 4.2 on investment is composed of the ease of protecting investors

index and three indicators on the level of transactions. Besides stock market capitalisation, the total value of shares traded (as percentage of GDP) is also taken into account to show if market size is matched by market dynamism. Data on venture capital deals (a total of 13,703 deals in 95 countries in 2015) are also exploited.

Sub-pillar 4.3 considers trade, competition, and market scale. The market conditions for trade are measured by two indicators: the average tariff rate weighted by import shares and a metric on non-agricultural market access conditions to foreign markets (five major export markets weighted actual applied tariffs for non-agricultural exports). The last indicator is a result from a survey: the intensity of competition in local markets. “Efforts made at finding hard data on competition have so far proved unsuccessful.” (Cornell University et al., 2014: 53) Domestic market scale has been added to GII as new indicator to reflect the impact that the size of an economy has on its capacity to introduce and test innovations in the market place. It is measured by an economy’s GDP.

Pillar 5: Business sophistication

The fifth pillar is intended to capture the level of business sophistication to assess “how conducive firms are to innovation activity”. Sub-pillar 5.1 on knowledge workers is built by five indicators: employment in knowledge-intensive services; the availability of formal training at the firm level; R&D performed by business enterprise (BERD) as a percentage of GDP; the percentage of gross expenditures of R&D (GERD) financed by businesses, and the percentage of females employed with advanced degrees.

Sub-pillar 5.2 on innovation linkages exploits data on business-university R&D collaborations, “the prevalence of well-developed and deep clusters”, the ratio of GERD financed from abroad, and “the number of deals on joint ventures and strategic alliances. The latter covers a total of 1,512 deals announced in 2015, with firms headquartered in 92 participating economies. In addition, the total number of Patent Cooperation Treaty (PCT) and national office published patent family applications filed by residents in at least two offices proxies for international linkages.”

“The rationale behind sub-pillars 5.3 on knowledge absorption (an enabler) and 6.3 on knowledge diffusion (a result) — two sub-pillars designed to be mirror images of each other — is precisely that together they will reveal how good economies are at absorbing and diffusing knowledge. Sub-pillar 5.3 includes five metrics that are linked to sectors with high-tech content or are key to innovation: royalty and license fees payments as a percentage of total trade; high-tech imports (net of re-imports) as a percentage of total imports; imports of communication, computer and information services as a percentage of total trade; and net inflows of foreign direct investment (FDI) as a percentage of GDP.

(...) the percentage of research talent in business was added this year to provide a measurement of professionals engaged in the conception or creation of new knowledge, products, processes, methods, and systems, including business management.” (Cornell University et al., 2016: 53–54; some obvious mistakes are corrected – A.H.)

The name of this pillar is not explained, although it does not seem to be self-explanatory. It is not clear, either, why firms should be conducive to innovation activity. Usually analyses have a different logic: market and regulatory conditions, that is, factors external to the firms, are assessed if they are conducive for – or hamper – innovation activities performed by businesses. The name of sub-pillar 5.2 (innovation linkages) only partially matches its components, of which two concern R&D activities, and a third one (on patents) is also more relevant to characterise R&D activities than reflect innovation activities. Data on high-tech imports can only partially reflect knowledge absorption.

Pillar 6: Knowledge and technology outputs

The sixth pillar is also composed of 3 sub-pillars. Sub-pillar 6.1 on knowledge creation “includes five indicators that are the result of inventive and innovative activities: patent applications filed by residents both at the national patent office and at the international level through the PCT; utility model applications filed by residents at the national office; scientific and technical published articles in peer-reviewed journals; and an economy’s number of articles (H) that have received at least H citations”.

Sub-pillar 6.2 on knowledge impact is composed of five indicators: increases in labour productivity, the entry density of new firms, spending on computer software, the number of certificates of conformity with standard ISO 9001 on quality management systems issued, and the ratio of high- and medium-high-tech industrial output in total manufacturing output.

Sub-pillar 6.3 on knowledge diffusion “includes four statistics (...) linked to sectors with high-tech content or that are key to innovation: royalty and license fees receipts as a percentage of total trade; high-tech exports (net of re-exports) as a percentage of total exports (net of re-exports); exports of ICT services as a percentage of total trade; and net outflows of FDI as a percentage of GDP.” (Cornell University et al., 2014: 54– 55)

The first sub-pillar is meant to be composed of indicators on “the result of inventive and innovative activities”. Yet, *most of these indicators are relevant to characterise R&D (and not innovation) activities. As for the knowledge impact sub-pillar, only two of the five components is related to knowledge impacts. As for knowledge diffusion, all the four components of that sub-pillar can indicate knowledge*

diffusion outside a given country (with certain limitations), and thus *none of these seems to be relevant to characterise knowledge diffusion inside a given country.*

Pillar 7: Creative outputs

Sub-pillar on intangible assets includes data on trademark applications by residents at the national office; industrial designs included in applications at a regional or national office; and results obtained via two survey questions on the use of ICTs by businesses in business and organisational models.

Sub-pillar 7.2 on creative goods and services is aimed to capture creativity and the creative outputs of an economy by using five indicators: cultural and creative services exports, including information services, advertising, market research and public opinion polling, and other personal, cultural, and recreational services (as a percentage of total trade); national feature films produced in a given country (per million population); global entertainment and media output (per thousand population); printing and publishing output (as a percentage of total manufacturing output); and creative goods exports (as a percentage of total trade).

Sub-pillar 7.3 on online creativity is composed of four indicators, all by population aged 15–69 years: generic (biz, info, org, net, and com) and country-code top level domains, average monthly edits to Wikipedia, and video uploads on YouTube. “Attempts made to strengthen this sub-pillar with indicators in areas such as Internet and machine learning, blog posting, online gaming, and the development of applications have so far proved unsuccessful.” (Cornell University et al., 2014: 55–56)

It is not clear why “the use of ICTs in business and organizational models” is an output indicator. Only a small fraction of printing and publishing output is a creative output, with the bulk being revenues to cover printing costs (paper, other raw materials and labour). It would be rather costly to establish what portion of video uploads on YouTube constitutes creative output.

In sum, the GII is a remarkable effort both in terms of its geographic and thematic coverage, but it suffers from severe weaknesses concerning business innovation activities. In several cases there is a non-negligible mismatch between the ‘headline’ notions (pillars and their sub-pillars) and the actual components (indices or indicators) selected. Just as in the case of the EIS and IUS indicators, there is a bias towards R&D-based (S&T mode) innovations, and thus the DUI mode is eclipsed. It is even worse when R&D and innovation are conflated.

6. Summary and conclusions

This paper has reviewed innovation indicators from theoretical and policy

perspectives. The main findings can be summarised as follows. Various economics paradigms treat innovation (if not neglect it altogether) in diametrically different ways: they consider different notions as crucial ones (e.g. risk vs. uncertainty, information vs. various forms, types and sources of knowledge, skills and learning capabilities and processes); offer diverse justifications (policy rationales) for government interventions; interpret the significance of various types of inputs, efforts, and results differently, and thus – implicitly – identify different ‘targets’ for measurement, monitoring and analytical purposes (what phenomena, inputs, capacities, processes, outcomes and impacts are to be measured and assessed).

The science-push model of innovation, reinforced by the sophisticated – and thus appealing and compelling – models of mainstream economics emphasises the economic impacts of R&D-based innovation efforts, advances the market failure argument and the concomitant set of policy advice. Hence it focuses the attention of decision-makers and analysts to the so-called S&T mode of innovation. Measurement and monitoring systems influenced by this way of thinking – the European Innovation Scoreboard of the European Commission, as well as the Global Innovation Index – tend to pay attention mainly to the S&T mode of innovation, at the expense of the so-called DUI mode of innovation. It is a major concern, however, as the latter one is equally important from the point of view of enhancing productivity, creating jobs and improving competitiveness.

In contrast, evolutionary economics of innovation – in line with the networked model of innovation – stresses the systemic nature of innovation and thus advocates rectifying any systemic failure that hinders the generation, circulation and exploitation of any type of knowledge required for successful innovation processes. This way of thinking has influenced the measurement and monitoring practices of the European Commission to a significantly lesser extent than mainstream economics.

The EIS/ IUS indicators in principle could be useful in settings where the dominant mode of innovation is the S&T mode. In practice, however, both the ST and DUI modes of innovation are fairly important. (Jensen et al., 2007) Moreover, the so-called Summary Innovation Index – calculated from the IUS indicators – does not provide sufficient information to assess a given innovation system: its low value could reflect either a low level of innovation activities altogether or a low level of R&D-based innovation activities (while other types of innovations are abundant). Yet, that is a fairly important distinction both from an analytical and a practical (policy) point of view: these two innovation systems are fundamentally different, necessitating bespoke policy actions. Analysts and policy-makers dealing with innovation, therefore, should pay attention to both R&D-based (S&T) and non-R&D-based (DUI) innovations. In other words, new indicators that better reflect the evolutionary processes of

learning and innovation would be needed to support STI policy-making. Developing, piloting and then widely collecting these new indicators would be a major, demanding and time-consuming project, necessitating extensive international co-operation.

There is a fairly strong – sometimes implicit, at other times rather explicit – pressure to devise so-called composite indicators to compress information into a single figure in order to compile eye-catching, easy-to-digest scoreboards. A major source of complication is choosing an appropriate weight to be assigned to each component. By conducting sensitivity analyses of the 2005 European Innovation Scoreboard (EIS), Grupp and Schubert (2010: 72) have shown how unstable the rank configuration is when the weights are changed. Besides assigning weights, three other ranking methods are also widely used, namely: unweighted averages, Benefit of the Doubt (BoD) and principal component analysis. Comparing these ranking methods, the authors conclude: “Not only utilizing the rankings highly sensitive to weighting (...), but even using accepted approaches like BoD or factor analysis may result in drastically changing rankings.” (ibid: 74) Hence, they propose using multidimensional representations, e.g. spider charts to reflect the multidimensional character of innovation processes and performance. That would enable analysts and policy-makers to identify strengths and weaknesses, thus pinpoint more precise targets for policy actions. (ibid: 77)

Other researchers also emphasise the need for a sufficiently detailed characterisation of innovation processes. For example, a family of five indicators – R&D, design, technological, skill, and innovation intensities – offers a more diversified picture on innovativeness than the Summary Innovation Index of the EIS. (Laestadius et al., 2005) Using Norwegian data, they demonstrate that the suggested method can capture variety in knowledge formation and innovativeness both within and between sectors. It thus supports a more accurate understanding of creativity and innovativeness inside and across various sectors, directs policy-makers’ attention to this diversity (suppressed by the OECD classification of sectors), and thus can better serve policy needs.

In other words, given the diversity among innovation systems, one should be very careful when trying to draw policy lessons from the ‘rank’ of a country as ‘measured’ by a composite indicator. A scoreboard can only be constructed by using the same set of indicators across all countries, and by applying an identical method to calculate the composite index. Yet, it is important to realise that poor performance signalled by a composite indicator, leading to a low rank on a certain scoreboard, does not automatically identify the area(s) necessitating the most urgent policy actions.

In contrast, a high rank on a scoreboard, such as Sweden's top position in the 2015 Innovation Union Scoreboard – achieved in several other years, too –, does not necessarily reflect a satisfactory performance. By taking into account the input and output nature of various IUS indicators Edquist et al. (2018) calculated the productivity of national innovation systems covered by the IUS and using this assessment – which is, no doubt, highly relevant from a policy point of view – Sweden ranks a mere 23.

The most recent edition of the Oslo Manual also highlights several disadvantages of composite indicators. These include the frequently limited theoretical basis of the composite indicators, which can easily lead to “problematic combinations of indicators, such as indicators for inputs and outputs”. Weighting of different indicators – as already stressed by Grupp and Schubert (2010) is also an issue, as it “is often dependent on the subjective views of those constructing the composite index. Factors that are minor contributors to innovation can be given as much weight as major ones.” Further, “structural differences between countries are seldom taken into account when calculating composite performance indexes. Aggregation results in a loss of detail, which can hide potential weaknesses and increase the difficulty in identifying remedial action.” (OECD/ Eurostat, 2018: 220)

Analysts and policy-makers, *therefore, need to avoid the trap of paying too much attention to simplifying ranking exercises.* Instead, it is of utmost importance to conduct detailed, thorough comparative analyses, identifying the reasons for a disappointing performance, as well as the sources of – opportunities for – balanced, and sustainable, socio-economic development.

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Appendix

The global innovation index indicators

The first, 2007 edition of the GII was composed of the following indicators, grouped into eight “pillars”, of which 5 meant to represent inputs, while 3 were to reflect on outputs:

Inputs	
Institutions and Policies Independence of judiciary Demanding regulatory standards Prevalence of laws relating to ICT Quality of IPR Soundness of banks Quality of scientific research institutions	
Quality of management/business schools Legal obstacles to foreign labour Time required to start a business Time required to obtain licenses Rigidity of employment index Investor protection index ICT priority for government	The quality of organisations is not an institution (“rule of the game”) [Same as above]
Human Capacity Brain drain Quality of human resource approach Quality of maths and science education Graduates in engineering Graduates in science Population 15-64 Urban population Schools connected to the internet	[At best indirectly – and vaguely – related to human capacity]
General and ICT Infrastructure Quality of general infrastructure Quality of national transport network Quality of air transport Fixed line penetration Mobile penetration Internet penetration International bandwidth ICT expenditure Personal computer penetration Mobile price basket	[This is access to infrastructure]

Business, Markets and Capital Flows Access to loans Sophistication of financial markets Issuing shares in local share market Corporate governance Buyer sophistication	
Customer orientation of firms Domestic credit to private sector FDI net inflows Gross private capital flows Gross capital formation Extent of clusters Commercial services imports Manufactured imports Private investment in ICT Informal economy estimate	[Why among these indicators?]
Technology and Process Sophistication Country's level of technology E-Participation index E-Government index Government procurement of advanced technology Internet use by businesses Competition among ISP providers	[Why among these indicators?]
Company technology absorption Telecom revenue Secure internet servers per 1,000 people Spending on R&D Royalty and license fee payments Business/university R&D collaboration	[Why among these indicators?]
OUTPUTS Knowledge Local specialised research and training	[Not output]
Nature of competitive advantage	[Not output]
Quality of production process technology	[Not output]
High-tech exports Manufactured exports ICT exports Insurance and financial services Patents registered (domestic and non-domestic) Royalty and license fee receipts	[Not output]
Competitiveness Growth of exports to neighbouring countries Intensity of local competition	

Reach of exporting in international markets Commercial services export Merchandise exports Goods exported Service exports Listed domestic companies	
	[Why among these indicators?]
Wealth Final consumption expenditure GDP per capita, PPP GDP growth rate Industry, value added Manufacturer, value added Services, value added International migration stock Value of stocks traded FDI net outflows	

Notes

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- ¹ “The Innovation Union Scoreboard 2013 gives a comparative assessment of the innovation performance of the EU27 Member States and the relative strengths and weaknesses of their research and innovation systems.” (EC, 2013a: 4)
 - ² Classical economists, in contrast, had pursued dynamic analyses, that is, been interested in technological, organisational, and institutional changes, as well as in the opening up of new markets. (see section 3.1)
 - ³ For further details, see, e.g., Fagerberg et al. (2011: 898) and Godin (2008: 64–66).
 - ⁴ The ensuing overview can only be brief, and thus somewhat simplified. More detailed and nuanced accounts, major achievements and synthesising pieces of work include Baumol (2002); Baumol et al. (2007); Castellacci (2008a); Dodgson and Rothwell (eds) (1994); Dodgson et al. (eds) (2014); Dosi (1988a), (1988b); Dosi et al. (eds) (1988); Edquist (ed.) (1997); Ergas (1986), (1987); Fagerberg et al. (eds) (2005); Fagerberg et al. (2012); Freeman (1994); Freeman and Soete (1997); Grupp (1998); Hall and Rosenberg (eds) (2010); Klevorick et al. (1995); Laestadius et al. (2005); Lazonick (2013); Lundvall (ed.) (1992); Lundvall and Borrás (1999); Martin (2012); Metcalfe (1998); Mowery and Nelson (1999); Nelson (ed.) (1993); Nelson (1995); OECD (1992), (1998); Pavitt (1999); Smith (2000); and von Tunzelman (1995).
 - ⁵ This brief account can only list the most influential models. Balconi et al. (2010); Caraça et al. (2009); Dodgson and Rothwell (1994); and Godin (2006) offer detailed discussions on their emergence, properties and use for analytical and policy-making purposes.
 - ⁶ It is telling that a recent review of this discussion by Di Stefano et al. (2012) draws on one hundred papers.
 - ⁷ Marx explicitly distanced himself from classical economics: it is not by accident that his major book is entitled „Capital: A critique of political economy”.
 - ⁸ The so-called new or endogenous growth theory is not discussed here separately because its major implicit assumptions on knowledge are very similar to those of mainstream economics. (Lazonick, 2013; Smith, 2000) Moreover, knowledge in new growth models is reduced to codified scientific knowledge, in sharp contrast to the much richer understanding of knowledge in evolutionary economics of innovation. When summarising the “evolution of science policy and innovation studies” (SPIS), Martin (2012: 1230) also considers this school as part of mainstream economics: “Endogenous growth theory is perhaps better seen not so much as a contribution to SPIS but rather as a response by mainstream economists to the challenge posed by evolutionary economics.”
 - ⁹ On the nature of innovation, and how it is treated in economics, see also Dosi (1988b), (2013); Dosi and Grazzi (2010); Dosi and Nelson (2010); Dosi et al. (eds) (1988); Metcalfe (1998), (2010); as well as Salter and Alexy (2014).
 - ¹⁰ Arrow (1962) was already discussing „The Economic Implications of Learning by Doing”, and Rosenberg (1982) stressed the importance of learning by using (ch. 6). Recently, learning has become amore regular subject in mainstream economics, most notably in game theory. For instance, while „learning” only appeared twice in the title of NBER working papers in 1996, it occurred 5 times in 1999, 6 times in 2002, 13 times in 2008, 10 times in 2013, and 12 times in 2014, among others in the forms of „learning by doing”, „learning from experience”, and „learning from exporting” – but also „learning from state longitudinal data systems” and „learning millennial-style”. (It should be added that at least 15-20 NBER working papers are published a week.) Taking the titles and abstracts of articles published in the American Economic Review, „learning” occurred first in 1999, then 2-3 times a year in 2002- 2006; 4 times in 2008, 2011, and 2012; 5 times in 2013; 6 times in 2007, 2010, and 2014; and 7 times in 2009. These articles discuss a wide variety of research themes – e.g. behaviour of firms and

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- other organisations, business cycles, stock exchange transactions, forecasting of economic growth, mortgage, art auctions, game theory, behavioural economics, energy, health, labour market – and modes of learning. Thus, not all these articles are relevant from the point of analysing innovation processes (e.g. „learning [one’s] HIV status” is not part of an innovation process). Further, in several cases knowledge is narrowed down to patents, which is clearly a misconception. Yet, a detailed analysis of the substance of these articles is beyond the scope of this paper.
- ¹¹ Figures 6–7 are to be replaced to present more recent data.
- ¹² Figures 6–7 are to be replaced to present more recent data.
- ¹³ The so-called indirect R&D intensity has been also calculated as R&D expenditures embodied in intermediates and capital goods purchased on the domestic market or imported. Yet, it has been concluded that indirect R&D intensities would not influence the classification of sectors. (Hatzichronoglou, 1997: 5)
- ¹⁴ In an attempt to systematically compare the market and systemic failure policy rationales, Bleda and del Río (2013) introduce the notion of evolutionary market failures and reinterpret „the neoclassic market failures” as particular cases of evolutionary market failures, relying on the crucial distinction between knowledge and information.
- ¹⁵ The European Innovation Scoreboard (EIS) was introduced in 2002. The indicators used for the EIS have been revised several times. The scoreboard was renamed as Innovation Union Scoreboard (IUS) in 2010. Since 2016 it is called EIS again
- ¹⁶ A fairly detailed, partly technical, partly substantive discussion would be needed to refine this simple classification. Another important question could be as follows: to what extent are non-R&D-based innovation activities needed for successful R&D-based innovations?
- ¹⁷ Although it goes without saying that not all technological innovations are based on R&D results, people tend to forget this basic fact. Certain organisational, managerial, marketing and financial innovations, in turn, draw on R&D results (but usually not stemming from R&D activities conducted or financed by firms). For these two reasons it would be a mistake to equate technological innovations with R&D-based innovations.
- ¹⁸ This overview was discontinued in the 2015 edition of the Innovation Union progress report.
- ¹⁹ BERD in the ‘Manufacture of computer, electronic and optical products (C26)’ sector was €152–155m in Ireland, €53–56m in Hungary, while €527m in Austria in 2009–2010. (Eurostat) Austria has been chosen for comparison given her similar size (in terms of population) and lower ranking by knowledge- intensity of economy in Table 5. BERD in pharmaceuticals is not considered here given the sector’s small share in Hungarian high-tech exports (around 10% of the electronics exports [sector C26]).
- ²⁰ Radosevic (2002) offers a thorough survey of the electronics industry in Central and Eastern European countries, Scotland and Wales. His analysis of plant closures and downsizing is a good illustration of the behaviour of ‘foot-loose’ investors.
- ²¹ There are important differences among the ‘anchored’ firms, too. This simple dichotomy is meant just to highlight some elementary policy implications, not as a basis for sound policy recommendations.
- ²² This section has to be checked for accuracy concerning the 2022 edition of GII. For some more detailed comments on the GII indicators, see Appendix.
- ²³ The intensity of competition is included in Pillar 4.

Priorities of health research in India: Evidence of misalignment between research outputs and disease burden

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Abstract

This study examines whether India's research efforts address the country's health needs. It does so by investigating the degree of alignment between burden of diseases in India and knowledge production in health and biomedical sciences by Indian institutions. WHO data from Global Health Estimates on Disability-Adjusted Life Years (DALYs) is used as the indicator of disease burden, and number of publications in the Web of Science as the proxy measure of research efforts.

We find that the alignment between publications and DALYs of India is much lower than in High- Income Countries (HICs) and lower than in countries such as China or Brazil. This is due to some disease areas having little research in relation to their burden, while others receiving high attention in spite of low burden. For example, cardiovascular and respiratory diseases contribute to ~23% of the disease burden in India, but their publication share is ~6% of the total publications. In contrast, cancer diseases contribute to ~5 % of the burden, while their publication share is almost 25%.

We discuss some of the major driving factors behind this misalignment such the market demand associated with the diseases prevalent in HICs, the academic prestige of certain disease areas, and

funding opportunities in global health. We also explore where the misalignment is likely to be mainly due to weaknesses in healthcare delivery systems in India (e.g., in neonatal conditions), rather than lack of research.

Introduction

Strategically planned health research is crucial for improving the health conditions of people in a country (WHO, 2014). However, in India lack of a systemic approach to relating research efforts with public health priorities is a prominent hurdle in making progress in health outcomes (Dandona et al., 2011). In a recent interview Dr. Swaminathan, former chief scientist of WHO and an Indian scientist, stated that with health research as a priority in India, it is important that the country adopts a systems approach to promote advanced research in health and biomedical sciences (Kupferschmidt, 2022). To streamline the efforts toward improving India's health system, it is crucial to understand the funding landscape, research outputs, and priorities in health and biomedical research. Given India's limited research investment, it is even more important for policymakers to distribute resources in a well-informed manner.

The prioritization of research efforts according to societal needs is an issue that has become increasingly relevant in health and science policies (Chalmers et al., 2014; Wallace and Rafols, 2015). The theoretical issues at stake revolve around how the making of knowledge 'is shaped and shapes local, national and global inequality', in particular in relation to (neo-)colonialism and dependent development (Hess et al., 2017, p. 320). The political economy of research and innovation is constituted of durable structures which have a strong influence on which types of problems (e.g. which diseases) are mainly tackled and which types of knowledge (e.g. on prevention vs. treatment) are produced (Tyfield, 2012; Yegros et al., 2020). Yet in the face of these institutional forces, political and social movements do sometimes manage to influence research in directions that conduct 'undone science' and respond to their demands and needs (Frickel et al., 2010). For a democratic discussion on which priorities should be addressed (Stirling, 2014), it is important to have empirically sound estimates on existing priorities and needs (Ciarli and Rafols, 2019).

Disease burden is one of the indicators that can help in guiding the priorities of health and biomedical research in India. A prior study by Dandona et al. indicated a misalignment between research funding (i.e., inputs) and disease burden in India (Dandona et al., 2017). Continuing in a similar trajectory, in this study we explore the potential misalignment of India's disease burden and research attention as measured by biomedical publications (i.e., outputs)

relevant to those diseases as a proxy. We find that biomedical research publications are weakly correlated with the country's disease burden, with important misalignment in many disease areas. In particular, we show that a significant amount of Indian publications are focused on some diseases of high-income countries (mainly cancers) that have relatively low disease burden in India.

We aim to provide a picture of publications against disease burden to identify gaps in research efforts and guide the attention of policymakers and researchers toward under-explored disease areas. Thus, the study contributes to evidence-informed agenda-setting for research priorities in Indian health research.

Background

India has made considerable progress in life expectancy and child mortality rate in the past decades, however, numerous health challenges still are a serious concern for the population. India's disease burden is generally dominated by communicable diseases such as tuberculosis, diarrhoea, lower respiratory infections, as well as non-communicable diseases such as cardiovascular diseases, chronic pulmonary disease, and diabetes (Narain 2019). India is facing a dual challenge: while the country's communicable disease burden has not been reduced, the burden of non-communicable diseases (NCDs) is increasing alarmingly (Yadav & Arokiasamy, 2014). Multiple studies pointed out that in past three decades the burden of non-communicable diseases (NCDs) has risen from 37.9% to 61.8%. (Ram & Thakur, 2021).

Low expenditure on health in India is a serious concern. Though, India's public health expenditure increased from 0.9% of GDP in 2015-16 to 1.1% in 2020-21 (Demand for Grants 2021-22 Analysis, n.d.), this is still very low (The National Health Policy, 2017). The national health policy recommends increasing public health expenditure to 2.5% of the GDP by 2025 (Backdrop to the National Health Policy, 2017).

Expenditure on health research is also low. The main public institutions that fund health research in the country (Verma, et. al. 2022; Srinivasan, et. al. 2020) are the Indian Council of Medical Research (ICMR), Defence Research and Development Organisation (DRDO), Science and Engineering Research Board (SERB), India Alliance, Department of Science and Technology (DST), Department of Biotechnology (DBT), Council of Scientific and Industrial Research (CSIR), Department of Health Research (DHR). The nodal agency for health-related policies and programs in India is the Ministry of Health and Family Welfare (MoHFW). MoHFW comprises two departments: the Department of Health and Family Welfare and the Department of Health Research (DHR). The DHR is responsible for conducting medical research. The Indian Council of Medical Research (ICMR) falls under the purview of the DHR.

In FY 2021-22, the MoHFW has an allocation of about Indian Rupees (INR) 739 billion. The Department of Health and Family Welfare's allocation is about INR 712 billion, which accounts for 96% of the total. The other department, the DHR, received about INR 26 billion, 4% of the allocation, with a significant portion earmarked for the ICMR (Demand for Grants 2021-22 Analysis: Health and Family Welfare, n.d.).

Yet the concern of this study is not the overall expenditure in health research, but whether the resources spent in health research are addressing Indian health need. In other words: How is the allocation of scarce funds for health research in India utilized by funding agencies? And which disease areas are prioritized, as shown by outputs?

To strengthen the health research system and make the research more relevant for the health system and policies in India, it is essential to understand the diseases that cause a substantial burden yet are under-studied. This will help in thinking systematically on whether it is necessary to channel research efforts toward these diseases. For example, in the US considerable attention has been directed toward understanding the funding landscape of the National Institute of Health (NIH) in addressing national and global disease burden. Studies have highlighted the lack of appropriate attention to some conditions given their disease burden (Gross et al., 1999; Gillum et al., 2011; Manton et al., 2009). Counterarguments state that the NIH employs a dynamic, need-based funding strategy that considers public health needs, scientific opportunities, budgetary considerations, and portfolio balance as key factors (Collins, 2016). According to Collins NIH strategizes the funding priorities through the inclusive participation of various communities while allowing for a high proportion of investigator-initiated research. However, a report by the Government Accountability Office (U.S. Government Accountability Office 2014) highlighted the lack of transparency in the NIH's fund allocation strategy (U.S. Government Accountability Office, 2017).

NIH's working group in 1997 recommended public health needs as criteria for priority setting in health research (Gross, 1999). The world health report (WHO, 2004) recommends a well-planned strategy to support health research. Improving the health research fund allocation based on disease burden as the reference is an established strategy (Xu, 2014; Viergever, 2010). Researchers also pointed out that to increase the benefits of public spending on health research, disease burden among the population must be one of the guiding factors in South Asia (Swaminathan, et al. 2017).

However, previous studies by Dandona et al. on disease burden and public health research output from India showed that several diseases with high burden are under-represented in the health research-related publications

between 2002-2007 (Dandona et. al., 2009). Another study focused on bibliometric analysis of the Global Burden of Disease and health research output from India (2000-2010) using PubMed and IndMed databases (Kalita, 2015), where the authors reported the same issue of underrepresentation of research on leading causes of disease in India. Their study also manifested a skewed relationship between the burden of disease and the geographic distribution of research.

Dandona et al. (2017) mapped the health research funding in India through a survey to 1150 health research institutions. According to their estimation, the total health research funding available in India in 2011-12 was USD 1.42 billion, which was 0.09% of the year's GDP. They also pointed out only 0.02% comes from public sources. Their finding shows that between the FY 2007-08 and 2011-12, about 20% of research funding are from public sources, while 79% of funding came from the Indian pharmaceutical industry. The Indian pharma industry is a leader in the global generic pharma market and has become the "Pharmacy of the world" (Invest India, n.d.). However, the Indian pharmaceutical industry focuses on manufacturing generic drugs in specific disease areas; the top ten therapeutic areas being anti-infectives, gastro, vitamin/nutrients, pain/analgesic, neuro/central nervous system, cardiac, anti-diabetics, respiratory, and derma (FICCI, 2021). Therefore, efforts from the industry are concentrated only on a few disease areas, and there is a mismatch between the country's disease burden and the industry's priorities. However, since Indian industry has very few publications, this has little impact in the results discussed in this article.

Health and biomedical research from academic institutions is the major contributor to the knowledge generation to bridge the existing gaps in health research in India. One way of addressing the disease burden in India is to conduct domestic health research (other strategies would involve improving the healthcare system, education or nutrition, which are beyond the scope of this paper). However, the directions of academic research are frequently influenced by the priorities of journals. Since scholars often use peer-reviewed journal research articles to communicate their findings journal articles are viewed as an indicator of research efforts. Hence, studying the relationship between research publications produced in India and disease burden can provide helpful information about research efforts to address the country's health research needs. Previous studies have highlighted the imbalances in global health research, which focuses relatively more on high-income countries' needs and disease burden. Research on diseases with a high burden in low- and middle-income countries is heavily underrepresented.

In this article, we analyze the disease burden of India and how the research output addresses the health needs of India. For our study, we have taken the

WHO data from Global Health Estimates on Disability- Adjusted Life Years (DALYs) for disease burden and Web of Science publication data as a proxy of the number of research efforts. The use of publications as a proxy for research efforts can be contested is well established in the literature (Evans et al., 2014; Yegros-Yegros et al., 2020), and previous studies using this proxy have been found useful by policymakers and the public to discuss uneven funding distributions and non-transparent methods of research fund allocation. Our findings highlight the misalignment between disease burden and research efforts. We observe that in some areas, Indian disproportionately follows high-income country (HIC) publication patterns, which are more correlated to HICs own disease burdens.

Methods

Health research is defined in various ways, which makes it difficult to compare with global trends. We have used scientific publications extracted from the CWTS in-house version of the Web of Science (WoS) as a proxy measure to understand how much research each country is doing for various diseases. We have taken the 2000-2019 Global Health Estimates on Disability-Adjusted Life Years (DALYs) published by the World Health Organisation (WHO) as estimates for disease burden (Global Health Estimates 2020).

We have considered the average country-level estimates of DALYs per 100,000 inhabitants corresponding to the entire populations (i.e. both sexes and all ages) in the period 2015-2019. As for the diseases included in the study, all communicable and non-communicable diseases have been considered, with the exception of the categories 'other' (e.g. GHE code 370; 'Other infectious diseases'). All causes related to injuries have been also excluded from the study.

In order to enable the comparison between countries' research efforts on specific diseases with the corresponding disease burden, we followed the approach developed by Yegros-Yegros et al. (2020), updating the period. First, we identified one or more MeSH descriptors in the US National Library of Medicine MeSH database for each GHE cause, as considered by WHO. The selected MeSH descriptors by GHE cause can be found in the supplementary materials.

Second, to identify in PubMed all scientific publications related to specific GHE causes during the period 2015-2019, we used the selected MeSH descriptors and qualifiers where necessary, as well as all the specific descriptors beneath them as represented in the MeSH tree structure. This was possible thanks to the full integration of the databases WoS and PubMed available at CWTS. Also, in order to ensure all selected publications relate to human diseases, we removed from our dataset all publications classified under the MeSH tree branch C22 (animal diseases) or classified with the qualifier 'veterinary'.

Third, the assignment of publications to countries is based on the author affiliations, as recorded in WoS. The later assignment of countries to the various income levels (i.e. high-income countries -HIC, Upper middle-income countries -UMIC- and low-income countries -LIC) corresponds to the year 2017 in the historical classification of countries by income provided by the World Bank¹.

Results

A first observation is that India has publishes substantially less in health areas than the world average. Whereas very broadly defined health-related areas make up about 41% of WoS, for India health-related fields are only 25% of its total output. Similarly, publications explicitly classified with a disease associated with a GHE burden represent 9.1% of all WoS, but only 5.5% of Indian publications.

Next, we analyse the distribution of publication across diseases in comparison to disease burden. Table 1 shows the correlation between publications and DALYs of India, the world, high-income countries (HIC), upper-middle income countries (UMIC) and low-income countries (LIC), Brazil (BR), and China (CN). The first finding is that the lowest correlation of DALYs with their publication is exhibited by India (0.28). This result indicates that research efforts do not align well with the disease burden in the country. HIC publications have a higher correlation with their disease burden (0.60). This is in agreement with previous studies also reported that research publications tend to align with the national health needs of HIC, as represented by the DALYs (Evans et. al., 2014). Kinge et al., 2014 also report that Norwegian research investment across therapeutic areas correlates well with the local disease burden while the correlation is much lower for the global disease burden. Similarly, another bibliometric study call attention to the significant correlation between the burden of disease and Australia's National Health and Medical Research Council fund allocations (Auon et al. 2004).

Interestingly, two other BRICS countries, Brazil and China, prioritize their disease burden in the research agenda more than India, as observed from the correlation factors, 0.41 and 0.52, respectively. Likewise, LICs also show better alignment with disease burden and publications; here, the correlation factor is 0.40.

Table 1: Pearson correlations between disease burden (rows) and publications (columns) of diseases categories for various countries and country groups.

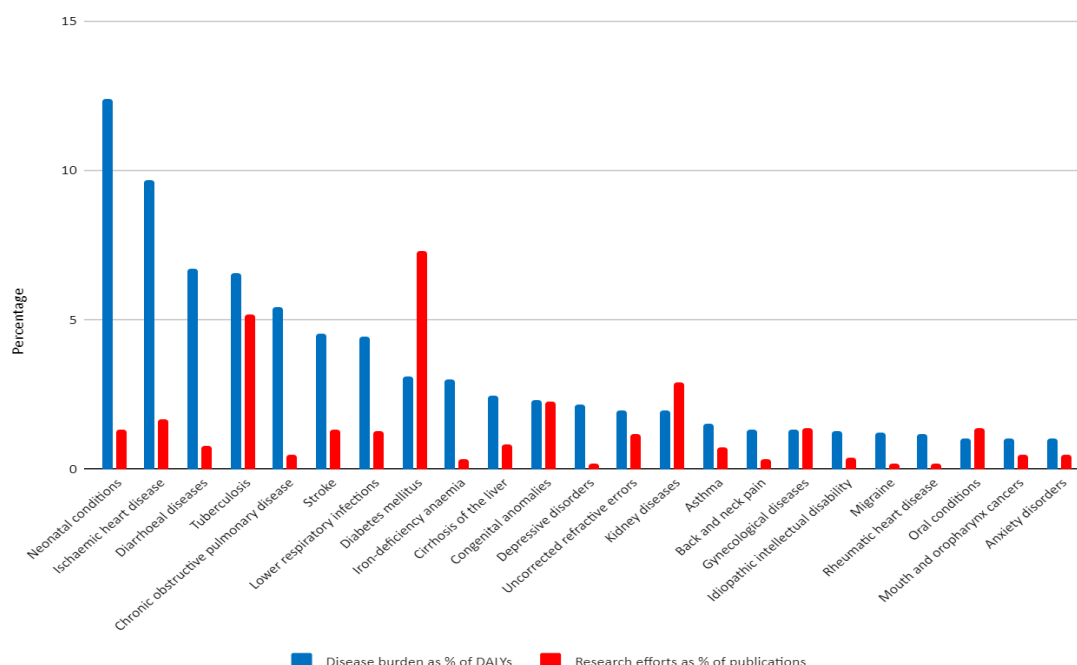
	IN	World	HIC	UMIC	LIC	BR	CN
IN	0.28	0.30	0.30	0.28	0.13	0.24	0.23
World	0.34	0.45	0.44	0.41	0.32	0.34	0.34
HIC	0.34	0.60	0.60	0.59	-0.01	0.39	0.57
UMIC	0.38	0.57	0.57	0.54	0.24	0.42	0.47
LIC	0.21	0.18	0.18	0.13	0.40	0.18	0.07
BR	0.36	0.55	0.56	0.51	0.08	0.41	0.45
CN	0.22	0.47	0.46	0.49	-0.02	0.27	0.52

Note: IN = India, W = World, HIC = High-income countries, UMIC = Upper middle-income countries, LIC = Low-income countries, BR = Brazil, and CN = China.

India's disease burden is standing in a paradoxical situation. Cardiovascular diseases associated with overeating and an affluent lifestyle are on the rise. On the other hand, the prevalence of diseases like TB and diarrhoea, associated with undernutrition, is also of concern (Patel et. al., 2019). Traditionally, discussion on the disease burden in India has focused on comparing the impact of communicable diseases (CDs) and non-communicable diseases (NCDs). But in recent decades some NDCs have emerged as a concern for the country by causing substantial fallouts in India's overall health. (Yadav, 2014).

However, our analysis shows that simply classifying the diseases into two groups of CDs and NCD does not reveal the nuance of misalignments between burden and research efforts. Figure 1 represents the relative disease burden (estimated by % of DALYs) vs. research efforts (estimated by % of publications) in India for the top 50 DALYs. A variety of patterns of under-studied topics (% of DALYs overshoot the % of publications significantly) and over-studied topics (when % of publications overshoot the % of DALYs significantly) can be observed for both CDs, such as TB, HIV/AIDS, and NCDs such as heart disease, diabetes, Alzheimer's. For example, tuberculosis (TB) still has a high burden, but it also benefits from significant research efforts. However, some other CD diseases, such as AIDS/HIV or malaria, are not a primary challenge for India; still, considerable research efforts are directed toward their research (which is welcome from a global health perspective as it is needed in LICs with little research capacity). Within NDCs, some diseases such as Ischemic heart disease are under-researched, but others such as diabetes over-researched. In short, CD vs. NCD is not a useful classification to analyse research efforts.

Figure 1: Relative disease burden (estimated by % of DALYs) vs. relative research efforts (estimated by % of publications) in India for the top diseases with the highest burden.



Overall we can see from the disease categories with highest burden (Figure 1) that there are relatively low research efforts for many diseases where the burden is considerably high for the country, which indicates a general misalignment between disease burden and research efforts in India. To comprehend the general picture of disease burden and subsequent research effort, we have divided our discussion into the following five categories, with examples for each category to convey our research findings.

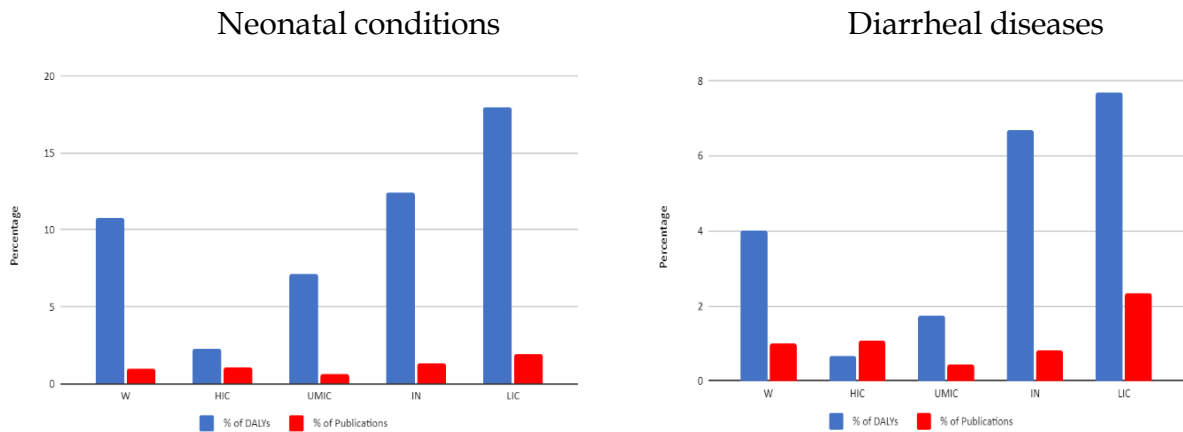
A. Diseases that need robust healthcare delivery in India

The maximum burden (~14%) for a single disease category in India is for neonatal conditions, with a very low research effort (~ 2%) (Figure 2). Similar situation is observed for diarrheal diseases, where disease burden is ~7% compared to publications of ~1% (Figure 2). However, one reason for low research effort can be the less need for research toward a particular disease since existing medical knowledge with a sound healthcare delivery system can substantially reduce disease burden as shown in HICs. Therefore, we can't always directly conclude that relative high burden can be solved through more research efforts. Deaths due to neonatal conditions are likely to be associated with inadequate health infrastructure.

An indicator that helps in identifying diseases in this category is the ratio of disease burden of India (or other country) in comparison to disease burden

HICs. If this ratio is high, we are dealing with a disease with a low burden in HIC, which means that knowledge is available to address the disease, but that it is not implemented. In other words, lack of knowledge and research efforts are not the major issues; the research systems of HIC have given adequate attention to biomedical knowledge generation. Under these conditions, a small amount of research on how to implement existing knowledge towards improving healthcare delivery can result in substantive health gains. Consequently, we can attribute the higher DALYs for diseases like neonatal conditions, diarrhoeal diseases, and anaemia, as an outcome of the country's poor health delivery system despite solutions being available.

Figure 2: Relative disease burden (estimated by % of DALYs) vs. research efforts (estimated by % of publications) for neonatal conditions and diarrheal diseases for the World (W), High-Income Countries (HIC), Upper Middle-Income Countries (UMIC), India (IN), and Lower Income Countries (LIC).



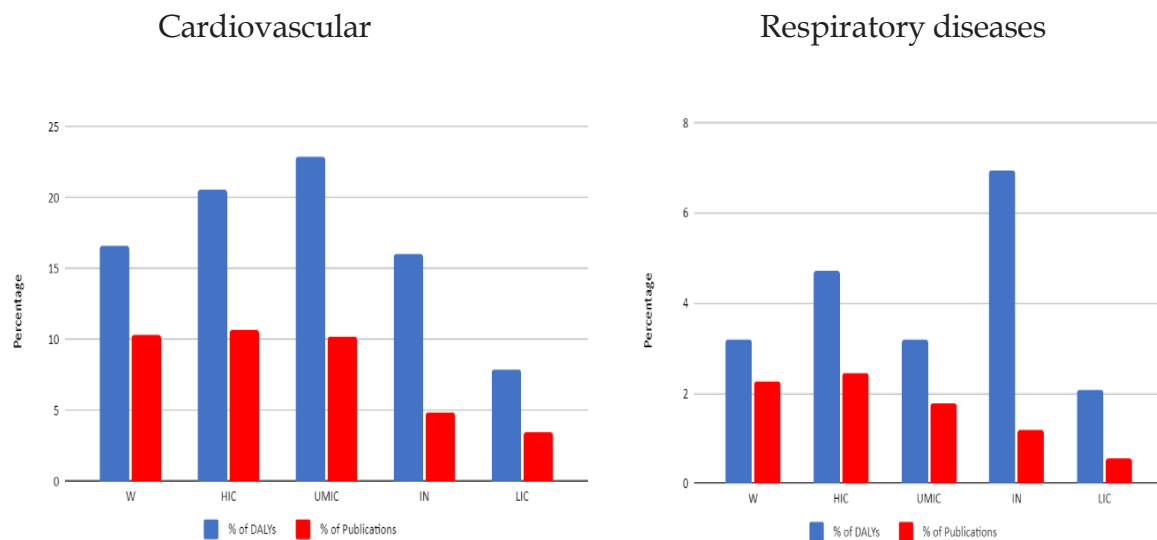
B. Diseases understudied in India and globally

We classify in this category the diseases that have low research efforts in spite of having a high disease burden, both in India and globally. We observe for India, a ratio of relative disease burden (in % DALYs) over research efforts (in % of publications) around 3-5, but lower ratios in HICs and UMICs.

Representative examples of this category are cardiovascular and respiratory diseases (Figure 3). Cardiovascular diseases are understudied in all income group countries. They contribute more than 20% disease burden in HIC and even more (~ 22%) in UMIC. However, when we look into the publications share, both HIC and UMIC contribute about 10% each, indicating low research effort. In the case of India, the research effort for cardiovascular diseases is even lower, only about 5% of the total publication share, although they make up

~16% disease burden for India. A similar pattern is observed in the case of respiratory diseases, which are understudied in all income groups and even more so in India. These diseases generate about 7% burden, while the publication share is about 1%.

Figure 3: Relative disease burden (estimated by % of DALYs) vs. research efforts (estimated by % of publications) for cardiovascular and respiratory diseases for the World (W), High-Income Countries (HIC), Upper Middle-Income Countries (UMIC), India (IN), and Lower Income Countries (LIC).

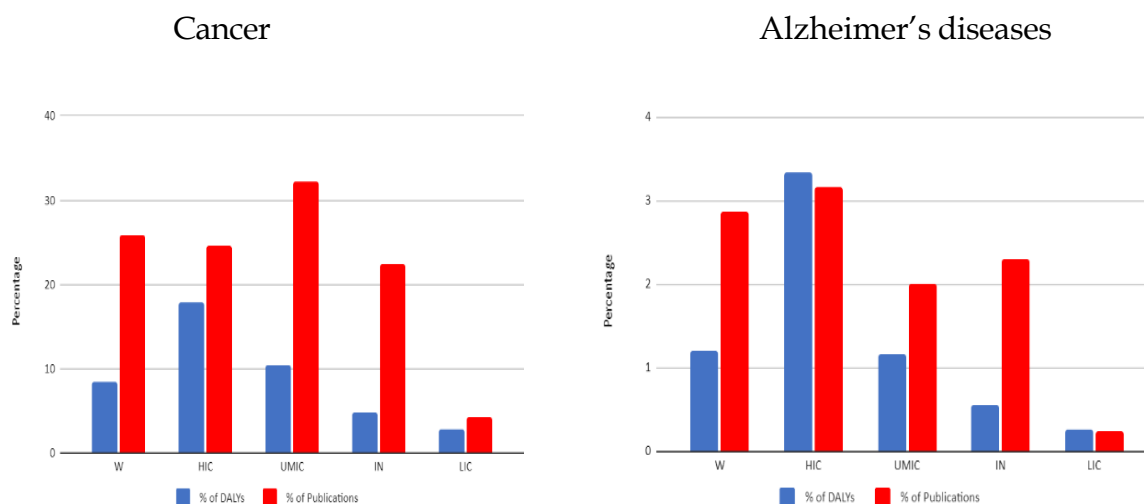


C. Diseases overstudied in India and globally

This category comprises diseases that have high research efforts in spite of having a low disease burden in India and globally, but high burden in HICs. In India, the ratio of relative disease burden in India (estimated by % of DALYs) over research efforts in India (estimated by % of publications) is 1/5 to 1/3.

Representative examples of this category are cancer diseases and dementias (Figure 4). In contrast to the previous category of diseases, these are over-researched studied across most income group countries. In cancer, India is producing nearly a quarter (~22%) of its publications in the area of cancer diseases while the burden is below 5%. A similar situation is observed in the case of Alzheimer's diseases and other dementias; all are generally overstudied. In the case of India, they contribute to 0.5% of the disease burden, but the publication share is more than 2%. The high percentage of research on these diseases in India as well as in UMICs seems to be associated to the importance of these diseases in the global literature, funding or markets, rather than national health needs.

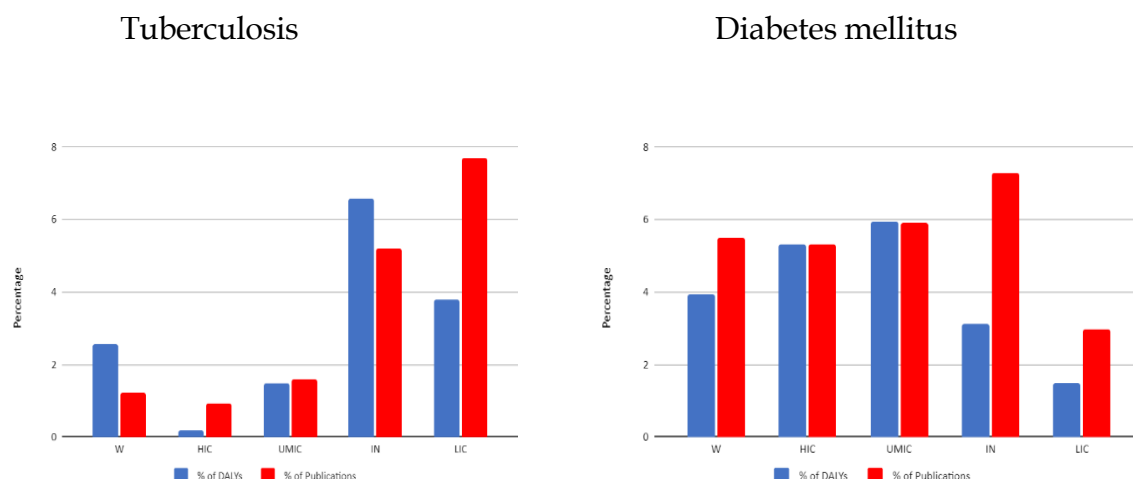
Figure 4: Relative disease burden (estimated by % of DALYs) vs. research efforts (estimated by % of publications) for cancer and Alzheimer’s diseases for the World (W), High-Income Countries (HIC), Upper Middle-Income Countries (UMIC), India (IN), and Lower Income Countries (LIC).



D. Disease with significant burden and considerable research effort in India

Representative examples of diseases with significant burden and research efforts are tuberculosis (TB) and diabetes (Figure 5). TB receives attention globally: we see that all the income country groups make some contribution to research efforts. For HICs, TB’s burden is very low, but publication share is about 1% of their total. For the UMIC, TB’s share is ~1.8% compared to the burden of about ~1.7%. The disease burden of TB in India is about 7%, and the publication share is about 5%. India is thus contributing significantly toward the global knowledge generation as globally TB is understudied compared to DALYs of the world (~2.5% of burden vs. ~1% of publication share).

Figure 5: Relative disease burden (estimated by % of DALYs) vs. research efforts (estimated by % of publications) for tuberculosis and diabetes for the World (W), High-Income Countries (HIC), Upper Middle-Income Countries (UMIC), India (IN), and Lower Income Countries (LIC).



TB is a severe concern for India and has garnered attention to the severity of the disease, especially the multidrug-resistant variant (Thakur et al., 2020). Similarly, TB is a significant concern from LIC (~4% of %DALYS), and they show substantial research efforts toward TB (~8% publication share).

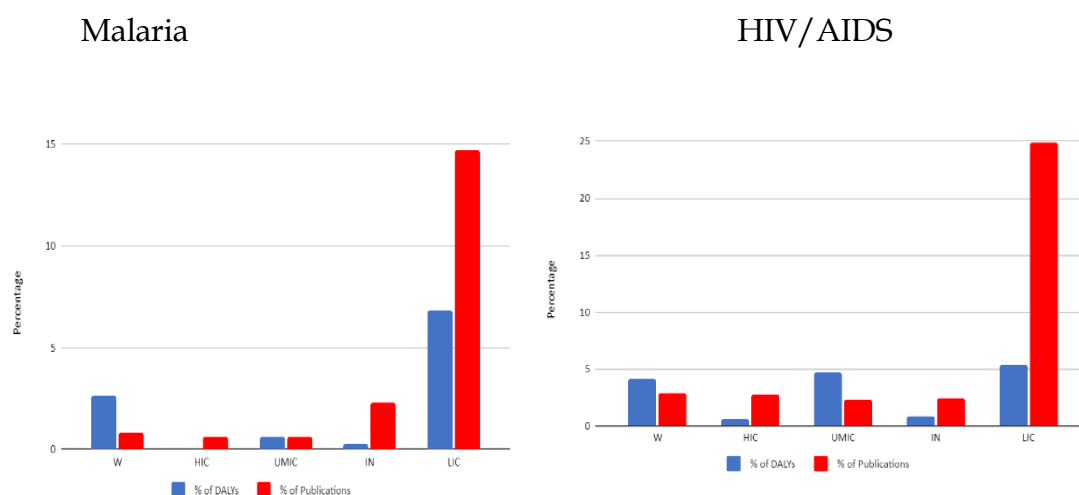
In the case of diabetes, India again is contributing significantly to the global knowledge pool. Diabetes is relatively overstudied in India (~2.5% of DALYs vs. ~7% in publication share) as well as in LIC (~1.5 % DALYs vs. ~3% publication share), but given its growing health effects, this is a case in which this might be a wise choice. In contrast, the publication share vs. disease burden shows a 1:1 relationship for both HIC and UMIC.

E. Diseases only prevalent in low-income countries,

This category includes diseases with a very low burden yet considerable research efforts in India, but with significant global burden.

Representative examples of this category are Malaria and HIV/ AIDS (Figure 6). AIDS/HIV or malaria are not major challenges for India, nor in HICs or UMICs in terms of DALYs. Still, considerable research efforts are directed toward their research in order to address a global health challenge. For example, the DALYs of malaria in India is ~0.5%, and the publication share is ~2.5%. In the case of HIV/ AIDS, the DALYs of India are ~1%, and the publication share is ~2.5%. Investing in this category may be meaningful for India, as it may help address the disease burden concentrated in LICs with limited research capacity.

Figure 6: Relative disease burden (estimated by % of DALYs) vs. research efforts (estimated by % of publications) for malaria and HIV/AIDS for the World (W), High-Income Countries (HIC), Upper Middle-Income Countries (UMIC), India (IN), and Lower Income Countries (LIC).



Summary and discussion

In this study we have found that *de facto* research priorities (as revealed by publications) are poorly correlated with disease burden in India. In average, the degree of misalignment is significantly higher in India than in other middle countries and regions.

The analysis reveals a variety of patterns in the relation between disease burden and research efforts, which do not fit with the older classification of communicable and non-communicable diseases:

- 1) Health issues, such as diarrheal diseases and neonatal conditions for which little research is conducted because medical solutions are available
- 2) Diseases understudied globally and even more so in India, such as cardiovascular and respiratory diseases
- 3) Diseases overstudied globally and even more so in India, such as cancers and neurological diseases
- 4) Diseases with particularly high burden in India in which there is a substantial Indian research response, such as tuberculosis and diabetes.
- 5) Diseases with high burden in low-income countries but not in India, in which India is a substantial global contributor, such as malaria and HIV/AIDS.

The analyses have limitations associated with the data availability as discussed by Yegros et al. (2020): disease burden estimates can be contested (Anand et al., 1997); publications do not necessarily reflect amount of investment, and the database WoS under-estimate the number of publications from the Global South particularly in social sciences and engineering areas. A study by Dandona et al. (2017) also reported misalignment between disease burden and research efforts in India's health research by collecting funding data. According to their study, neonatal disorders, cardiovascular disease, chronic respiratory disease, mental health, and musculoskeletal disorders are some of the leading diseases that substantially contribute to the disease burden. But research funding in these areas is considerably lower. Our findings are consistent with these observations. It is clear that strategizing the funding decision according to disease burden and research need of the country is essential at this stage.

In order to improve health research priorities in India, it is important to inquire into the causes behind the misalignments observed. The patterns observed suggest four main reasons for misalignments.

In the first place, one can attribute the higher burden for diseases like neonatal conditions, diarrhoeal diseases, and anaemia, as an outcome of the country's poor health delivery system despite solutions being available. The importance of healthcare delivery extends to other major conditions such as cardiovascular or respiratory diseases (disease group 2 in the list). For example, ischemic heart disease was reported to be one of India's leading causes of premature deaths in 2013 (GBD, 2019). Some major risk factors contributing to many such diseases in the country are alcohol consumption, insufficient physical activity, tobacco use, and an unhealthy diet (Sinha, 2017). In these cases, health system and implementation research should be supported (Coburn et al., 2022).

A second driver for the misalignment is market demands in health. Higher research efforts for cancer can be attributed to the attention of private R&D investments, mainly by the pharmaceutical industry. Previous studies pointed out that market demand predominantly revolves around therapeutic interventions to chronic conditions with high prevalence in HICs. Private companies make up more than 50% of health R&D (around 60% according to Røttingen et al., 2013). Considering this large share of investment, the research priorities of pharmaceutical companies provide additional demand for research in specific diseases based on market conditions rather than disease burden (Evans et al. 2014). While market-based research priorities are driven by diseases in HICs with wealthy healthcare providers, they may influence the research agendas across the world including India, as observed from cancer-related publication patterns (Figure 4).

A third driver for misalignment are the incentives of publishing in prestigious international journals in hot (i.e. highly cited) topics, the associated recognition among peers in the global research community and evaluation practices. That academic prestige is then related to diseases relevant to HICs is not surprising, considering that knowledge production is highly concentrated in the Global North (Chan et. al., 2011). In fact, the effect of private funding may be synergistic with the pressure of publishing in prestigious international journals. Prioritisation of the research agenda of HICs over local needs has been observed both in the Global South (Vessuri et al., 2014) and in 'peripheral' HICs like Spain (López et al., 2015).

Finally, a driver behind the focus on some global health issues is the high concentration of funding for global public health in specific disease areas such as Tuberculosis, HIV/AIDS, and malaria. This preferential attention of a few diseases is already well-studied (Dandona et al. Al., 2010; Moran, et. al., 2009). Some of these diseases, such as HIV and malaria, do not respond any more to India's disease burden, but due to a cascading effect of international attention and funding, they also receive higher priorities in national research programs.

Conclusions

In summary, the present study shows that disease burden and health research priorities are particularly misaligned in India. The correlation between the research priorities of HICs and publications from India in certain diseases (cancers and cardio-vascular) suggests three main drivers: i) market demand, ii) scientific reputation of topics aligned with health needs of HICs., iii) funding availability for global health.

Our analysis provides some ideas for policy making in India. First, the country needs to improve its public health system to tackle the situation – and this includes to conduct research on public health, health system and implementation science in clinical medicine. The government of India has taken several initiatives to improve the public health situation in the country. The “National Digital Health Mission (NDHM)”, launched by GOI in 2021, aims to create a national digital health ecosystem and better health facilities. Proper implementation of various health-related schemes is key to ensuring the quality of the public healthcare system. Improving healthcare delivery and awareness building can help reduce the burden of a certain disease.

Second, India science policy needs to respond to the heavily under-research diseases such as cardiovascular and respiratory diseases, and perhaps stop expanding its support to cancer areas which are already well-funded. Governance of health research in general is in an aspect that needs more attention. Setting the right policies and priorities requires a serious debate. The main public agencies that fund health research need to work collaboratively to

devise strategies for medium and long-term goals. The lack of alignment between national health research priorities and funding is a common issue across the Global South (Evans et al., 2014). In Latin America and the Caribbean (LAC) it has been argued that improvements in governance practices have made a crucial contribution in advancing research for health. Through the establishment of clear policies, priorities, and health research governance systems, LAC countries have made substantial progress in addressing local research needs. India could follow to follow up with similar reforms.

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Note

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- 1 <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>

Connecting the dots: The role of internationally mobile scientists in linking home with foreign scientists

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Abstract

Going abroad, mobile scientists meet scientists from different countries and become carriers of knowledge not readily available in their country of origin. The benefits of a mobility experience might extend to the home scientists who did not move but entered contact with a mobile scientist. In our paper, we investigate the role played by mobile scientists in acting as brokers connecting home non- mobile scientists with foreign ones. We consider mobile those scientists who move abroad to pursue their Ph.D. Looking at the case of Colombia and Brazil, we find that mobile scientists boost the share and the number of publications with foreign co-authors of the home non-mobile scientists with whom they enter contact. Interestingly, we observe that the most effective in creating connections are the mobile diaspora scientists, i.e., those who never return to their country of origin, followed by the mobile intermitted scientists, i.e., those who move in and out of their country of origin. Our paper contributes to the literature on mobility, generally focused on the impact of mobility experiences on individual performances, and provides insights to scholars and policymakers on the spillover effects of mobility experiences.

Keywords: International Scientific Mobility. Co-authorship networks. Social capital spillovers. Colombia. Brazil.

1. Introduction

Governments in high- and low-income countries have long been promoting policies to support the training of students and scientists abroad (Baruffaldi, Marino, and Visentin, 2020; Jonkers and Tijssen, 2008). Policy actors worldwide recognize the role of international mobility in fostering knowledge creation and diffusion, which contribute to economic growth (Baruffaldi and Landoni, 2012; Cañibano, 2017). Internationally mobile scientists and students who spend time abroad absorb tacit knowledge through face-to-face interactions, access scientific infrastructures, and expand their social capital (Bozeman, Dietz, and Gaughan, 2001). International mobile scientists' time abroad improves their research productivity (Netz, Hampel, and Aman, 2020). For those mobiles' origin countries, benefits arise when sojourners return, carrying the knowledge that can be applied to research on local socio-economic needs and training new students and scientists (Cañibano, 2017; Trippel, 2013).

Mobile scientists may also contribute to the internationalization of their home scientific systems by connecting the local scientific community to the global community (Velema, 2012). Empirical studies demonstrate that time spent abroad to do research leads internationally mobile scientists (henceforth "mobile scientists") to have larger international co-authorship networks than scientists who spend their careers in their home countries (henceforth "non-mobile scientists") (Cao et al., 2020; Gibson and McKenzie, 2014; Jonkers and Cruz-Castro, 2013). Many studies suggest that, given their larger stock of international co-authors, mobile scientists may benefit non-mobile scientists from their country of origin by connecting them to foreign scientists. Nonetheless, these studies rarely analyze whether and how non-mobile scientists establish collaboration with foreign scientists through mobile scientists. As such, the literature is unclear on the extent to which mobile scientists are an essential resource for non-mobile scientists to form foreign ties.

This paper addresses this gap by investigating how much collaboration with mobile scientists affects the probability that a non-mobile scientist collaborates with foreign scientists located abroad. We examine whether co-authoring with mobile scientists increases the number of publications with foreign scientists. We investigate the extensive and intensive margin, distinguishing between science, technology, engineering, mathematics (STEM), social science, and humanities (SSH). Because mobility patterns influence both the likelihood that non-mobile scientists form ties with mobile scientists, and the foreign networks of the mobile scientists, we distinguish three types of mobile scientists: diaspora (never return to the country of origin), returnees (return indefinitely to the country of origin), and intermittent (work for part of their academic career in the country of origin).

We also ask about the effect of repeated collaboration with mobile scientists. Collaborating with a mobile scientist might introduce a non-mobile to a foreign collaborator. We ask whether that event has a long-lasting effect or whether repeated interactions with mobile scientists must support sustained interaction with foreigners. We conduct an event study to identify the causal impact of mobile scientists on the foreign collaborations of non-mobile scientists.

Our work studies scientists from Colombia and Brazil. In recent decades, both federal governments have established standardized scientific curriculum vitae (CV) platforms to track scientists' careers. These platforms are unique scientific databases with information on a scientist's trajectory, including academic and biographical background and publications. We rely on this database to identify mobile and non-mobile scientists using their academic formation and work locations after the Ph.D. Because some scientists might not update their CVs after moving abroad, we combine the CV data with scholarship data. We merge bibliometric data from OpenAlex to complete the information on the scientists' publications and all their co-authors and complete their mobility information through affiliations.

Our findings show that interacting with a mobile scientist positively correlates with more publications co-authored with foreign scientists. The share of publications co-authored with foreign scientists also increases, indicating that non-mobile scientists shift their portfolio towards international collaborations. Results also hold when we control for the non-mobile scientist's visibility and past stock of partnerships with foreign scientists. Increasing the number of unique mobile scientists with whom they co-publish, is associated with rising collaborations with foreign scientists.

Not all mobile scientists are made equal. Their relevance to increasing the international collaborations of non-mobile colleagues is inversely proportional to the average time they spend in their home countries, roughly speaking. That is, publishing with returnees is not associated with increasing collaborations with foreign scientists once we control for the non-mobile scientist's visibility and past foreign collaborations. The elasticity between the number of partnerships with mobiles and foreigners is more significant for the diaspora than for intermittent, particularly in the Colombian case.

We also find that not all non-mobile scientists benefit equally. STEM non-mobile scientists benefit less from co-authoring with mobile scientists than scientists in the social sciences and humanities in Colombia, probably because STEM scientists have a higher propensity of being included in international teams by the nature of their work, e.g., to run experiments in local contexts, regardless of their interactions with mobile colleagues. Another explanation is

that STEM scientists may need more infrastructure to conduct research, which is available in Brazil, but not in Colombia: co-authoring with mobile scientists may bring networks, but not labs. However, STEM non-mobile scientists benefit from diaspora scientists as much as non-mobile scientists in SSH, even in Colombia.

The Difference-in-Difference event study results confirm that non-mobile scientists who co-author with a mobile scientist publish more with foreign colleagues than their Brazilian or Colombian peers who do not co-author with mobile scientists. The more mobile scientists they co-author with, the greater the extent to which their work includes foreign scientists. Before co-authoring with mobile, there was no significant difference between non-mobile scientists concerning the number of publications co-authored with foreign scientists. However, as soon as they collaborate with mobile scientists, the number of publications with foreign scientists increases by 20% concerning their non-mobile peers. However, this positive effect is due to the non-mobile scientist joining a team including mobile and foreign scientists. The Colombian non-mobile scientist who collaborates with one or two mobile scientists experiences this benefit only for the year of the collaboration. The effect is longer-lived with three or more such associations, but continuous interactions with mobile scientists sustain it. In Brazil, the pattern is similar, though longer lasting for fewer interactions with mobiles. In both cases, the benefit of a single collaboration with a mobile scientist quickly goes to zero. To sustain a higher publication rate with foreign scientists, non-mobile scientists must continue collaborating with mobile scientists. In other words, mobile scientists connect the non-mobile to foreign scientists but retain the role of obligatory gateways for further connections.

Results from the event study are similar for STEM and SSH. One interesting difference is that in Colombia, SSH non-mobile scientists need to collaborate with more mobile scientists to maintain their connections to foreign scientists than in STEM.

We also observe a minor difference between mobility patterns than in the OLS results. In Brazil, collaborating with returnees has longer-lasting effects on future collaborations than collaborating with diaspora or intermittent. These longer-term patterns of remaining commenced to foreign scientists need further investigation.

The paper is structured as follows. Section 2 presents a literature review. Section 3 explains the institutional setting. Section 4 describes the data and the empirical strategy. Section 5 presents OLS regression results. Section 6 documents the Event studies methods and results. Section 7 concludes the paper.

2. Literature review

2.1 International scientific mobility

As knowledge has become a critical economic asset, creating new knowledge is vital to countries' socioeconomic development (Romer, 1990). Given that old knowledge is the primary input to new and that creation is often a form of re-combination, knowledge creation can be perceived essentially as a network process in which agents share resources, cooperate, and learn from each other to advance science (Nowotny et al., 2003). Re-combination is more successful if agents access diverse knowledge sources, implying links between different parts of the knowledge network could be significant (Mohnen, 2022). Scientists and policymakers understand this network feature which duly appears in various mechanisms and policies to promote it. One mechanism is international scientific mobility: scientists access different knowledge by crossing borders. Upon returning to their home countries, they bring unknown knowledge that can be applied to socio-economic issues (Cañibano, 2017).

The idea that international scientific mobility affects countries' scientific performance has been in the literature for several years. Studies build on opinions implicit in the concept of the Scientific and Technical Human Capital model (STCH) (Bozeman, Dietz, and Gaughan, 2001). First, an experience abroad will likely increase a scientist's human capital (e.g., Knowledge, skills, and abilities) by allowing the scientist to tap into novel knowledge, absorb tacit knowledge, and access infrastructure. Second, an experience abroad may enlarge personal and professional networks. These imply that international mobility should be positively associated with a scientist's higher research capacity and social capital (see Jonkers and Cruz-Castro, 2013; Liang, Gu, and Nyland, 2022). Starting with the idea that mobility may increase a scientist's Scientific and Technical Human Capital, studies primarily focus on demonstrating the positive impact of mobility on a scientist's performance and network.

The first group of studies investigates the performance of mobile scientists, concluding that mobile scientists have higher performance than scientists with foreign experience (non-mobile scientists) across different scientific fields and countries. For example, relying on bibliometric data, Jonkers and Cruz-Castro (2013), looking at 124 life-science Argentinean scientists, find that mobile scientists have more international co-publications than non-mobile scientists. Relatedly, Aykac (2021) documents that Turkish mobile scientists with research stay in the United States obtain more citations than non-mobile scientists without foreign experience. Combining bibliometric and survey data on 47,000 scientists from 16 countries, Franzoni, Scellato, and Stephan (2014) find

that international mobility increases the number of articles they publish in high-impact journals.

The second group investigates scientists' social capital by testing whether mobile scientists have more extensive co-authorship networks – a proxy for professional networks – than non-mobile scientists (Gibson and McKenzie, 2014; Petersen 2018; Scellato et al., 2015). A recurring finding is that mobile scientists display more co-authors than non-mobile scientists (Gibson and McKenzie, 2014; Petersen, 2018). But studies also tend to agree that collaboration with host country scientists falls when mobile scientists return to their home countries (Jonkers and Tijssen, 2008; Kahn and MacGarvie, 2012). Nonetheless, despite the reduction of international collaboration when they return home, mobile scientists collaborate more with foreign scientists and have larger foreign capital than home country's non-mobile scientists (Wang et al., 2019).

A third group compares the performance of diaspora, returnees, and non-mobile scientists. (Cao et al., 2020; Scellato et al., 2015). Several studies report that diaspora scientists have a higher performance (e.g., publish more articles and receive more citations) and have more extensive networks (number of foreign co-authors) than the other two types of scientists (Aykac, 2021). Generally, diaspora scientists have specific expertise and networks, allowing them to remain at highly competitive institutions abroad. Second, these scientists usually work in environments with high-quality infrastructures, leading researchers, and more funding opportunities (Liang et al., 2022; Velema, 2012). Hence, they access more scarce resources in their home countries, enabling them to research at the scientific frontier. Studies also recount that non-mobile scientists cite returnees more frequently and co-author more with returnees than diaspora scientists. Geographical proximity and returnees' willingness to align the research agenda to topics investigated in their home countries explain this latter finding (Kahn and MacGarvie, 2012, 2016; Trippel, 2013).

2.2 Cooperation in science

It is commonplace now that science is a cooperative endeavor. Between 2000 and 2009, the proportion of papers on the Web of Science with multiple authors rose from 69 to 78% (Gazni et al. 2011). Similarly, the number of authors per paper rose from 3.3 to 4.1 on average. Driving this may be the importance of interpersonal ties for knowledge flows (for example, Breschi and Lissoni, 2006 or Singh, 2005) and increased specialization. Thus, making links with collaborators becomes part of the scientific process. Trust (cohesiveness), similarity (homophily), and structural position have all been found to explain tie formation in general (Abbasi, 2016), and these factors are present in tie formation among scientists (Dahlander and McFarland, 2013; Rivera León, Cowan, and

Müller, 2016).

However, in general, less studied than link formation is how a scientist's (non-network) properties might affect either link formation or performance of nearby (in network space) scientists. One such example investigating the structural position of star medical scientists in a co-authorship network finds that scientists who provide more access to unique nodes have a more significant impact on the scientific output of their peers (Mohnen, 2022). Another study that investigates the peer effect of Chinese returnee scientists finds that returnees do not increase their peers' international collaborations (Yang, Cai, and Li 2022). Contrarily, Barnard, Cowan, and Müller (forthcoming) find different results. Investigating whether there is a social capital spillover among South African scientists, the authors find that scientists with cumulated foreign social capital help other scientists to form foreign ties. This paper is closest in spirit to the current paper, in that both ask whether a mobile scientist's foreign social (scientific) capital facilitates certain types of link formation of non-mobile colleagues.

2.3 Mobility, cooperation, and tie formation

Different studies suggest that mobile scientists connect the science systems in their home countries and those in which they have sojourned. (Gibson and McKenzie, 2014; Jöns 2009). Based on the premise that mobile scientists have greater foreign social capital, these studies argue that mobile scientists, especially returnees, serve as bridges between the local and global scientific systems. These studies focus on “first-order effects”. They compare the properties of various types of mobile scientists with non-mobile scientists. Trippel (2013), for example, shows that mobile star scientists retain links of different kinds (including co-authorship) with home scientists (who themselves might or might not be mobile). Gibson and McKenzie (2014) find that mobile scientists (diaspora or returnees) in three small Pacific Island countries have more international co-authors than non-mobile scientists. Scelleto et al. (2015) show that, in general, migrants have more internationally focused collaboration networks than non-mobile scientists.

These studies show that mobile scientists may connect the home science system to the broader world of science. And they can do it in various ways. What needs to be explicitly addressed in these studies, however, is whether mobile scientists assist non-mobile scientists in forming international connections. Does a mobile scientist provide a conduit through which a non-mobile scientist can interact *directly* (more specifically, become co-authors) with scientists in the rest of the world?

To our knowledge, only Müller et al. (forthcoming) provide initial evidence on this role. But they consider only returnees and home scientists, neglecting

the part of the diaspora scientists (who may have ties in the home country) and scientists who return only for short periods. We extend their work to analyze the complete set of scientists, including diaspora scientists and scientists who produce only temporarily to serve as brokers. Unlike their work, we rely on a quasi-experiment methodology to demonstrate the role of mobile scientists in helping non-mobile scientists form foreign ties inferred through academic co-publications.

3. Institutional context

We focus on Brazil and Colombia for the following reasons. Brazil has Latin America's most extensive scientific system (Negri, 2018). Brazil ranks as the country with the highest share of scientific publications and the 13th position relative to the world, with 370,00 articles indexed on the Web of Science between 2015 and 2020, representing 3.2% of the world's scientific publications (CGEE, 2021).

Colombia ranks 5th in Latin America in terms of publication counts. The country has been recently upgrading its scientific system. For instance, Colombia has increased the number of graduate programs by 500% in 10 years and established a ministry of Science and Technology (Observatorio Colombiano, 2021). The number of Colombian publications in top journals displays exponential growth (Lemarchand, 2012).¹

Despite recent improvements in their scientific systems, Brazil and Colombia are less productive than high-income countries in producing knowledge outputs. One policy these countries adopt to promote scientific productivity is the Ph.D. training of citizens abroad. In Brazil, the CAPES and CNPq support Brazilian citizens in obtaining a Ph.D. abroad. In Colombia, Colciencias and Colfuturo have sponsored Colombian citizens to conduct doctoral training overseas. Hence, Brazil and Colombia are noteworthy examples of countries with a developing scientific system where the national government supports international scientific mobility from the Ph.D. stage.

Given that national governments from Brazil and Colombia have invested extensively in mobility programs for citizens to obtain a Ph.D. abroad, we investigate the impact of these mobility experiences. The effect at the individual level has been broadly researched in the literature. As such, we have opted to explore the externalities (if any) in creating channels to connect the country of origin with foreign scientists.

4. Data and empirical strategy

4.1 Data

4.1.1 Sources

We combined data on Curriculum Vitae (CVs), Ph.D. scholarships, and bibliometric data of a large sample of scientists in Colombia and Brazil.

CVs. Federal governments have established public CV platforms (Lattes and CvLAC) to track national research progress and standardize recruitment in research and teaching positions. Lattes and CvLAC are unique datasets with detailed, self-reported information on scientists' academic backgrounds, publications, and careers. We use these sources to extract information on 1) the nationality of researchers to distinguish Colombian and Brazilian scientists at home and abroad from non-Colombian/Brazilian scientists; 2) academic background information to identify whether a scientist has conducted a full Ph.D. abroad; and 3) a set of self-reported publications to improve the matching with bibliometric data. We extracted these data from CVs by accessing available governmental open data repositories. In the Brazilian case, these were complemented with previously removed data (Mena-Chalco and Junior, 2009).

Ph.D. scholarships. Because not all mobile scientists are incentivized to update their CVs on Lattes and CVLAC when moving abroad to study, we retrieved data on scholarship holders from the central Brazilian and Colombian funding agencies' web pages. For Brazil, we obtained data from CNPq and Capes. For Colombia, we got data from the official lists published by the Ministry of Science, the Colfuturo Foundation, and Fulbright Colombia. We extracted information on the names of the scholarship holders, their Ph.D. starting date, disciplines, and the countries to which they applied.

Bibliometric data. To build the mobility pattern and co-authorship network of Brazilian and Colombian scientists, we retrieved bibliometric data from OpenAlex, a global open-access database with more than 200 million scientific publications, which builds on Microsoft Academic Graph and is regularly updated using several sources (Singh Chawla, 2022). We use the bibliometric data to determine the publication records of the Brazilian and Colombian scientists retrieved from Lattes and CVLAC and compute: 1) their mobility patterns based on country of affiliation; 2) their co-authorship networks (including with foreign scientists); 3) academic seniority, and 4) scientific productivity.

4.1.2 Data matching

We match information from the scholarship and the bibliometric data to build our database. First, we matched scholarship lists to Lattes and CVLAC using fuzzy matching of names, disciplines, and institutions. We manually checked the results.

Second, we matched all scientists in Lattes and CVLAC with their publications in OpenAlex using disambiguation procedures developed in the scientometrics literature (D'Angelo & van Eck 2020).² We combined the following information: author names fuzzy match, ORCID identifiers, publications title, other bibliographic metadata (e.g., ISSN, DOI, year, volume), DOI, and self-citations. We defined several selection criteria based on the above data to maximize precision and recall.

The initial number of scientists in Brazil is 139,655, and in Colombia is 28,729. We matched with high precision a large sample of 102,422 (73%) scientists in Brazil and 19,661 (68%) in Colombia.

4.2 Definition of mobility patterns

In our analysis, we distinguish between three main groups of scientists: mobile, non-mobile, and foreigner. Following the literature, we define mobile scientists who have moved abroad to obtain full doctoral training (Brazil and Colombia) or after their Ph.D. (Brazil) (Liang et al. 2022; Turpin et al. 2008).

We define non-mobile scientists who have done graduate training in home country and have yet to move to a foreign country for more than 12 months to work in academia. We focus on researchers registered in Lattes and CVLAC with a Ph.D. in progress, completed, or listed as grantees of scholarships to study abroad. Because it is possible in Colombia to access academic careers without a Ph.D., we extended our definition of non-mobile scientists to those without a Ph.D. but with at least three publications.

We need to identify foreign collaborators — those holding neither Colombian nor Brazilian nationality — of our non-mobile scientists. Following Barnard, Cowan, and Moritz (forthcoming), we identified as foreigners all co-authors not present in Lattes and CVLAC. Because scientists may migrate before their Ph.D. or obtain a foreign scholarship, some foreigners may be Colombian or Brazilian. We identified them as foreigners who would overestimate collaborations with foreign scientists and underestimate collaborations with mobile scientists. In three steps, we recognized Colombian and Brazilian mobile scientists in OpenAlex who did not appear in Lattes and CVLAC. First, we created a list of common Brazilian or Colombian name-surname combinations from the most frequent combinations in CVLAC and Lattes databases and national registries of

names in Colombia and Brazil. Second, we matched common name-surname combinations with the foreign coauthors identified in OpenAlex. Third, we redefined as mobile-matched authors that have published only in national journals, or affiliated only with national organizations throughout their careers, based on OpenAlex. All other co-authors were defined as foreigners.

We further divide mobile scientists into three types that may have different patterns of interaction with non-mobile scientists and other connectivity to foreign scientists: returnees (R), diaspora (D), and intermittent (I). Returnees are scientists who have returned home indefinitely at most one year after the Ph.D. and spent only one year abroad over the rest of their career until the last year of observation (no foreign affiliations among their publications since their Ph.D.). Diaspora are scientists who never returned home to work in academia after finishing their Ph.D. abroad (no Colombian/Brazilian affiliation among their publications). Intermittent are scientists who returned home to work for at least one year and worked abroad for at least one year (this includes Brazilian scientists who obtained a Ph.D. in Brazil and moved after).

4.4. Empirical strategy

Our objective is to study whether the collaboration between non-mobile and foreign scientists is influenced by collaboration with mobile scientists. In other words, does collaborating with mobile scientists connect the non-mobile with foreign scientists and thus increase the chances of further collaboration with them? We identify collaboration as a co-authorship. First, we investigate the intensive margin of collaborating with a mobile scientist by estimating the probability that a home scientist collaborates with any number of foreign scientists as a function of collaborating with a mobile scientist. Second, we investigate the extensive margin: we estimate the number of collaborations of non-mobile scientists with foreign scientists as a function of collaborating with mobile scientists. Third, we explore how results differ for different groups of scientists. We explore field heterogeneity and ask whether non-mobile science, technology, engineering, and mathematics (STEM) gain from collaborations with mobile scientists relative to social sciences and humanities (SSH) scientists. We also distinguish between different types of mobile scientists (returnees, intermittent, and diaspora).

We estimate two main equations separately for Brazil and Colombia.

Intensive Margin. We use Ordinary Least Square (OLS) and estimate the following linear probability model (LPM):

$$y_{it} = \beta_0 + \beta_1 X_{i,t} + \beta_2 STEM_i + \beta_3 STEM_i * X_{i,t} + \Gamma E_{i,t-1} + E_{i,t} \quad (1)$$

where y_{it} is a binary variable indicating whether a non-mobile scientist collaborates at least once with a foreign scientist (at least one co-authored publication); $X_{i,t}$ is our main variable of interest, which measures the collaborations of non-mobile with mobile scientists using two different specifications: a dummy variable equal to one if the non-mobile scientist has collaborated with at least one mobile scientist ($AMM_{i,t}$), or the cumulative sum of unique mobile scientists with whom they have collaborated ($StkMobSciEncou_{i,t}$); $STEM_i$ is a dummy equal to one for non-mobile scientists in the STEM fields; $\Xi_{i,t-1}$ is a set of control variables : ($AvPub_{i,t-1}$) is the logarithm of the lagged value of average annual publications of the non-mobile scientist over the years since first publication, to control for productivity; ($AvCit_{i,t-1}$) measures the logarithm of the lagged average of citations over the years since first publication to control for scientist i 's visibility; ($StkFRGN_{i,t-1}$) is the logarithm of the non-mobile scientist i 's past stock of foreign co-authors; ($YrSinFP_{i,t}$) years of experience measured as the number of years since the first publication; ($Gender_i$) takes the value of one for male non-mobile scientists. In this first specification, all observations are pooled in one period, such that different persons.

Extensive Margin. To estimate the extensive margin wet a home scientist that appears more than one year is considered to use a panel model with fixed effects as defined in Equation 2:

$$y_{it} = \beta_0 + \beta_1 X_{i,t} + \beta_2 STEM_i + \beta_3 STEM_i * X_{i,t} + \Gamma \Xi_{i,t-1} + \varphi_i + \theta_i + E_{i,t} \quad (2)$$

where y_{it} can be one of the following outputs: 1) share of publications with foreign co-authors; 2) the share of foreign co-authors; 3) the logarithm of the number of publications with foreign co-authors;

4) the logarithm of several foreign co-authors; $STEM_i$ is a dummy equal to one for non-mobile scientists in the STEM fields; $\Xi_{i,t-1}$ is the set of control variables described above; $\varphi_i + \theta_i$ are, respectively, discipline and non-mobile scientist fixed effects.

Table 1 presents the descriptive statistics for Brazilian and Colombian non-mobile scientists. We observe a sample of 61,831 Brazilian and 6,663 Colombian scientists.

Table 1 – Variables descriptive statistics

Country	Variables	N	Mean	Median	SD	Min	Max
Brazil	Foreign collaboration	61831	0,38	0	0,48	0	1
	Average Foreign Co-author	61831	3,06	0,5	71,99	0	13640,67
	Average Foreign Publication	61831	0,78	0,33	1,57	0	202
	Average Share Foreign Publication	61831	0,25	0,18	0,26	0	1
	Average Share Foreign Co-author	61831	0,14	0,08	0,17	0	1
	After Meeting Mobile	61831	0,54	1	0,5	0	1
	Stock of Mobile Scientists Encounters	61831	2,37	1	4,77	0	185
	STEM	61831	0,7	1	0,46	0	1
	Average Publication	61831	1,51	1	1,62	0,04	182
	Average Citation	61831	4,16	0,5	19,44	0	4173
	Stock of Foreign co-author	61831	12,72	2	197,66	0	43283
	Years Since First Publication	61831	8,44	7	6,49	0	31
Colombia	Foreign collaboration	6663	0,31	0	0,46	0	1
	Average Foreign Co-author	6663	5,43	0,33	113,07	0	8543,5
	Average Foreign Publication	6663	0,68	0,33	2,05	0	125,33
	Average Share Foreign Publication	6663	0,24	0,11	0,3	0	1
	Average Share Foreign Co-author	6663	0,2	0,08	0,26	0	1
	After Meeting Mobile	6663	0,5	0	0,5	0	1
	Stock of Mobile Scientists Encounters	6663	1,59	1	2,38	0	46
	STEM	6663	0,56	1	0,5	0	1
	Average Publication	6663	1,33	1	1,49	0,04	66,5
	Average Citation	6663	3,58	0,25	36,74	0	3182,23
	Stock of Foreign co-author	6663	21,13	2	334,84	0	22272
	Years Since First Publication	6663	6,82	6	5,48	0	31

5. Results

This section reports results based on LPM and panel fixed effects estimation in Equations 1 and 2.

5.1. Probability of collaborating with at least one foreign co-author

Tables 2A and B report result from Equation 1, estimating the probability that a non-mobile scientist co-authors with at least one foreign scientist if they have co-authored with any number of mobile scientists. In columns 1 to 4, the critical, independent variable is a dummy taking the value one if the non-mobile scientist has had at least one co-authorship with a mobile scientist.

Columns 5 to 8 contrast the total number of unique mobile scientists with whom the non-mobile scientist has co-authored.

The tables show that collaborating at least once with a mobile scientist (column 1) is related to a 19 percentage points higher probability of collaborating with a foreign scientist in Colombia and 27 percentage points in Brazil. This value falls to 11 percentage points when we add the controls (columns 2, 3, and 4). Nonetheless, the results remain highly significant at 0.01% in both countries. This implies that, once we control for observable features that influence the probability of foreign co-authorship (including previous experience of co-authoring with them), scientists who have spent their entire careers at home are 11% more likely to co-author (again) with a foreign scientist after having co-authored with at least one mobile scientist.

As the number of collaborations with mobile scientists increases, the probability of collaborating with a foreign scientist increases (cols 5-8). In Colombia (Table 2A), column 6 shows that a 10% increase in the stock of mobile scientists with whom the non-mobile collaborates is related to 8 percentage points in the probability of having a foreign co-author. Similarly, in the Brazilian case (Table 4B), a 10% increase is associated with a rise of 6 percentage points in the probability of having a foreign co-author.

The drop in the coefficient when adding controls shows that the past performance of a non-mobile scientist is correlated with collaborating with both mobile and foreign scientists. The estimates for the coefficients of the rules are intuitively appealing and concord with the results in the literature. In columns 2 and 6, we find that an increase of 10% in the average number of past publications is related to an 11-percentage-point positive change in the probability of having a foreign co-author for Colombian scientists and around 19 percentage points change for Brazilian scientists. In cols 3, 4, 7, and 8, we find that scientists' visibility measured by the average number of past citations is statistically and positively correlated with co-authoring with a foreign scientist. Finally, having co-authored in the past with foreign scientists is also related to a higher likelihood of co-authoring with foreign scientists in the future.

Gender and seniority also correlate to the probability of having foreign collaboration. We observe a gender bias: a male non-mobile scientist is more likely to have a foreign co-author than a female after controlling for all other observable characteristics. Additionally, seniority is negatively correlated with the likelihood that non-mobile scientists co-author with foreign scientists, especially in Colombia (although the coefficient is relatively small).

Results suggest a difference between STEM and SSH subjects (columns 4 and 8), especially in Colombia. First, Colombian non-mobile STEM scientists are two to four percentage points more likely to have at least a foreign co-author.

In Brazil, though, the effect is slightly negative (one percentage point less likely). Second, in both Colombia and Brazil in STEM, the gain from collaboration with more mobiles is smaller than in SSH. The probability of co-authoring with a foreign scientist for a 100% increase in mobile co-authors decreases from 11% to 7% in Colombia and 11% to 9% in Brazil (col 8). Finally, we do not find significant disciplinary differences (between STEM and SSH) in the probability that a non-mobile scientist collaborates with at least one foreign scientist

Table 2A – Foreign collaboration (Colombia)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FRGN	FRGN	FRGN	FRGN	FRGN	FRGN	FRGN	FRGN
	Collab	Collab	Collab	Collab	Collab	Collab	Collab	Collab
AfterMeetingMobile	0.186***	0.110***	0.116***	0.118***				
	(0.00340)	(0.00368)	(0.00362)	(0.00519)				
Log_Stk					0.163***	0.0838***	0.0699***	0.105***
MobSciEncou					(0.00259)	(0.00289)	(0.00281)	(0.00401)
Log_AvPub_lag		0.116***				0.117***		
		(0.00439)				(0.00438)		
Log_StkFRGN_lag		0.110***	0.0970***	0.0966***		0.106***	0.0611***	0.0923***
		(0.00167)	(0.00189)	(0.00190)		(0.00168)	(0.00188)	(0.00190)
YrsSinceFirstPub		0.000736	-0.00323**	-0.00316***		0.000552	-0.00351***	-0.00332***
		(0.000385)	(0.000366)	(0.000367)		(0.000388)	(0.000362)	(0.000370)
Gender (Male: 1)		0.0175***	0.0206***	0.0201***		0.0169***	0.0190***	0.0192***
		(0.00335)	(0.00335)	(0.00335)		(0.00335)	(0.00329)	(0.00335)
Log_AvCits_lag			0.0700***	0.0694***			0.136***	0.0701***
			(0.00257)	(0.00258)			(0.00242)	(0.00258)
STEM				0.0151**				0.0365***
				(0.00484)				(0.00476)
STEM*c.Log_StkMobSciEncou								-0.0300***
								(0.00504)
STEM*				-0.00439				
AfterMeetingMobile				(0.00667)				
_cons	0.229***	-0.00322	0.0789***	0.0718***	0.215***	0.00403	0.0904***	0.0698***
	(0.00238)	(0.00663)	(0.00608)	(0.00652)	(0.00238)	(0.00663)	(0.00594)	(0.00649)
N	72548	66683	66683	66683	72548	66683	66683	66683
R ²	0.040	0.166	0.167	0.167	0.052	0.165	0.195	0.167

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2B – Foreign collaboration (Brazil)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FRGNCo llab	FRGNCo llab	FRGNCo llab	FRGNCo llab	FRGNCo llab	FRGNCo llab	FRGNCo llab	FRGNCo llab
AfterMeetingMobile	0.266*** (0.000985)	0.0983*** (0.00117)	0.115*** (0.00119)	0.110*** (0.00192)				
Log_StkMob SciEncou					0.184*** (0.000550)	0.0658*** (0.000832)	0.0909*** (0.000941)	0.105*** (0.00163)
Log_AvPub_lag		0.202*** (0.00142)				0.188*** (0.00148)		
Log_StkFRGN_lag		0.0650*** (0.000667)	0.103*** (0.000609)	0.103*** (0.000609)		0.0600*** (0.000681)	0.0979*** (0.000624)	0.0973*** (0.000626)
YrsSinceFirstPub		0.00292*** (0.000112)	- 0.00338** *	- 0.00345*** (0.000107)		0.00206*** (0.000115)	- 0.00363*** (0.000106)	- 0.00371*** (0.000107)
Gender (Male: 1)		0.0153*** (0.000966)	0.0188*** (0.000976)	0.0193*** (0.000977)		0.0154*** (0.000966)	0.0185*** (0.000975)	0.0188*** (0.000976)
Log_AvCits_lag			0.0383*** (0.000700)	0.0389*** (0.000717)			0.0145*** (0.000809)	0.0164*** (0.000821)
STEM				-0.0146*** (0.00135)				-0.00238 (0.00126)
STEM*AfterMeeting Mobile				0.0112*** (0.00221)				
STEM*log_stkMobScie ntistEncou								-0.0164*** (0.00162)
constant	0.218*** (0.000687)	0.0392*** (0.00122)	0.163*** (0.000944)	0.172*** (0.00122)	0.225*** (0.000627)	0.0687*** (0.00126)	0.186*** (0.000917)	0.187*** (0.00120)
N	862551	862551	862551	862551	862551	862551	862551	862551
R ²	0.074	0.161	0.143	0.144	0.108	0.160	0.144	0.144

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5.2. Share of publications with foreign co-authors (over total publications)

Tables 3A and B display results for the yearly average share of publications with foreign co-authors (over total publications of a non-mobile scientist), including scientific field (cols. 1 and 4) or individual fixed effects (cols 3 and 6) to control for unobserved characteristics that vary across disciplines or scientists. We

report the results for independent variable specifications: co-authoring with any number of mobile scientists (columns 1-3), and the number of mobile scientists with whom the non-mobile co-authors (columns 4-6).

After controlling for foreign co-authors' non-mobile visibility and stock, interacting with a mobile scientist is positively associated with the share of publications with foreign co-authors. The magnitude of the leading independent variable coefficient in col 1 with field fixed effects suggests that meeting a mobile is associated with an increase in the share of publications with foreign co-authors by 3.7 for Colombian scientists and 4.3 for Brazilian scientists. The coefficient increases when the estimation uses individual fixed effects: 5.8 in the Colombian case and a 5.6 higher share for Brazil. This suggests that collaboration with a mobile scientist is more relevant to explain an increase in collaborations with foreign authors when comparing within the career of a non-mobile scientist than when comparing non-mobile scientists collaborating with mobile scientists with those who do not.

The general result is the same when we use a count of collaborations (columns 4-6) rather than a binary indicator. Individual fixed effects seem to matter a lot – their inclusion significantly affects coefficient estimates and improves the regression's predictive power. The coefficient estimates (column 6) indicate that the elasticity of increasing the number of mobile collaborators on the of foreigners among non-mobile scientists' co-authors is about 6 percent in both countries.

Disciplinary effects are challenging to identify. Discipline does not affect foreign collaboration patterns when individual fixed effects are included. This might not be surprising as a discipline is primarily captured in individual fixed effects (few change from STEM to SSH over their careers). However, when the field is explicitly treated (excluding individual effects), we see that STEM researchers are more international than SSH researchers (column 5). At the same time, though, discipline interacts with the main effect of interest in Colombia rather than Brazil. On average, the elasticity of an increase in mobile interactions is about 0.03. However, the interaction between STEM discipline and several interactions is about -0.026. This suggests that the net effect of increasing interactions with mobile scientists for a Colombian STEM researcher is close to zero.

Table 3A – Average share of foreign publication, panel (Colombia)

	(1)	(2)	(3)	(4)	(5)	(6)
	AvShare	AvShare	AvShare	AvShare	AvShare	AvShare
	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub
AfterMeeting Mobile	0.0366***	0.0420***	0.0580***			
	(0.00218)	(0.00309)	(0.00399)			
Log_StkMob SciEncou				0.0135***	0.0300***	0.0565***
				(0.00172)	(0.00239)	(0.00337)
Log_StkFRGN_lag	0.119***	0.118***	0.0850***	0.118***	0.117***	0.0832***
	(0.00114)	(0.00113)	(0.00185)	(0.00114)	(0.00113)	(0.00187)
YrsSinceFirstPub	-0.00672***	-0.00672***	0.00473***	-0.00630***	-0.00628***	0.00479***
	(0.000219)	(0.000218)	(0.000288)	(0.000220)	(0.000220)	(0.000292)
Gender (Male: 1)	0.0118***	0.0105***	0	0.0116***	0.0102***	0
	(0.00204)	(0.00199)	(.)	(0.00204)	(0.00199)	(.)
Log_AvCits_lag	0.0352***	0.0355***	-0.0363***	0.0375***	0.0382***	-0.0409***
	(0.00153)	(0.00153)	(0.00231)	(0.00154)	(0.00154)	(0.00233)
STEM		0.0191***	0		0.0344***	0
		(0.00288)	(.)		(0.00284)	(.)
STEM*After Meeting Mobile		-0.00736	0.00622			
		(0.00397)	(0.00482)			
STEM*Log_StkMo b					-0.0263***	-0.00944*
SciEncou					(0.00300)	(0.00393)
_cons	0.0944***	0.0862***	0.0982***	0.113***	0.0947***	0.101***
	(0.00368)	(0.00388)	(0.00183)	(0.00214)	(0.00257)	(0.00181)
Field FE	Yes	No	No	Yes	No	No
Individual FE	No	No	Yes	No	No	Yes
N	66683	66683	66637	66683	66683	66637
R ²	0.297	0.296	0.562	0.295	0.294	0.562

Standard errors in parentheses

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 3B – Average share of foreign publication, panel (Brazil)

	(1)	(2)	(3)	(4)	(5)	(6)
	Avgshare	Avgshare	Avgshare	Avgshare	Avgshare	Avgshare
	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub
AfterMeetingMobile	0.0438***	0.0318***	0.0564***			
	(0.00405)	(0.00611)	(0.00456)			
Log_StkMobSciEncou				0.0300***	0.0268**	0.0618***
				(0.00307)	(0.00788)	(0.00749)
Log_StkFRGN_lag	0.0725***	0.0740***	-0.0218***	0.0712***	0.0728***	-0.0251***
	(0.00182)	(0.00189)	(0.00216)	(0.00201)	(0.00208)	(0.00234)
YearsSinceFirstPub	-	-	0.00872***	-0.00455***	-0.00450***	0.00879***
	0.00450***	0.00447***				
	(0.000315)	(0.000326)	(0.000509)	(0.000359)	(0.000370)	(0.000606)
Gender (Male: 1)	0.00814*	0.0107***	0	0.00760*	0.0104***	0
	(0.00347)	(0.00222)	(.)	(0.00336)	(0.00222)	(.)
Log_AvCits_lag	-0.00265	-0.00525*	-0.00344	-0.00964***	-0.0113***	-0.0238***
	(0.00166)	(0.00187)	(0.00266)	(0.00240)	(0.00239)	(0.00322)
STEM		0.00967	0		0.0170**	0
		(0.00628)	(.)		(0.00579)	(.)
STEM*After		0.0169*	0.0134*			
MeetingMobile		(0.00671)	(0.00580)			
STEM*Log_					0.00224	-0.00427
StkMobSciEncou					(0.00748)	(0.00739)
_cons	0.164***	0.155***	0.157***	0.173***	0.160***	0.169***
	(0.00176)	(0.00429)	(0.00149)	(0.00241)	(0.00442)	(0.00220)
Field FE	Yes	No	No	Yes	No	No
Individual FE	No	No	Yes	No	No	Yes
N	862551	862551	862551	862551	862551	862551
R2	0.129	0.127	0.397	0.128	0.126	0.397
Standard errors in parentheses * p < 0.05, ** p < 0.01, *** p < 0.001						

5.3. Number of publications with foreign co-authors

The share of publications with foreign co-authors (Tables 3A and B) is affected by the overall productivity of the non-mobile scientist. Interaction with a mobile scientist may have two effects: it may change publications overall and the extent of “internationality” of a scientist’s co-authors (publications with foreign scientists). Thus, an increase in the proportion of “foreign” papers may be driven by a reduction in “domestic” articles rather than an increase in publications with

foreign authors. To address this, we report results for the number of publications with foreign co-authors in Tables 4A (Colombia) and 4B (Brazil) (for at least one collaboration with mobile scientists in columns (1-3) and for stock of collaborations with mobile scientists in columns (4-6)).

Results are very similar to those discussed in Section 5.2, suggesting that the higher share of publications with foreign co-authors following collaboration with mobile scientists is driven by an increase in the number of publications with foreign co-authors rather than a decrease in purely domestic publications. Collaborating with a mobile scientist is associated with a rise of 5% (7%) in the number of publications with foreign co-authors (column 2 in a log-log specification) for Colombian (Brazilian) non-mobile scientists. When we control for individual fixed effects, the magnitude of the coefficient is higher: 7% and 11% increase, respectively (column 3). This finding corroborates the previous results: meeting a mobile may be necessary for a home scientist to forge a strategy for accessing foreign collaborators.

The coefficients on the log stock of unique mobile scientists' collaborations in the last three columns (4-6) show that an increase in mobile scientists' collaborators is positively related to the rise in average publications with foreign scientists. For example, in col 6 (with individual fixed effects), the elasticity of foreign publications regarding the number of unique mobile scientists with whom non-mobile collaborate is 0.1 (0.15) for Colombia (Brazil). So, a doubling in the stock of mobile collaborators in a non-mobile scientist's career leads to a 10% increase in the number of publications with foreign co- authors in the case of Colombia and 16% in the case of Brazil.

Table 4A – Average foreign publication, panel (Colombia)

	(1)	(2)	(3)	(4)	(5)	(6)
	Log_	Log_	Log_	Log_	Log_	Log_
	AvFRGp ub	AvFRGp ub	AvFRGp ub	AvFRGp ub	AvFRGp ub	AvFRGp ub
AfterMeetingMobile	0.0506*** (0.00329)	0.0515*** (0.00325)	0.0743*** (0.00596)			
Log_StkMobSci Encou				0.0440*** (0.00259)	0.0554*** (0.00360)	0.104*** (0.00502)
Log_StkFRGN_lag	0.175*** (0.00171)	0.174*** (0.00170)	0.127*** (0.00276)	0.173*** (0.00172)	0.171*** (0.00171)	0.120*** (0.00278)
YrsSinceFirstPub	-0.0111*** (0.000330)	-0.0113*** (0.000329)	0.00357*** (0.000430)	-0.0114*** (0.000332)	-0.0115*** (0.000332)	0.00174*** (0.000434)
Gender	0.0302*** (0.00307)	0.0313*** (0.00300)	0 (.)	0.0299*** (0.00307)	0.0307*** (0.00300)	0 (.)
STEM			0 (.)		0.0184*** (0.00427)	0 (.)
AfterMeetingMobile* STEM			0.0307*** (0.00719)			
STEM*Log_StkMobSciEncou					-0.0201*** (0.00452)	0.0289*** (0.00585)
Log_AvCits_lag	0.146*** (0.00232)	0.147*** (0.00231)	0.0296*** (0.00345)	0.146*** (0.00232)	0.147*** (0.00232)	0.0170*** (0.00346)
constant	0.0784*** (0.00556)	0.0786*** (0.00546)	0.123*** (0.00273)	0.111*** (0.00322)	0.103*** (0.00388)	0.120*** (0.00269)
Field FE	Yes	No	No	Yes	No	No
Individual FE	No	No	Yes	No	No	Yes
N	66683	66683	66637	66683	66683	66637
R2	0.394	0.392	0.630	0.394	0.393	0.633

Standard errors in parentheses

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 4B – Average foreign publication, panel (Brazil)

	(1)	(2)	(3)	(4)	(5)	(6)
	log_Avg	log_Avg	log_Avg	log_Avg	log_Avg	log_Avg
	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub
AfterMeeting Mobile	0.0733*** (0.00485)	0.0703*** (0.00666)	0.118*** (0.00666)			
Log_StkMob SciEncou				0.0890*** (0.00629)	0.0951*** (0.00940)	0.156*** (0.0128)
Log_	0.166***	0.170***	0.00378	0.157***	0.162***	-0.00788
StkFRGN_lag	(0.00393)	(0.00446)	(0.00398)	(0.00426)	(0.00465)	(0.00438)
YrsSince	-0.00896***	-0.00894***	0.0138***	-0.00953***	-0.00950***	0.0128***
FirstPub	(0.000731)	(0.000841)	(0.000853)	(0.000848)	(0.000898)	(0.00128)
Gender	0.0293**	0.0312**	0	0.0283**	0.0315**	0
(Male: 1)	(0.00783)	(0.00835)	(.)	(0.00789)	(0.00891)	(.)
STEM			0		-0.00858	0
			(.)		(0.0106)	(.)
AfterMeeting Mobile*STEM			0.00294 (0.0133)			
STEM*Log_Stk					-0.0130	-0.0141
MobSciEncou					(0.00995)	(0.0135)
Log_AvCits_lag	0.0821*** (0.00566)	0.0769*** (0.00746)	0.0596*** (0.00435)	0.0541*** (0.00654)	0.0517*** (0.00698)	0.00832 (0.00635)
_cons	0.186*** (0.00458)	0.185*** (0.0114)	0.194*** (0.00632)	0.196*** (0.00586)	0.200*** (0.00937)	0.213*** (0.00825)
Field FE	Yes	No	No	Yes	No	No
Individual FE	No	No	Yes	No	No	Yes
N	862551	862551	862551	862551	862551	862551
R ²	0.297	0.293	0.550	0.303	0.299	0.555

Standard errors in parentheses

* p < 0.05, ** p < 0.01, *** p < 0.001

5.4. The role of different types of mobile scientists

Finally, we separate mobile scientists by types (returnee, diaspora, and intermittent) (Tables 5A and B) for both the share (columns 1-5) and the number (6-8) of publications with foreign scientists.

In column 1, we report results without controls. In the case of Colombia, collaborating with a higher stock of mobile diaspora scientists is associated with an increase in the share of publications with foreign co-authors that is six times as large as that of increasing the stock of returnee mobile scientists; and three times as large as that of increasing the stock of returnee mobile scientists. Indeed, when we add controls and discipline fixed effects (cols 2 and 3), we find that for the

Colombian case, an increase in the number of collaborations with returnees is not associated with a significant increase in the portfolio of publications with foreign co-authors for non-mobile scientists. Similar results are found in the Brazilian case, where diaspora and intermittent mobile scientists have a three times higher positive correlation with the share of publications with foreign co-authors than increasing the stock of returnee mobile scientists (column 1). In the Brazilian case, there is less difference between the intermittent and the diaspora scientists in connecting Brazilian non-mobile scientists with the rest of the world.

In column 4, we see that the significant difference in the role of different types of mobile scientists in Colombia arises partly in STEM. For all non-STEM non-mobile scientists, the correlation between co-authoring with returnees and the share of publications with foreign coauthors is positive and significant even when controlling for observable features. However, for STEM scientists collaborating with mobile returnees, it is negative.

Because STEM non-mobile scientists are more likely to co-author with foreign scientists than SSH scientists, this result suggests that, in Colombia, returnee substitute for foreign scientists: non-mobile STEM scientists collaborate with either returnees or foreign co-authors, not with both. Once more, results are different with individual fixed effects, suggesting a positive association for all scientists when assessing the role of returnees over their careers.

In the Brazilian case (col 2), we also find that an increase in the stock of returnees is not correlated with the share of foreign publications. Nonetheless, we see a positive and slightly statistically significant result when we control for field-fixed effects (col 3), although the coefficient magnitude is small.

Collaborating with Colombian scientists that do not come back (diaspora) or that are intermittent abroad is instead associated with an increased share of publications with foreign co-authors for all scientists. Results are very similar for the number of publications with a foreign scientist (cols 6-8). We find similar results in the Brazilian case. The notable difference is that increasing the number of collaborations with diaspora scientists is not correlated with the number of foreign publications when we do not control for fixed effects (discipline or individual).

Table 5A – Average share of foreign publication (by different mobility categories),
panel (Colombia)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Avgshare FRGNpu b	Avgshare FRGNpu b	Avgshare FRGNpu b	Avgshare FRGNpu b	Avgshare FRGNpu b	log_Avg FRGNpu b	log_Avg FRGNpu b	log_Avg FRGNpu b
log_stkRTRN	0.0314*** (0.00231)	-0.00172 (0.00211)	-0.00347 (0.00212)	0.0158*** (0.00322)	0.0337*** (0.00483)	0.0214*** (0.00319)	0.0353*** (0.00485)	0.0596*** (0.00719)
log_stkDiasp1	0.197*** (0.00823)	0.0570*** (0.00716)	0.0574*** (0.00716)	0.0621*** (0.0118)	0.0649*** (0.0145)	0.0801*** (0.0108)	0.0615*** (0.0178)	0.0498* (0.0215)
log_stkInterm1	0.0962*** (0.00231)	0.0183*** (0.00214)	0.0169*** (0.00215)	0.0262*** (0.00327)	0.0468*** (0.00497)	0.0423*** (0.00324)	0.0517*** (0.00492)	0.0913*** (0.00740)
Log_AvCits_lag		0.0385*** (0.00153)	0.0374*** (0.00154)	0.0382*** (0.00154)	-0.0427*** (0.00234)	0.145*** (0.00232)	0.146*** (0.00232)	0.0136*** (0.00348)
Log_StkFRGN_lag		0.117*** (0.00114)	0.117*** (0.00115)	0.116*** (0.00114)	0.0820*** (0.00187)	0.171*** (0.00173)	0.170*** (0.00172)	0.119*** (0.00279)
YrsSinceFirstPub		-0.00627** (0.000220)	-0.00614** (0.000220)	-0.00612** (0.000220)	0.00508** (0.000287)	-0.0114*** (0.000332)	-0.0115*** (0.000332)	0.00247** (0.000426)
Gender (Male: 1)		0.0117*** (0.00200)	0.0120*** (0.00204)	0.0108*** (0.00199)	0 (.)	0.0304*** (0.00307)	0.0313*** (0.00300)	0 (.)
STEM				0.0351*** (0.00267)	0 (.)		0.0204*** (0.00403)	0 (.)
STEM*				-0.0312***	-0.0110		-0.0218***	0.00704
c.log_stkRTRN				(0.00413)	(0.00631)		(0.00622)	(0.00938)
STEM*				-0.00777	-0.0278		0.0235	0.0270
c.log_stkDiasp1				(0.0148)	(0.0182)		(0.0222)	(0.0270)
STEM*				-0.0145***	-0.00252		-0.0172**	0.0261**
c.log_stkInterm1				(0.00413)	(0.00639)		(0.00622)	(0.00950)
_cons	0.200*** (0.00146)	0.115*** (0.00210)	0.115*** (0.00211)	0.0969*** (0.00251)	0.106*** (0.00178)	0.116*** (0.00318)	0.106*** (0.00378)	0.132*** (0.00265)
Field FE	No	No	Yes	No	No	Yes	No	No
Individual FE	No	No	No	No	Yes	No	No	Yes
N	72548	66683	66683	66683	66637	66683	66683	66637
R2	0.052	0.293	0.296	0.295	0.562	0.395	0.394	0.633

Standard errors in parentheses

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 5B - Average share of foreign publication (by different mobility categories), panel (Brazil)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Avgshare	Avgshare	Avgshare	Avgshare	Avgshare	log_Avg	log_Avg	log_Avg
	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub	FRGNpub
log_stkRTRN	0.0263**	0.00639	0.00629*	0.0176**	0.0279**	0.0664**	0.0653**	0.0782**
	(0.00829)	(0.00419)	(0.00289)	(0.00465)	(0.00538)	(0.00508)	(0.00420)	(0.00744)
log_stkDiasp	0.0794**	0.0369**	0.0390**	0.0386	0.0505*	0.112***	0.0805	0.104*
	(0.00809)	(0.00630)	(0.00620)	(0.0256)	(0.0223)	(0.0219)	(0.0429)	(0.0385)
log_stkInterm	0.0699**	0.0282**	0.0271**	0.0218**	0.0536**	0.0803**	0.0871**	0.142***
	(0.00463)	(0.00350)	(0.00317)	(0.00735)	(0.00669)	(0.00692)	(0.00944)	(0.0109)
Log_AvCits_lag		-0.00908**	-0.00912**	-0.0106**	-0.0236**	0.0528**	0.0505**	0.00571
		(0.00289)	(0.00243)	(0.00244)	(0.00329)	(0.00659)	(0.00714)	(0.00630)
Log_StkFRGN_lag		0.0726**	0.0714**	0.0729**	-0.0244**	0.157***	0.161***	-0.00722
		(0.00200)	(0.00203)	(0.00209)	(0.00234)	(0.00422)	(0.00461)	(0.00449)
YrsSinceFirstPub		-0.00459***	-0.00449***	-0.00444***	0.00907***	-0.00959***	-0.00956***	0.0132**
		(0.000353)	(0.000359)	(0.000365)	(0.000598)	(0.000858)	(0.000892)	(0.00128)
Gender (Male: 1)		0.0113**	0.00755*	0.0105**	0	0.0277**	0.0306**	0
		(0.00262)	(0.00333)	(0.00222)	(.)	(0.00775)	(0.00878)	(.)
STEM				0.0181**	0		-0.00726	0
				(0.00563)	(.)		(0.0103)	(.)
STEM*				-0.0134	-0.0175*		-0.00596	-0.00614
c.log_stkRTRN				(0.00714)	(0.00789)		(0.0120)	(0.0168)
STEM				0.00059	-0.0199		0.0355	-0.0293

				6				
*c.log_stkDias p				(0.0258)	(0.0233)		(0.0503)	(0.0462)
STEM*				0.00449	- 0.00094 8		-0.0129	-0.0116
c.log_stkInter m				(0.00684)	(0.00650)		(0.0110)	(0.0119)
constant	0.188***	0.172***	0.175***	0.161***	0.171***	0.201***	0.204***	0.217***
	(0.0057 7)	(0.00605)	(0.00245)	(0.00439)	(0.00215)	(0.00548)	(0.00911)	(0.00855)
Field FE	No	No	Yes	No	No	Yes	No	No
Individual FE	No	No	No	No	Yes	No	No	Yes
N	862551	862551	862551	862551	862551	862551	862551	862551
R2	0.065	0.124	0.128	0.125	0.397	0.304	0.300	0.555

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

6. Difference in difference event study

6.1. Empirical strategy

Co-authoring with mobile scientists does not occur randomly. The opportunity for non-mobile scientists to meet with colleagues that have studied or worked abroad depends on their academic careers. Mobile scientists may seek to collaborate with non-mobile scientists based on observable (e.g. past publications) and non-observable (e.g. social skills) characteristics. Results presented in Section 5 control for several observable features that may influence the co-authorship patterns of non-mobile scientists with foreign and mobile scientists (academic tenure, gender, discipline, past publications, citations, and co-authored publications with foreign scientists). Yet, other non-observable features of non-mobile scientists may influence the probability of co-authoring with foreign and mobile colleagues, which may overestimate the role of mobile scientists in connecting them with foreign scientists. For instance, a higher propensity to participate in national and international conferences, communication and writing skills, or where they have studied during their undergraduate or master's degrees and the connections they formed then. Additionally, non-mobile scientists may collaborate with mobile scientists at different points in their careers, on different topics, in various capacities, and in other consortia.

We rely on a difference-in-difference event study design to identify the causal effect of co-authoring with mobile scientists on the number of co-authored

publications of non-mobile with foreign scientists (Borusyak et al., 2022). We use the difference-in-differences estimator with treatment over multiple periods developed by Callaway and Sant’Anna (2021) to estimate the average treatment effect for non-mobile scientists treated in different years. This setup follows a staggered treatment: once treated, a non-mobile scientist remains treated for the following years. In our study, the treatment group is formed by Brazilian and Colombian non-mobile scientists who have co-authored with mobile scientists at least once during the period we observe them. The control group is formed by all other non-mobile Brazilian and Colombian scientists who have never co-authored with a mobile scientist. The estimated outcome indicates the intensity of co-authoring with foreign scientists. To simplify, we use the number of publications co-authored with foreign scientists.

Formally, our difference-in-differences specification is then expressed as:

$$Y_{i,t} = \alpha_1^{g,t} + \alpha_2^{g,t} G_g + \alpha_3^{g,t} 1\{T = t\} + \beta (G_g \cdot 1\{T = t\}) + x_i' \theta + \varepsilon_{it} \quad (3)$$

where $Y_{i,t}$ is the (log-transformed) number of publications co-authored with foreign scientists by the non-mobile scientist i in year t ; G_g is a binary variable that equals one if a non-mobile scientist belongs to the treatment group and becomes first treated in year g and equals zero for the control group; $\alpha^{g,t}$ is the coefficient for the treatment group dummy; β represents the average treatment effect; $\alpha^{g,t}$ represents the coefficient for the post-treatment dummy; x' represents a vector of control variables that are not influenced by the treatment: tenure (years since first publication) and gender.

³ We have checked that there is no statistically significant difference for observable features that can be endogenous but can also be influenced by the treatment (publications and citations) before the treatment between treated and non-treated non-mobile scientists. Following Callaway and Sant’Anna’s (2021) recommendations and Abadie et al. (2023), we clustered standard errors at the individual level.

As observed in Section 4, throughout their career, non-mobile scientists may co-author with more than one mobile scientist in one or more years. This means that some of the non-mobile scientists are treated more than once. To distinguish the effect of one versus multiple treatments, we split the sample according to the number of unique mobile scientists with whom a non-mobile scientist has co-authored. We consider the treatment to be the year of the first co-authored publication because our research question is about the effect of the interaction with a mobile, which does not exclude that the interaction can last for more than one period (although this occurs in a minority of cases in our data – Section 4). Future research may distinguish different types of stable collaborations. We thus

estimate the impact of the first co-authorship with a mobile scientist on the number of co-authored publications with foreign authors for the following samples: 1) non-mobile scientists that have co-authored with any number of mobile scientists (all collaborations); 2) non-mobile scientists that have co-authored with one unique mobile co-author; 3) with two unique mobile co-authors; and 4) with three unique mobile co-authors. We analyze the Colombian and the Brazilian samples separately.

6.2. Results

This section presents the results of the difference in differences event studies, separately for Colombia and Brazil. Each figure has four panels for non-mobile scientists who co-authored with 1) any number of unique mobile scientists; 2) one unique mobile scientist; 3) two unique mobile scientists; and 4) three unique mobile scientists.

Figures 1 and 2 report the estimated effect of co-authoring with mobile scientists on the number of publications co-authored with foreign scientists for the total sample of non-mobile Colombian and Brazilian scientists, respectively.

First, in the five years before co-authoring with a mobile, treated and non-treated non-mobile scientists are similar in the number of papers they co-authored with foreign scientists, regardless of the number of unique mobile co-authors (panels 1-4).

Second, when considering any number of unique mobile co-authors (Figures 1 and 2 panels 1) we observe that after the first co-authorship with a mobile scientist, non-mobile scientists co-author significantly more papers with foreign scientist than the control group of non-mobile scientists that never co-author with a mobile scientist.

Third, the difference is always most significant in the year of the first co-authorship with the mobile scientist. In all scenarios, an average Colombian non-mobile scientist publishes approximately 20% more papers co-authored with a foreign scientist than a Colombian non-mobile scientist who has never co-authored with a mobile. In Brazil, the difference can be as high as 28%. This is a significant effect.

Fourth, in panel 1, there is a significant drop in the probability of foreign collaboration from year zero (the year of the first collaboration with mobile) and year 1 (the first year after). When we consider publishing with any number of mobile co-authors (panel (1)), the difference between treated and non-treated drops to around 10% in the first year after co-authoring. This suggests that the mechanism connecting non-mobile to foreign scientists is a joint publication with

non-mobile, mobile, and foreign co-authors.

Unfortunately, this ‘mechanical’ effect tends not to be sustained through time, i.e., non-mobile Colombian scientists do not remain connected to foreign scientists more than their untreated peers beyond that first co-authorship involving the mobile scientists. We observe this in Figures 1 and 2, panels (2-4). Colombian non-mobile scientists who co-author with only one or two unique mobile scientists are less likely to co-author with foreign scientists in the following years than their untreated peers. Only Colombian scientists who co-author with at least three mobile scientists (in one or multiple years) still see a positive effect after three years. But this effect is because, in these three years, they have a higher probability to co-publish with the foreign co-authors and the mobile, rather than independently. In other words, Colombian non-mobile scientists, on average, need to be re-connected every time to foreign scientists (by a mobile colleague) to continue collaborating with foreigners.

The Brazilian case shows more promising results. Non-mobile scientists who co-author with one single mobile scientist are more likely than their non-treated peers to publish with foreign scientists after one year. Moreover, although in each of the following three years, there is no significant difference between treated and non-treated non-mobile scientists, considering all years together, the average treatment effect is always above zero. The effect of co-authoring with two mobile persists for four time periods (panel 3), and co-authoring with three different mobile scientists persists for at least five years (panel 4). But we need to distinguish if this persistence is because the non-mobile scientist co-authors with the same two mobile and foreign scientists several times or because the non-mobile independently co-authors with foreign scientists. The figure shows that the effect decreases over time, suggesting that the connection may need to be maintained by mobile co-authors throughout the years, also in the Brazilian case.

Fifth, the event study results confirm that increasing the number of unique mobile co-authors positively affects the number of publications co-authored with foreign scientists, as discussed in the OLS regressions (Tables 4A and 4B). However, they also qualify the OLS results, showing that most of that effect is explained by including non-mobile scientists in publications that the mobile co-authors with the foreign scientists. While that may have other positive impacts, we find weak evidence that it helps establish long-lasting links between non-mobile Colombian and foreign scientists. In the Brazilian case, the effect persists longer.

In general, these results demonstrate that interacting with several mobile scientists can benefit non-mobile scientists in expanding their portfolio of foreign collaborations: as non-mobile scientists diversify their network of

mobile scientists, the number of foreign publications increases. Nonetheless, although we find the role played by mobile scientists in leveraging the home scientists’ internationalization process, it is unclear how long the effect of collaborating with mobile last. Understanding the impact length of each interaction in future research is crucial.

Figure 1 - Number of papers with foreign co-authors per year in log (Colombia)

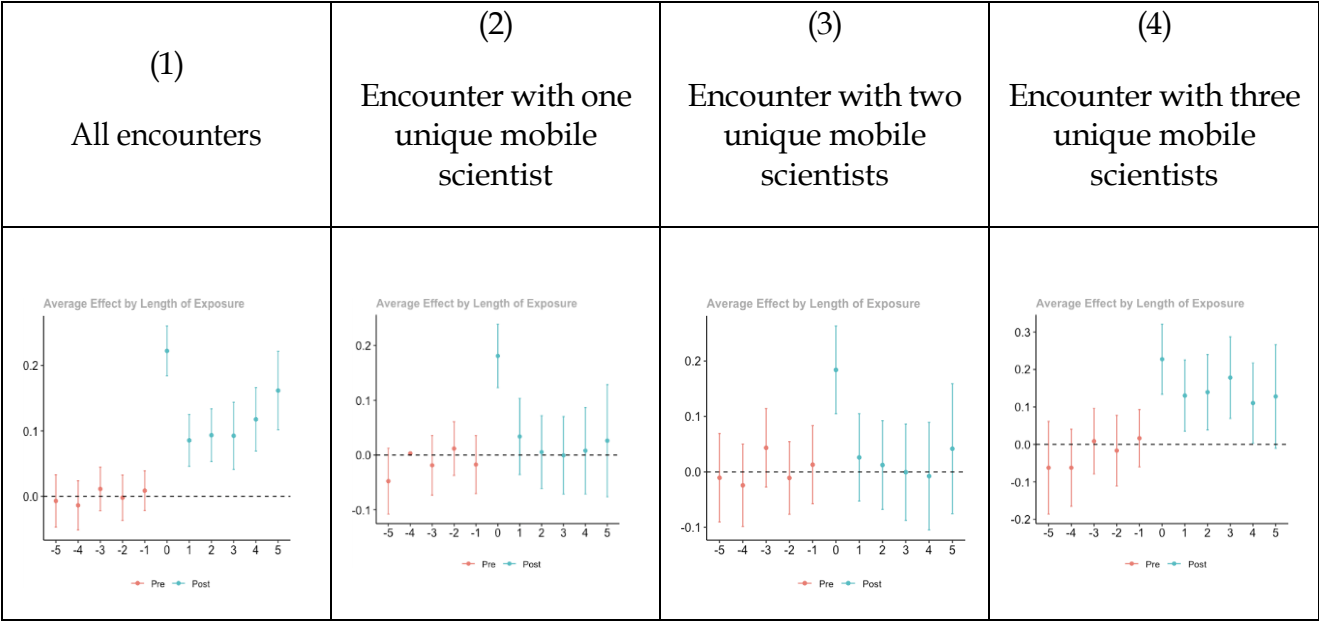
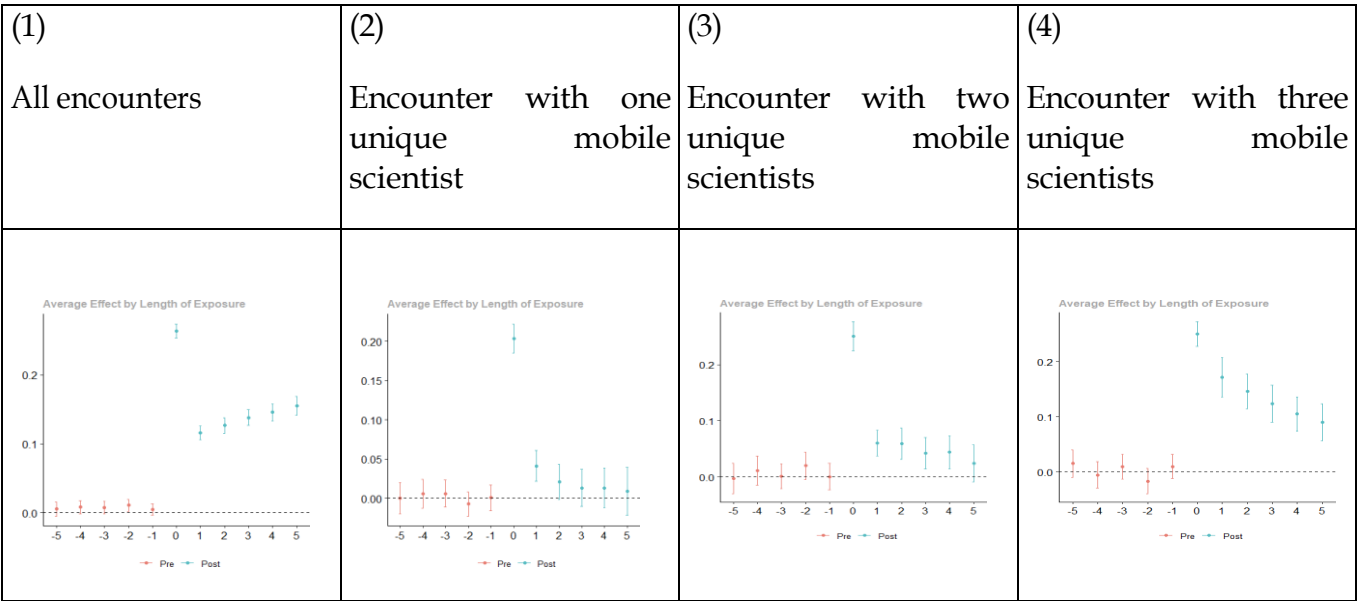


Figure 2 - Number of papers with foreign co-authors per year in log (Brazil)



We next examine whether these effects change for different non-mobile and mobile scientists groups.

We first split non-mobile scientists between STEM and SSH. Figures 3 and 4 compare results for both subsamples for Colombia and Brazil, respectively.

In the case of Brazil, we observe no difference between the two disciplinary groups concerning the average effects in Figure 4. This is consistent with the OLS results that showed no significant difference in the role of mobile scientists between STEM and SSH non-mobile scientists.

In the case of Colombia, the difference in difference estimates does not confirm the OLS results that SSH non-mobile scientists publish more with foreign scientists than STEMs if they also co-author with mobile scientists. We almost see the opposite results, especially when they co-author with only one or two unique mobile scientists. In neither case, there is a significant persistent effect in the years following the ‘mechanical’ increases in publications with foreign co-authors in the year non-mobile scientists co-authors with the mobile ones. But while STEM non-mobile scientists are always likelier to publish more with foreign scientists in the five years after co-authoring with a mobile scientist, SSH non-mobiles are not. Combined with the OLS evidence, this suggests that SSH non-mobile scientists gain more from more mobile co-authors precisely because the effect is less long-lasting. For a given number of mobile co-authors, STEM earns more in terms of number of publications with foreign scientists.

Next, we study the heterogeneous effect of co-authoring with the two groups of mobile scientists on co-authoring with foreign scientists. Figures 5 and 6 compare results for Colombia and Brazil, respectively.

In the case of Colombia (Figure 5), the results are similar for the two groups. Point estimates are usually more significant for intermittent and diaspora mobile scientists, but this may be because these scientists work abroad and are more likely to publish with foreign authors. When they also include non-mobile scientists, they involve them in more publications than the returnee mobile scientists would do.

In the case of Brazil (Figure 6), we observe an interesting difference. Point estimates are, in general, similar for the two groups. Still, collaboration with returnees has a more persistent effect than collaborations with diaspora and intermittent, even when the non-mobile co-author is with a single mobile returnee scientist. When a non-mobile scientist co-authors with a single mobile scientist who works abroad, they publish more with foreign scientists only that same year. Mobile scientist is always more likely to collaborate with foreigners in the following years. Still, the difference concerning peers who do not cooperate

with mobile scientists is insignificant each year. When a non-mobile scientist co-authors with a single mobile scientist who has returned to Brazil right after the Ph.D., they open long-lasting collaborations with foreign scientists. Further work is needed to explore the mechanisms behind this difference, but it may be related to creating stronger ties with returnees than with diaspora or intermittent scientists.

Figure 3 - Number of papers with foreign co-authors per year (Colombia) – STEM and SSH

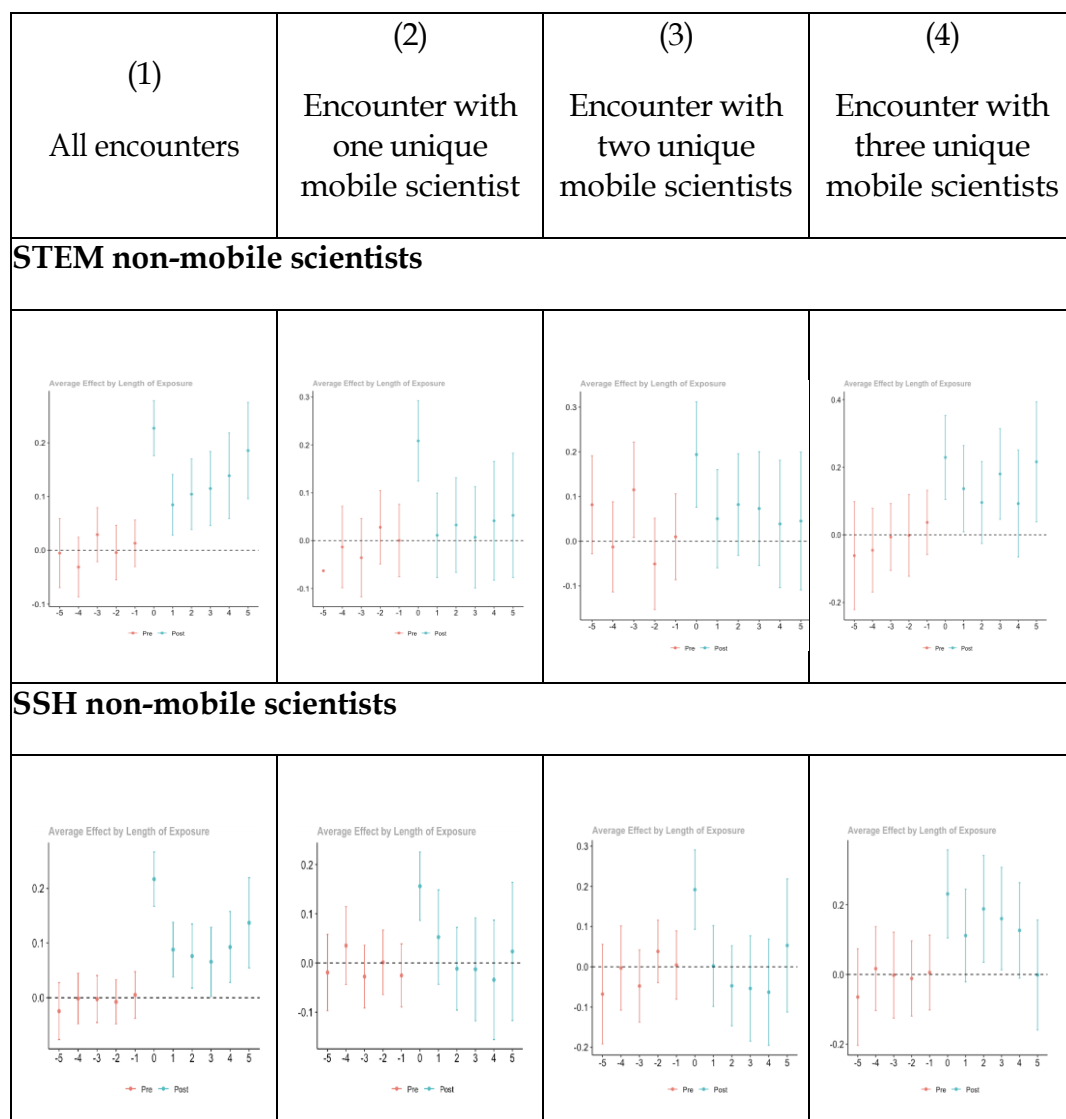


Figure 4 – Number of papers with foreign co-authors per year (Brazil) – STEM and SSH

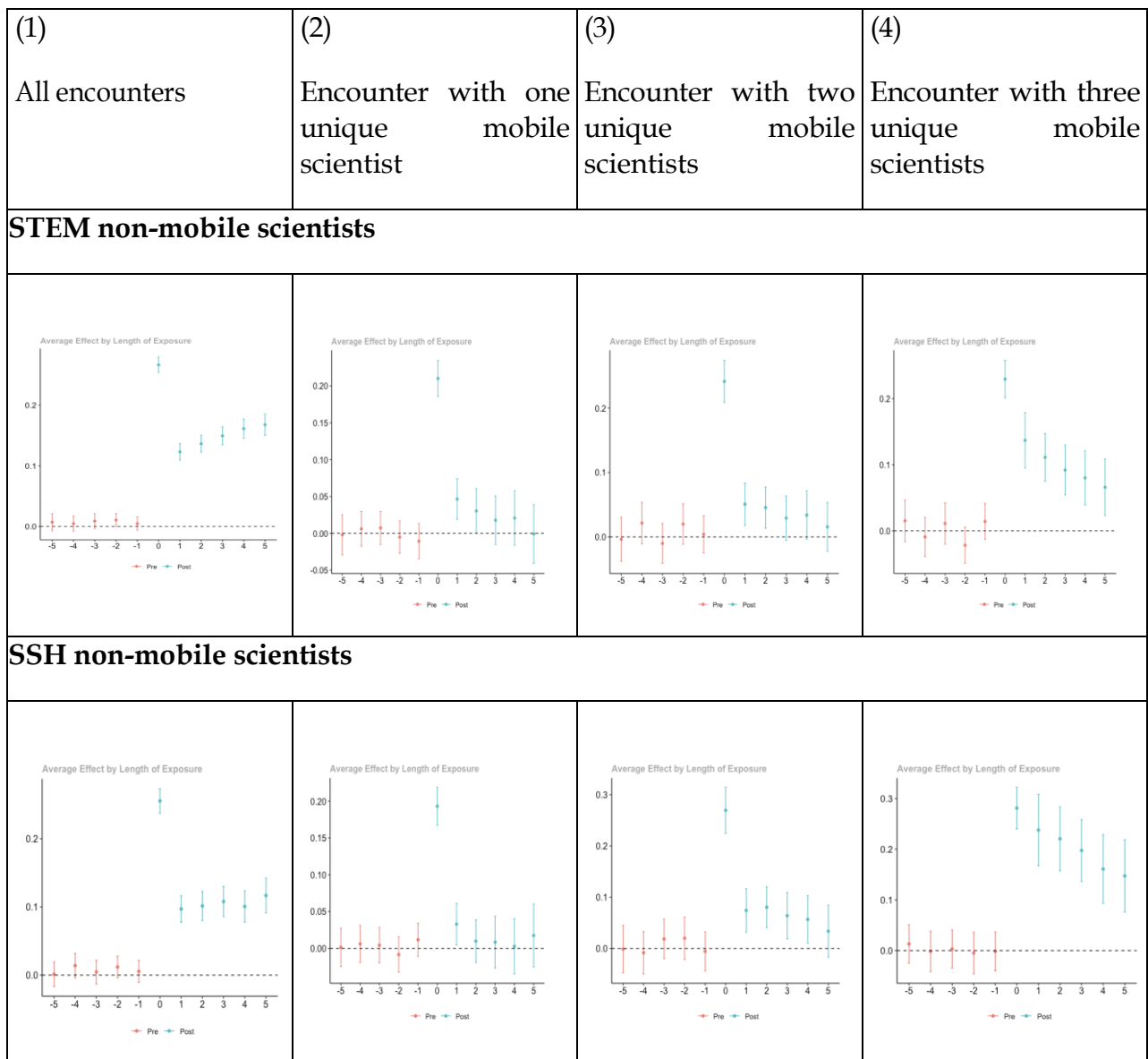


Figure 5 - Number of papers with foreign co-authors per year (Colombia) - Different groups of mobile scientists

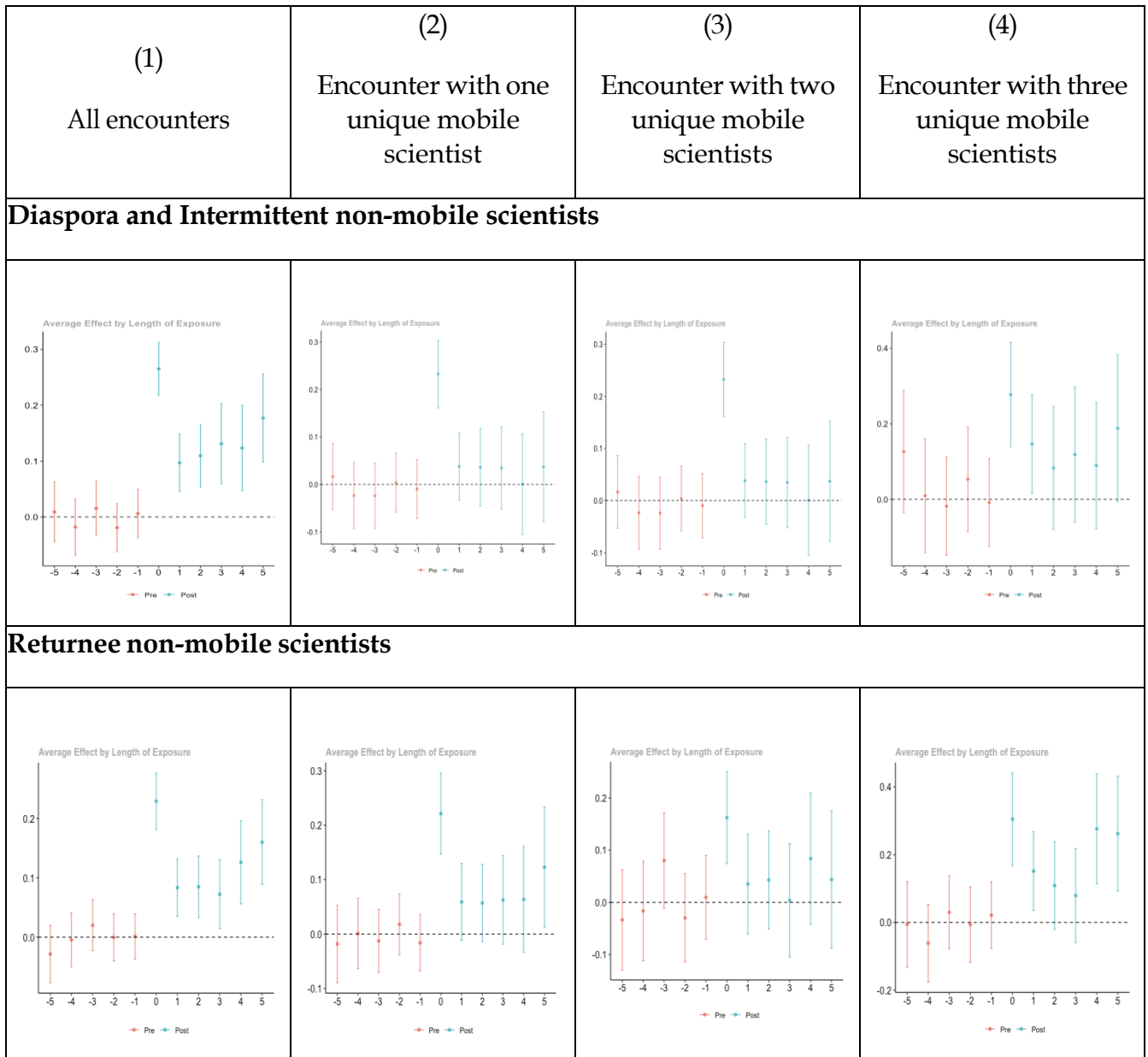
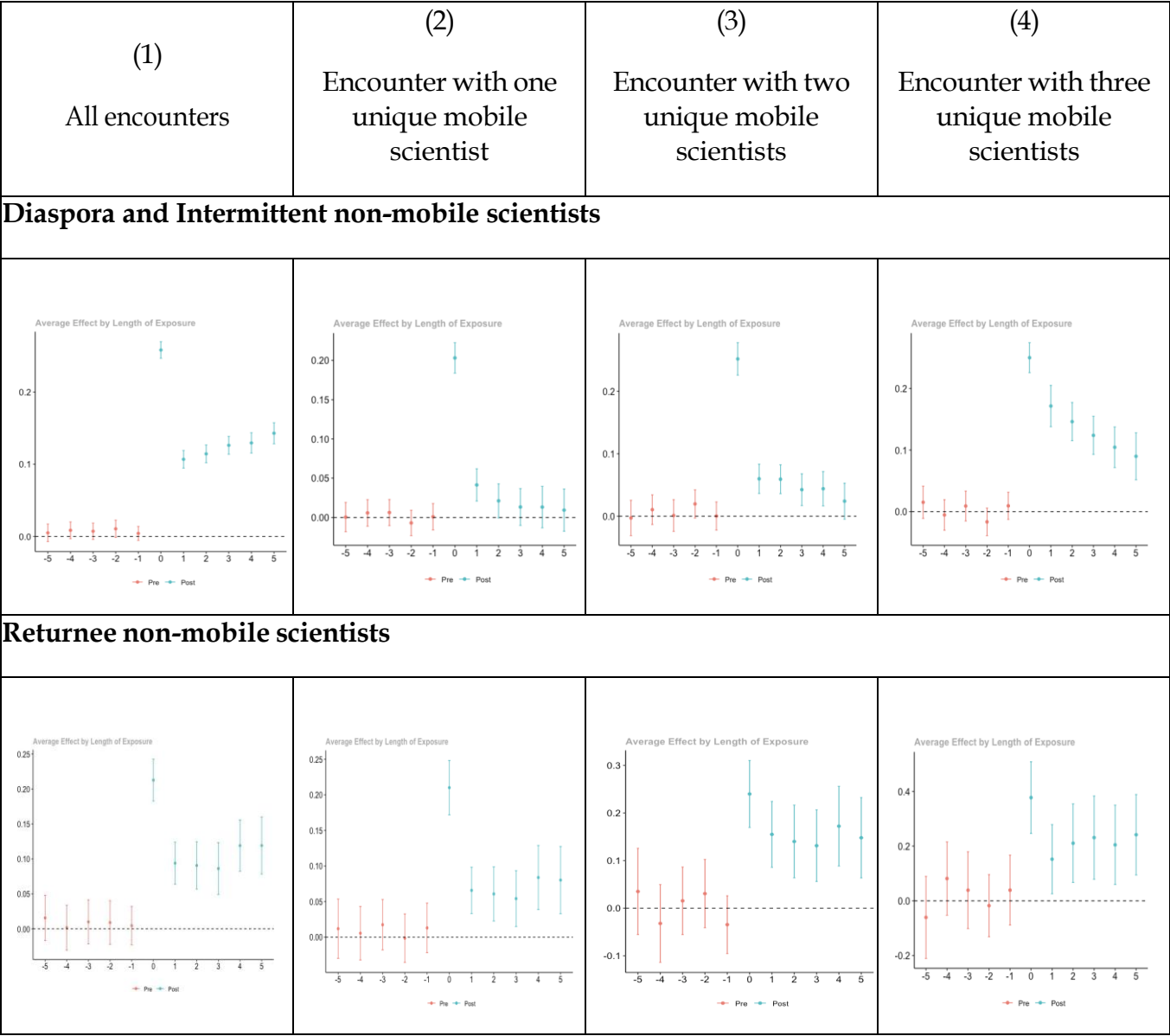


Figure 6 - Number of papers with foreign co-authors per year (Brazil) – Different groups of mobile scientists



7. Discussion and conclusion

In this paper, we have matched unprecedented (publicly available) data from CVs, scholarships, and publications to study a simple question for which no evidence yet exists in the literature: do mobile scientists connect non-mobile scientists from their country of origin to foreign scientists located abroad? We use panel fixed effects, controlling for many observable characteristics that influence collaborations between non-mobile and foreign scientists. We use an event study approach to isolate the mobile scientists' effect further. Our results are consistent throughout increasing the number of mobile scientists with whom non-mobile scientists interact and increasing the number (and share) of publications they co-authored with foreign scientists. Results are remarkably similar for Brazil and Colombia.

First, the average non-mobile scientist from Brazil and Colombia is likelier to co-author a paper with a foreign scientist if they have published at least once with a mobile scientist. As the number of unique mobile scientists increases, the probability of co-authoring with foreign scientists also rises. Second, the number of collaborations with mobile scientists is positively associated with the share and number of publications that non-mobile scientists co-author with foreign scientists. The association is higher when controlling for individual fixed effects. On average, non-mobile scientists from Colombia and Brazil increase by 10% and 15% of their foreign publications, respectively, when the number of mobile scientists with whom they collaborate doubles. STEM non-mobile scientists gain less from interacting with mobile scientists, but only in Colombia. This suggests that their more extensive international network is independent of the mobile scientists.

Strikingly, coefficients are significantly more significant for diaspora and intermittent scientists than for returnees. This result contributes to the debate on brain drain: scientists who work abroad may benefit the sending country more than returnees, at least in connecting non-mobile scientists with international scientists. However, caveats apply here: as we note below, mobile scientists do not give away their networks of foreign scientists to non-mobile scientists; instead, to a large extent, the influence of mobile scientists arises from including non-, mobile colleagues in their projects with foreigners.

Our Difference-in-Difference event study identification strategy confirms the OLS results. However, they raise a concern. The effects on the “internationalization” of non-mobile scientists from a small number of collaborations with mobile scientists are short-lived. The benefits are strongly localized in precisely the period in which the mobile and non-mobile collaborate. This suggests we are observing a collaboration among mobile, non-mobile, and foreign scientists as co-authors of the same paper(s). In Brazil, the positive effect lasts slightly longer, but we cannot rule out that this is due to multiple collaborations with the same mobile scientists. Only for non-mobile scientists that diversify their network of mobile scientists (at least three), the impact remains statistically significant over five years. We find more minor differences between STEM and SSH and different types of mobility patterns, which raises further caveats concerning brain gain.

Our overarching message is that mobile scientists play a relevant role in internationalizing middle- income countries’ scientific systems. Our results contribute to the international scientific mobility literature by showing a solid pattern indicating that mobile scientists from Brazil and Colombia serve as bridges connecting their home and foreign scientific systems. Also, adding to the brain drain versus brain circulation debate, we show that having scientists abroad may not necessarily harm the sending countries. But these results need further investigation as they do not pass our identification tests. More research is also required to study how lasting the positive effect of mobile scientists is. Our results suggest that they can be relatively short-term., which raises the question of whether steps can be taken to extend their impact.

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Notes

¹ a

² Despite the growth in the use of unique identifiers such as ORCID, it is estimated that only 45% of Brazilian authors and 50% of Colombian authors use it (Porter, 2022, p. 6). Because of this, homonyms are a source of inaccuracy.

³ a

How does SDG related research differ?

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Abstract

There is a growing demand for research addressing societal challenges. This paper examines the characteristics and impact of research related to the United Nations' Sustainable Development Goals (SDGs), and it aims to understand specific features of SDG-related research compared to non-SDG related research. The findings reveal that research focusing on SDGs related to people and society, such as poverty alleviation, education, gender equality, and justice, are less likely to receive funding compared to non-SDG related research. However, these publications are more likely to be cited in policy documents, indicating their relevance for public use. Furthermore, across most SDGs, SDG-related research is more likely to adopt features of open science, such as open access and interdisciplinary approaches. However, SDG related publications are generally less likely to be cited in academic publications compared to non-SDG related research, suggesting a disconnect between potentially more impactful research and academic recognition. Taken together, our results suggest some potential gaps in research funding priorities and emphasize the importance of considering the societal relevance of research alongside traditional excellence criteria.

Keywords: Research priorities, Sustainable Development Goals, Science Policy, Bibliometrics

1. Introduction

There is an increasing demand for research to be directed towards societal challenges such as those expressed in the Sustainable Development Goals (Ciarli, 2022; Sarewitz and Pielke Jr., 2007). Given that society is not on track to solve some of its major challenges such as climate change, loss of biodiversity and poverty reduction (Sachs et al., 2022), and given that resources for research are scarce, there is a need to prioritise research that contributes to challenges which affect most of the population. However, it is very difficult to empirically analyse how certain research communities/areas contribute to a certain challenge, and even harder to examine which characteristics make research more prone to contribute to a certain challenge.

In this paper we study if there are specific characteristics that make some research more likely to be SDG related and that funders should target. Alongside scientific excellence indicators, we use indicators that measure collaboration types and the public use of research. Specifically, we ask the following research questions: Are there specific research characteristics (e.g. industry, international, interdisciplinary) that makes it more likely to produce SDG related research? Does SDG related research also appear more often in policy reports, news and social media outlets?

To identify research related to the SDGs we devised a method to assign research areas/clusters to specific SDGs. This approach reduces the uncertainty and ambiguity of assigning individual publications to an SDG, and allows us to include publications that contribute to SDG related research even if they do not use SDG-specific language in the title or abstract. To understand whether research related to SDGs differs from non-SDG related research in its potential for societal impacts, we used publications meta-data and citations to characterize publications according to several features. Specifically, we ask if research related to particular SDGs is more likely to be funded, interdisciplinary, open, done by industry and in international collaboration. We also ask if SDG related research is more likely to have societal impact via different avenues, including policy reports, news, social media outlets and citations in academic publications.

In the next section, we explain the background and motivate this paper. Section 3 presents and discusses data and methods. Section 4 presents and discusses the main results, and Section 5 concludes.

2. Background

Although scientific research has contributed to increasing human prosperity

(Jones, 2021), these benefits have impacted more specific challenges that do not necessarily affect the majority of the population (Nelson, 2011). For instance, in health, research focuses mainly on the diseases that mostly affect people from the richest parts of the world, even if these are not the diseases with the highest burden on human life (Evans et al., 2014; Yegros-Yegros et al., 2020). In agriculture, ‘revealed’ research priorities in agriculture only partially relate to ‘revealed’ demands for new science (Ciarli and Ràfols, 2019).

There are several reasons why research priorities do not align well with the societal demands, including: path dependence (Cowan and Gunby, 1996), difficulty in navigating the sheer complexity of research and societal demands, as priorities are influenced by several, competing and related factors and actors (Bozeman and Sarewitz, 2005; Dosi, 1984; Dosi and Nelson, 2013; Freeman, 1995, 1991; Johnstone and Stirling, 2020; Smith et al., 2005), with different interests and incentives (Chataway et al., 2004; Wallace and Ràfols, 2018), which are unequally represented in research and decision making organisations (Cheng and Weinberg, 2021; Klerkx and Leeuwis, 2008; Koning et al., 2021; Odekunle, 2020).

Behind these systemic reasons is also how researchers themselves respond to incentives that shape their research trajectories. The evaluation of research based on the scientific excellence of its outputs, reduces funder’s decision making to only one of the potential objectives of investment in research and might push the research frontier in directions that do not maximize social wellbeing. And in evaluating this objective, it misses out the multiple, combinatorial ways, in which research may advance the frontier and, equally importantly, its multiple directions (Hicks et al., 2015) and their potential impacts on societies.

SDGs present an opportunity for rethinking how science is funded and undertaken, with a focus on global collaboration. Overall, poorer countries – low-income countries (LICs) and lower- middle-income countries (LMICs), tend to face the largest SDG challenges (Sachs et al., 2022). At the same time, the benefits of research are typically localized geographically, necessitating a pool of researchers connected to international professional networks and local users of research (Pavitt, 1998; Salter and Martin, 2001). While knowledge from abroad can be used to tackle national SDGs, investing in research related to those goals in lower income contexts, empowers national researchers to identify diverse pathways and effectively adapt and apply knowledge to their specific context.

In this paper, building on prior research that considers the use of science within a given public domain (Fortunato et al., 2018; Yin et al., 2022) we give a step back and empirically examine publications meta-data to characterize SDG related publications according to measurable features associated with potential societal impacts (Bornmann, 2013; Molas-Gallart et al., 2002). This characterization can

offer quantitative evidence to inform discussions around public interest features of science and can shed light on how research funders can set their incentives to push SDG related research.

3. Data and Methods

3.1 Data

The main dataset we use is CWTS WoS dataset, which we integrate with Overton¹ (which contains citation links to more than 8 million policy documents) and Altmetric (which contains citation links to news stories and twitter posts). In total, we analyse the potential societal impact of around 3 million unique scientific publications (articles and reviews) in 2019.

3.2 Features

To understand whether research related to SDGs differs from non-SDG related research in its potential for societal impacts, we used publications meta-data and citations to characterize publications according to several features associated with the potential societal impact of research (Bornmann, 2013; Molas-Gallart et al., 2002):

- Industry authorship: Publications with at least one affiliation from a corporation (Confraria and Vargas, 2019; Tijssen, 2012)
- Collaborations between high-income countries and the rest of the world: Co-authorships between authors in the “Global South” and “Global North” (Confraria et al., 2017)
- Funded research: Publication acknowledgments with at least one funder (Confraria and Wang, 2020; Grassano et al., 2017)
- Multidisciplinarity (Bromham et al., 2016): Rao-Stirling diversity measure across subject categories (Rafols et al., 2012)
- Citation impact: Top 10% highly cited paper within its research area and year (Waltman, 2016)
- Public use (Noyons, 2019; Yin et al., 2022)
 - Policy documents: Citations in policy documents (Overton)
 - News stories: Citations in news (Altmetric)
 - Twitter posts: Citations in twitter posts (Altmetric)

3.3 SDG related research

To identify research related to the SDGs we devised a method to assign research areas/clusters to specific SDGs (Confraria et al., 2023). This approach reduces the uncertainty and ambiguity of assigning individual publications to an SDG (Armitage et al., 2020; Rafols et al., 2021), and allows us to include publications that contribute to SDG related research even if they do not use SDG- specific language in the title or abstract. First, we built a query with a set of terms that are strongly associated with each SDG, using policy reports, grey literature, scientific publications and web forums, alongside United Nations sources. We extracted relevant fragments from these texts, then selected keywords within them, first using text-mining techniques and then a manual selection. We then used those SDG related queries to search 4,013 clusters of publications in the Web of Science (WoS) published between 2015 and 2019. A cluster comprises a number of published documents which are related to each other because of their citation pattern (Waltman and Van Eck, 2012). Each cluster, then, represents a research area covering broadly similar topics. Based on the results of the search, we connected each research area to one or more SDGs, depending on the proportion of publications that included our SDG query terms in their title and abstracts. For example, 22% of publications in the ‘multidimensional poverty’ research area used terms relating to SDG1. The proportion of publications for each SDG was determined by manually reviewing the topic of the research area, and the title and abstract of the most cited publications.

We then associated with a certain SDG all publications that belong to research areas that have a relatively high share of publications with a certain SDG query term. Given that the distribution of the shares of publications retrieved by the SDG query across research areas differ between SDGs, we defined two thresholds for each SDG:

1. Strict: the share of publications containing the SDG keywords over all publications in the research area that identifies only research areas that the authors considered related to the SDG and its targets, based on information contained in the labels² of the research area (main topics of the cluster) and on abstract information of a sample of most cited publications.
2. Loose: the share of publications containing the SDG keywords over all publications in the research area that identifies a relevant number of research areas the authors considered related to the SDG and its targets, among some research areas less clearly relevant, based on information contained in the labels of the research area (main topics of the cluster) and on abstract information of a sample of most cited publications.

In this paper, the results correspond to our strict thresholds for SDG related research to allow for a stringent understanding of SDG related research (694 565 publications), and to our loose thresholds for non-SDG related research to allow for a stringent understanding of non-SDG related research. All publications (research areas) in between are not considered for our comparisons between SDG and non-SDG related research.

The characterisation of SDGs in certain features is calculated partially using a comparative specialisation index (Balassa, 1965) that allows to compute if research related to a certain SDG is more or less prone to show certain features than non-SDG related research. The SDG specialisation in certain features can be expressed as follows:

$$SI\_SDG_{sf} = \frac{P_{sf} / \sum_f P_{sf}}{P_f / \sum_f P_f} \quad (1)$$

where P is the number of publications in SDG s which feature f . This index can be interpreted as a “revealed comparative advantage”. If SDG s has a higher relative publication specialisation in feature f , it means that SDG s has more scientific research focused on feature f than non-SDG related research ($SI\_SDG > 1$). The calculation of this index (1) implies that the values are necessarily null or positive but are not bound by an upper limit. For this reason, later we normalize the specialization level between -1 and 1, where 1 = high specialization; 0 = world average; and -1 = low specialization.

$$RCA_{cs} = \frac{(SI\_SDG_{cs} - 1)}{(SI\_SDG_{cs} + 1)} \quad (2)$$

3.4 Econometric analysis

We next study the probability that each paper is related to one of the 16 SDGs controlling for all the above characteristics. Because around 9% of the papers pertain to clusters related to more than one SDG, we run separate logit regressions for each SDG.

Formally, we estimate the probability p that a paper is related to no SDG ($p=0$) or is related to one of the 16 SDGs ($p=1$)

$$P(y_s = 1|X) = \frac{e^{\alpha + BX}}{1 + e^{\alpha + BX}}$$

or

$$\log\left(\frac{p}{1-p}\right) = \alpha + BX$$

where y_s equals to one when the publication is related to one of the first 16 SDGs s ; α is a constant; B is a vector of coefficients; and X is the vector of binary variables discussed in the previous section: whether a publication is open access (*oa*), has received funding (*funded*), was written in collaboration between authors in HIC and non-HIC (*HICnonHIC*), was written in collaboration between authors in the same country (*CollNat*), or authors in at least two different countries (*CollInt*), has a value of the interdisciplinarity index above the median (*idrBin*), was cited in a policy document (*policyCit*), on tweeter (*tweetCit*), in a news outlet (*newsCit*), and was among the 10% cited publications in a research area (*top10Bin*). We run a separate estimation for each SDG.

In the results, we present the odds ratio, that is, the ratio of the odds of a publication being related to one of the SDGs (as opposed to no SDGs) given that each of the characteristics of the publication is present ($X=1$) – e.g. the publication is open access or has been cited in policy documents. That is, to which extent each of the characteristics changes the odds of a publication being related to an SDG. To assess the extent to which the odds change (the magnitude of the role of each characteristic in predicting that a publication is related to an SDG), we also present the marginal effects.

4. Results

4.1 Descriptive analysis

We set out to understand the specific characteristics of SDG related research, including whether it is more or less likely to have an impact than other research, and whether there are specific types of research that are more likely to be SDG related and that research funders should therefore target to support the SDGs. Our analysis is divided in two sections. First, we present descriptive results showing relative (average) differences between SDG related publications and non-SDG related publications (see section 3.3. for more details); Second, we compute a regression analysis that shows the probability that each paper is related to one of the 16 SDGs controlling for all characteristics associated with the potential societal impact of research.

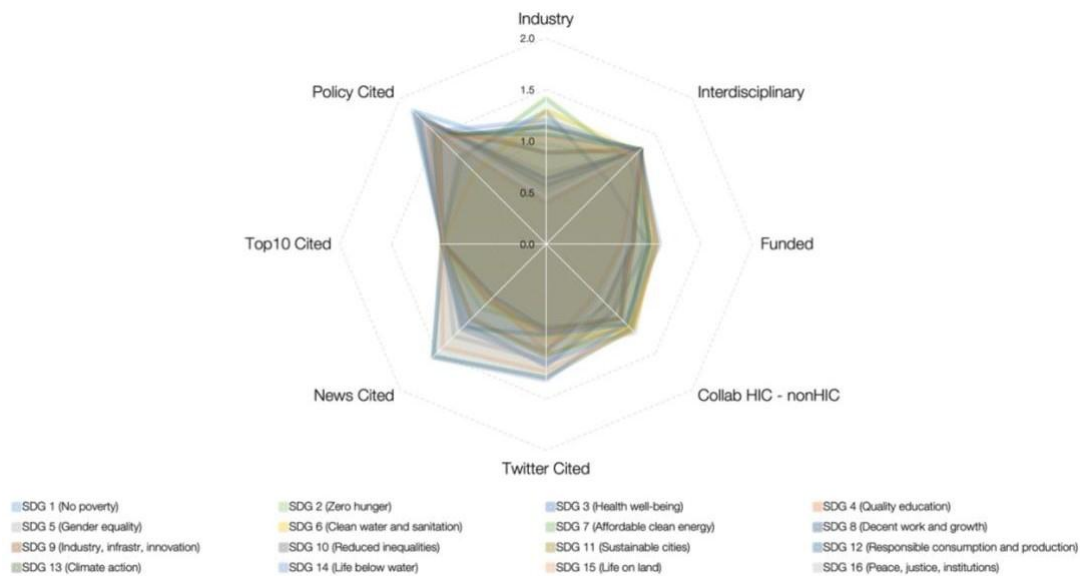
In Table 1, we observe that, on average, SDG-related publications tend to have more often an industry author, be more interdisciplinary, be more cited by tweets, news and policy reports. On average, SDG-related publications tend to be similarly funded, highly cited in publications and international collaborative as non-SDG related research.

Table 1. Average Characteristics of SDG related publications vs non-SDG related publications

	Industry	Interdiscip	Funded	Collab HIC - nonHIC	Twitter Cited	News Cited	Top10 Cited	Policy Cited
Mean SDG0	2.0%	46.2%	66.9%	13.1%	4.1%	0.4%	9.1%	0.7%
Mean SDG (all)	4.8%	57.0%	66.2%	13.5%	6.7%	0.7%	9.3%	4.0%
Std Dev SDG	0.21	0.50	0.47	0.34	0.25	0.08	0.29	0.20
Var Coef SDG	4.47	0.87	0.71	2.53	3.73	12.01	3.11	4.90

These results change substantially between SDG. The level of dispersion around the SDG mean (variation coefficient) is higher for industry authorship, citations from news and policy reports. This variation and can also be observed in Figure 1, which reveals the specialisation of certain SDG in certain features. A more detailed specialisation analysis of each SDG in each feature can be observed in Figure 2 and 3 (in the appendix).

Figure 1. SDG specialisation in certain features



Source: Own calculation

4.2 Regression analysis

Table 2 reports the odds ratio of 16 Logistic regressions (one peer SDG regression, estimating the probability that a publication is related to each SDG vs being related to no SDG.³ The constant term confirms that, besides SDG (good health and wellbeing), the probability that a publication is related to an SDG, overall, is small. In most cases below 1%, and 2% for the second most frequent SDG7 (affordable and clean energy).

Our main research question analysis if features related to the collaborations, public use, and open access nature of the publication predict if a publication is related to an SDG? The short answer is yes, SDG related publications display certain characteristics that significantly distinct them from non-SDG related publications.

First, we find that, for most SDGs, publications related to SDGs are, on average, less funded than those not related to SDGs. The SDG related publications that are more likely to be funded are those associated with the natural environment (SDG 13 (Climate action), 14 (Life below water) and 15 (Life on land)), basic services (SDG6 (Clean water and sanitation) and SDG7 (Affordable and clean energy)) and to some extent Zero hunger (SDG2). Most SDGs related to people and society (SDG 1 (No poverty), 4 (Quality education), 5 (Gender equality), 8 (Decent work and growth), 9 (Industry, infrastructure, innovation), 10 (Reduced inequalities) and 16 (Peace, justice, institutions)) are less likely to be funded than non-SDG related publications in the WoS. These likelihoods range from 66% lower in the case of SDG4 (Quality education) to 24% lower in the case of SDG1 (No poverty). To clarify, this does not mean that publications in these SDGs are 24-66% less likely to receive funding, but that the odds of receiving funding are 24-66% lower for those publications.

Table 3 provides the marginal effects. For instance, a publication in SDG4 is 0.2 percentage points (pp) less likely to be funded, than a non-SDG related publication. In contrast, a publication in SDG3 is five percent points (pp) less likely to be funded.

Second, in terms of collaborations, publications related to SDG 1 (No poverty), 2 (Zero hunger), 6 (Clean water and sanitation) and 7 (Affordable and clean energy) are more likely to be produced in collaboration between HIC and non-HIC. This is expected as they are the areas of research traditionally funded by donors to address challenges in lower income countries. Less expected is that also publications related to SDGs 11 (Sustainable cities and communities), 12 (Responsible production and consumption), 13 (Climate action) and 15 (Life below water) are more likely to be written in collaboration between HIC and non-HIC than publications unrelated to the SDGs.

Table 2. Logit regression by SDG: odds ratio

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Vars.	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16
oa	1.48*** (0.11)	1.44*** (0.09)	1.83*** (0.17)	1.04 (0.24)	1.41** (0.19)	0.77*** (0.03)	0.88*** (0.04)	1.18** (0.08)	1.16 (0.11)	1.56*** (0.14)	1.15* (0.09)	1.06 (0.06)	1.34*** (0.07)	1.15* (0.09)	1.29** (0.14)	0.98 (0.21)
funded	0.76* (0.12)	1.13* (0.07)	0.75*** (0.08)	0.34*** (0.06)	0.48*** (0.10)	1.82*** (0.18)	1.31*** (0.11)	0.41*** (0.03)	0.49*** (0.03)	0.51*** (0.08)	0.99 (0.04)	1.02 (0.05)	1.54*** (0.06)	2.16*** (0.28)	1.58*** (0.16)	0.41*** (0.09)
HICnonHIC	2.26*** (0.24)	1.89*** (0.19)	0.86*** (0.05)	0.68*** (0.06)	1.18 (0.15)	1.59*** (0.13)	1.52*** (0.09)	1.00 (0.07)	0.96 (0.06)	0.73*** (0.06)	1.47*** (0.10)	1.34*** (0.10)	1.15*** (0.04)	0.74*** (0.07)	1.19* (0.12)	0.77** (0.10)
CollNat	0.99 (0.17)	1.31*** (0.07)	1.66*** (0.15)	0.79 (0.13)	1.32** (0.18)	1.18*** (0.06)	0.89** (0.05)	0.84** (0.07)	0.91 (0.06)	1.02 (0.15)	1.06 (0.13)	1.01 (0.05)	1.32*** (0.10)	1.58*** (0.09)	1.60*** (0.08)	1.10 (0.16)
CollInt	0.75* (0.11)	1.02 (0.13)	1.25*** (0.08)	0.76** (0.10)	0.90 (0.19)	0.97 (0.04)	0.81*** (0.03)	1.30*** (0.10)	1.39*** (0.12)	1.10 (0.15)	0.99 (0.05)	0.98 (0.06)	1.55*** (0.11)	2.18*** (0.31)	1.72*** (0.22)	0.93 (0.21)
idrBin	10.48*** (2.21)	3.52*** (0.29)	0.68*** (0.05)	23.23*** (2.56)	4.16*** (0.20)	7.50*** (0.29)	2.76*** (0.21)	14.92*** (2.17)	18.50*** (1.51)	9.58*** (0.90)	14.87*** (1.11)	12.47*** (1.12)	14.59*** (1.28)	8.56*** (0.51)	5.20*** (0.46)	8.68*** (0.55)
policyCit	24.87*** (2.88)	7.09*** (0.43)	3.53*** (0.20)	6.03*** (0.74)	11.28*** (2.34)	1.94*** (0.12)	3.37*** (0.29)	13.26*** (1.29)	7.76*** (0.45)	17.50*** (2.49)	5.23*** (0.25)	5.07*** (0.48)	5.47*** (0.40)	6.06*** (0.84)	5.22*** (0.49)	9.73*** (1.55)
tweetCit	1.20** (0.10)	1.05 (0.05)	1.51*** (0.05)	1.46*** (0.14)	1.31*** (0.12)	0.95 (0.03)	0.78*** (0.06)	0.75*** (0.06)	0.81*** (0.05)	1.00 (0.08)	1.22*** (0.05)	0.74*** (0.04)	1.51*** (0.05)	1.60*** (0.12)	1.40*** (0.06)	1.60*** (0.17)
newsCit	0.64** (0.14)	0.82 (0.10)	0.86*** (0.03)	0.45*** (0.10)	1.05 (0.18)	0.60*** (0.06)	0.97 (0.11)	0.51*** (0.06)	0.58*** (0.07)	0.65* (0.15)	0.62*** (0.05)	1.23 (0.19)	1.40*** (0.08)	1.41*** (0.12)	1.18** (0.08)	0.78** (0.09)
top10Bin	0.63*** (0.05)	0.83*** (0.04)	0.91*** (0.02)	0.96 (0.05)	0.81* (0.09)	0.95 (0.03)	0.96 (0.05)	0.79*** (0.04)	0.87*** (0.05)	0.70*** (0.08)	0.88 (0.08)	0.91 (0.07)	0.74*** (0.02)	0.71*** (0.03)	0.77*** (0.02)	0.82 (0.11)
Constant	0.00*** (0.00)	0.00*** (0.00)	0.26*** (0.02)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.02*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)
Obs.	1,346,447	1,359,038	1,792,305	1,353,878	1,357,923	1,378,093	1,398,241	1,357,177	1,359,290	1,349,276	1,372,439	1,358,662	1,388,767	1,363,031	1,388,324	1,352,546
Pseudo R2	0.127	0.0535	0.0371	0.138	0.0851	0.0854	0.0344	0.149	0.130	0.127	0.113	0.0923	0.136	0.107	0.0861	0.109

NOTE: Coefficients report the odds ratio of a logistic regression estimating the probability that a publication is related to each of the SDGs 1-16 or not. We consider the following binary characteristics of a publication: *oa*: equals one if a publication is open access; *funded*: equals one if a publication has received funding; *HICnonHIC*: equals one if a publication was written in collaboration between authors in HIC and non-HIC; *CollNat*: equals one if a publication was written in collaboration between authors in the same country; *CollInt*: equals one if a publication was written by authors in at least two different countries; *idrBin*: equals one if a publication has a value of the interdisciplinarity index above the median; *policyCit*: equals one if a publication was cited in at least one policy document; *tweetCit*: equals one if a publication was cited in at least on tweet; *newsCit*: equals one if a publication was cited in at least news outlet; *top10Bin*: equals one if a publication was among the 10% most cited publications in a research area. SE clustered at country level. *** p<0.01, ** p<0.05, * p<0.1

Table 3. Logit regression by SDG: Marginal effects

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Vars.	SDG 1	SDG 3	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16
oa	0.000***	0.003***	0.111***	0.000	0.002***	-0.004***	-0.004***	0.001**	0.001	0.001***	0.001*	0.000	0.004***	0.001**	0.005***	-0.000
	(0.000)	(0.000)	(0.015)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.002)	(0.001)
funded	-0.000***	0.001*	-0.051***	-0.002***	-0.005***	0.009***	0.009***	-0.003***	-0.003***	-0.001***	-0.000	0.000	0.006***	0.005***	0.010***	-0.003***
	(0.000)	(0.001)	(0.018)	(0.000)	(0.001)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.002)	(0.003)	(0.001)
HICnonHIC	0.000**	0.005***	-0.027***	-0.001***	0.001	0.007***	0.013***	0.000	-0.000	-0.000***	0.004***	0.002***	0.002***	-0.002***	0.004	-0.001**
	(0.000)	(0.001)	(0.009)	(0.000)	(0.001)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)	(0.002)	(0.000)
CollNat	-0.000	0.002***	0.093***	-0.000	0.002	0.002***	-0.004**	-0.001**	-0.000	0.000	0.001	0.000	0.004***	0.003***	0.010***	0.000
	(0.000)	(0.000)	(0.019)	(0.000)	(0.002)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)	(0.002)	(0.000)
CollInt	-0.000	0.000	0.041***	-0.001	-0.001	-0.000	-0.007***	0.001***	0.001***	0.000	-0.000	-0.000	0.006***	0.005***	0.011***	-0.000
	(0.000)	(0.001)	(0.010)	(0.000)	(0.002)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)
idrBin	0.001***	0.010***	-0.070***	0.007***	0.009***	0.030***	0.033***	0.009***	0.012***	0.004***	0.025***	0.013***	0.038***	0.015***	0.034***	0.006***
	(0.000)	(0.001)	(0.010)	(0.001)	(0.003)	(0.002)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.004)	(0.002)
policyCit	0.002***	0.016***	0.230***	0.004***	0.016***	0.010***	0.039***	0.009***	0.008***	0.004***	0.016***	0.008***	0.024***	0.013***	0.035***	0.007***
	(0.001)	(0.002)	(0.010)	(0.001)	(0.005)	(0.001)	(0.004)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.004)	(0.002)
tweetCit	0.000*	0.000	0.075***	0.001***	0.002***	-0.001	-0.008***	-0.001***	-0.001***	0.000	0.002***	-0.002***	0.006***	0.003***	0.007***	0.001***
	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
newsCit	-0.000**	-0.002	-0.027***	-0.002**	0.000	-0.008***	-0.001	-0.002***	-0.002***	-0.001**	-0.004***	0.001	0.005***	0.002***	0.003**	-0.001**
	(0.000)	(0.001)	(0.007)	(0.001)	(0.001)	(0.002)	(0.004)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.000)
top10Bin	-0.000***	-0.002***	-0.017***	-0.000	-0.001***	-0.001*	-0.001	-0.001***	-0.001***	-0.001***	-0.001	-0.001	-0.004***	-0.002***	-0.005***	-0.001*
	(0.000)	(0.001)	(0.004)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Obs.	1,346,447	1,359,038	1,792,305	1,353,878	1,357,923	1,378,093	1,398,241	1,357,177	1,359,290	1,349,276	1,372,439	1,358,662	1,388,767	1,363,031	1,388,324	1,352,546

NOTE: Coefficients report the marginal effects computed at the mean of each variable of a logistic regression estimating the probability that a publication is related to each of the SDGs 1-16 or not. We consider the following binary characteristics of a publication: *oa*: equals one if a publication is open access; *funded*: equals one if a publication has received funding; *HICnonHIC*: equals one if a publication was written in collaboration between authors in HIC and non-HIC; *CollNat*: equals one if a publication was written in collaboration between authors in the same country; *CollInt*: equals one if a publication was written by authors in at least two different countries; *idrBin*: equals one if a publication has a value of the interdisciplinarity index above the median; *policyCit*: equals one if a publication was cited in at least one policy document; *tweetCit*: equals one if a publication was cited in at least on tweet; *newsCit*: equals one if a publication was cited in at least news outlet; *top10Bin*: equals one if a publication was among the 10% most cited publications in a research area. SE clustered at country level. *** p<0.01, ** p<0.05, * p<0.1

The latter is probably explained by the evidence that publications related to the natural environment are also, in general, more likely to be done in collaboration, nationally or internationally (*CollNat* and *CollInt*). This is not the case for all SDGs. The only other SDG for which publications are more likely to be written in collaboration nationally or internationally is SDG3 (Good health and well-being), but these are mainly collaborations among HIC. While publications related to SDG 8 (Decent work and economic growth) and 9 (Industry, innovation and infrastructure) are more likely to be written in collaboration among different countries, but not nationally.

Third, we find that features of open science (open access (*oa*) and interdisciplinarity (*idrBin*)) are more likely associated to SDG related publications. On the one hand, more interdisciplinary publications are more likely to be related to all SDGs, with the notable exception of SDG3 (Good health and well-being), which is a self-contained discipline. For example, being related to SDG4 (Quality education) has 23 times higher odds than not being related to SDGs for interdisciplinary publications. Given the small number of publications, this translates in a 0.7 pp higher probability of being related to SDG4 when interdisciplinary. The average interdisciplinary publication has 4 pp higher probability of being related to SDG13 (climate action) than not being related to any SDG. Whereas for SDG3 the probability is 7pp lower. Publications related to SDGs are also more likely to be published with open access, the only two exceptions being those related to SDG6 (Clean water and sanitation) and 7 (Affordable and clean energy).

Fourth, we find important differences with respect to the use of SDG related publications. Publications that are cited by at least one policy document have odds of being related to an SDG that goes from twice as large for SDG6 (Access to clean water and sanitation) to 25 as large for SDG1 (No poverty), with substantial variations between SDGs. Odds tend to be higher for publications related to SDGs related to people and society, followed by those related to the natural environment, and then those related to social functions, infrastructures, and technical solutions. This is an interesting result because it reveals that SDG research related to these people and society themes is of more immediate relevance to policymakers than technical solutions. Given that this is also the type of research that is less funded, this might be a potential research funding gap.

Next, use in society (measured as being cited in tweets) is associated with a higher odd that publications are related to most SDGs, but not all. The exceptions are SDG 7 (Affordable and clean energy), 8 (Decent work and economic growth), 9 (Industry, innovation and infrastructure) and 12 (Responsible consumption and production). When it comes to mentions in the news, though, it is associated with the likelihood that a publication is related to

an SDG only for those related to the natural environment (SDG2, 13, 14, 15), similar to funding. For all other SDGs, odds then to be higher that publications mentioned in the news are not related to the SDG.

Finally, use in science, measured by publications that are among the top 10% most cited in a research area, is less likely to predict publications related to an SDG, for all of them except a few for which the difference with respect to non-SDG related publications is not significant (SDGs 4, 6, 7, 11 and 12). This indicates a potential misalignment between what is “excellent” research and research more relevant to societal challenges.

In sum, when it comes to the use of publications, there seem to be a divide between publications that are used in policy and society and those that are used in science. The former are more likely to be related to SDGs, the latter not. SDG related publications tend to be less cited in scientific publications than non-SDG related research.

We do not find substantial differences when we distinguish between LIC and LMIC, UMIC, and HIC (Table 4, Table 5 and Table 6). Results are driven by HIC, which produce most of the publications in the WoS. Three differences are worth mentioning. First, collaborations between HIC and non-HIC are more likely to be associated to SDG related publications in LIC and LMIC than in other country groups. In general collaborative publications between countries in LIC, LMIC, and UMIC, are more likely to be associated with SDG related publications. Second, in LIC and LMIC citations in tweets are less likely to be associated to SDG related publications. Whereas citations in policy documents are more likely to be associated with SDG related publications in LIC and LMIC than in HIC. Third, in UMIC there is a lower difference between SDG and non- SDG related publications when it comes to citations in science.

5. Conclusions

There is an increasing demand to produce research related to societal challenges such as the SDGs. However, given the complexity of many of those challenges, it is difficult to identify research that contributes to them and even more difficult for funders to identify which research they should prioritise or incentivise to contribute to solving those challenges. In this paper, we set out to understand specific characteristics of SDG related research, including the likelihood of it having more societal impact than other research. Specifically, we ask if research related to particular SDGs is more likely to be funded, interdisciplinary, open, done by industry and in international collaboration. We also ask if SDG related research is more likely to have societal impact via different avenues, including policy reports, news, social media outlets and citations in academic publications.

An important finding is that research related to SDGs oriented towards people and society (SDG 1 (No poverty), 4 (Quality education), 5 (Gender equality), 8 (Decent work and growth), 9 (Industry, infrastructure, innovation), 10 (Reduced inequalities) and 16 (Peace, justice, institutions)) are less likely to be funded than non-SDG related publications. At the same time, we find that research related to these SDGs is also much more likely to be cited in policy documents, revealing its relevance for public use, and a potential gap in research funding priorities.

Another interesting finding is that publications related to SDG 1 (No poverty), 2 (Zero hunger), 6 (Clean water and sanitation) and 7 (Affordable and clean energy) are more likely to be produced in collaboration between HIC and non-HIC. This is expected as they are the areas of research traditionally funded by donors to address challenges in lower income countries, and often it is mandatory for this type of research to be performed in international collaboration to promote knowledge exchange and diffusion.

We also find that features of open science (open access (*oa*) and interdisciplinarity (*idrBin*)) are more likely associated with publications related to SDGs. SDG 3 (Good health and well-being) is an exception. Regarding public use, SDG related publications are often more cited in tweets, but not on all SDGs. The exceptions are SDG 7 (Affordable and clean energy), 8 (Decent work and economic growth), 9 (Industry, innovation and infrastructure) and 12 (Responsible consumption and production). When it comes to mentions in the news, publications related to most SDGs tend to be less cited. The exceptions are publications related to SDG 2 (Zero hunger), 13 (Climate action), 14 (Life on water), and 15 (Life on Land). As for international collaboration, we didn't find significant disparities between research done by different groups of countries, only that collaborations between HIC and non-HIC are more likely to be associated with SDG related publications.

Finally, another important finding is that SDG related research tends to be less cited in academic publications than non-SDG related research. This indicates a potential divorce between high impact research in academia and research that might be more relevant to specific societal challenges.

Given that SDG related research tends to be less funded and less cited in scientific publications, but more interdisciplinary and more used in policy and media (especially on society-related SDGs), taken together, these findings indicate a need for greater public funding for research in SDGs oriented towards specific challenges related to people and society, and less on "excellence" grounds.

However, these overall summary results need to be interpreted with caution because the level of dispersion across SDGs for different features is generally

high. Also, as with all studies that map research published in academic journals, the methods are subject to certain limitations. In particular, the WoS does not cover most non-English language journals or those with high local relevance. Also, much research in low-income contexts is not published in academic journals. However, our findings are still crucial in mapping and characterizing the contribution to the SDGs of academic research, which accounts for a large proportion of research funding and is widely used in policy and industry.

As for the next steps, to explore even further common patterns between SDGs, we aim cluster SDGs based on the similarity in each of the above indicators, and we also aim to explore features of publications that are associated with more than one SDG.

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7. Appendix

Figure 2. Industry, Collaboration between HIC and non-HIC, Interdisciplinarity and funding characterisation by SDG

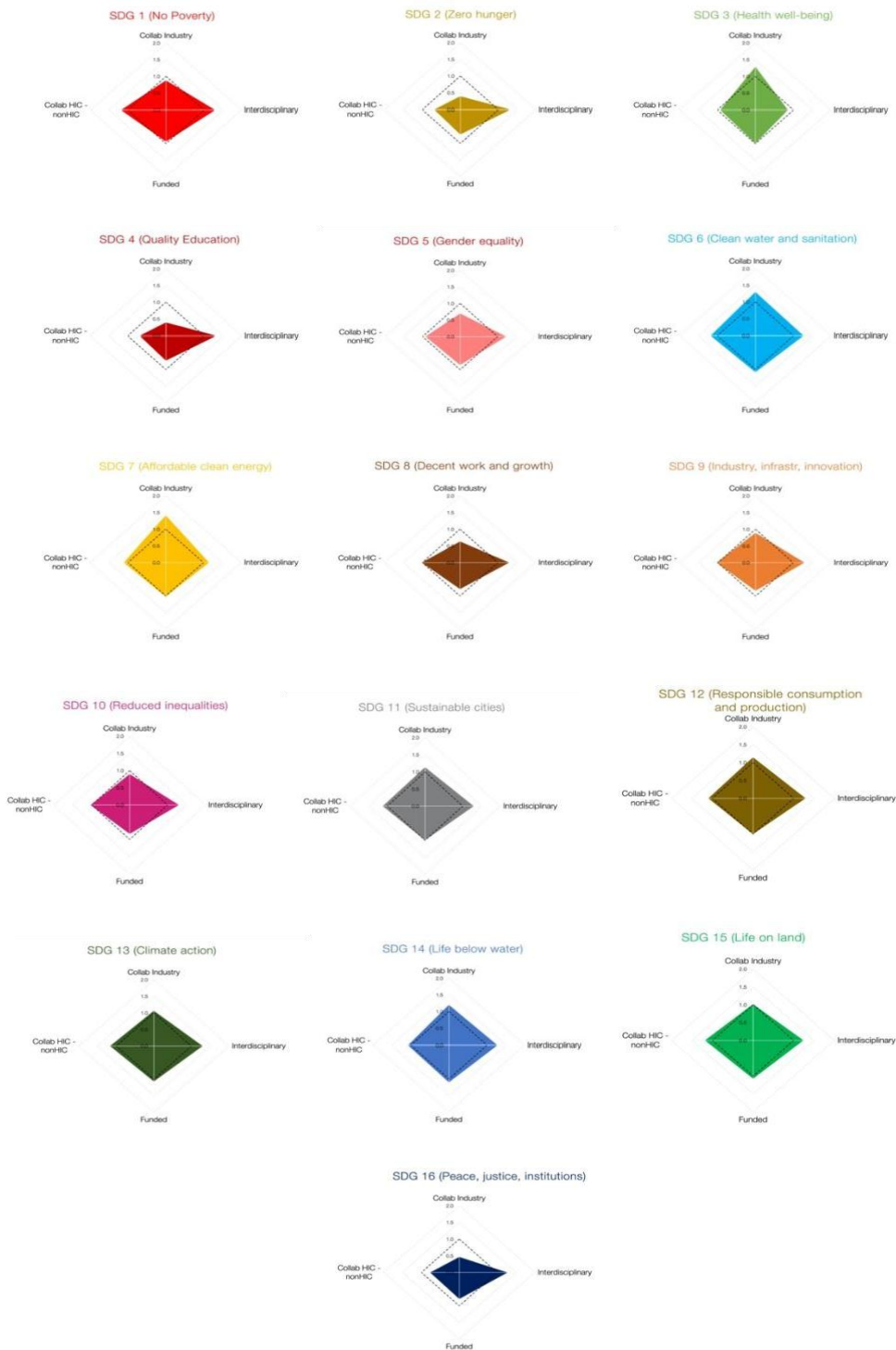
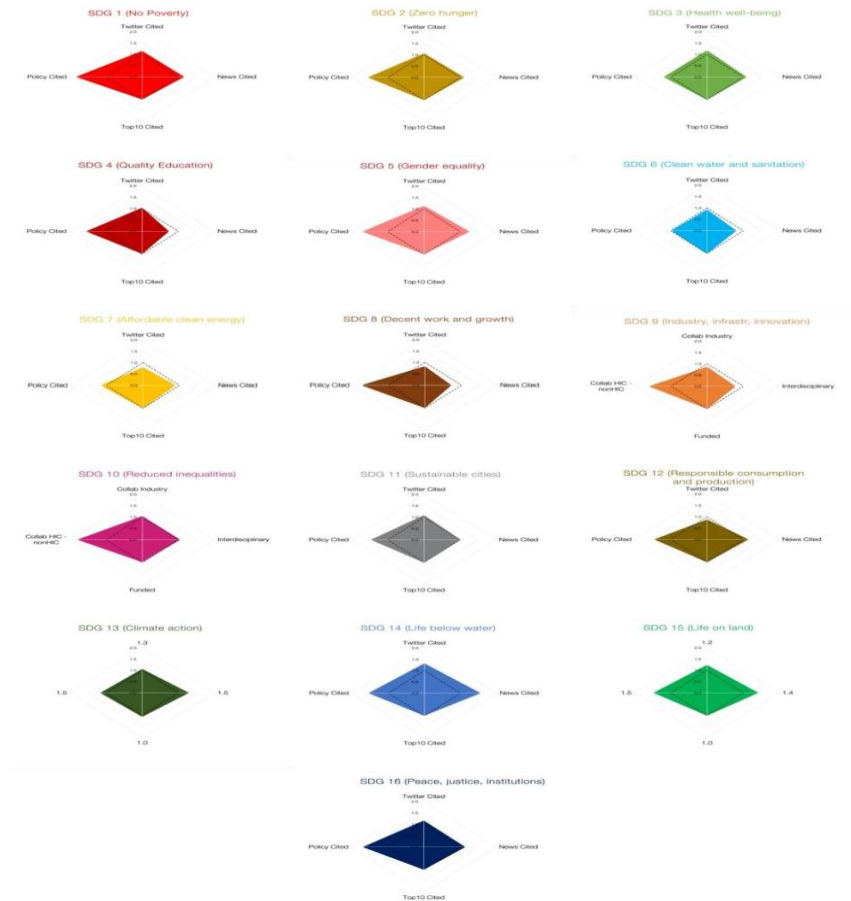


Figure 3. Public use and citation impact characterisation by SDG



Source: Own calculations

Table 4. Logit regression by SDG: odds ratio (LIC and LMIC)

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
oa	1.71*** (0.17)	2.16*** (0.34)	2.56*** (0.31)	1.29* (0.17)	3.58*** (0.65)	1.03 (0.09)	0.92 (0.08)	0.97 (0.13)	1.08 (0.12)	1.19 (0.20)	1.11 (0.09)	1.00 (0.13)	1.31*** (0.11)	1.30** (0.13)	1.59*** (0.09)	2.22*** (0.49)
funded	0.96 (0.20)	1.81*** (0.19)	1.06 (0.08)	0.28*** (0.05)	1.10 (0.23)	1.63*** (0.09)	1.00 (0.04)	0.29*** (0.05)	0.33*** (0.07)	0.46*** (0.07)	1.00 (0.06)	1.12 (0.10)	1.63*** (0.11)	2.28*** (0.14)	2.12*** (0.18)	0.95 (0.31)
HICnonHIC	2.91*** (0.95)	1.24* (0.15)	1.88*** (0.14)	1.46 (0.63)	2.78*** (0.54)	1.00 (0.09)	1.05 (0.13)	0.70 (0.16)	0.74 (0.23)	2.34** (0.86)	1.09 (0.19)	0.71** (0.11)	1.02 (0.15)	1.67** (0.36)	1.15 (0.14)	5.64*** (3.27)
CollNat	0.87 (0.25)	1.18** (0.08)	1.28*** (0.11)	0.44*** (0.07)	1.07 (0.15)	1.09 (0.09)	0.86** (0.06)	0.67*** (0.06)	0.66*** (0.07)	0.59*** (0.10)	1.02 (0.04)	0.99 (0.07)	1.19** (0.10)	1.16** (0.07)	1.45*** (0.08)	1.12 (0.20)
CollInt	0.82 (0.29)	1.44* (0.27)	0.93 (0.05)	1.06 (0.39)	1.09 (0.33)	1.31*** (0.12)	1.03 (0.12)	2.87*** (0.67)	3.13*** (0.92)	0.77 (0.26)	1.58*** (0.21)	2.04*** (0.27)	1.96*** (0.25)	0.92 (0.15)	2.12*** (0.31)	0.56 (0.32)
idrBin	21.67*** (9.14)	3.97*** (0.46)	0.90 (0.06)	5.97*** (1.07)	4.05*** (0.49)	8.13*** (0.74)	2.96*** (0.13)	29.81*** (7.50)	21.81*** (5.18)	14.00*** (2.94)	19.99*** (2.24)	12.56*** (1.34)	20.78*** (1.16)	12.88*** (3.41)	6.13*** (1.07)	4.05*** (0.82)
policyCit	25.87*** (6.29)	12.64*** (1.14)	4.84*** (0.47)	11.48*** (2.92)	18.30*** (4.80)	2.76*** (0.32)	2.08*** (0.28)	9.90*** (2.20)	7.92*** (1.31)	28.65*** (5.70)	8.11*** (1.62)	4.03*** (0.98)	8.13*** (0.70)	6.71*** (1.46)	11.59*** (1.13)	17.48*** (5.34)
tweetCit	0.69 (0.36)	1.14 (0.14)	1.44*** (0.09)	2.33*** (0.72)	0.73 (0.14)	1.03 (0.11)	0.74*** (0.09)	0.99 (0.31)	1.07 (0.40)	1.34 (0.37)	1.46*** (0.13)	1.09 (0.25)	2.08*** (0.17)	1.68*** (0.17)	1.71*** (0.24)	0.68 (0.31)
newsCit	0.88 (1.18)	0.25* (0.19)	1.17 (0.17)		0.26 (0.30)	0.56 (0.20)	0.64 (0.33)	1.06 (1.00)	1.43 (1.34)	0.83 (0.86)	0.70 (0.36)		0.57 (0.25)	1.12 (0.67)	1.58 (0.70)	
top10Bin	0.89 (0.20)	0.78** (0.09)	0.80*** (0.03)	0.48* (0.21)	0.61** (0.13)	0.98 (0.05)	1.19*** (0.06)	0.82* (0.10)	0.90 (0.15)	0.61* (0.16)	0.92 (0.12)	1.18 (0.17)	0.66*** (0.04)	0.49*** (0.10)	0.51*** (0.03)	0.83 (0.24)
Constant	0.00*** (0.00)	0.00*** (0.00)	0.13*** (0.02)	0.00*** (0.00)	0.00*** (0.00)	0.01*** (0.00)	0.03*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)
Observations	95,901	97,326	117,694	95,781	96,444	99,000	100,340	96,210	96,372	95,906	97,184	96,532	98,163	96,453	98,203	95,851
Pseudo R2	0.178	0.113	0.0570	0.0955	0.158	0.100	0.0356	0.158	0.156	0.152	0.139	0.102	0.175	0.123	0.150	0.114

NOTE: Coefficients report the odds ratio of a logistic regression estimating the probability that a publication is related to each of the SDGs 1-16 or not. Sample of publications produced by authors in LIC and LMIC. We consider the following binary characteristics of a publication: *oa*: equals one if a publication is open access; *funded*: equals one if a publication has received funding; *HICnonHIC*: equals one if a publication was written in collaboration between authors in HIC and non-HIC; *CollNat*: equals one if a publication was written in collaboration between authors in the same country; *CollInt*: equals one if a publication was written by authors in at least two different countries; *idrBin*: equals one if a publication has a value of the interdisciplinarity index above the median; *policyCit*: equals one if a publication was cited in at least one policy document; *tweetCit*: equals one if a publication was cited in at least on tweet; *newsCit*: equals one if a publication was cited in at least news outlet; *top10Bin*: equals one if a publication was among the 10% most cited publications in a research area. SE clustered at country level. *** p<0.01, ** p<0.05, * p<0.1

Table 5. Logit regression by SDG: odds ratio (UMIC)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
VARIABLES	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16
oa	1.71*** (0.20)	1.74*** (0.15)	2.17*** (0.18)	1.69 (0.66)	2.11*** (0.27)	0.82*** (0.04)	0.89*** (0.02)	1.18* (0.10)	1.25*** (0.09)	1.60*** (0.22)	1.37*** (0.10)	1.13** (0.06)	1.46*** (0.12)	1.15 (0.14)	1.64*** (0.14)	1.65*** (0.27)
funded	0.58*** (0.10)	0.94 (0.13)	0.70** (0.12)	0.22*** (0.04)	0.36*** (0.10)	1.55*** (0.23)	1.14 (0.13)	0.48*** (0.08)	0.54*** (0.07)	0.34*** (0.06)	1.03 (0.06)	0.99 (0.10)	1.38*** (0.13)	1.54** (0.30)	1.26** (0.12)	0.26*** (0.07)
HICnonHIC	0.99 (0.23)	1.00 (0.17)	1.38*** (0.08)	1.75** (0.45)	1.90** (0.51)	0.72*** (0.05)	0.87** (0.06)	1.11 (0.16)	1.19 (0.17)	1.24 (0.31)	1.27** (0.13)	0.73** (0.11)	1.13 (0.15)	1.30 (0.24)	1.04 (0.20)	2.15** (0.81)
CollNat	0.82 (0.16)	1.52*** (0.14)	1.28*** (0.10)	0.57*** (0.05)	0.90 (0.14)	1.23*** (0.06)	0.99 (0.02)	1.02 (0.11)	0.96 (0.08)	0.79* (0.11)	1.36** (0.20)	1.13*** (0.05)	1.56*** (0.19)	1.50*** (0.23)	1.64*** (0.17)	0.90 (0.15)
CollInt	1.91** (0.55)	1.82** (0.51)	0.75** (0.10)	0.56** (0.15)	0.97 (0.25)	1.59*** (0.19)	1.31*** (0.08)	1.46** (0.28)	1.24 (0.23)	1.39 (0.42)	1.27 (0.28)	1.73** (0.37)	1.75** (0.41)	1.51 (0.44)	2.19*** (0.52)	0.90 (0.35)
idrBin	12.56*** (2.19)	3.87*** (0.77)	0.55*** (0.04)	18.00*** (2.40)	3.75*** (0.42)	6.93*** (0.15)	2.47*** (0.20)	19.31*** (5.12)	20.59*** (2.93)	8.63*** (1.23)	16.28*** (1.53)	12.01*** (2.80)	16.86*** (3.18)	7.24*** (1.32)	4.59*** (1.39)	5.69*** (1.35)
policyCit	33.92*** (4.79)	5.94*** (1.63)	4.34*** (0.50)	5.09*** (1.31)	20.21*** (2.28)	2.18*** (0.21)	2.21*** (0.22)	11.03*** (1.95)	7.76*** (1.28)	23.43*** (3.83)	5.40*** (0.35)	4.73*** (0.68)	5.42*** (0.57)	9.43*** (1.57)	6.01*** (0.86)	19.50*** (3.78)
tweetCit	1.44* (0.30)	1.11 (0.10)	1.59*** (0.02)	1.28 (0.33)	1.74*** (0.24)	1.11** (0.06)	1.07 (0.12)	0.79 (0.21)	0.76** (0.10)	1.32 (0.40)	1.18*** (0.04)	0.67*** (0.10)	1.48*** (0.06)	1.94*** (0.15)	1.53*** (0.14)	1.98*** (0.29)
newsCit	0.62 (0.67)	0.45** (0.15)	0.88 (0.10)	0.36 (0.39)	0.34*** (0.14)	0.54*** (0.07)	0.81* (0.09)	0.44 (0.24)	0.72 (0.24)	0.87 (0.56)	0.70*** (0.10)	0.49 (0.23)	1.31*** (0.13)	1.33 (0.28)	1.11 (0.22)	0.37 (0.31)
top10Bin	0.62* (0.17)	0.86** (0.07)	0.89*** (0.02)	0.80 (0.12)	0.59*** (0.07)	1.01 (0.03)	1.11* (0.06)	0.93 (0.06)	1.07 (0.09)	0.84 (0.11)	1.14*** (0.03)	1.07** (0.04)	0.79*** (0.02)	0.55*** (0.04)	0.74*** (0.05)	0.54*** (0.09)
Constant	0.00*** (0.00)	0.00*** (0.00)	0.25*** (0.05)	0.00*** (0.00)	0.00*** (0.00)	0.01*** (0.00)	0.02*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)
Observations	475,257	479,223	589,925	476,507	476,173	489,771	496,605	478,341	479,082	475,534	484,187	480,082	488,164	479,498	487,017	475,637
Pseudo R2	0.112	0.0491	0.0465	0.142	0.0863	0.0797	0.0243	0.117	0.115	0.108	0.114	0.0877	0.131	0.0811	0.0736	0.104
NOTE: Coefficients report the odds ratio of a logistic regression estimating the probability that a publication is related to each of the SDGs 1-16 or not. Sample of publications produced by authors in UMIC. We consider the following binary characteristics of a publication: <i>oa</i> : equals one if a publication is open access; <i>funded</i> : equals one if a publication has received funding; <i>HICnonHIC</i> : equals one if a publication was written in collaboration between authors in HIC and non- HIC; <i>CollNat</i> : equals one if a publication was written in collaboration between authors in the same country; <i>CollInt</i> : equals one if a publication was written by authors in at least two different countries; <i>idrBin</i> : equals one if a publication has a value of the interdisciplinarity index above the median; <i>policyCit</i> : equals one if a publication was cited in at least one policy document; <i>tweetCit</i> : equals one if a publication was cited in at least on tweet; <i>newsCit</i> : equals one if a publication was cited in at least news outlet; <i>top10Bin</i> : equals one if a publication was among the 10% most cited publications in a research area. *** p<0.01, ** p<0.05, * p<0.1																

Table 6. Logit regression by SDG: odds ratio (HIC)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
VARIABLES	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16
oa	1.25***	1.23***	1.46***	0.78	1.04	0.82***	0.96	1.16**	1.09	1.33***	1.05	1.09	1.24***	1.00	1.05	0.74*
	(0.06)	(0.06)	(0.08)	(0.17)	(0.06)	(0.03)	(0.05)	(0.08)	(0.11)	(0.06)	(0.08)	(0.06)	(0.06)	(0.05)	(0.06)	(0.12)
funded	0.93	1.25***	0.81***	0.42***	0.57***	2.07***	1.48***	0.38***	0.48***	0.61***	0.98	1.00	1.65***	2.56***	1.79***	0.50***
	(0.10)	(0.07)	(0.04)	(0.03)	(0.04)	(0.19)	(0.11)	(0.03)	(0.03)	(0.05)	(0.05)	(0.05)	(0.08)	(0.16)	(0.13)	(0.04)
HICnonHIC	2.07***	1.94***	0.81***	0.60***	1.06	1.85***	1.66***	1.00	0.93	0.61***	1.47***	1.51***	1.16***	0.71***	1.17**	0.68**
	(0.24)	(0.12)	(0.07)	(0.05)	(0.12)	(0.09)	(0.10)	(0.07)	(0.08)	(0.04)	(0.12)	(0.10)	(0.05)	(0.05)	(0.08)	(0.11)
CollNat	1.08	1.26***	1.95***	0.88	1.45***	1.10**	0.79***	0.77***	0.89	1.12	0.91	0.92**	1.22***	1.71***	1.64***	1.18
	(0.20)	(0.07)	(0.13)	(0.14)	(0.17)	(0.04)	(0.03)	(0.06)	(0.08)	(0.15)	(0.06)	(0.03)	(0.09)	(0.09)	(0.12)	(0.16)
CollInt	0.63***	0.92	1.23**	0.63***	0.70**	1.06	0.80***	1.16	1.30*	0.89*	0.89**	0.89*	1.40***	2.00***	1.53***	0.71**
	(0.07)	(0.07)	(0.11)	(0.04)	(0.10)	(0.06)	(0.05)	(0.15)	(0.19)	(0.06)	(0.05)	(0.06)	(0.06)	(0.13)	(0.09)	(0.10)
idrBin	9.05***	3.32***	0.71***	25.83***	4.12***	8.33***	3.05***	12.87***	17.21***	9.30***	13.67***	12.80***	13.15***	8.77***	5.37***	9.24***
	(1.90)	(0.20)	(0.04)	(2.64)	(0.25)	(0.37)	(0.23)	(1.39)	(1.35)	(1.02)	(1.00)	(0.89)	(0.51)	(0.34)	(0.18)	(0.40)
policyCit	20.81***	6.56***	3.04***	4.97***	8.27***	2.13***	4.05***	13.16***	7.53***	13.85***	5.17***	5.46***	5.27***	5.22***	4.52***	7.06***
	(2.04)	(0.39)	(0.09)	(0.51)	(1.36)	(0.14)	(0.30)	(1.64)	(0.59)	(1.62)	(0.24)	(0.52)	(0.46)	(0.59)	(0.41)	(0.71)
tweetCit	1.15*	1.05	1.41***	1.26***	1.12	1.00	0.74***	0.72***	0.80***	0.86**	1.23***	0.77***	1.48***	1.44***	1.31***	1.33***
	(0.09)	(0.04)	(0.03)	(0.08)	(0.08)	(0.04)	(0.02)	(0.05)	(0.04)	(0.06)	(0.06)	(0.04)	(0.06)	(0.09)	(0.05)	(0.11)
newsCit	0.62**	0.93	0.84***	0.43***	1.08	0.65***	1.10	0.53***	0.57***	0.62**	0.65***	1.42**	1.45***	1.39***	1.18**	0.78***
	(0.13)	(0.10)	(0.02)	(0.11)	(0.14)	(0.06)	(0.11)	(0.06)	(0.07)	(0.15)	(0.06)	(0.20)	(0.08)	(0.12)	(0.09)	(0.07)
top10Bin	0.61***	0.86**	0.92**	0.99	0.83**	0.91***	0.85***	0.74***	0.80***	0.68***	0.76***	0.80***	0.73***	0.77***	0.82***	0.84
	(0.05)	(0.06)	(0.03)	(0.04)	(0.08)	(0.03)	(0.04)	(0.05)	(0.04)	(0.08)	(0.04)	(0.06)	(0.03)	(0.03)	(0.04)	(0.11)
Constant	0.00***	0.00***	0.31***	0.00***	0.01***	0.00***	0.01***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.01***	0.00***
	(0.00)	(0.00)	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	775,289	782,489	1,084,686	781,513	785,306	789,322	801,296	782,626	783,836	777,836	791,068	781,971	802,440	787,080	803,104	780,981
Pseudo R2	0.123	0.0510	0.0332	0.143	0.0835	0.0920	0.0453	0.160	0.134	0.125	0.111	0.0964	0.134	0.113	0.0873	0.113

NOTE: Coefficients report the odds ratio of a logistic regression estimating the probability that a publication is related to each of the SDGs 1-16 or not. Sample of publications produced by authors in UMIC. We consider the following binary characteristics of a publication: *oa*: equals one if a publication is open access; *funded*: equals one if a publication has received funding; *HICnonHIC*: equals one if a publication was written in collaboration between authors in HIC and non- HIC; *CollNat*: equals one if a publication was written in collaboration between authors in the same country; *CollInt*: equals one if a publication was written by authors in at least two different countries; *idrBin*: equals one if a publication has a value of the interdisciplinarity index above the median; *policyCit*: equals one if a publication was cited in at least one policy document; *tweetCit*: equals one if a publication was cited in at least on tweet; *newsCit*: equals one if a publication was cited in at least news outlet; *top10Bin*: equals one if a publication was among the 10% most cited publications in a research area. SE clustered at country level. *** p<0.01, ** p<0.05, * p<0.1

Notes

- ¹ <https://www.overtton.io/>
- ² The analysis of most frequent keywords from relevant clusters in both approaches was crucial to check differences and understand which terms retrieve which clusters.
- ³ The sample of publications related to no SDG does not change, whereas the sample related to an SDG differs by SDG. Some publications may be considered for more than one SDG (9% in our 2019 sample), as some research areas are related to more than one SDG.

Do international rankings appropriately capture the changing functions of universities?

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Abstract

Institutional rankings are one of the most impactful factors for many decisions of stakeholders such as funding agencies, potential collaboration partnerships, faculty engagement and student admissions etc. In addition, the funding agencies now seek information about performance indicators such as rankings, research publications, impact and reputation of university etc. which marks a gradual shift from a trust-based funding system to a performance-based funding system. In the past few decades, several ranking systems have been established with varying methodologies to fulfil this demand for information. This has also led to profound changes in university ecosystem, as, in addition to their mandate for education, research and development, universities also strive to rank higher on the ranking parameters. However, most ranking systems

have not responded to this systemic shift leading to them becoming selective, biased and non-inclusive. This is especially concerning for developing countries, as government support and development schemes/programmes also use these rankings; leading to the recognition and subsequent growth opportunities for only a select few elite institutions which feature on these rankings. This limited coverage and myopic nature of university ranking parameters is the primary motivation for this study. A closer look at the three highly popular ranking frameworks (ARWU, QS, THE) shows that although parameters of teaching, research, and knowledge transfer are included, some crucial aspects such as social impact, societal impact, environmental impact, and technological impact of universities still remain unaddressed. With new advances in informatics and scientometrics, it is now possible to incorporate more sophisticated metrics for performance assessment. This paper presents a case for the inclusion of indicators covering five different aspects of university ecosystem.

Key Words: Institutional rankings, STI ecosystem, Higher education, Performance Assessment, Societal development, Indian science

1. Introduction

1.1. About university rankings

The role of university rankings has been very important for various purposes, and for multiple stakeholders. From individual researchers deciding on collaboration partners to funding agencies awarding research grants to universities, different ranking frameworks have found their uses in different avenues. Multiple global and regional university ranking frameworks are currently active (Vernon, Balas & Momani, 2018). These focus on different aspects of the performance of universities, at regional as well as global levels. The university ranking frameworks since their origin in 1980s (US News & World Report¹), and wider adoption after the Shanghai league table in 2003 (Stergiou & Lessenich, 2014), have gained much importance among academic as well as administrative groups. University rankings provide a convenient and widely accepted assessment of performance. They enable comparison

between heterogeneous characteristics through application of standardisation methods such as classification, normalization and standardization. This allows for comparison between different institutions for expertise, reputation, students and funding (Hazelkorn, 2011; De Rijcke et al., 2016, Lathabai et al., 2021). Among the several institutional ranking systems available globally, the most notable and used ranking platforms are listed in table 1.

Table 1. List of Global ranking systems available (College and university rankings)

Global Ranking Systems (Abbreviation)	Initial Year	Sponsoring organization	Total # of Indicators
<i>Academic Ranking of World Universities / Shanghai Rankings (ARWU)</i>	2003	Shanghai Ranking Consultancy	6
<i>Center for World University Rankings (CWUR)</i>	2012	Center for World University Rankings	8
<i>CWTS Leiden Ranking (Leiden)</i>	2012	Leiden University, Netherlands	18
<i>Times Higher Education (THE)</i>	2010	TES Global Limited	13
<i>Quacquarelli Symonds (QS)</i>	2004-09 (with THE) 2010	Quacquarelli Symonds Limited	6
<i>SCImago Institution Rankings (SIR)</i>	2009	SCImago Lab	12
<i>Round University Ranking (RUR)</i>	2010	RUR Ranking Agency	20
<i>U-Multirank (UMR)</i>	2011	European Union and Advisory Board	30
<i>University Ranking by Academic Performance (URAP)</i>	2010	Middle East Technical University	6

1.2. Shortcomings in university rankings and the need for change

With the rapid rise in importance as well as popularity of university rankings, enormous literature is available related to these ranking frameworks. These rankings not only affect university policies but also national policies. For instance, Russia's 5 Top 100 initiative², India's Institute of Eminence³ (IOE) schemes are aimed at bringing the respective national universities in world's top ranked universities. However, their role and methodologies have been a

topic of discussion among the scientific community. Some alternative frameworks have also been suggested by researchers citing different issues with existing university rankings. In addition, the functions of universities have evolved to include more of societal aspects which are scarcely considered in existing university rankings. The evolving functions of universities and the adoption of a 'global and interdisciplinary' knowledge system⁴ have led to the development of new criteria which should be included in the assessment of university performance and outputs. However, these are not yet included in any of the ranking systems.

This article focuses on these aspects of performance assessment, identifies some criteria to reflect the university's functions in the evolving R&D systems, and provides suggestions for incorporation of these criteria in major ranking frameworks.

This study looks at both aspects, identifies the different criteria where ranking frameworks are weak and suggests relevant evaluation criteria that can improve the rankings. The following section presents a short summary of existing literature on university rankings and the different issues related to them. The insights drawn from the literature review are used to frame a research question and design the research methodology for the study. The observations and discussion section presents a detailed analysis of three popular ranking frameworks and contextualises them with respect to the changing functions of universities.

2. Related work

The available literature on university rankings is vast and existing reviews categorize them into three types, namely studies looking at the origins (epistemological explorations of university roles and their role in development of systems for rankings), methodologies used for assessments, and studies about the influence and effects of ranking exercises on the university ecosystem (Hammarfelt, De Rijcke, & Wouters, 2017). This classification of literature can further be qualified based on the criteria addressed by them. Among the first type are the critical studies focusing on the conceptualization of the rankings. The general purpose and motivation behind knowledge production are discussed with authors exploring the utility and effectiveness of comparisons provided by the ranking frameworks. The common thread connecting these studies is commercialization of knowledge and a discussion on the purpose of university rankings. The idea of commercialization and marketization as a result of commodification of knowledge, leading to use of specialized knowledge of universities vis-à-vis their long-term goals of academic research was explored in works such as 'Universities in the Marketplace' (Bok, 2009), 'Academic Capitalism and the New Economy'

(Slaughter and Rhoades, 2004; Altbach, 2013), 'The Commodification of Academic Research' (Radder, 2010), 'Beyond the multiversity' (Shore, 2010) etc. The studies focused more specifically on the conceptualization of rankings discuss about the role of factors such as quality of universities and looked at the models for defining and evaluating quality (Blanco-Ramírez and Berger, 2014) and suggested frameworks to address the concerns about them.

Second category of literature focuses on the understanding and exploring the assessment methodologies used by the ranking frameworks. These studies review the appropriateness and utility of broad assessment criteria and specific indicators used and the calculation methods for them (Billaut, Bouyssou & Vincke, 2010; Huang, 2012). Choice of parameters, weight assignment to the individual indicators (Buela-Casal et al., 2007; Van Raan 2005), selection biases (national bias, language bias, citation errors, and bias towards certain document types) (Kokko and Sutherland, 1999; Van Leeuwen, Moed & Reedijk, 1999; Leimu and Koricheva, 2005; Liu, Cheng & Liu, 2005; Van Raan, 2005; Wong and Kokko, 2005; Pusser & Marginson, 2013; Vernon, Balas & Momani, 2018), and the resulting positional variations in the ranks assigned to universities by different systems have been explored (Dehon, McCathie, & Verardi, 2010; Marginson, 2014; Saisana, d'Hombres & Saltelli, 2011; Moed, 2017; Fauzi et.al, 2020; Jeremic & Jovanovic-Milenkovic, 2014). For instance, it was highlighted that universities which published their research in English language journals based in USA, and indexed in Web of Science had a higher score in ARWU rankings (Van Raan, 2005). In-depth methodological studies and criticisms pertaining to technical aspects of ranking frameworks have pointed to the many problems associated with calculating the quality of universities (Bougnol and Dulá, 2015), and attempts at coming up with new rankings are present (Docampo, 2013). Some studies on the existing ranking systems have also suggested new criterion for assessment of university performance. A comparative study of the Times Higher Education Supplement (THES) World University Rankings and the Shanghai Jiao Tong Academic Ranking of World Universities suggested an ideal international university ranking system (Taylor & Braddock, 2007).

Other available literature addresses at the impact of university rankings on the practices and behavior of universities and other stakeholders (Johnes, 2018; Goglio, 2016, Mussard & James, 2018). To understand the observed effects, these studies employ concepts such as 'performativity' (Callon, 1998) and 'reactivity' (Espeland and Sauder, 2007), often building on interviews and questionnaires recording the opinions of the different stakeholders (Hazelkorn, 2011; Collins and Park, 2016; Huang, 2012) or analysis of rankings in popular media (Wedlin, 2006). The organizational effectiveness in terms of quality and quantity of higher education (Shin, Toutkoushian and Teichler,

2011; Pratasavitskaya and Stensaker, 2010), ability to secure resources such as financial and human capital (Mussard & James, 2018), and aspects of gaming in influencing assessment results by leveraging available advantages in assessment criterion (Thakur, 2007; Hazelkorn, 2011) are some important aspects that have been explored by these studies.

The dimension that relates to the new roles taken up by universities with respect to the changing environment and university ecosystem has however remained untouched by the existing studies. Several studies employing the innovation ecosystem and entrepreneurship ecosystem perspectives (Rothaermel, Agung and Jiang, 2007) have noted the transition of universities from closed innovation systems (focussed on academic peer-reviewed outputs) to open innovation systems (interfacing with industry and identifying applications of the research outside academia) (Chesbrough, 2003) producing entrepreneurial outcomes. These include, aspects of societal contributions, innovation, technology transfer beyond commercialisation and sustainable development etc. This is a gap in the literature that needs to be explored. Motivated by this research gap, the present study suggests indicators that should be added to the university ranking frameworks in context of the changing functions of universities.

3. Analysis

This study uses a set of secondary data sources to develop an analytical framework and review the impact and utility of existing ranking systems. The data for the analysis of ranking systems is collected from in-depth analysis of university ranking data from three popular ranking systems namely, The Academic Ranking of World Universities (ARWU)/ Shanghai, Quacquarelli Symonds (QS), and Times Higher Education (THE). The data about the selected ranking systems are collected and ranking criteria for these platforms are analysed.

3.1 Analytical framework

In order to effectively explore the appropriateness of university rankings, first step is to explore the underlying framework for evaluation of the university's performance. This section develops this understanding and presents the conceptual framework for assessment of university rankings with respect to the research question.

3.2 Characteristics and differentiators of university ranking systems

Ranking systems utilise various strategies for evaluation of university performances, these include, the general key pillars of ranking systems

namely – “teaching”, “research”, “knowledge transfer”, and “global outlook”. Many of the ranking systems use information collected from various sources ranging from government databases; bibliometric and citation data gathered through proprietary, electronic, or web-based sources; institutional data; and student, peer, employer, or other stakeholder surveys etc. They use quantitative performance indicators such as the number of publications in highly reputed journals, achievements of the faculty and alumni etc. The framework showing the different categorisations and data used in ranking frameworks is presented in **Table 2**.

Table 2. Different categorisations and data used in ranking frameworks.

Type		Criteria		Data	
Global	General (THE, QS, ARWU etc.)	Teaching	Faculty : Student	Bibliometric	Publications
			Awards		
			Institutional Income	Bibliometric	Citations
			Degrees Awarded		
	Specific (Young University Ranking, Impact Ranking, Graduate Employability Ranking etc.)	Research	Publications	Survey	Teaching
			Citations		Research
Regional	Geographic Area (Asia, Arab, Latin America, USA, BRICS, China, India)	Knowledge Transfer	Industry Income		Reputation
				Economic	
	Economic Area (Emerging University)	Global Outlook	International Student Ratio	Demographic	
			International Faculty Ratio		
			International Collaboration		

This study has employed this framework to assess the ranking methodologies, their criticisms and shortcomings. This analysis is linked with changing functions of the universities which for the basis for the discussion and recommendations for improved university ranking frameworks.

3.3 General assessment of popular ranking frameworks

Out of the various available ranking systems (**Table 1**), there are three major ranking frameworks which are highly popular among the stakeholders. These are ARWU, QS and THE world university rankings. A closer look at their methodologies, ranking criterion and popular criticisms have enabled the authors to identify and underline the various shortcomings of these frameworks with respect to changing functions of the university systems. The methodologies of these ranking systems are reviewed from the lens of structure defined in **Table 2** to include the four major criteria of assessment.

3.3.1 Academic ranking of world universities / shanghai rankings (ARWU)

ARWU is a Global university ranking which uses Bibliometric and

Demographic data. It assesses (a) the quality of education through awards won by the alumni and faculty of the university, and citations received on high impact publications. (b) research output of university by the number of articles published top journals and (c) per capita performance by the number of full-time academic staff at the university. The assessment exercise assigns different weights to each indicator in these criteria (**Table 3**).

Six indicators about academic award and publications are used in ARWU. Nobel prizes and field medals received by alumni and staff of university are considered with different weights assigned to different time periods. Highly cited researchers, papers published in Nature and Science, and publications in SCI-E and SSCI listed journals are considered for the assessment of research performance. The sixth indicator is per capita performance (PCP) which is a derivative indicator based on scores of the other five indicators taken with respect to the total number of academic staff in the university. There are no indicators on knowledge transfer, global outlook and no use of surveys.

Table 3. Criteria and weights of different indicators considered by ARWU

ARWU/Shanghai Rankings		
Criteria	Indicators used	Type of data used
Teaching	Alumni (10%) Award (20%) Highly Cited Researchers (HiCi) (20%)	Demographic Demographic Bibliometric (Citation Data)
Research	Nature and Science (N&S) (20%) Publications (PUB) (20%)	Bibliometric (Publication Data) Bibliometric (Publication Data)
Knowledge Transfer	-	-
Global Outlook	-	-
Others	Per Capita Performance (PCP) (10%)	Demographic Data

3.3.2 Quacquarelli symonds (QS)

QS Ranking system is a Global system which ranks universities mainly focused on capacities and reputation of universities. It considers, Demographic, Bibliometric and Survey data. It assesses (a) the quality of education, and (b) university's global outlook, by using faculty and student ratios, (c) research performance, by citations received by the faculty members and (d) reputation by surveys of academics and employers about competency of university's graduate students.

Four indicators based on data, which comes from each participating entity (*Faculty/ Student Ratio, Citations per Faculty, International Faculty Ratio, International Student Ratio*), whereas two indicators evaluated using global

survey (*Academic Reputation, Employer Reputation*). The global survey was taken from academics and employers, and hold a share of 50% out of overall score. For academic survey, QS utilizes the expert opinion of 130,000 individuals worldwide. Whereas Employer Survey includes 75,000 responses. This survey asks

the employers to identify those institutions from which they source the most competent, innovative, effective graduates. A respondent can nominate up to 30 universities excluding their own. The median number of nominations was about 20.

Table 4. Criteria and weights of different indicators considered by QS WUR

Quacquarelli Symonds (QS) World University Rankings		
Ranking Criteria	Indicators used	Type of data used
Teaching	Faculty/Student Ratio (20%)	Demographic Data
Research	Citations per faculty (20%)	Bibliometric (Publication Data)
Knowledge Transfer (Graduate Outcome)	Academic Reputation (40%) Employer Reputation (10%)	Survey Survey
Global Outlook	International Faculty Ratio (5%) International Student Ratio (5%)	Demographic Data Demographic Data
Others	-	-

To assess the teaching quality of university, it uses 'Faculty/Student Ratio' as a metric. Similarly, research output is represented using the 'Citations per faculty' metric. Here citations are evaluated for five-year time window using Elsevier's *Scopus Database*. To measure the global outlook, two indicators, 'international faculty ratio' and 'international student ratio' are used. Global outlook demonstrates an ability of university to attract the faculty and students from across the world. All of these indicators are associated with different weights (**Table 4**).

3.3.3 *Times higher education (THE) world university rankings*

Times Higher Education (THE) ranking is considered to be one of the most comprehensive evaluations of university performance. It considers (a) quality of teaching, measured by survey and academic ratios related to staff and student (b) research performance/impact, measured by survey and publications (c) international outlook, measured using details related to international collaboration, international students and faculty, and (d) industry income generated by the universities.

It includes thirteen indicators for assessing the four criteria. Teaching

composed of Reputation survey, Staff-to-student-ratio, Doctorate-to-bachelor's ratio, Doctorates-awarded-to-academic- staff ratio and Institutional income. Academic reputation Survey (runs annually) is utilized to examine the prestige of university in teaching and research. The responses were statistically representative of the geographical and subject mix of academics globally. The institutional income component provides a broad sense of infrastructure and facilities available to students and staff. And all the remaining proportions are utilized to provide a sense of how committed a university in nurturing the next generation of academics.

Similar to teaching, research indicator is also a composite score. It consists of Reputation Survey, Research income and Research productivity. The same academic survey (described above) is utilized here also. Research income is a controversial indicator because it is influenced by national policy and economic situations of various countries. This is scaled against academic staff numbers. Research productivity reflects the university's ability to get papers published in quality peer-reviewed journals (journals indexed by Elsevier's Scopus Database).

Citations are evaluated to look at universities function of spreading new knowledge and ideas. Similar to other indicator, international outlook is also a composite score including proportion of international students, proportion of international staff, international collaboration. It reflects the ability of institution at international platform in attracting students, faculty, and international co-operation for enhancement of knowledge. Next, Industry income indicates the university's ability to help industry with *innovations, interventions* and *consultancy* (Table 5).

Table 5. Criteria and weights of different indicators considered by THE rankings.

Times Higher Education University Rankings		
Ranking Criteria	Indicators used	Type of data used
Teaching	Reputation Survey (15%) Staff to Student Ratio (4.5%) Doctorate to bachelor's ratio (2.25%) Doctorates awarded to academic staff ratio (6%) Institutional income (2.25%)	Survey Demographic Demographic Demographic Economic
Research	Reputation Survey (18%) Research income (6%) Research Productivity (6%) Citations (30%)	Survey Economic Bibliometric (Publication Data) Bibliometric (Citation Data)
Knowledge Transfer	-	-
Global Outlook	Proportion of International student (2.5%) Proportion of International staff (2.5%) International Collaboration (2.5%)	Demographic Demographic Bibliometric
Others	Industry Income (2.5%)	Economic

Major points of concern in existing ranking frameworks

The assessment exercise assigns different weights to each indicator in these criteria, which relates to the most common criticism of these ranking systems, i.e., assigning arbitrary weights to the indicators in various criteria (Jeremic et al., 2011; Buela-Casal et al., 2007; Van Raan, 2005) as well as the seemingly arbitrary selection of parameters for measuring broader criteria's (Billaut, Bouyssou, & Vincke, 2010; Huang, 2012). For instance, QS rankings use faculty/student ratio at 20% weightage (**Table 4**) whereas, THE rankings use 5 indicators at a total of 30% (**Table 5**) and ARWU uses 3 indicators at a total of 50% weightage for assessment of teaching criteria (**Table 3**). Secondly, the methodology used for data collection and assessment is also debatable. For example, QS and THE utilize 50% (academic and employer reputation) and 33% (reputation surveys in teaching and research) survey data respectively. Multiple studies have concentrated on the issues of response rates, fairness and weights, uneven distribution of returned questionnaires, and regional bias in the computation of survey-based data. (Billaut, Bouyssou, & Vincke, 2010; Huang, 2012; Jovanovic et al., 2012; Docampo & Cram, 2014; Marginson, 2014). The other issues will focus on problems with the impact of data normalisation on rankings (Jeremic & Jovanovic-Milenkovic, 2014; Moed, 2017; Fauzi et.al, 2020) and inconsistencies between university ranks in different ranking frameworks (Dehon, McCathie, & Verardi, 2010; Saisana, d'Hombres & Saltelli, 2011; Marginson, 2014). However, there is an issue concerned towards relative focus of ARWU only on the specific dimensions and ignorance of dimensions relating to essential aspects of university functions. Teaching quality, graduate employability, social work, and internationalisation etc. are some of the ignored dimensions (Marginson, 2014).

The critical analysis of the three ranking systems reveals some of the strengths and significant flaws in their methodologies, based on existing literature as well as observations made while explaining these systems. To put these observations into context with the research question, the following section delves into the concept of the university ecosystem and the changing functions of universities in response to changes in the socio-politico-economic environment.

3.4 Changing role of universities

The overall university ecosystem can be understood as collection of stakeholders (university, researchers, government bodies, innovators, startups, firms, etc.) and their interconnections (institutions and different tools for collaboration and coordination). Over the course of time, the number of stakeholders has increased to include non-academic entities under the influence of extrinsic factors such as changing policies, globalization etc. (Deshpande & Guthrie, 2019). This in turn, leads to development of new interconnections

within the university ecosystem. Therefore, universities have been evolving to incorporate new functions in addition to their traditional functions of teaching and research⁵. They are now shifting from knowledge creation and diffusion to technology driven innovation & entrepreneurship activities. University researchers are now engaging with the societal problems and needs, and working towards development of useful solutions for local and regional challenges (ibid). This is termed as *“society-science connect”* which calls for *collaboration between universities and communities to identify problems and develop scientific and technological solutions* for them. The interactions between scientists and society can facilitate two-way flow of facts, knowledge and ideas, which in turn can benefit both science and society (Delanty, 2001; Fagerberg, Landström, & Martin, 2012).

3.4.1 Achieving society-science connect

In the recent past universities and the research institution have embraced their changing roles and now becoming centers of innovation and entrepreneurship (Mok, 2012). The most recent examples of this change have been seen in the development of technological solutions in healthcare, medicinal products, societal change programmes etc. (Bornmann, 2013). Universities are collaborating with various stakeholders namely industry, government bodies and entrepreneurs (Etzkowitz & Zhou, 2017). This UIG collaboration is highly relevant for assessing the quality and capability of universities in contemporary scenarios (Rupika & Singh, 2016). However, the university ranking systems do not provide necessary importance to this aspect. Out of the three frameworks only one i.e., THE WUR considers Industry income as an indicator with only 2.5% weightage in the overall score.

3.4.2 Transforming university research into viable products

Further, one of the most common criticisms of university research has been its disconnect from society. More often than not research conducted in universities remains at the proof-of-concept level (TRL1- TRL3)⁶. There is increasing call for promoting research into actionable technology/solution and the university across the globe have started focused towards this, for example, Oxford/AstraZeneca⁷ Vaccine for Covid-19.

Although these perspectives are now gaining their importance in the major roles of university but these perspectives are not captured by the existing ranking framework. For instance, ARWU considers (1) number of publications, (2) achievements of faculties but does not consider the contributions of universities at local levels such as participation in government programmes for entrepreneurship development, technology business incubators, character building for students etc (Astebro & Bazzazian, 2011). Next section highlights

some of the other indicators/criteria's that are not yet considered in the evaluation of universities performance i.e., ranking frameworks.

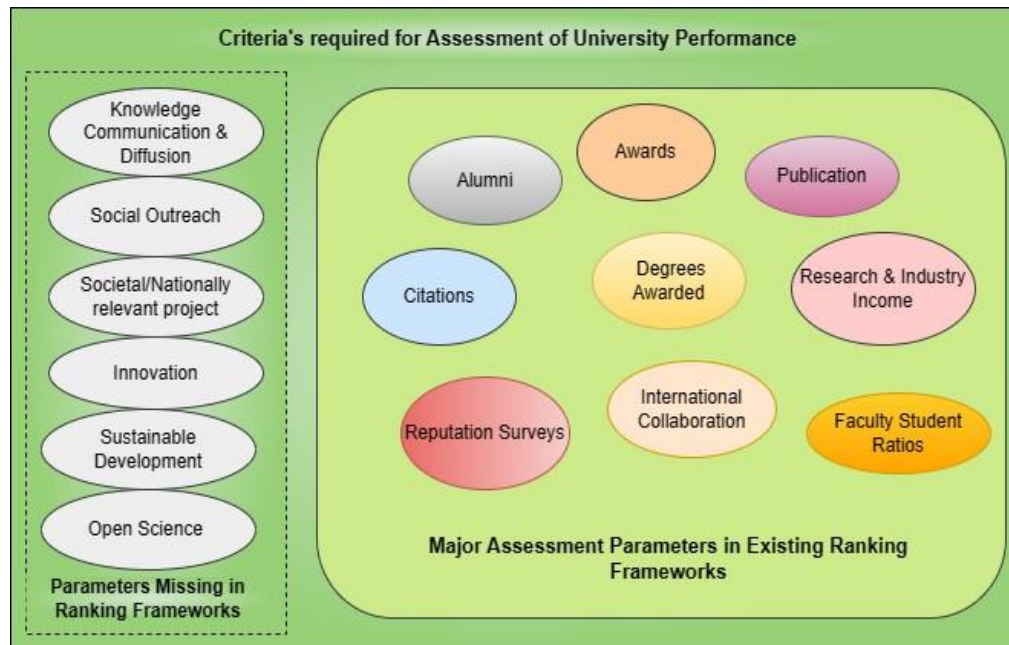
3.5 Criteria and indicators which are missing from existing university ranking system

(a) *Innovation:*

Universities in the changing environment are taking up new functions in national innovation activities since in the knowledge economy innovations is increasingly the result of interactions between enterprises, universities, government agencies, and individuals. Hence, many countries have started promoting individual-level as well as institutional- level initiatives to promote manufacturing, infrastructure, societal services, and environmental services (Boulton, 2011).

- i. University Innovation Centres have been promoted across the world in order to support new technologies from individual entrepreneurs and researchers. For example, the Indian government has promoted programs like Atal Innovation Mission and Start-up India; the Australian government formulated policies like NISA (National Innovation and Science Agenda) to enhance local innovation activities.
- ii. Technology partnerships with overseas universities have also been increasing among the universities⁸. Bilateral academic collaboration agreements between north-south, north-north, and south-south are common and are also measured in many existing rankings^{9,10}. However, technology partnerships are complex and difficult to capture, as their outputs are not quantified in terms of articles, but rather by the development of varied resources.
- iii. Unable to capture severely fragmented research ecosystems (such as specialized institutions focused towards particular fields like agriculture, architecture, pharmaceuticals, entrepreneurship, and so on).

Figure 1: Criteria's / indictors required for University Performance Assessment



(b) *Open science:*

A major part of research and development activities in universities are public funded by government agencies. In this context, there has been an increasing call for making the research results available for public use. 'Open science is an inclusive concept that combines various movements and practices aimed at making multilingual scientific knowledge openly available, accessible, and reusable for all, increasing scientific collaborations and information sharing for the benefit of science and society, and opening the processes of scientific knowledge creation, evaluation, and communication to societal actors other than the traditional scientific community.' (UNESCO, 2021).

Open Science practices help to reduce resource demand by making tools and other resources readily available to the researchers¹¹. Hence it promotes sustainable research (Govaart, Hofmann and Medawar, 2022). It is also crucial to promote more inclusive research practices by allowing access to data for all¹². Universities adopting practices for making Science more transparent, reproducible, and accessible. But, none of the ranking frameworks include indicators that estimate these activities.

(c) Societal/nationally relevant project

The contemporary discourse on the role of universities has largely shifted from universities being centers of knowledge creation (through *Science-Science Connect*) to platforms and facilitators for knowledge dissemination and application (Snellman, 2015; Olcay & Bulu, 2017). They have developed a more intricate mission of contributing towards society by-

- i. Partnering with municipal corporations, and other city and state bodies to address local challenges such as water management, traffic, waste management, local area development, etc. Natural disasters or calamities, GIS mapping of amenities and resources,
- ii. Collaboration and guidance with newly created institutions, resource sharing, and student exchange.
- iii. Facilitating regional development through dialogue and diplomacy.

(d) Knowledge communication & diffusion, and social outreach

University rankings do not give emphasis to the activities done by universities toward the development of cognitive skills and similar learning outcomes (Byrne, 1998). Universities across the globe have shifted focus on Educational and Information dissemination initiatives for the local population in response to the movement for inclusive, sustainable, and equitable growth (Larrán Jorge & Andrades Peña, 2017).

(e) Sustainable development

Since, the adoption of SDGs, they have become the central agenda for activities of major institutions such as universities, government bodies, ministries, civic societies, etc. Among these universities hold key-position as an influencer of opinion, and sources of expertise in research and education in all sectors. For instance, Universities have started programs for teaching courses on sustainable development (Filho *et al.*, 2022). For example- University College London (UCL)¹³, University of London¹⁴ offers degree courses based on sustainable development. However, some other universities like the University of Copenhagen, and Columbia University introduces courses on sustainable development on several online educational platforms like Coursera¹⁵. These offerings are prompted by the initiatives supported by the United Nations such as the Higher Education Sustainability Initiative, the Principles of Responsible Management Education Initiative, and the Sustainable Development Solutions Network (SDSN Australia/Pacific 2017¹⁶).

Because of the growing importance of sustainability, some ranking systems tried to elaborate the importance of universities concerned with sustainability (Calderon, 2023). For example- UI GreenMetric World University Rankings¹⁷, Sustainability Tracking, Assessment & Rating System (STARS)¹⁸.

- i. Contribution to the development of the local ecosystem for sustainable development. (Captured in THE Impact Rankings since 2019).
- ii. Policy interventions in the local governance byelaws. Such as norms for water conservation, waste management, electricity usage, agricultural consultancy to local farmers, etc.

3.6 Possible approach for including alternative assessment criteria

In the five proposed criteria, indicators for measurement need to be identified. Some emerging ranking agencies like QS, THE, SCIMago are using some indicators (Table 6) for area specific rankings.

Table 6. List of rankings which cover some of the criteria for changing university functions

New ranking frameworks	Included ranking criteria	Weightage assigned
QS Star Rankings	- Social Responsibility - Innovation - Environmental Impact	N/A
SciMago Research and Innovation Rankings	- Innovation • Innovative Knowledge (10%) • Patents (10%) • Technological Impact (10%) -Societal • Altmetrics (10%) • Inbound Links (5%) • Web Size (5%)	30% 20%
THE Impact Rankings by SDGs	- SDG Score (Overall) - SDG Collaboration Level	26% each for Top Three SDGs 22% for SDG 17

sharing mechanisms, encouraging international collaboration and exchange programmes. The adoption of sustainable development paradigm has shifted the focus of developmental activities on regional challenges and the engagement of the local stakeholders. Universities are uniquely placed to lead the cross- sectoral implementation of the SDGs, providing an invaluable source of expertise in research and education on all sectors of the SDGs, in addition to being widely considered as neutral and influential players. While the focus of this article is on the functions of universities, it is acknowledged that think tanks and other institutions involved in the production and communication of knowledge also have an important role in advancing the SDG agenda. A set of criteria for the evaluation of changing university functions have been suggested. Innovation, social outreach, societal/ nationally relevant projects undertaken by the university, and the dimension of sustainable development if included in the university ranking can further improve the inclusiveness and applicability of ranking systems.

The adoption of these criteria in the popular ranking frameworks will: (a) broaden the assessment framework hence shading the narrow view of university function, and (b) field- specific criteria like SDG, Innovation, and entrepreneurship provide fair opportunity to domain-specific/ specialized institutions/ universities. Hence, this radical change will help to redistribute R & D resources among institutions which may otherwise had been overshadowed by the legacy of the large university with established alumni and formal as well as informal linkages with the stakeholders in STI ecosystem. In this regard, it is possible to make global rankings systems more multidimensional, and multileveled. These changes will truly bring about a shift from trust-based funding to performance-based funding in Science and Technology and related system.

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Notes

- ¹ <https://www.usnews.com/education/best-global-universities/rankings>
- ² Aimed to bring at least 5 Russian universities among the top 100 in the global university rankings.
- ³ Aimed to provide funding support to Indian universities which rank above 500 in global university rankings
- ⁴ By global and interdisciplinary knowledge system, we refer to the extensive network of institutions and individuals working together on knowledge production across disciplinary boundaries. For instance, use of Artificial Intelligence tools is as common in medical sciences, environmental sciences and physical sciences as much as in engineering.
- ⁵ <http://www.professor-frithjof-kuhn.de/publications/agricultural-colleges/2.htm>
- ⁶ Bhattacharya, Sujit & Kumar, Vipin & Nishad, Shiv Narayan. (2022). Technology Readiness Level: An Assessment of the Usefulness of this Scale for Translational Research. *Productivity*. 62. 112-124. 10.32381/PROD.2021.62.02.2.
- ⁷ <https://www.who.int/news-room/feature-stories/detail/the-oxford-astrazeneca-covid-19-vaccine-what-you-need-to-know>
- ⁸ DWIH (dwi-netzwerk.de): <https://www.dwi-netzwerk.de/en/>
- ⁹ IFCPAR/CEFIPRA: <http://www.cefipra.org/>
- ¹⁰ Indo-Korea Science & Technology Centre (ikst.res.in): <https://ikst.res.in/>
- ¹¹ <https://unesdoc.unesco.org/ark:/48223/pf0000379949/PDF/379949eng.pdf.multi>
- ¹² Open science: enabling a more inclusive, collaborative, transparent world of research (elsevier.com)
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- ¹⁴ <https://www.london.ac.uk/courses/sustainable-development>
- ¹⁵ <https://www.coursera.org/courses?query=sustainable%20development>
- ¹⁶ <https://ap-unsdsn.org/>
- ¹⁷ UI GreenMetric WUR - <https://greenmetric.ui.ac.id/about/methodology/>
- ¹⁸ STARS - <https://stars.aashe.org/about-stars/>
- ¹⁹ Methodology (scimagoir.com)

Innovation and export Performance in the Indian pharmaceutical sector: A study of R&D, embodied and disembodied technology strategies

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Abstract:

This study investigates the relationship between innovation strategies and the export performance of 590 pharmaceutical firms in India, using data from the Centre for Monitoring Indian Economy (CMIE) for the period of 2000 to 2021. We employ a bivariate probit model to estimate the effect of different innovation strategies (R&D, embodied technology, and disembodied technology) on the likelihood of exporting. Our results reveal that firms using a combination of R&D and either embodied or disembodied technology exhibit a higher probability of exporting than those using only one type of innovation strategy. Additionally, we find that the impact of firm size and age on the link between innovation and export is nonlinear. These findings provide important insights into the role of innovation in enhancing the export performance of pharmaceutical firms in India.

Keyword: innovation; strategy; firms; export; R&D

1. Introduction

The relationship between innovation and exporting has been recognized as a crucial driver of firm and economic growth in both developed and developing countries. However, the mechanisms underlying this interrelationship remain

underexplored, and the literature suggests that the relationship can vary depending on the type of innovation strategy employed by the firm. There is growing scholarly emphasis on the significance of adopting a comprehensive innovation strategy to achieve competitive advantage and expansion in international markets (Edeh et al., 2020). While previous research has focused on exploring the relationship between innovation and exporting in developed countries, there is evidence of a positive relationship between innovation and export performance in developing countries particularly in the high-tech industry like pharmaceuticals. A crucial yet unexplored question in the literature is whether younger firms outperform their older counterparts in terms of innovation and export performance, or whether older firms are hindered by organizational inertia, leading to a slower pace of innovation. This question gains added significance in the context of new-age firms, which operate in more symmetrical information networks. Investigating this issue could provide valuable insights into the dynamics of innovation and export performance among firms of different ages (Balasubramanian & Lee, 2008).

Various studies have investigated the relationship between innovation and export performance across different contexts. For instance, (Gkypali et al., 2018) employed Structural Equation Modelling to demonstrate that a firm's absorptive capacity is essential in integrating external knowledge from R&D collaborations, which indirectly affects innovation and export activities. (Olabode et al., 2018) on the other hand, found that an export market-oriented culture contributes to better export performance and stronger export learning capabilities, with the latter mediating the relationship between culture and performance. However, the high turbulence of the export environment weakens this relationship. (Fu et al., 2018) explored the impact of outward direct investment (ODI) on the innovation performance of Chinese MNEs and revealed that ODI and learning through exporting are complementary, with ODI in high-tech industries serving as a valuable knowledge source for firms with limited internal R&D capabilities. More recently, (Danish et al., 2021) investigated the two-way relationship between various types of innovation (product, process, and a combination of both) and the export performance of pharmaceutical firms in India. Despite these research efforts, there is still a research gap on the potential influence of R&D, embodied, and disembodied innovation strategies in combination on the export and innovation behavior of pharmaceutical firms in India.

The domestic pharma market turnover in India has reached Rs. 1.4 lakh crores (equivalent to \$ 20.03 billion) in 2019 as per the government data. This is an increase from Rs. 1.29 lakh crores in 2018 (Shah et al., 2020). In India, the healthcare industries consist of both private sector and public sector. India plays an important role in the global pharma sector and has a great pool of scientists/engineers with good potential to steer the industry ahead to greater

heights(Behera & Rath, 2021). India is the third largest producer of drugs in terms of volume and the vaccine production accounts to 60 per cent global production (Behera & Rath, 2021).

India is a significant player in the global pharmaceutical market, accounting for 20% of all worldwide exports and serving as the largest provider of generic medications (Macaulay et al., 2018). At present, there are more than 11,000 manufacturing units and over 3,000 pharma companies in India. However, the industry is highly fragmented, with the top ten firms, including multinational companies (MNCs), accounting for only one-third of the total sector revenues (Gulaldavar, 2019).

India's pharmaceutical market is dominated by generic products, which account for 71% of the total market share and 20% of global exports in terms of volume, making India the largest supplier of generics globally (Pharmaceutical Companies in India, Indian Pharma Industry- IBEF, 2016), with particular importance in the field of vaccines (Chattopadhyay & Bercovitz, 2020). The Indian biotechnology market was valued at 64 billion USD in 2019 and is projected to reach 150 billion USD by 2025 (Kesik-Brodacka, 2018). In 2021, India traded 24.44 billion USD worth of drugs and prescriptions, and this trend is expected to continue in the coming years (Kesik-Brodacka, 2018).

This paper aims to provide a comprehensive understanding of the relationship between export behavior, innovation strategy, size, and age in the context of the high-tech pharmaceutical industry. Resource Based View (RBV) is a theoretical framework that explains why firms perform differently and can sustain competitive advantage (Barney, 1991; Hitt et al., 2001). It assumes that firms are a bundle of resources that are heterogeneously distributed and can persist over time (Teece et al., 1997), which aligns with the objectives of this study. The research seeks to address the current gaps in the literature on this topic and advance the understanding of the dynamics between these factors, which can have significant implications for firm performance and competitiveness. Through an empirical investigation of the relationship between these variables, this study aims to provide insights into the strategic decisions of firms operating in the high-tech pharmaceutical industry in India and contribute to the development of effective policies and interventions to support the growth and sustainability of this sector.

In this study, we applied bivariate probit model to analyze data gathered from Indian pharmaceutical firms between 2000 and 2021. The bivariate probit model is an appropriate statistical technique in this context because it allows us to investigate the relationship between innovation strategy and export performance while taking into account the possibility of intertwined decision-making processes. In many industries, including the pharmaceutical industry, the

decision to innovate and the decision to export are not independent of each other. Innovation can lead to the development of new products that are more competitive in foreign markets, and firms may be more likely to invest in R&D if they expect to be able to sell their products abroad. Similarly, exporting can generate additional revenue that can be used to finance innovation activities. Therefore, there is a possibility that firms' innovation and export decisions are related and that both decisions should be jointly analyzed to fully understand their impact on export performance. The bivariate probit model is an appropriate statistical tool for this analysis.

2. Literature review

In recent years, the role of innovation in firms' export performance has attracted much attention in academic literature. The resource-based view (RBV) of the firm (Penrose, 1959) suggests that a firm's own resources and skills can give it a long-term competitive advantage. This view has been applied to explain the relationship between innovation and export in developed countries such as the United States, Germany, and Japan. Studies have found that firms that engage in innovation activities are more likely to export, and that innovation has a positive impact on export performance (Cassiman & Golovko, 2011; Fagerberg et al., 2012; Tether et al., 2012). Further, Product-cycle models, such as (Krugman, 1979) have emphasized the role of innovation in driving the export performance of industrialized countries. Additionally, recent models of international economics, such as (Melitz, 2003) and (Grossman et al., 2013) have highlighted the importance of investment in firm-specific assets to increase innovativeness and productivity, which facilitates entry into foreign markets. Another theoretical advancement in this field is the open-economy growth models proposed by (Aghion & Howitt, 2007) which suggest that international trade can push innovative activity, indicating a mutual causation between innovation and exports.

Several studies have investigated the relationship between innovation and export performance in different contexts. (Belderbos et al., 2015) studied Dutch manufacturing firms and found that product innovation has a positive relationship with exporting. (Krammer, 2016) examined German manufacturing firms and found that process innovation has a positive effect on export performance. (Bernard et al., 2018) focused on the U.S. manufacturing sector and found that exporters are more productive than non-exporters, indicating a positive relationship between productivity, innovation, and export. (Dong et al., 2022) investigated Chinese firms and found that innovation has a positive impact on exporting, especially for private firms. They also found that firms that pursued a combination of product and process innovation had a greater likelihood of exporting than those that pursued only one type of innovation. (Dohse & Niebuhr, 2018) analyzed German firms and found that incremental

innovations positively impact firms' propensity to export, while radical innovations require more time to affect exporting.

These studies provide insights into the relationship between innovation and export performance in different industries and countries. However, the generalizability of these findings to other contexts is still unclear, and more research is needed to explore the heterogeneity of markets and the applicability of these relationships across different contexts. Additionally, the effects of different innovation strategies on export performance warrant further investigation, as the type of innovation pursued by firms may affect their ability to successfully enter and compete in foreign markets.

The relationship between innovation and export has been extensively researched in developed countries, but the literature on developing countries is relatively scarce. Some scholars argue that the relationship between innovation and export may be weaker in developing countries due to a lack of adequate infrastructure, market institutions, and financial resources (Ayyagari et al., 2011; Katou & Budhwar, 2007). (Bernard et al., 2018) focused on the U.S. manufacturing sector and found that exporters are more productive than non-exporters. However, their analysis ignored the role of innovation strategies in the export performance of firms.

(Dong et al., 2022) studied Chinese firms and found that innovation is positively associated with exporting, with the effect being stronger for private firms. Nonetheless, their analysis did not differentiate between different types of innovation or investigate how various innovation strategies could impact export activities. (Dohse & Niebuhr, 2018) investigated the relationship between innovation and export propensity in Germany and found that incremental innovations positively impact firms' export propensity. However, their study did not examine how different innovation strategies may affect exports.

Further, (Wu et al., 2022) investigated the role of institutional and financial resources in the export performance of firms in China. The study found that firms with access to institutional and financial resources had a higher likelihood of exporting their products. The results suggested that institutional and financial resources played a crucial role in firms' ability to innovate and adopt new technologies, which in turn positively impacted their export performance. Other study on innovation capacity by (Oura et al., 2016) examined the relationship between innovation capacity and export performance of SMEs in Brazil. The study found that innovation capacity positively influenced firms' export performance. The results showed that SMEs with higher innovation capacity had a greater ability to adapt to international markets and customer needs, which translated into better export performance.

In terms of innovation strategy and export performance, (Edeh et al., 2020) investigated the effect of innovation strategies on the export performance of firms in developing countries. The study found that firms that adopted innovation strategies, such as product innovation and process innovation, had better export performance than those that did not. The results suggested that innovation strategies played a crucial role in firms' ability to differentiate their products and services, improve operational efficiency, and meet customer demands in the international market. Further different types of innovation impact on the export were explored by (Cieřlik et al., 2018) examined the impact of innovation forms on the export performance of firms in emerging and developing European countries. The study found that firms that invested in product innovation had a higher likelihood of exporting their products than those that invested in process innovation. The results suggested that firms that focused on product innovation were better able to create differentiated products that meet customer demands in the international market.

Innovation capability is another important aspect that studies focused on. (Bhat & Momaya, 2020) examined the relationship between innovation capabilities, market characteristics, and export performance of EMNEs from India. The study found that firms with higher innovation capabilities had better export performance. The results suggested that innovation capabilities played a crucial role in firms' ability to create differentiated products, enter new markets, and adapt to changing market conditions.

The studies reviewed in this literature review provide strong evidence of the positive link between innovation strategies and export performance. Firms that invest in innovation, adopt new technologies, and focus on product differentiation are more likely to succeed in the international market. The studies also suggest that institutional and financial resources, as well as market characteristics, play a crucial role in firms' ability to innovate and export their products. Based on these findings, it can be inferred that a strong innovation strategy is essential for the success of Indian firms in the international market.

Based on the literature review, it appears that there is a significant amount of research on the relationship between innovation strategy and export performance. However, there is a lack of specific focus on the pharmaceutical sector in India. Therefore, there is a literature gap in understanding how innovation strategy impacts the export performance of pharmaceutical firms in India. This gap is particularly important to address given the significant growth of the Indian pharmaceutical industry in recent years and its increasing importance in global markets. By exploring this topic, this study has the potential to contribute to the existing literature on innovation strategy and export performance while also providing valuable insights into the Indian pharmaceutical industry.

3. Hypothesis development

H1: Firms using a mix of R&D, embodied and disembodied technology strategies are more likely to export than those using only one strategy, after accounting for size and age.

At the firm level, technology-based models of international trade, such as Posner's technology-gap theory of trade (Posner, 1961) and Vernon's product life-cycle approach to trade (Vernon, 1966), suggest that innovation provides firms with market power and thereby facilitates better export performance (Roper & Love, 2002). Furthermore, research has shown that for science-based firms, the technology profile is a structural factor that positively affects export performance (Nassimbeni, 2001; Pla-Barber & Alegre, 2007). However, there is a lack of research that explores the extent to which different types of innovation strategies (R&D, embodied, and disembodied) and their combination influence the export behavior and innovation behavior of firms, particularly in the pharmaceutical industry in India.

The literature suggests that firms adopting a mix of R&D, embodied and disembodied technology strategies tend to have higher levels of innovation and are more likely to export their products (Cieřlik et al., 2018; Oura et al., 2016; Wu et al., 2022). This is because a combination of different strategies allows firms to take advantage of various technological opportunities, leading to a broader range of product offerings and increased competitiveness in foreign markets. However, this relationship may be moderated by factors such as firm size and age. Therefore, we hypothesize that firms using a mix of R&D, embodied and disembodied technology strategies are more likely to export than those using only one strategy, after accounting for size and age.

H2: The link between innovation and exports varies nonlinearly by firm size and age.

Different studies have investigated whether young firms are faster and more aggressive than older firms, while older firms are slower and more cautious than their younger counterparts ((Coad et al., 2018; Colombelli et al., 2020). The nonlinear effect of firm age on innovation activities has been widely discussed in the literature (Balasubramanian & Lee, 2008). Learning-by-doing has been found to decrease marginal production costs as firms gain experience, while research has suggested that firms' innovative abilities may also improve with time (Cohen & Levinthal, 1989, 1990).

One critical factor that affects a firm's innovative performance is its ability to acquire and utilize external knowledge, known as absorptive capacity. Performing R&D can increase a firm's absorptive capacity, enabling them to

utilize external knowledge more effectively to create new innovations relevant to their needs. The relevance of external knowledge and its characteristics play a crucial role in the ease of learning (Cohen & Levinthal, 1990).

Organizational inertia is another critical factor that can influence a firm's performance. This refers to the limited ability of organizations to make significant changes in their strategies and structures in response to environmental changes. The high costs and difficulties associated with creating and adjusting organizational capabilities such as skills, routines, processes, and structures make it economically suboptimal for firms to engage in large adjustments to their capabilities once they make an initial investment (Hannan & Freeman, 1984; Nelson & Winter, 1982). Consequently, if innovations of higher technical quality require greater capability adjustments, firms may reduce their technical quality as they gain more experience to maximize their profits.

The relationship between firm size and export intensity has been a subject of extensive research in the field of international business. Firm size has been identified as a contributing factor to export performance in several studies, mainly due to greater financial and human resources, as well as higher levels of economies of scale associated with large firms. Furthermore, the size of the firm can impact the level of risks associated with foreign markets, making it easier for larger firms to enter international markets (Majocchi et al., 2005; Mittelstaedt et al., 2003; Piercy et al., 1998).

Two theoretical approaches have commonly been used to explain the relationship between firm size and export intensity: the transaction cost approach and the resource-based view (RBV) of the firm ((Dhanaraj & Beamish, 2003; Verwaal & Donkers, 2002). However, the applicability of these approaches in the Indian pharmaceutical industry needs to be explored.

Unlike traditional industries, the Indian pharmaceutical industry is driven by the need for affordable healthcare and availability of generic drugs. In this context, the RBV approach suggests that strategic resources such as research and development capabilities, patent portfolio, and regulatory compliance are important determinants for achieving international competitiveness (detail on resource and knowledge based view in Cooper et al., 2023).

Therefore, in the context of the Indian pharmaceutical industry, the RBV approach can help to identify the non-size-related resources that are the determinants for achieving international competitiveness. Future research can explore how these resources can be effectively utilized to enhance the export intensity of small and medium-sized enterprises in the industry.

H3: Foreign firms adopting innovation strategies have higher export likelihoods than domestic firms, after adjusting for size and age.

Foreign firms operating in India may have access to different resources and networks than domestic firms, which may enable them to adopt more advanced innovation strategies and export their products more effectively (Bhat & Momaya, 2020). Additionally, foreign firms may have a better understanding of foreign markets and may be better equipped to navigate the complex regulatory and cultural environments associated with exporting. Therefore, we hypothesize that foreign firms adopting innovation strategies have higher export likelihoods than domestic firms, after adjusting for size and age.

The exploration of these hypotheses is important as it can help policymakers and firms in the pharmaceutical sector in India to better understand the relationship between innovation strategies and export performance. By identifying the most effective innovation strategies for firms of different sizes and ownership structures, policymakers can design targeted policies to support innovation and export activities in the pharmaceutical sector. Additionally, firms can use the findings to inform their innovation and export strategies, leading to increased competitiveness and market share in foreign markets.

4. Data

This study utilizes a comprehensive database of Indian plants from the Center for Monitoring Indian Economy (CMIE) covering the period from 2000 to 2022. To examine the relationship between innovation and financial performance, we combine innovation data from the CMIE Prowess database with financial information from the same source. Specifically, we focus on a sample of 596 pharmaceutical firms listed on the Bombay Stock Exchange in India. The selection of firms is based on their sales information, and any firms with incomplete sales data are excluded from the analysis. The sample comprises both innovative and non-innovative firms. Table 1 provides a summary of the variables used in the study, including their calculation methods, means, and standard deviations.

Table 1: Summary statistics

	N	Mean	Frequency	Measurement
R&D_D	6266	.463	0=4,992 1=1,274	if a firm is involved in R&D =1 otherwise 0
Embodied_D	6266	.303	0=5843 1=423	if a firm is have imported embodied technology =1 otherwise 0
Disembodied_D	6266	.13	0=5940 1=326	if a firm is have imported disembodied technology =1; otherwise, 0
R&D* Embodied* Disembodied_D	6266	.039	0=6022 1=2440	Interaction term: it ticks all three categories =1; otherwise, 0
R&D* Embodied_D	6266	.228	0=5082 1=1184	Interaction term: if it ticks two innovation strategy =1; otherwise, 0
R&D* Disembodied_D	6266	.07	0=6069 1=197	Interaction term: if it ticks two innovation strategy =1; otherwise, 0
Embodied* Disembodied_D	6266	.046	0=6220 1=46	Interaction term: if it ticks two innovation strategy =1; otherwise, 0
Ownership	6266	.066	0=5850 1=416	foreign =1; otherwise, 0
Size	6266	2485.22		log of gross fixed assets
Age	6266	29.09		log of age from date of incorporation as of 2021

5. Methodology

Empirical Strategy We use a binary choice model to estimate the impact of different innovation strategies on the likelihood of exporting. Our dependent variable is a binary variable that takes the value of one if a firm exports and zero otherwise. We classify firms into four categories based on their use of R&D, embodied technology, and disembodied technology: (i) firms that use R&D only, (ii) firms use only disembodied strategy, (iii) firms that use only embodied strategy, (iv) firms that use R&D and embodied technology, (v) firms that use R&D and disembodied technology, and (vi) firms that use all three types of innovation strategies, and (vii) firm use only embodied and

disembodied innovation strategy. We also included control variables commonly used in the firm-level analysis, such as age, size, and ownership, which have been used in previous studies (Danish et al., 2021; Dhanora et al., 2018). The age of the firm indicates its stage of development, while size reflects the scale of operation. Ownership influences corporate policies and business strategies, and we considered both domestic and foreign ownership, including firms from Europe and the US. We developed two models to examine how innovation strategy at the firm level affects the probability of exporting activities.

The bivariate probit model is a statistical technique commonly employed when the outcome variable of interest is binary and there is a qualitative explanatory variable in the model that may be endogenous, meaning its value is affected by the same unobservable factors as the outcome variable. This model allows for the estimation of the relationship between the two binary variables while considering the potential endogeneity of the explanatory variable, even after controlling for other covariates. This approach is particularly useful in economics research, where many variables may be endogenous, and traditional regression techniques may not adequately address this issue (Angrist & Pischke, 2009).

In this study, we have a binary variable that may be endogenous, and we want to investigate its impact on the outcome of interest, a bivariate probit model can help to address the endogeneity issue and provide unbiased estimates of the coefficients. To proceed with empirical estimation, we would first need to identify the variables that may affect the endogeneity of the binary variable of interest. Once we identified the variables that may affect the endogeneity of the binary variable, we can include them in the bivariate probit model as control variables. We may also want to consider including additional variables that are likely to affect the outcome of interest.

To estimate the relationship between the export decision and the innovation strategy, age, size, and ownership, a bivariate probit model can be used to account for potential endogeneity issues. The model specification is as follows:

Export decision equation:

$$y_i^* = \beta_0 + \beta_1 R\&D + \beta_2 Embodied + \beta_3 Disembodied + \beta_4 R\&D * Embodied * Disembodied \\ + \beta_5 R\&D * Embodied + \beta_6 R\&D * Disembodied + \beta_7 Embodied \\ * Disembodied + \beta_8 Age + \beta_9 Age^2 + \beta_{10} Size + \beta_{11} Size^2 + \varepsilon_1$$

Innovation strategy equation:

$$R\&D = \gamma_0 + \gamma_1 \ln(age) + \gamma_2 \ln(age)^2 + \gamma_3 \ln(size) + \gamma_4 \ln(size)^2 + \gamma_5 \ln(ownership) \\ + \varepsilon_2$$

Where y_i^* is a binary variable indicating whether a firm exports or not, β_1 to β_7 coefficient of seven innovation strategies, $\ln(\text{age})^2$, $\ln(\text{size})$, $\ln(\text{age})^2$, and $\ln(\text{size})^2$ are the natural logarithm of the firm's age, size, age square and size square respectively, and ownership is a binary variable indicating whether the firm is domestically or foreign-owned. ε_1 and ε_2 are error terms.

The bivariate probit model allows for the estimation of two equations simultaneously, with the error terms being correlated. By using this model, we can account for potential endogeneity issues, which could arise due to unobserved variables that affect both the export decision and the choice of innovation strategy. Further we conducted the sensitivity analysis to see if the results are stable.

6. Results and discussion

The bivariate probit analysis conducted in Model 1 provides evidence that the use of embodied technology has a positive and significant impact on both the export and R&D activities of pharmaceutical firms in India. This finding aligns with previous research that has established a strong link between technology adoption and firms' innovation and export performance (Dutta et al., 2019). Interestingly, our results reveal that foreign-owned affiliates are more likely to engage in innovation and exporting activities compared to their domestic counterparts in India. This finding is consistent with the argument put forward by (Kumar & Siddharthan, 1994) that foreign firms often enjoy advantages such as vertical integration and geographical diversity, which may hinder the entry of developing country firms into high technology industries. Our findings suggest that foreign firms are more likely to excel in terms of their export behavior in the pharmaceutical sector in India. Furthermore, despite the dominance of Indian firms in the generic drug market, many foreign firms operating in India are actively involved in drug development and export activities. This indicates a shift towards higher value-added activities in the pharmaceutical sector in India.

The Indian pharmaceutical industry is a significant contributor to the country's economy, and the growth of the sector is dependent on the performance of both large and small firms. The existing literature suggests that new and small firms play a critical role in generating employment and driving innovation, making them essential for the sustained growth of the industry (Kirchhoff, 1994).

However, little empirical evidence exists on the impact of institutional quality on the performance of new and small firms in emerging economies. Some scholars argue that formal institutional support for large, established firms may impede the survival and growth of new and small firms (McDermott & Mejstrik, 1992). In the Indian pharmaceutical industry, we found that new and small firms are less likely to engage in export activities, which may limit their growth potential.

However, as these firms mature and gain experience, they become more likely to engage in export activities and contribute to the growth of the industry.

This highlights the importance of institutional quality in supporting the growth of new and small firms in the Indian pharmaceutical industry. Access to formal institutional support, such as regulatory frameworks, patent protection, and trade agreements, can play a vital role in enhancing the export activities of these firms and supporting their long-term growth potential. The development of a supportive institutional environment for new and small firms can, in turn, contribute to the dynamic and productive growth of the industry and generate long-term social welfare through macroeconomic development (FitzRoy, 1993).

Further, firms' age has been found to have a nonlinear effect on the export and R&D activities of pharmaceutical firms in India. The findings of our analysis on the pharmaceutical sector in India are consistent with literature (Balasubramanian & Lee, 2008). Our results show that younger firms are more likely to engage in innovation activities. However, as firms age, the coefficient turns negative, indicating a reduction in innovative activities. This could be due to a decline in absorptive capacity as firms become more established, and as their capabilities become more entrenched, it becomes more difficult and costly for them to adjust to changes in the environment (Cohen & Levinthal, 1990). This is in line with previous research that has shown that organizational inertia can be a significant barrier to innovation (Hannan & Freeman, 1984).

The negative association between small firm size and export activity has been widely discussed in the literature, and our findings in the Indian pharmaceutical industry are consistent with this trend. Small firms face a variety of challenges in exporting, including limited financial resources, lack of experience, and a limited customer base (Majocchi et al., 2005; Verwaal & Donkers, 2002). These challenges may make it difficult for small firms to enter international markets and compete with larger, more established players.

Interestingly, as firms grow larger, the relationship between size and export activity turns positive, indicating a non-linear relationship between firm size and export intensity. This suggests that there may be a critical size threshold beyond which firms are better able to overcome the barriers to international trade and increase their export activity. Larger firms may have greater financial resources, established customer bases, and experience in navigating the complex regulatory and legal frameworks of foreign markets, which can enhance their competitiveness in the global marketplace. In other literature (Calof, 1993) argued that small firms could overcome the perceived barrier of firm size in exporting by implementing internationalisation strategies that align with their available resources. In other words, the key to successful internationalisation for small firms lies in their ability to develop strategies that are appropriate for their size

and resources. However, such phenomenon is not observed in Indian case.

Moreover, our findings are in line with the export development process models proposed by (Katsikeas & Leonidou, 1996), which suggest that firms go through various stages of export development. In the pre-engagement phase, firms are not involved in exporting but are considering the option, while in the initial phase, firms engage in sporadic exporting. In the advanced phase, firms are consistent exporters. It is possible that as firms grow larger, they move through these different phases of export development, and are more likely to become consistent exporters. Policymakers and industry stakeholders may need to consider targeted interventions to support small firms in their efforts to enter international markets, while also recognizing the important role that larger firms play in driving export growth and economic development.

Our findings suggest a non-linear relationship between firm size and R&D engagement in the Indian pharmaceutical industry. Smaller firms are less likely to engage in R&D activities, but as they grow in size, the relationship turns positive. These results are consistent with previous studies conducted in Japan's electrical machinery industry (Wakasugi & Koyata, 1997), which found that large firms were more aggressive in their innovation efforts than small firms, and that the number of new products increased with sales volume.

However, earlier literature suggested that small firms may have certain advantages over larger firms in terms of flexibility and fluid communication (Rogers, 2004; Sosa et al., 2002). It is important to note that firm size may also lead to other disadvantages, such as inefficiency and slack in research units (Wakasugi & Koyata, 1997). In the case of Swiss manufacturing firms, (Arvanitis, 1997) found no evidence for the existence of economies of scale in the innovation activity. In contrast, (Rogers, 2004) research revealed a higher innovation ratio per employee in small Australian firms.

However, our findings suggest that the relationship between firm size and R&D engagement is not consistent across all industries or countries. In the Indian pharmaceutical industry, smaller firms may face more challenges in terms of resource allocation and funding for R&D activities, which can be a barrier to innovation. Larger firms may have a greater capacity to invest in R&D, and therefore, they are more likely to engage in innovation activities. These results suggest that policymakers and industry stakeholders should consider the unique characteristics of the industry and the country when designing policies to support R&D and innovation activities in the pharmaceutical industry.

The study conducted a regression analysis to examine the impact of firms' innovative strategies on their exports and R&D activities in the Indian pharmaceutical industry. The findings suggest that the use of embodied

technology has a significant positive impact on firms' export and R&D activities, whereas disembodied technology has a significant positive impact only on R&D (Model 1 and Model 2) (Narayanan & Srinivasan, 2019). However, the combination of all three strategies was found to be significant only with export and not with innovative effort (Model 3).

Moreover, the interaction between R&D and embodied technology was found to have a positive and significant impact on the probability of exporting (Model 4). This implies that firms that use both R&D and embodied technology are more likely to engage in export activities, indicating the complementarity between different types of innovation strategies ((Bogliacino et al., 2020; Laursen & Salter, 2006). Interestingly, this interaction did not significantly affect the likelihood of conducting R&D activities, indicating that the use of these strategies does not necessarily lead to increased R&D investment.

Furthermore, firms that use both embodied and disembodied technology were found to have a higher probability of engaging in export activities and conducting R&D activities (Models 5 and 6), suggesting that different types of innovation strategies can complement each other to enhance firms' competitiveness in the global market (Laursen & Salter, 2006).

The study's results provide empirical evidence on the relationship between technology adoption, innovation strategies, and firms' export and R&D activities in the Indian pharmaceutical industry. These findings have significant implications for policymakers and firms in terms of promoting technology adoption and innovation strategies to enhance the competitiveness of the Indian pharmaceutical industry in the global market.

The results highlight the importance of firms' adoption of technology and implementation of innovative strategies to remain competitive in the global market. Firms in the Indian pharmaceutical industry should consider adopting a combination of embodied and disembodied technology to enhance their exports and R&D activities, ultimately leading to increased competitiveness. Policymakers should also prioritize promoting technology adoption and innovation strategies to support the industry's growth and competitiveness in the global market.

Table 1: Bivariate probit result

Outcome variable: Export_D	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Embodied_D	1.336*** (.05)	NA	NA	NA	NA	NA
Disembodied_D	NA	.018 (.05)	NA	NA	NA	NA
R&D* Embodied* Disembodied_D	NA	NA	1.394*** (.171)	NA	NA	NA
R&D* Embodied_D	NA	NA	NA	1.494*** (.065)	NA	NA
R&D*Disembodied_D	NA	NA	NA	NA	.39***(.073)	NA
Embodied* Disembodied_D	NA	NA	NA	NA	NA	1.062*** (.123)
Age	-4.746*(2.526)	-3.972*(2.39)	-3.891 (2.403)	5.58*** (2.524)	4.575*(2.396)	-3.447 (2.4)
Age Sq	2.161*(1.212)	1.768 (1.147)	1.727 (1.153)	3.03** (1.21)	2.049*(1.15)	1.516 (1.151)
Size	3.718*** (1.026)	3.728*** (1.049)	6.08*** (1.046)	9.76*** (1.052)	6.97*** (1.047)	5.28*** (1.044)
Size Sq	4.391*** (.509)	4.448*** (.521)	4.384*** (.519)	4.915*** (.522)	4.429*** (.52)	4.345*** (.519)
Ownership_D	.337*** (.087)	.528*** (.078)	.454*** (.081)	.317*** (.087)	.494*** (.079)	.461*** (.08)
Constant	1.243*** (.458)	.941** (.432)	.957** (.435)	1.699*** (.459)	1.112** (.434)	.856** (.434)
Embodied_D	.562*** (.043)	NA	NA	NA	NA	NA
Disembodied_D	NA	.159*** (.054)	NA	NA	NA	NA
R&D* Embodied* Disembodied_D	NA	NA	6.369 (627.08)	NA	NA	NA
R&D* Embodied_D	NA	NA	NA	7.302 (674.47)	NA	NA
R&D*Disembodied_D	NA	NA	NA	NA	6.603 (450.156)	NA
Embodied* Disembodied_D	NA	NA	NA	NA	NA	.785*** (.1)

Age	15.082*** (2.759)	15.366*** (2.715)	15.821*** (2.74)	13.314*** (3.212)	14.491*** (2.789)	15.962*** (2.719)
Age Sq	7.056***(1.324)	7.22***(1.303)	434***(1.315)	134***(1.543)	819***(1.338)	502***(1.304)
Size	-10.353*** (2.321)	-9.951*** (2.345)	-9.458*** (2.318)	-12.038*** (2.388)	-8.301*** (2.312)	-9.796*** (2.331)
Size Sq	5.322***(1.156)	.151***(1.168)	902***(1.154)	127***(1.188)	327***(1.151)	5.071*** (1.16)
Ownership_ D	.384***(.083)	.466***(.082)	.384***(.086)	.342***(.102)	.408***(.087)	.408***(.083)
Constant	-5.708*** (.501)	-5.792*** (.495)	-5.89*** (.499)	-5.577*** (.57)	-5.606*** (.509)	-5.894*** (.496)
athrho	.332*** (.026)	.4*** (.025)	.376*** (.025)	.2*** (.027)	.384*** (.026)	.385*** (.025)
Chi-square	2695.169***	2011.847***	1970.874***	1760.077***	1896.767***	2089.640***
Number of obs	6266	6266	6266	6266	6266	6266

*Note: All values in parenthesis are standard error. Significance level is describing as *** $p < .01$, ** $p < .05$, * $p < 0.1$*

Our sensitivity analysis reveals the robustness of the results obtained in our two studies. Both studies show that innovation strategies have a significant positive effect on the outcome variable of interest, namely export and R&D activities in the pharmaceutical sector in India. The results of the panel probit model in the second study indicate that the R&D dummy has a significant positive effect on the adjusted independent variable (export dummy). Similarly, the bivariate probit model of Table 1 finds that firms that conduct R&D are more likely to export and engage in R&D activities. Our findings thus support the view that R&D investments play a crucial role in promoting export activities and innovation in the Indian pharmaceutical sector. Both studies emphasize the importance of considering non-linear relationships between independent and dependent variables. The first study identifies a U-shaped relationship between firm age and export activity, indicating that firms at the beginning and end of their life cycle are more likely to export. Similarly, the second study finds an inverted U-shape relationship between firm age and R&D activities, and a U-shape relationship between firm size and export activity. These findings suggest that firms should adopt different strategies at different stages of their life cycle to optimize their export and innovation outcomes.

Table 2 Sensitivity analysis probit model

y_adj	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
R&D	.365*** (.09)							.254* (.143)
Embodied_D		1.656*** (.185)						1.406*** (.217)
Disembodied_D			.136 (.112)					-.007 (.167)
R&D* Embodied* Disembodied_D				.69*** (.40)				.658 (.528)
R&D* Embodied_D					1.834*** (.261)			.648** (.292)
R&D*Dise mbod ied_D						.023 (.146)		.053 (.268)
Embodied* Disembodied_D							.774*** (.133)	-.646 (.425)
Age	-41.229*** (4.843)	-34.838*** (5.402)	-32.416*** (8.517)	-59.24*** (10.39)	-35.518*** (5.189)	- 25.844*** (9.472)	-41.738*** (5.939)	-43.232*** (9.4)
Age Square	19.196*** (2.322)	16.233*** (2.596)	14.868*** (4.113)	27.56*** (- 16.52)	16.519*** (2.481)	11.626** (4.586)	19.423*** (2.864)	20.103*** (4.44)
Size	-7.103*** (.955)	-6.12*** (1.025)	-7.001*** (1.187)	-16.52* (9.17)	-5.458*** (.956)	-7.71*** (1.193)	-6.468*** (1.146)	-12.961* (6.948)
Size Square	3.558*** (.471)	3.064*** (.507)	3.532*** (.587)	8.27* (2.24)	2.754*** (.472)	3.873*** (.592)	3.259*** (.567)	6.481* (3.471)
Ownership	1.569*** (.232)	1.143*** (.241)	1.608*** (.243)	.24*** (.50)	.889*** (.165)	1.44*** (.236)	1.718*** (.208)	1.459*** (.428)
Constant	12.791*** (.93)	10.875*** (.966)	11.887*** (1.343)	15.75*** (2.38)	11.115*** (.998)	11.588*** (1.407)	12.921*** (.993)	11.339*** (2.124)
Insig2u	-4.195 (1.595)	-2.305*** (.393)	-1.717 (.365)	1.556*** (.166)	-2.399*** (.394)	-2.001 (.384)	-3.041*** (.859)	1.199 (.152)
Chi-square	296.914***	235.745***	194.962***	79.61***	174.969***	232.467*** *	324.045***	171.297***
Number of obs	6266	6266	6266	6266	6266	6266	6266	6266

Note: All values in parenthesis are standard error. Significance level is describing as *** $p < .01$, ** $p < .05$, * $p < 0.1$

7. Conclusion

The relationship between innovation strategy, export behavior, firm size, and firms age has been widely examined in the literature, but there is still a lack of consensus regarding the nature of this relationship. Previous studies have mainly concentrated on manufacturing industries and have not considered the potential impact of varying technology profiles. In contrast, the current research has proposed hypotheses specifically for firms operating within a particular technology context- pharmaceutical sector in India.

Prior research has typically examined the association between different types of innovation such as product, process, and combination of these as variables of interest. In contrast, our study has developed and evaluated a theoretical framework that concurrently investigates bivariate relationship between innovation strategy and export. We have used three different innovative strategies namely R&D, embodied, disembodied and their combination along with age, size and their square term.

Our study provides important insights into the innovation strategies and export activities in the pharmaceutical sector in India. Our findings show that R&D investments are crucial for firms to engage in export activities and that the use of both embodied and disembodied technology can enhance the probability of engaging in both R&D and export activities. Firm size was found to have a negative impact on the probability of exporting, suggesting that smaller firms have a competitive advantage in international markets.

Previous studies have presented conflicting results regarding the relationship between firm size and innovation and export behavior. We argue that these inconsistencies can be attributed to differences in industry characteristics. Our findings suggest that the non-linear impact of firm size on innovation and export behavior is driven by the need for production efficiency in science-based industries such as the pharmaceutical sector, where effectiveness in research is also important. In contrast to the findings of (Pla-Barber & Alegre, 2007) in a science-based setting, our study found that firm size is a significant determinant of both innovation and export intensity. These findings are consistent with the production efficiency rationale and highlight the importance of considering industry-specific factors when examining the relationship between firm size, innovation, and export behavior.

Our study contributes to the resource-based view of the firm by providing empirical evidence that the impact of firm size on innovation and export behavior is contingent on the technology profile of the industry. In the science-based industry of pharmaceuticals, we found that firm size is a determinant for innovation and export intensity. This finding supports the resource-based

view's prediction that in industries where size-related resources are critical, there is a positive link between size and exports. In industries where the most relevant resources are the competence to develop cutting-edge technology, such as pharmaceuticals, the resource-based view suggests that export performance is better explained through innovation strategy, firms' size, and firms age.

Our study provides valuable insights for policymakers seeking to promote innovation and exports in science-based industries. The results suggest that firm size plays a crucial role in driving innovation and international activity in such industries. Therefore, policy interventions should focus on innovation strategies in conjunction with size and age to enhance export performance. These findings align with the resource-based view of the firm, which emphasizes the importance of critical resources in determining firm behavior. In science-based industries, innovation is a critical resource for competitiveness, and policies that facilitate multiple innovation strategies can enhance firms' access to global markets and promote outstanding export performance.

One limitation of our study is the lack of consideration of networking capabilities of firms, which could play a role in their innovation and export activities. Additionally, our analysis is limited by the five-digit level of disaggregation, which may not provide a complete picture of the types of pharmaceutical products being exported. Future research could benefit from examining the intra-industry profile of firms in this sector to inform more targeted policy making.

While our study has focused on the Indian pharmaceutical industry, it is important to acknowledge that generalizing our findings to other industries should be done with caution. Future research that examines industries with different technological profiles and characteristics can provide a more comprehensive understanding of the linkages between innovation, export intensity, and firm size in the Indian context. Additionally, considering more granular data on the intra-industry profile of firms, including their networking capabilities, could further enhance the policy implications of our findings.

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Evolution of brazil's innovation performance : An analysis of possible improvement actions

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Abstract

“Innovation is a complex process that requires investments and efforts from economies and their companies. The Global Innovation Index (GII) is an important international reference for measuring innovation performance and innovation systems in an economy, guiding public policies. Literature highlights that Brazil's innovation performance is below expectations, despite recent advances, and needs improvement. This research aims to investigate the factors that significantly impacted Brazil's performance in the GII in recent years. Data collected from Brazil's official annual GII rankings from 2011 to 2020 across its 7 pillars were investigated and analyzed, and in some cases, sub-pillars and indicators. In addition, the period from 2021 to 2022 was analyzed. In general, this study identified the need for improvements in at least 4 pillars, 10 sub-pillars, and 34 indicators. On one hand, measures are recommended to improve innovation performance due to significant challenges in the "institutions," "market sophistication," and "creative products/outputs" pillars, which are the weaknesses. On the other

hand, measures are recommended to strengthen the success of the "business sophistication" and "infrastructure" pillars, which are strong points, and the "human capital & research" pillar, which has shown a significant growth trend. Specifically, the results showed that to strengthen the "institutions" pillar, the focus should be on improving its 3 sub-pillars and 7 related indicators. For the "market sophistication" pillar, the focus should be on improving its 3 sub-pillars and 10 indicators. For the "creative outputs" pillar, the focus should be on improving 2 sub-pillars and 9 indicators. In addition, studies suggest that, in addition to improvements in the highlighted pillars, adjustments to the "human capital and research" pillar are also strategic to improve Brazil's innovation performance. To strengthen this pillar, the focus should be on improving 2 sub-pillars and 8 indicators. In conclusion, the findings of this scientific study provide relevant insights into understanding the challenges and opportunities in Brazil's innovation landscape. These discoveries can serve as a basis for policy makers, academics, and industry professionals to develop strategies and actions that drive innovation and competitiveness in the country. They can also offer information and support to internal and external stakeholders, including government, businesses, universities, and research institutes, in their efforts to increase funding, efficiency, and productivity in innovative processes. While this study has limitations due to being based on secondary data and a specific analysis of Brazil's innovation performance, its findings can still enrich knowledge in the field of innovation and stimulate future research and debates on the subject. This investigation proposes guidelines for actors involved in the innovation system and in the formulation of public policies in Brazil, enabling them to focus their improvement strategies on relevant points identified, creating a more conducive environment for innovation and improving the performance of the Brazilian economy. Future studies could investigate more detailed factors influencing Brazil's innovative performance and analyze the practical implications of these findings on policy and strategy formulation in the country."

Keywords: Global Innovation Index. Innovation Performance. Innovation Systems. Policymakers. Stakeholders.

Introduction

Innovation is a complex process that requires investments, efforts, and technological capabilities. In an economy, both the State and companies have important roles in promoting and performing Science, Technology, and Innovation (ST&I) within the ecosystem and national innovation system. However, the understanding of these roles is not well understood by policymakers, so it is important to have a common understanding of the role of actors involved in the innovation process at the national level (TERRA; OHAYON, 2019; DE FIGUEIREDO et al., 2018; LEAL; FIGUEIREDO, 2018; DE NEGRI, 2018; BELL; FIGUEIREDO, 2012; ADNER; KAPPOR, 2010).

In this sense, economies recognize the importance of innovative companies for growth, because Innovation can quickly improve the financial performance of companies in countries experiencing economic crisis and can position companies for better recovery at the national or global level. (OECD, 2020a; OECD, 2020b; DE NEGRI; KOELLER, 2020; PAULA; SILVA, 2018).

The literature recognizes innovation as a factor for economic growth in countries and how policymakers worldwide are investing in and improving conditions to promote it. Advancements in the field of innovation occur within the context of institutions and their interactions within a country, forming what is known as an innovation system. It can be affirmed that innovation systems represent a crucial component and an essential driver in the economic development strategy of nations. Understanding innovation systems, whether at the national, regional, or local level, also allows policymakers to focus on possible systemic deficiencies that may hinder the innovative performance of the industry. Therefore, the identification of innovation performance indicators and the development of measurement frameworks for innovation systems are of great importance so that policymakers can effectively address challenges (BAKHTIAR et al., 2022).

In this context, the Global Innovation Index (GII) is a crucial tool to guide countries in increasing well-being and formulating innovation policies and is composed of points that are related to and measure innovation performance in an economy. Therefore, it is important to establish connections between the different factors that make up the GII and understand the relationship between the factors that a country should focus on to improve its innovation capacity and performance, in order to formulate and determine appropriate, efficient and effective innovation policies for itself. The UN General Assembly on ST&I made a positive indication regarding the usefulness and importance of the GII in measuring innovation performance (WIPO, 2022 a; OTURAKCI, M.; 2021; UN, 2019).

Recently, in a global context, the GII report of 2022 highlighted that 2 (two)

new waves of innovation are coming our way, one being the Wave of Digital Era, and the other being the Wave of Deep Science (WIPO, 2022 a).

Despite recent improvements in Brazil's GII performance as highlighted by WIPO (2022a), the literature since 2016 has highlighted and evidenced a recurring Brazilian pattern of weaknesses in the innovation ecosystem, ineffective National Strategies for Science, Technology, and Innovation, and the position of the Brazilian economy falling short in the GII ranking and innovation efficiency rate, pointing out that there are recurring "weak spots" and "targets" in the GII structure that need to be addressed and adjusted. Therefore, actors highlight that such relevant points indicate the need to develop a new generation of strategies and public policies focused on better investments and more effective and efficient results, as well as deeper research on these or other relevant points that need to be highlighted (LEAL; FIGUEIREDO, 2018; DE NEGRI, 2018; DE FIGUEIREDO ET AL; 2018; MAZZUCATO; PENNA, 2016; MONTEIRO, 2019).

As another relevant point, among other characteristics and indicators, we have the continental size of Brazil and its large population of 214 (two hundred and fourteen) million inhabitants. Not surprisingly, recent studies by the World Bank have identified and highlighted several structural obstacles that have resulted in weak average GDP (gross domestic product) growth of 0.3% in the last decade. Brazil's productivity is affected by various factors, including complex taxation, an unfavorable business environment, a lack of investment in human capital, ineffective sectoral policies, low savings rates, as well as the limitation of public investment to accommodate high current spending and growing pension obligations. Such facts impose proportional challenges to its growth in any area, especially regarding innovation performance within the entire GII structure, which involves a total of 81 (eighty-one) indicators (WBG, 2023b; WIPO, 2022a).

Along the same line, Bakhtiar et al. [2] evaluated the performance of innovation systems based on the 2019 GII and classified Brazil's efficiency and effectiveness as medium to low with respective scores of 0.49 and 0.72, describing it as not only inefficient but also ineffective (BAKHTIAR et AL., 2022).

Given these highlighted points, and the motivation and potential relevance (including social) of this topic, the following research question was formulated: "Which factors have significantly impacted Brazil's performance in the GII in recent years?" In this context, this research aims to investigate the factors that have impacted Brazil's performance in the GII in recent years.

The methodology used consisted of collecting and selecting data for the research corpus longitudinally, through official annual data from Brazil on the world ranking of innovation performance (GII), delimited in a time frame from

2020 to 2011, down to the level of its 7 (seven) pillars. Discrimination at the sub-pillar level was highlighted in the most significant points, and in some cases, with a description of the indicators. The analysis, investigation, and evaluation of the data were carried out using a longitudinal data collection technique. In addition, for reflections, the period from 2021 to 2022 will also be analyzed.

1 Literature and hypotheses

1.1 Concept and structure of the global innovation index - GII

The Global Innovation Index (GII) is an important tool that measures and tracks innovation globally, with the aim of improving the measurement and understanding of innovation, identifying policies and best practices to promote it, and providing tools to adapt innovation policies. The GII is composed of points that are related and measure the performance of innovation in an economy, structured by 2 (two) sub-indices (Innovation Inputs and Innovation Outputs), built around 7 (seven) fundamental pillars, divided into 21 (twenty-one) sub-pillars, and 81 (eighty-one) individual indicators. The GII calculation method uses specific measures to score the sub-pillars and pillars, enabling a comprehensive analysis of a nation's innovation environment (WIPO, 2022a; CORNELL UNIVERSITY; INSEAD; WIPO, 2022; CORNELL UNIVERSITY; INSEAD; WIPO, 2021; CORNELL UNIVERSITY; INSEAD; WIPO, 2020; CORNELL UNIVERSITY; INSEAD; WIPO, 2019).

The Global Innovation Index is published annually and covers a wide range of countries and economies. The Global Innovation Index (GII) project was initiated in 2007 and since 2021, it is published by WIPO in partnership with the Portulans Institute, with the support of academic and corporate network partners. The GII is published annually and covers around 130 (one hundred and thirty) economies/countries, representing 91.8% of the world's population and 96.8% of the world's GDP. The GII also reveals the world's most innovative countries and the latest global innovation trends, measuring the pace of technological progress and adoption and capturing the main innovation trends in the four stages of the innovation journey: investment in science and tech; tech progress; tech adoption; and socio-economic impact. The 15th edition of 2022 and the 14th edition of 2021, both after the start of the Covid-19 pandemic, included 132 (one hundred and thirty-two) countries and economies. (WIPO, 2022a; CORNELL UNIVERSITY; INSEAD; WIPO, 2022; CORNELL UNIVERSITY; INSEAD; WIPO, 2021; CORNELL UNIVERSITY; INSEAD; WIPO, 2020).

The Innovation Inputs sub-index, which comprises the first five pillars, measures a nation's innovation potential. The Innovation Outputs sub-index, composed of the last two pillars, evaluates a nation's innovation results. The overall score of the GII is the simple average of the input and output sub-indices.

Governments from various countries use the GII to evaluate and improve their innovation ecosystems and as a reference in economic public policies and plans (WIPO, 2022a; CORNELL UNIVERSITY; INSEAD; WIPO, 2022; CORNELL UNIVERSITY; INSEAD; WIPO, 2021; CORNELL UNIVERSITY; INSEAD; WIPO, 2020; CORNELL UNIVERSITY; INSEAD; WIPO, 2019).

Finally, the central benefit of the GII is the inclusion of data-driven evidence and metrics in the assessment, development, and implementation of innovation policies. The process involves bringing together statisticians and decision-makers to evaluate a country's innovation performance based on GII metrics, followed by seeking out innovation opportunities and addressing specific weaknesses (factors or weak points) of each country. Essential for the success of this process, which ideally uses the GII as a coordination tool, is coordination between different public and private innovation actors, as well as between government entities at the local, regional, and national levels (WIPO, 2022a).

1.2. Description of the 7 (seven) pillars of the GII framework

For a better understanding, below is the description of the 7 (seven) pillars of the GII structure (WIPO, 2022a; CORNELL UNIVERSITY; INSEAD; WIPO, 2022; CORNELL UNIVERSITY; INSEAD; WIPO, 2020):

1. "Institutions" - points related to the business, political, and regulatory environment of the country, and assesses the institutional structure that supports the business environment and promotes economic growth through good governance, protection, and incentives for innovation;
2. "Human Capital & Research" - points related to the level and quality of education and research in a country, which are important factors for its innovation capacity. It involves education, higher education (continuing education), and research and development (R&D), including metrics such as problem-solving facilities, government funding, enrolment in higher education, gross expenditure on R&D, and the performance and world ranking of universities - QS World University Rankings;
3. "Infrastructure" - points related to transport, communication, and energy infrastructure that are essential for the exchange of ideas, services, and goods that stimulate innovation and sustainable growth. It involves information and communication technologies (ICTs), general infrastructure, and ecological sustainability, including access and use of ICTs, online government services, logistics performance, gross capital formation, GDP by energy use and consumption, environmental performance, and ISO 14001 environmental certificates;

4. "Market Sophistication" - points related to a set of indicators that assess the sophistication of market conditions, level of competition, and total commercial transactions. It involves credit, investment, and trade, competition and market size/scale measured by microfinance loans, protection of minority investors, market capitalization, venture capital deals, fees and tariffs, local competition intensity, and domestic market scale;
5. "Business Sophistication" - points related to the level of sophistication of companies to assess how prepared they are for innovation activities. It involves knowledge workers, innovation linkages, and knowledge absorption, including issues such as knowledge-intensive employment, formal training offered by companies, R&D spending financed by companies, university/industry collaboration in R&D, strategic alliance agreements, patents in more than two offices, imports, among others;
6. "Knowledge & Technology Outputs" - points related to the variables considered as the result of inventions, creations, and/or innovations. It involves knowledge creation, impact of knowledge, and diffusion of knowledge measured by variables such as patents, utility models, scientific and technical articles, software spending, ISO 9001 certifications, high and medium-high technology manufacturing, intellectual property revenues, net exports of high technology and ICT services;
7. "Creative Outputs" - points related to the results and role of creativity in innovation, involving intangible assets, creative goods and services, and online creativity, including trademarks, industrial designs, intangible assets, exports of cultural and creative goods and services, entertainment and media market, other media, domains, and mobile app creation.

1.3 Recent studies on brazil's innovation performance and hypotheses

The recent positions of Brazil in the Global Innovation Index (GII), prior to the pandemic, were 66th in 2019 and 62nd in 2020, and, after the onset of the Covid-19 crisis and in the post-pandemic period, Brazil ranked 57th in 2021 and 54th in 2022. The literature on the performance of the Brazilian economy in innovation since 2016 has consistently highlighted recommended measures to increase the effectiveness and efficiency of national spending on R&D, innovation rates, and the GII. Thus, weaknesses in Brazil's innovation ecosystem, the ineffectiveness of the National Strategies for Science, Technology, and Innovation, and especially Brazil's position below other economies in the GII ranking and its innovation efficiency rate have been emphasized. Various recommendations have been made, highlighting the need to develop a new generation of strategies and public policies focused on better

investments, as well as more effective and efficient results (WIPO, 2022a; CORNELL UNIVERSITY; INSEAD; WIPO, 2022; CORNELL UNIVERSITY; INSEAD; WIPO, 2021; CORNELL UNIVERSITY; INSEAD; WIPO, 2020; CORNELL UNIVERSITY; INSEAD; WIPO, 2019; LEAL; FIGUEIREDO, 2018; DE NEGRI, 2018; DE FIGUEIREDO ET AL; 2018; MAZZUCATO; PENNA, 2016).

Monteiro (2019), in his studies on the evolution of Brazil's performance in the GII structure, highlighted in his results from the time analysis of this structure that there are "weak points" and "targets" that need to be addressed and adjusted, as well as "strong points" that need to be highlighted to improve Brazil's performance in the GII. Therefore, he suggests more in-depth research on these or other points to be highlighted.

In the same vein, a recent study by Bakhtiar et al. (2022) aimed to present and evaluate the performance of innovation systems globally, considering two indicators: efficiency and effectiveness, depending on each country's situation. To this end, a statistical model was used to evaluate the performance of innovation systems in 126 (one hundred and twenty-six) economies, comparing and referencing countries in terms of the efficiency and effectiveness of their innovation systems through the input/output relationship of the 2019 GII report and the 2019 Global Competitiveness Index (GCR) report. In its results, it classified Brazil's performance as medium to low (in orange), framing Brazil's efficiency and effectiveness as medium to low with respective scores of 0.49 and 0.72. Finally, the study highlighted among its results that innovation systems in countries like Brazil and Zimbabwe are not only inefficient but also ineffective (BAKHTIAR et AL.,2022).

Also in line with this direction, recent studies by Oturakci, M. (2021) aimed to examine the fundamental relationship between innovation input and output. The study investigated the relationship between the factors that make up the GII structure, using canonical correlation analysis to analyze 8 (eight) years of data compiled from the GII reports from 2013 to 2020. Based on the results, they concluded that the "Business sophistication" (69.2%) and "Human capital and research" (68.7%) factors, which are part of the input index, and the "creative outputs" (98.8%) factor, which is part of the output index, were considered the most important and explanatory factors in the formation of the GII innovation score. Therefore, the authors highlight that since the two basic indices in the calculation of the GII are the Input and Output indices, it was concluded that these three significant and explanatory factors for the input and output indices are also the most important factors for the Global Innovation Index - GII. Furthermore, it is worth noting that the results of this study were compared with relevant studies in the literature and were found to be supported by them (OTURAKCI,M.; 2021).

Oturakci, M. (2021) demonstrated that regarding the "institutions" pillar, there is a very weak correlation between the "institutions" - "infrastructure" and "institutions"

"Market sophistication" variables. Concerning the "market sophistication" pillar, Oturakci, M. (2021) showed that the strongest relationship between the factors in the input index of the GII is at the level of 85.58% between "market sophistication" and "business sophistication".

Oturakci, M. (2021) found that the "business sophistication" pillar explains 69.2% of the Innovation Input Sub-Index, indicating its crucial role in enhancing a country's production and competitiveness in the global market, particularly, reflecting that the quality of business networks and the development of business strategies are important factors for a country's overall development.

Oturakci, M. (2021) demonstrated that regarding the "creative outputs" pillar, the "creative outputs" factor explains the Sub-index of Results, Production and Innovation Outputs (Output index) at a level of 98.8%. In this sense, it should be noted that creative outputs are achieved through the use of complex technologies and intensive information production in countries, and that the production variable is important in determining the well-being of countries together with the innovation index (OTURAKCI, M.; 2021).

Another relevant point that is not a weakness, but rather evidence of the strategic potential for growth of a strength, is the "human capital & research" pillar, as evidenced in the studies by Oturakci, M. (2021). The author demonstrates and highlights that the "human capital & research" factor and pillar explains the Innovation Input Sub-Index (input index sub-index) at the level of 68.7%, concluding that it is one of the most important and effective input variables in the total calculation of the GII.

It is worth remembering that the "human capital and research" pillar and variable includes sub-variables such as education, higher education, and research and development. The innovation capacity of a nation is primarily determined by the educational level and research activity of the country. Human capital is essential in creating and evolving ideas in a country and to enhance it, adequate investment in national educational systems is required (OTURAKCI, M., 2021).

In this sense, the literature emphasizes that to foster innovation in a country, it is necessary to invest in quality education and efficient research and development (R&D) centers, creating a solid foundation for innovative activities that rely on well-developed human capital. Investing in education offers long-term benefits, improving human capital and increasing a nation's innovation

capacity, regardless of its ranking in the Global Innovation Index (GII). Therefore, it is not by chance that the literature highlights that human capital and the rate of research and innovation are complementary and interdependent (OTURAKCI, M., 2021; CORNELL UNIVERSITY;INSEAD; WIPO, 2020).

Finally, it should be noted that the GII 2022 report highlighted that Brazil has been improving its performance in the GII since 2019 and, for the first time, is among the top 3 most innovative economies in the Latin America and Caribbean region, and is part of the group of 9 (nine) upper-middle-income economies that perform above expectations given their level of development. However, the challenges for its growth, especially in the GII, are proportional to its continental size and population of 214 (two hundred and fourteen) million people (WIPO, 2022a; WIPO, 2022b).

Based on the insights and evidence highlighted in this section, which also informed the research question of this study, 3 (three) hypotheses were developed: H1 - There are significant weaknesses (with low performance) that have significantly impacted Brazil's performance in the GII in recent years.

H2 - There are significant strengths (with high performance) that have significantly impacted Brazil's performance in the GII in recent years.

H3 - For the purpose of recommendations, it is possible to classify and rank, based on their impact, the factors that have significantly impacted Brazil's performance in the GII in recent years.

1.4 Brazil and the GII 2022

During the last decade, Brazil faced several structural obstacles that prevented robust GDP growth, registering only an average of 0.3%, despite advantageous demographic conditions. The low productivity can be attributed to various factors, such as the complexity of the tax system, an unfavorable business environment for entrepreneurship, limited accumulation of human capital, ineffective sectorial policies due to government intervention, low levels of savings, and a limitation of public investment due to high current expenditures and growing pension obligations (WBG, 2023b).

Recently, the report of the 15th edition of the Global Innovation Index (GII) 2022 highlighted that 2 (two) new waves of innovation are coming our way, one being the Digital Age Wave, and the other being the Deep Science Wave (WIPO, 2022a).

The GII 2022 report had the theme "What is the future of innovation-driven growth?" and tracked global innovation trends amidst the COVID-19 pandemic. Despite tensions in supply chains, trade, and geopolitics, the report showed that investments in science and innovation continued to grow in 2021,

contradicting the general decline observed in periods of economic turbulence (WIPO, 2022a).

The GII 2022 suggests that the innovative sectors of the global economy are at a crossroads, with patent filings, R&D spending, scientific publications, and venture capital investments showing continued growth. The report ranked the innovative performance of 132 (one hundred and thirty-two) economies and hopes that the assessments will help find the best levers to drive innovation for the benefit of global economies and societies (WIPO, 2022a).

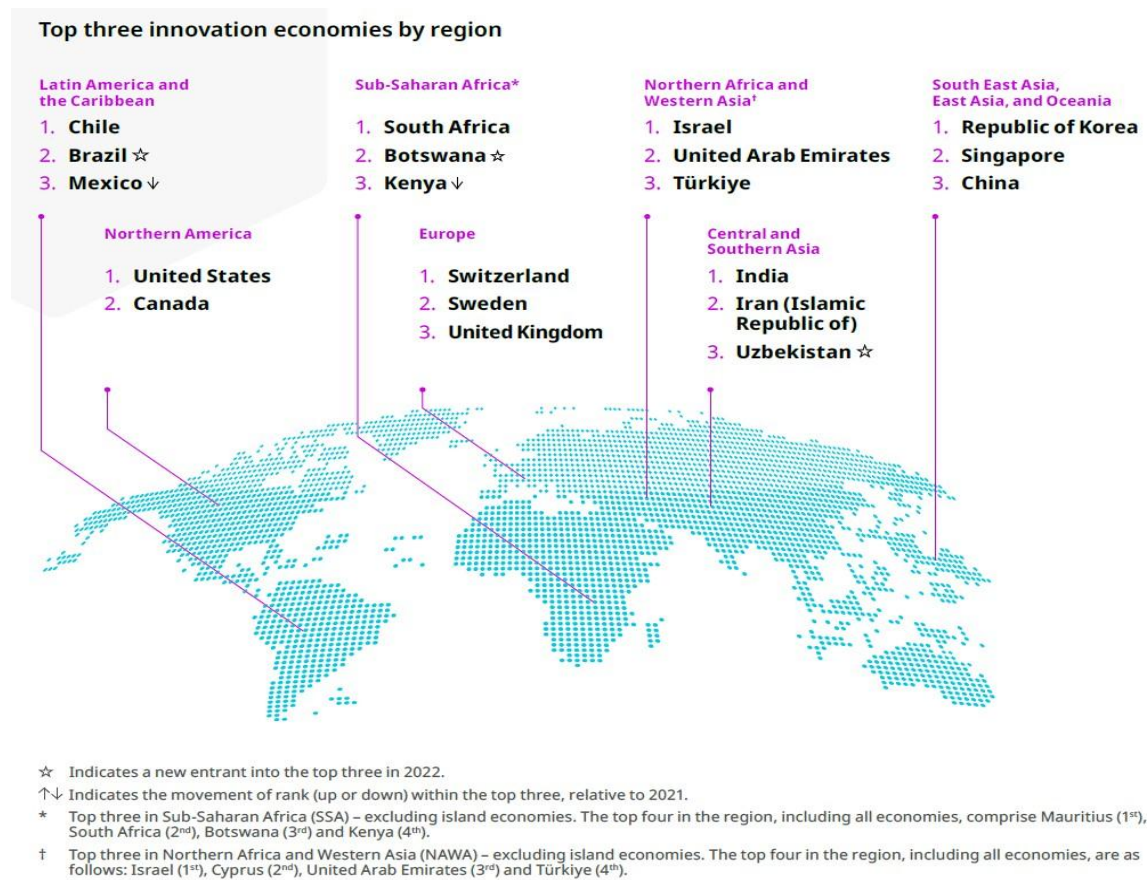
In this 2022 edition, Switzerland ranks 1st with a score of 64.6, and Brazil ranks 54th with a score of 32.5 (WIPO, 2022a). It is worth noting that in 2021, Brazil had a population of approximately 214 million people, and the sum of the Latin America and Caribbean (LAC) countries was almost 655 million people. Its Gross Domestic Product (GDP) in current US dollars was a total of 1.61 trillion dollars, and for all LAC countries, it was a total of 5.45 trillion dollars. Finally, its GDP per capita (current US dollars) was

7.5 thousand dollars per capita, and for all LAC countries, it was 8.3 thousand dollars per capita (WBG, 2023a).

Since 2019, Brazil has been improving its performance in the GII and, in context, in 2022 Brazil (WIPO, 2022a; WIPO, 2022b): managed to be a new entrant, ranking 2nd out of 18 countries in its Latin America and Caribbean group, among the 3 most innovative economies in that group, losing position only to Chile (50th position in the rank, score 34.0, first in its group); managed to be part of the group of 9 out of 36 upper-middle-income economies with above-expected performance relative to its level of development; had a better performance in innovation products (outputs) than in innovation inputs in its GII structure in 2022; ranks 4th out of the 5 BRICS countries (Brazil, Russia, India, China, and South Africa), gaining position only over South Africa (61st position in the rank, score 29.8) and losing position to Russia (47th position in the rank, score 34.3), India (40th position in the rank, score 36.6), and China (11th position in the rank, score 55.3).

Below are the global innovation leaders in 2022, with a sample of the top three from each group (WIPO, 2022a, p.18).

Figure 1. The 3 (three) best innovative economies by region (WIPO, 2022a, p.18)

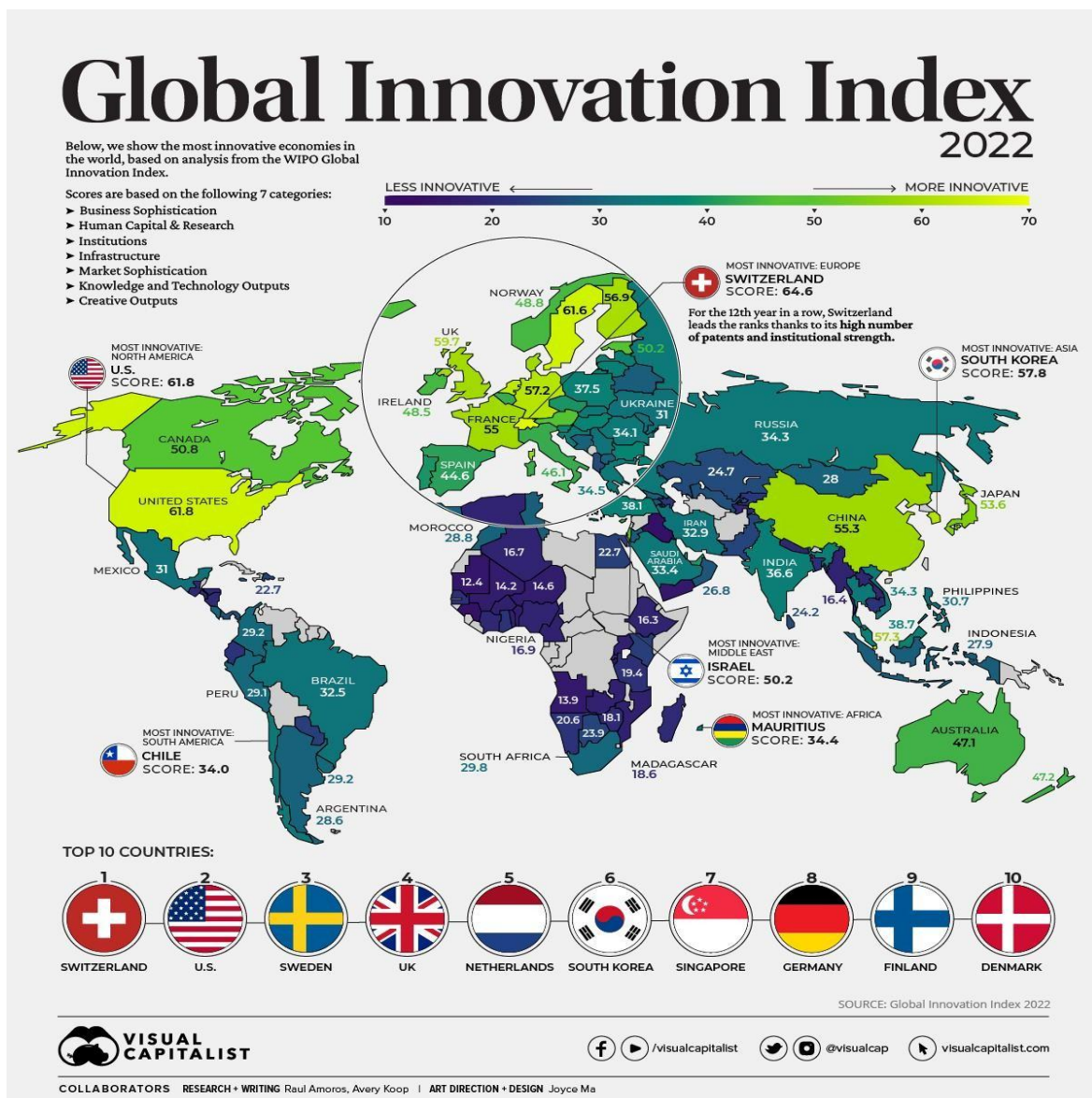


Top three innovation economies by income group

High-income	Upper middle-income	Lower middle-income	Low-income
1. Switzerland	1. China	1. India ↑	1. Rwanda
2. United States ↑	2. Bulgaria	2. Viet Nam ↓	2. Madagascar ☆
3. Sweden ↓	3. Malaysia	3. Iran (Islamic Republic of) ☆	3. Ethiopia ☆

The following is the Global Innovation Index 2022 - Mapped: The World's Most Innovative Countries in 2022 (VIRTUAL CAPITALISM, 2022).

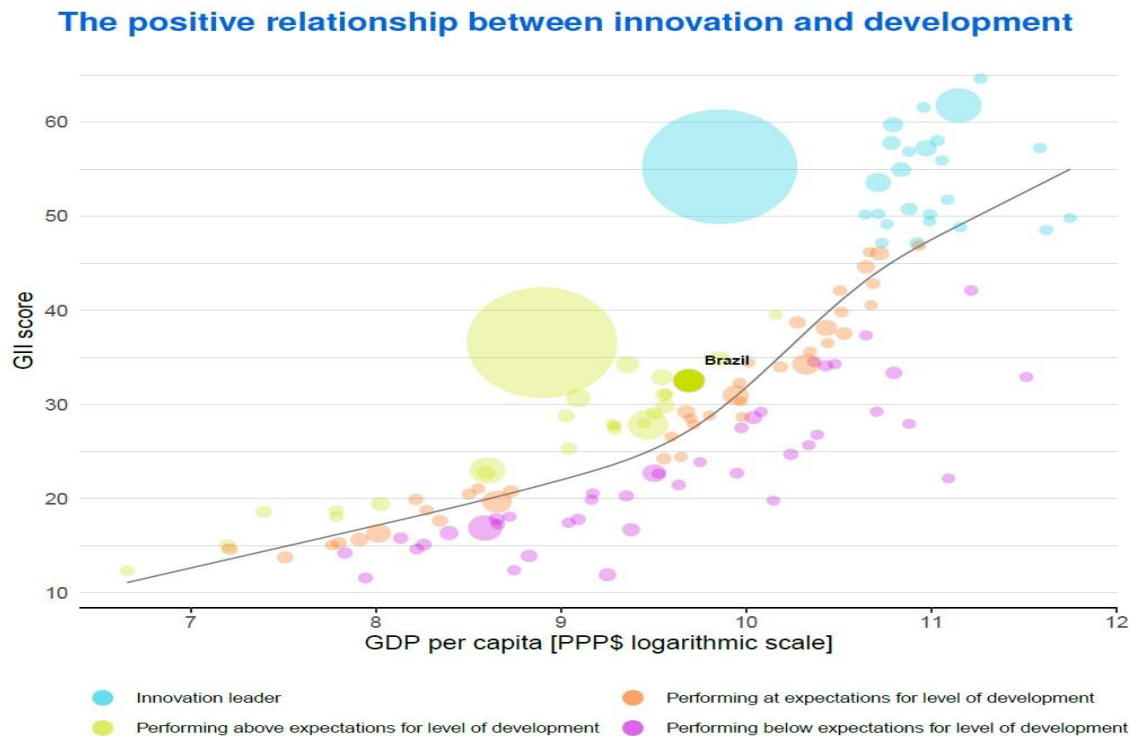
Figure 2. Global Innovation Index 2022 - Mapped: The Most Innovative Countries in the World in 2022 (VIRTUAL CAPITALISM, 2022).



Brazil's observed performance in relation to GDP is exceeding expectations for its level of development. A bubble chart presented below showcases the correlation between income levels (GDP per capita) and innovation performance (GII score). The trend line on the chart provides an indication of expected innovation performance according to the income level. Countries that appear above the trend line are performing better than expected, while those that fall below the trend line are underperforming or below expectations (WIPO, 2022b, p.2). Next, the positive relationship between innovation and development.

Figure 3. The positive relationship between innovation and development (WIPO,2022b, p.2)

Relative to GDP, Brazil's performance is above expectations for its level of development.



2.1 Methodology

2.2 Data collection and selection

The data that make up the research corpus, for the purpose of analysis and investigation, were collected at the level of the 7 (seven) pillars and 21 (Twenty-one) sub-pillars, and the most significant points will be highlighted in terms of their indicators, the structure of Brazil's GII from 2020 to 2011, and, complementarily, from 2022 to 2021.

2.2.1 Search delimitations

The analysis, investigation, and evaluation of the Corpus data were carried out using a longitudinal data collection technique, formed by the official annual assessments of Brazil found in the global innovation performance ranking (Global Innovation Index - GII), delimited by the time frame from 2020 to 2011 at the level of the seven pillars. In the most significant points, the sub-pillars were discriminated against, and in some cases, their indicators were described.

The data collection technique provides a quantitative or numerical description of trends, attitudes, or opinions of a population by studying a sample of it, and

delimitation refers to boundaries concerning variables, the points that will be addressed, or cross-sectional or longitudinal cuts. In this case, the nature of the data collection was longitudinal since the data was collected over time, allowing for an analysis comparing data collected at different points in time (CRESWELL, 2010; VERGARA, 2016).

When conducting a longitudinal research during or after the Covid-19 pandemic, characterized by WHO since 11/03/2020, it is important to include data collected before the pandemic in order to compare and analyze the changes that occurred over time and separate the effect of the pandemic from other changes that may have affected the variable in question. This allows for evaluating the direct impact of the pandemic on the variable in question and developing strategies to deal with these effects, especially due to the abrupt and significant economic, environmental, social, and humanitarian impacts triggered worldwide in all economies, which, per se, impact all metrics. In this logic, the temporal cutoff was chosen up to 2020 (data collected throughout 2019), as they are values relative to the period before the Covid-19 pandemic. Therefore, it was decided to avoid GII data from 2021 onwards (data collected throughout 2020), to avoid distortions. Additionally, for further reflection and contribution, the period from 2021 to 2022 will also be analyzed.

In this regard, Bakhtiar et al. (2022) point out that it is too early to determine the impact of COVID-19 on national innovation systems since the innovation indices that make up the GII are still in disagreement, making them not as parameters. The global recession caused by the Covid-19 pandemic has negatively affected the efficiency and effectiveness of the innovation systems of many countries and their respective innovation performances, resulting in varied impacts on the inputs and outputs of innovation of the countries (BAKHTIAR et al., 2022).

2.2.2 Strength and weakness point parameterization

The methodology for classifying and parameterizing the assessment of strengths, weaknesses, and mixed points (simultaneously weak and strong) for the investigated points was based on Monteiro's research methodology (2019) and adapted from the GII reports, particularly the WIPO's 2022 GII (2022).

In summary, in terms of graphical construction and data analysis tables, the following legend was adopted: If the ranking position is lower than the GII value of the same year, the point will be classified as a weakness (pink). If the ranking position is higher than the GII value of the same year, the point will be classified as a strength (blue). And if the ranking position is equal to the GII value of the same year, the point will be classified as a mixed point (white/uncolored).

2.3 Data classification

The hierarchical relevance of improvement priorities of the investigated points throughout the GII structure – 7 (seven) pillars, 21 sub-pillars, and 81 indicators – for the purpose of formulating public policies aimed at structural treatments and adjustments of the GII, was the result of the longitudinal quantitative hierarchical classification from 2020 to 2011, combined and compared with the qualitative highlights of relevance of points and factors of the GII structure resulting from research on this topic. The hierarchical classification was done quantitatively by the highest value evidenced in the research corpus sample for each point (pillar), and in the points considered most significant, they were highlighted at the level of their sub-pillars and, in some cases, with a description of their indicators.

3 Analysis of results

3.1 Mapping at the pillar level of strengths and weaknesses in performance - GII of Brazil from 2020 to 2011

Table 1 - Evidence of strengths and weaknesses in the GII of Brazil, from 2020 to 2011, at the pillar level

	2 Sub-indices	7 Pillars	21 Subpillars	81 Indicators
GII	Innovation inputs Sub-index - Inputs - IIS [High in 60% (ln 6 out of 10)]	1. "Institutions" [Down in 100% (ln 10 out of 10)]	1.1 political environment [Down in 100% (ln 10 out of 10)]	2 (two) indicators
			1.2 regulatory environment [Down in 80% (ln 8 out of 10)]	3 (three) indicators
			1.3 business environment [Down in 100% (ln 10 out of 10)]	2 (two) indicators
		2. "Human Capital & Research" [High in 60% (ln 6 out of 10)]	2.1. education [Mixed in 50% (ln 5 out of 10)]	5 (five) indicators
			2.2. tertiary education (continuing education) [Down in 100% (ln 10 out of 10)]	3 (three) indicators
			2.3. research & development (r&d) [High in 100% (ln 10 out of 10)]	4 (four) indicators
		3. "Infrastructure" [High in 90% (ln 9 out of 10)]	3.1. information and communication technologies (icts)	4 (four) indicators
			3.2. general infrastructure	3 (three) indicators
			3.3. ecological sustainability	3 (three) indicators
		4. "Market Sophistication" [Down in 90% (ln 9 out of 10)]	4.1. credit [Down in 100% (ln 10 out of 10)]	3 (three) indicators
	Innovation Outputs/ Products/ Results Sub-index - Outputs - IPS [Down in 80% (ln 8 out of 10)]		4.2. investment [Mixed in 50% (ln 5 out of 10)]	4 (four) indicators
			4.3. trade, competition and market scale [Mixed in 50% (ln 5 out of 10)]	3 (three) indicators
		5. "Business Sophistication" [High in 100% (ln 10 out of 10)]	5.1. knowledge workers	5 (five) indicators
			5.2. innovation linkages	5 (five) indicators
			5.3. knowledge absorption	5 (five) indicators
		6. "Knowledge & Technology Outputs" [Mixed in 50% (ln 5 out of 10)]	6.1. knowledge creation	5 (five) indicators
			6.2. knowledge impact	5 (five) indicators
			6.3. knowledge diffusion	4 (four) indicators
		7. "Creative Outputs" [Down in 80% (ln 8 out of 10)]	7.1. intangible assets [Down in 70% (ln 7 out of 10)]	4 (four) indicators
			7.2. creative goods (assets and property) and services [Down in 80% (ln 8 out of 10)]	5 (five) indicators
			7.3. online creativity [High in 80% (ln 8 out of 10)]	4 (four) indicators

Source: Adapted by the authors from Wipo (2022), Cornell university; Insead; Wipo (2021; 2020; 2019; 2018; 2017; 2016; 2015; 2014; 2013; 2012; 2011), and Monteiro (2019).

Legend: low performance/weak point: pink; high performance/strong point: blue; mixed performance/mixed point: white.

3.2 Mapping at the pillar level of strengths and weaknesses in performance - GII of Brazil from 2022 to 2021

Table 2 - Evidence of strengths and weaknesses in the GII of Brazil, from 2022 to 2021, at the pillar level

	2 Sub-indices	7 Pillars	21 Subpillars	81 Indicators
GII	Innovation inputs Sub-index - Inputs - IIS [Mixed in 50% (In 1 out of 2)]	1. "Institutions" [Down in 100% (In 2 out of 2)]	1.1 political environment [Down in 100% (In 2 out of 2)] 1.2 regulatory environment [Down in 100% (In 2 out of 2)] 1.3 business environment [Down in 100% (In 2 out of 2)]	2 (two) indicators 3 (three) indicators 2 (two) indicators
		2. "Human Capital & Research" [High in 100% (In 2 out of 2)]	2.1. education [Mixed in 50% (In 1 out of 2)] 2.2. tertiary education (continuing education) [Down by 2 times of 2] 2.3. research & development (r&d) [High in 100% (In 2 out of 2)]	5 (five) indicators 3 (three) indicators 4 (four) indicators
		3. "Infrastructure" [Down in 100% (In 2 out of 2)]	3.1. information and communication technologies (icts) [High in 100% (In 2 out of 2)] 3.2. general infrastructure [Down in 100% (In 2 out of 2)] 3.3. ecological sustainability [Down in 100% (In 2 out of 2)]	4 (four) indicators 3 (three) indicators 3 (three) indicators
		4. "Market Sophistication" [Mixed in 50% (In 1 out of 2)]	4.1. Credit 4.2. Investment 4.3. Trade, Competition and Market Scale	3 (three) indicators 4 (four) indicators 3 (three) indicators
		5. "Business Sophistication" [High in 100% (In 2 out of 2)]	5.1. Knowledge Workers 5.2. Innovation Linkages 5.3. Knowledge Absorption	5 (five) indicators 5 (five) indicators 5 (five) indicators
	Innovation Outputs/ Products/ Results Sub-index - Outputs - IPS [Mixed in 50% (In 1 out of 2)]	6. "Knowledge & Technology Outputs" [Mixed in 50% (In 1 out of 2)]	6.1. Knowledge creation 6.2. knowledge impact 6.3. knowledge diffusion	5 (five) indicators 5 (five) indicators 4 (four) indicators
		7. "Creative Outputs" [Mixed in 50% (In 1 out of 2)]	7.1. Intangible assets 7.2. creative goods (assets and property) and services 7.3. online creativity	4 (four) indicators 5 (five) indicators 4 (four) indicators

Source: Adapted by the authors from Wipo (2022) and Cornell university; Insead; Wipo (2021; 2020).

Legend: low performance/weak point: pink; high performance/strong point: blue; mixed performance/mixed point: white.

4 Discussions and considerations

The results confirm that all 3 (three) postulated hypotheses were accepted. As proposed in hypothesis 1, there are recurrent weak points found in 3 (three) pillars and 9 (nine) sub-pillars resulting from these that involve around 30 (thirty) indicators, which generate negative impacts and weaken the GII structure and innovation efficiency rate in its measurements. As proposed in hypothesis 2, there are recurrent strong points found in 4 (four) pillars and 12 (twelve) sub-pillars resulting from these that involve around 51 (fifty-one) indicators, which generate positive impacts and strengthen the GII structure and innovation efficiency rate in its measurements. As proposed in hypothesis 3, for the purpose of recommendations, it is possible to classify and prioritize, based on the impacts generated, the points that have significantly impacted Brazil's performance in the GII in recent years, highlighting the pillars and sub-pillars, and in some cases, their indicators, which in almost all editions analyzed of the GII, most significantly and recurrently impacted their measurements and innovation efficiency rate.

The analysis of the pillars of the Global Innovation Index (GII) of Brazil from 2020 to 2011 (ten years) demonstrated the relevance of certain factors for the success of innovation activity. It was identified that the first pillar "institutions" had a negative impact in 100% of the 10 measurements performed (10 out of

10), being responsible for evaluating and providing the institutional structure necessary to attract businesses and promote economic growth, as well as providing adequate governance and incentives for innovation involving the business, political and regulatory environment of the country.

In a detailed manner, this "institutions" pillar has 7 (seven) indicators and 3 (three) sub-pillars, and it should be highlighted that the 3 sub-pillars "political environment", "regulatory environment", and "business environment" had a negative impact in 100% of the 10 measurements taken (10 out of 10).

Thus, in its 3 (three) sub-pillars, the "institutions" pillar was negatively highlighted: in the "political environment" sub-pillar, it had a negative impact in 100% of the 10 (ten) measurements taken (10 out of 10), which contains 2 (two) indicators "Political and operational stability" and "Government effectiveness"; in the "regulatory environment" sub-pillar, it had a negative impact in 80% of the 10 (ten) measurements taken (8 out of 10), which contains 3 (three) indicators "Regulatory quality", "Rule of law", and "Cost of redundancy dismissal", and; in the "business environment" sub-pillar, it had a negative impact in 100% of the 10 (ten) measurements taken (10 out of 10), which contains 2 indicators "Policies for doing business" and "Entrepreneurship policies and culture".

Regarding this "institutions" pillar, recent studies by Oturakci, M. (2021) have shown that there is a very weak correlation between the variables "institutions" - "infrastructure" and "institutions" - "market sophistication".

Another pillar that had a significant negative impact, evidenced in 90% of the 10 (ten) assessments carried out (9 out of 10), was the fourth pillar "market sophistication", which is responsible for evaluating the sophistication of market conditions, competition, and the level of scale and total commercial transactions, including credit, investment, trade, competition, and domestic market size, becoming essential for innovation activity.

Discriminately, this "market sophistication" pillar has 10 (ten) indicators and 3 (three) sub-pillars, highlighting that within its 3 (three) sub-pillars, the "market sophistication" pillar was negatively evidenced: in the "Credit" sub-pillar, it had a negative impact in 100% of the 10 (ten) assessments made (10 out of 10), which contains 3 (three) indicators "Finance for startups and scaleups", "Domestic credit to private sector - % GDP", and "Loans from microfinance institutions - % GDP"; in the "Investment" sub-pillar, it had a mixed impact in 50% of the 10 (ten) assessments made (5 out of 10), which contains 4 (four) indicators "Market capitalization - % GDP", "Venture capital investors", "Venture capital recipients", and "Venture capital received % GDP", and; in the "Trade, Competition and Market Scale" sub-pillar, it had a mixed impact in 50% of the 10 (ten) assessments made (5 out of 10), which contains 3 (three) indicators

"Applied tariff rate - weighted avg", "Domestic industry diversification", "Domestic market scale".

Regarding this "market sophistication" pillar, recent studies by Oturakci, M. (2021) have shown that the strongest relationship between factors in the input index of the GII is at the level of 85.58% between "market sophistication" and "business sophistication". However, it was found that there is a very weak correlation between the variables "institutions" - "infrastructure" and "institutions" - "market sophistication".

The last pillar that had a significant negative impact, evidenced in 80% of the 10 (ten) assessments made (8 out of 10), was the seventh pillar, "creative outputs", which is responsible for evaluating the role of creativity in innovation and involves intangible assets, cultural and creative goods and services, online creativity, exports of cultural goods and services, mobile app creation, and sectors such as entertainment, media, and communication. It is important to note that the weakness identified in this "creative outputs" pillar directly affects the Results Sub-index, innovation output and production, with this negative impact being evidenced in 80% of the 10 (ten) assessments made (8 out of 10) for this sub-index and negatively impacting the innovation efficiency of the evaluated countries.

Discriminately, this "creative output" pillar has 13 (thirteen) indicators and 3 (three) sub-pillars, highlighting that in 2 (two) of its 3 (three) sub-pillars, the "creative outputs" pillar was negatively evidenced: in the "Intangible assets" sub-pillar, it had a negative impact in 70% of the 10 (ten) assessments made (7 out of 10), which contains 4 (four) indicators "Intangible asset intensity - top 15", "Trademarks by origin", "Global brand value - top 5,000", and "Industrial designs by origin", and; in the "creative goods (assets and property) and services" sub-pillar, it had a negative impact in 80% of the 10 (ten) assessments made (8 out of 10), which contains 5 (five) indicators "Cultural & creative services exports - % total trade", "National feature films", "Entertainment & Media market", "Printing and other media", and "Creative goods exports - % total trade".

However, in 1 (one) of its 3 (three) sub-pillars, the "creative outputs" pillar, curiously in a contrary sense, demonstrated not to be a weakness but a strength. The "online creativity" sub-pillar had a positive impact in 80% of the 10 (ten) assessments made (8 out of 10), which contains 4 (four) indicators "Generic top-level domains (TLDs)", "Country-code TLDs", "GitHub commit pushes received", and "Mobile app creation".

Regarding this "creative outputs" pillar, recent studies by Oturakci, M. (2021) have shown that the "creative outputs" factor explains the Results Sub-index, innovation output and production (output index) at a level of 98.8%.

On the other hand, the third and fifth pillars, "infrastructure" and "business sophistication," were identified and evidenced as strengths of the GII, with a significant positive impact in almost all of the 10 (ten) assessments.

The "infrastructure" pillar, which has 10 (ten) indicators and 3 (three) sub-pillars, was identified as another strength of the GII, showing a positive impact in 90% of the 10 (ten) assessments made (9 out of 10). This pillar measures the quality and infrastructure of communication, transportation, and energy, which are crucial for increased productivity and efficiency, creation of services and goods that stimulate innovation, as well as access to markets and sustainable growth, involving information and communication technologies (ICTs), general infrastructure, and ecological sustainability.

Regarding this "infrastructure" pillar, recent studies by Oturakci, M. (2021) have shown that there is a very weak correlation between the variables "institutions" - "infrastructure", "human capital and research" - "infrastructure", and "infrastructure" - "business sophistication".

The "business sophistication" pillar, which has 15 (fifteen) indicators and 3 (three) sub-pillars, was identified as a strength of the GII, showing a positive impact in 100% of the 10 (ten) assessments made (10 out of 10), and considered a facilitator for innovation activity as it evaluates how businesses are prepared for innovation activities and their propensity for innovation, involving the assessment of knowledge workers, innovation linkages, knowledge absorption, collaborations, alliances, R&D and patents pending, high-tech imports and ICT services.

Regarding this "business sophistication" pillar, recent studies by Oturakci, M. (2021) have shown that the Business Sophistication factor explains the Innovation Input Sub-index (input index) at a level of 69.2%.

Another significant and relevant point was highlighted by recent studies by Oturakci, M. (2021), which emphasized the strategic potential of the growth of the "human capital & research" factor and pillar, which was found to explain the Innovation Input Sub-index (input sub-index) at a level of 68.7%. In conclusion, this is considered one of the most important and effective input variables in the overall calculation of the Global Innovation Index (GII).

The "human capital & research" pillar measures the level and quality of education and research in a country, which are important factors for its innovation capacity, involving education, higher education (continuing education), and research and development (R&D). In this regard, regarding the relevance of the "human capital & research" pillar highlighted by Oturakci, M. (2021), it is worth noting a deeper reflection by combining the results of this study with our study, as the "human capital & research" pillar in our study was

found to be a strong point in 6 (six) out of 10 (ten) assessments.

Discriminately, this "human capital & research" pillar has 15 (fifteen) indicators and 3 (three) sub-pillars, "Education", "Tertiary education", and "research & development (R&D)". In 2 (two) of its 3 (three) sub-pillars, the "human capital & research" pillar was negatively evidenced: in the "Education" sub-pillar, it had a mixed impact in 50% of the 10 (ten) assessments made (5 out of 10), which contains 5 (five) indicators "Expenditure on education - % GDP", "Government funding/pupil, secondary% GDP/cap", "School life expectancy, years", "PISA scales in reading, maths, & science", and "Pupil-teacher ratio, secondary", and; in the "Tertiary education (continuing education)" sub-pillar, it had a negative impact in 100% of the 10 (ten) assessments made (10 out of 10), which contains 3 (three) indicators "Tertiary enrolment", "Graduates in science & engineering", and "Tertiary inbound mobility".

It is worth noting that in one of its three sub-pillars, the "human capital & research" pillar demonstrated a strength rather than a weakness. The "Research & development (R&D)" sub-pillar had a positive impact in 100% of the 10 (ten) assessments made (10 out of 10), which contains 4 indicators "Researchers, FTE", "Gross expenditure on R&D - % GDP", "Global corporate R&D investors - top 3", and "QS university ranking - top 3".

On the other hand, the "Tertiary education (continuing education)" sub-pillar and its 3 (three) indicators "Tertiary enrolment", "Graduates in science and engineering", and "Tertiary inbound mobility" had a negative impact in all 10 (ten) assessments, thus negatively impacting the "human capital & research" pillar.

In 50% of the 10 (ten) assessments made, or 5 (five) out of 10 (ten) assessments, the "Education" sub-pillar and its 5 (five) indicators "Expenditure on education", "Government funding/pupil, secondary", "School life expectancy, years", "PISA scales in reading, maths and science", and "Pupil-teacher ratio, secondary" had mixed impacts, which can be highlighted as both negative and positive, thus generating mixed impacts on the "human capital & research" pillar".

On the other hand, in 100% of the 10 (ten) measurements carried out (10 out of 10), a positive impact was observed on the sub-pillar "research & development (R&D)" and its 4 (four) indicators, "Researchers - Full-time equivalent (FTE)", "Gross expenditure on R&D", "Global corporate R&D investors", and "QS university ranking", generating, consequently, impacts on the "human capital & research" pillar.

Finally, for the sake of coherence with our conclusions, it is worth noting that recent studies by Oturakci, M. (2021) highlight that the factors "Business

sophistication" (69.2%) and "Human capital and research" (68.7%) - which are factors of the input index - and "creative outputs" (98.8%) - which is a factor of the output index were considered the most important and explanatory factors in the formation of the GII innovation score. It was concluded that these 3 (three) factors obtained as significant and explanatory for the input and output indices are also the most important factors for the Global Innovation Index - GII.

As a reflection and input for future research, in addition to all the knowledge construction evidenced within the scope and temporal delimitation of the research until 2020, in the years 2021 and 2022, strengths and weaknesses in the performance of the pillars of the GII in Brazil were also evidenced. On the one hand, in 2021 and 2022, the "institutions" pillar and its sub-pillars "political environment, regulatory environment, business environment" and the "infrastructure" pillar and two of its sub-pillars "general infrastructure and ecological sustainability" had a negative impact in 100% of the 2 (two) measurements carried out (2 out of 2). However, it is worth highlighting the curiosity that the "information and communication technologies (ICTs)" sub-pillar of the "infrastructure" pillar had the opposite impact, with 100% positive impact in the 2 (two) measurements carried out.

Therefore, in 2 (two) of its 3 (three) sub-pillars, the "Infrastructure" pillar was negatively evidenced: in the "general infrastructure" sub-pillar, it had a negative impact in 100% of the 2 (two) measurements carried out (2 out of 2), which contains 3 (three) indicators "Electricity output - GWh", "Logistics performance", and "Gross capital formation - % GDP", and; in the "ecological Sustainability" sub-pillar, it had a negative impact in 100% of the 2 (two) measurements carried out (2 out of 2), which contains 3 (three) indicators "GDP/unit of energy use", "Environmental performance", "ISO 14001 environmental certificates". In contrast, in 1 (one) of its 3 (three) sub-pillars, the "Infrastructure" pillar, demonstrating not to be a weakness but a strength, the "information and communication technologies (ICTs)" sub-pillar, had a positive impact in 100% of the 2 (two) measurements carried out (2 out of 2), which contains 4 (four) indicators "ICT access", "ICT use", "Government's online service", and "E-participation".

In all its 3 (three) sub-pillars, the "institutions" pillar was negatively evidenced: in the "political environment" sub-pillar, it had a negative impact in 100% of the 2 (two) measurements carried out (2 out of 2), which contains 2 (two) indicators "Political and operational stability" and "Government effectiveness"; in the "regulatory environment" sub-pillar, it had a negative impact in 100% of the 2 (two) measurements carried out (2 out of 2), which contains 3 (three) indicators "Regulatory quality", "Rule of law", and "Cost of redundancy dismissal", and; in the "business environment" sub-pillar, it had a negative impact in 100% of the 2 (two) measurements carried out (2 out of 2), which contains 2 (two) indicators

"Policies for doing business" and "Entrepreneurship policies and culture".

On the other hand, from 2021 to 2022, a possible trend of growth over time in Brazil was demonstrated, as the pillars "human capital & research" and "business sophistication" had a positive impact in both assessments. Comparing these results with those obtained in this study from 2021 to 2022 post-pandemic, it reinforces the importance of addressing the continuous weak point, the "institutions" pillar, highlighting the continuous strong point, the "business sophistication" pillar, and demonstrating a possible trend of growth over time in the "human capital & research" pillar, turning it into a strength.

In 2 (two) of its 3 (three) sub-pillars, the "human capital & research" pillar was negatively highlighted: in the "Education" sub-pillar, it was mixed in 50% of the 2 (two) assessments (2 out of 2), which contains 5 (five) indicators, "Expenditure on education - % GDP," "Government funding/pupil, secondary - % GDP/cap," "School life expectancy, years," "PISA scales in reading, maths, & science," and "Pupil-teacher ratio, secondary." In the "Tertiary education (continuing education)" sub-pillar, it was negatively highlighted in 100% of the 2 (two) assessments (2 out of 2), which contains 3 (three) indicators, "Tertiary enrolment," "Graduates in science & engineering," and "Tertiary inbound mobility."

However, in 1 (one) of its 3 (three) sub-pillars, the "human capital & research" pillar demonstrated not to be a weakness but a strength. The "Research & development (R&D)" sub-pillar had a positive impact in 100% of the 2 (two) assessments (2 out of 2), which contains 4 (four) indicators, "Researchers, FTE," "Gross expenditure on R&D - % GDP" "Global corporate R&D investors - top 3" and "QS university ranking - top 3".

Finally, corroborating with our findings from the complementary assessment of the years 2021 and 2022 and complementing the assessment from 2011 to 2020, it is worth noting that the GII report of 2022 highlighted, regarding this 2022 assessment, an overview of the strengths and weaknesses indicators of Brazil in this GII 2022 (WIPO, 2022a; WIPO, 2022b).

In this sense, the following indicators were highlighted as weaknesses or weak points (WIPO, 2022a; WIPO, 2022b), based on Brazil's GII 2022 (54th in rank): "Policies for doing business" and "Entrepreneurship policies and culture," which belong to the "business environment" sub-pillar of the "institutions" pillar; "PISA scales in reading, maths and Science," "Tertiary inbound mobility," and "Graduates in science and engineering," which belong respectively to the "education" and "tertiary education (continuing education)" sub-pillars of the "Human Capital & Research" pillar; "Gross capital formation," which belongs to the "general infrastructure" sub-pillar of the "Infrastructure" pillar; "Loans from microfinance institutions" and "Applied tariff rate," which belong respectively

to the "Credit" and "trade, competition and market scale" sub-pillars of the "Market Sophistication" pillar; "National feature films/mn" and "Printing and other media, % manufacturing," which belong to the "creative goods (assets and property) and services" sub-pillar of the "Creative Outputs" pillar.

Finally, also based on Brazil's GII 2022 (54th in rank), the "Business Sophistication" pillar and the following indicators were highlighted as strengths or strong points (WIPO, 2022a; WIPO, 2022b): "Intellectual property payments, % total trade," "High-tech imports, % total trade," and "ICT services imports, % total trade".

5 Conclusions

On one hand, Brazil has been improving its performance in the GII since 2019 and now, in 2022, with the 54th position in the GII, it is in the 2nd position among 18 (eighteen) countries in the Latin America and Caribbean (LA&C) group, being one of the two most innovative economies in this group, second only to Chile. Brazil also made it to the group of 9 (nine) out of 36 (thirty-six) medium-high income economies with performance above expected levels given their development status, and finally, it is ranked 4th out of the 5 (five) BRICS countries (Brazil, Russia, India, China, and South Africa), ranking higher only than South Africa. However, the continental size of Brazil and its large population of 214 million people present proportional challenges for its growth, especially in relation to the GII.

On the other hand, Brazil faced structural obstacles that limited the GDP growth to an average of 0.3% in the last decade, due to several factors such as complex tax system, unfavorable business environment, lack of investment in human capital, ineffective sectorial policies, and low savings (WBG, 2023b).

In the global context, in addition to this context of Brazil, recently, the report of the 15th edition of the Global Innovation Index (GII) from 2022 highlighted that two new waves of innovation are coming our way, one being the wave of the Digital Era, and the other being the wave of Deep Science (WIPO, 2022a).

Thus, based on the context of Brazil as a whole, this study concludes that, from the investigation and analysis of the results of the GII structure measurements in Brazil over the past 10 (ten) years, consisting of 7 (seven) pillars, 21 (twenty-one) sub-pillars, and 81 (eighty-one) indicators, highlighted the need for significant improvements in at least 4 (four) pillars, 10 (ten) sub-pillars, and 34 (thirty-four) indicators to enhance Brazil's innovation performance.

Specifically, it was evident that Brazil faces significant challenges in the pillars of "institutions", "market sophistication", and "creative outputs", which have consistently impacted negatively on Brazil's innovation performance and efficiency. In line with our conclusion and the results of the complementary

measurements for the years 2021-2022 and the 2011-2020 measurement, the GII 2022 report highlighted six indicators from the pillars of "institutions", "market sophistication", and "creative outputs" as weaknesses that need to be improved (WIPO, 2022b).

Therefore, measures are recommended in this direction to strengthen these pillars, aiming to promote a more favorable environment for innovation and its innovation activities, as well as to maintain the success in the "infrastructure" and "business sophistication" pillars, which are positive strengths.

In this sense, when thinking about strengthening the "institutions" pillar, it is necessary to focus on improving its 3 (three) sub-pillars "political environment", "regulatory environment", and "business environment", which were negatively evidenced, and its 7 (seven) indicators, respectively: "Political and operational stability", "Government effectiveness", "Regulatory quality", "Rule of law", "Cost of redundancy dismissal", "Policies for doing business", and "Entrepreneurship policies and culture". In addition, corroborating with our results, the GII 2022 report highlighted, regarding the 2022 assessment of this "institutions" pillar, the indicators "Policies for doing business" and "Entrepreneurship policies and culture" of the "business environment" sub-pillar as weaknesses to be improved.

In the same vein, when considering the strengthening of the "market sophistication" pillar, the focus should be on improving its 3 (three) sub-pillars, "Credit," "Investment," and "Trade, Competition and Market Scale," which were negatively highlighted, as well as its 10 (ten) indicators, namely: "Finance for startups and scaleups," "Domestic credit to private sector - % GDP," "Loans from microfinance institutions - % GDP," "Market capitalization - % GDP," "Venture capital investors," "Venture capital recipients," "Venture capital received - % GDP," "Applied tariff rate - weighted avg," "Domestic industry diversification," and "Domestic market scale." Additionally, the GII 2022 report corroborated our findings by highlighting the indicators "Loans from microfinance institutions" and "Applied tariff rate" from the sub-pillars "Credit" and "Trade, Competition and Market Scale" as weaknesses to be addressed. Continuing in this vein, when considering the strengthening of the "creative outputs" pillar, the focus should be on improving 2 (two) of its 3 (three) sub-pillars, "Intangible assets" and "creative goods (assets and property) and services," which were negatively highlighted, as well as its 9 (nine) indicators, namely: "Intangible asset intensity - top 15," "Trademarks by origin," "Global brand value - top 5,000," "Industrial designs by origin," "Cultural & creative services exports - % total trade," "National feature films," "Entertainment & Media market," "Printing and other media," and "Creative goods exports - % total trade." Additionally, the GII 2022 report highlighted the indicators "National feature films/mn" and "Printing and other media, % manufacturing" from the sub-pillar "creative goods (assets and

property) and services" as weaknesses to be addressed..

On the other hand, measures are recommended to maintain success in the pillars of "infrastructure" and "business sophistication", which are strengths that positively impact Brazil's innovation performance, with a significant positive impact in almost all 10 (ten) assessments. In this regard, corroborating with our conclusion and results from the complementary assessment of 2021-2022 and the assessment of 2011-2020, it should be noted that, based on the GII 2022 report, the pillar "Business Sophistication" and the following indicators "Intellectual property payments, % total trade", "High-tech imports, % total trade", and "ICT services imports, % total trade" were once again highlighted as strengths.

Another important strategic reflection for policymakers and managers is derived from the evidence in our results that highlights the weak points that impact the GII, combined with the studies of Oturakci, M. (2021), which demonstrate the significance of factors that impact the GII, especially in relation to the pillars of "humancapital & research", "market sophistication" and "creative outputs". These studies have shown that, in addition to adjustments and improvements to be made in the three highlighted weak points "institutions", "market sophistication" and "creative outputs", due to their significance, adjustments and improvements in the pillar "human capital & research", particularly in its sub-pillars of "Tertiary education (continuing education)" and "Education", become an efficient, effective, and strategic decision for policymakers and managers, aiming to improve Brazil's innovation performance (GII) and efficiency rate in innovation. In this regard, corroborating with our conclusion and results from the complementary assessment of 2021-2022 and the assessment of 2011-2020, it should be noted that the GII 2022 report highlighted three indicators from the "human capital & research" pillar as weaknesses to be improved. (WIPO; 2022b).

Therefore, specifically when thinking strategically about strengthening the "human capital & research" pillar, the focus should be on improving 2 (two) of its 3 (three) sub-pillars, "Education" and "Tertiary education (continuing education)", which were negatively highlighted, and their 8 (eight) indicators, respectively: "Expenditure on education - % GDP", "Government funding/pupil, secondary - % GDP/cap", "School life expectancy, years", "PISA scales in reading, maths, & science", "Pupil-teacher ratio, secondary", "Tertiary enrolment", "Graduates in science & engineering", and "Tertiary inbound mobility". Additionally, corroborating with our results, the GII report of 2022 highlighted, regarding the 2022 assessment of this "human capital & research" pillar, the indicators "PISA scales in reading, maths, and Science", "Tertiary inbound mobility", and "Graduates in science and engineering", respectively, from the "education" and "tertiary education (continuing education)" sub-pillars as weaknesses to be improved.

In essence, it is hoped that these contributions and implications provide evidence for understanding how important the interaction and inter and intra-relationships between actors that make up an innovation system and its respective performance are, thus helping policymakers to identify, through evidence and directions, possible systemic flaws that may hinder innovation and its performance in an economy (WIPO, 2022a; BAKHTIAR et al., 2022).

It is expected that these results contribute as new inputs for solutions aimed at the evidence brought by the literature since 2016, despite recent improvements, which indicate, due to their history and trend, the need to develop a new generation of strategies and public policies focused on Brazil's innovation performance, aiming for better investments and more effective and efficient results (LEAL; FIGUEIREDO, 2018; DE NEGRI, 2018; DE FIGUEIREDO et al., 2018; MAZZUCATO; PENNA, 2016; MONTEIRO, 2019; WIPO, 2022a).

It is also expected that these results contribute as new inputs for solutions aimed at recent evidence and findings brought by recent literature by Bakhtiar et al. (2022) and Oturakci, M. (2021) - who also based their studies on the structure and data of countries/economies in the GII longitudinally - which, among other evidence, as also done by Monteiro (2019), highlighted the impact between the factors that make up the GII structure in the GII calculation itself, and also assessed and classified Brazil as a medium-to-low performance, efficiency, and effectiveness economy in its innovation system and highlighted that innovation systems in countries like Brazil and Zimbabwe are not only inefficient but also ineffective.

It is also expected that these factors and directions identified can serve as inputs for improvement and enhancement, to be considered by internal and external stakeholders, policymakers, and companies - which are the leaders of the innovation process in economies (LEAL; FIGUEIREDO, 2018) - as strategies to increase efficiency and productivity in their innovation processes, thus promoting a more conducive environment for innovation that, as a consequence, would indicate a trend of better innovation performance of the Brazilian economy.

It should be noted that among these internal and external stakeholders involved in innovation policies and in the economic performance of an economy, we have, externally, investors, economies and external companies, and internally, the government, companies, universities and research institutes, the third sector, and especially policymakers.

Finally, it is concluded that this study contributes to the understanding of the factors that influence innovation performance in Brazil and provides guidance to internal and external stakeholders involved in the innovation system and innovation policy. Thus, internal and external stakeholders involved, along

with policymakers, could focus on improvement strategies to strengthen the relevant and significant points identified and highlighted, creating a more conducive environment for innovation and improving the performance of the Brazilian economy.

6 Research limitations and future research

Recent studies by Oturakci, M. (2021) highlight that the GII is calculated based on various sub-parameters, and the innovation input and output indices have their own sub-parameters, which can lead to limitations in studies that do not consider the interrelationships between them. Therefore, future studies should replicate this methodology in other economies/countries, analyze the parameters and sub-parameters in more detail, expand the analysis to include more years, and analyze the correlation and impacts of each indicator within the innovation system represented by the GII structure, hierarchizing them according to their impact.

Finally, in addition to the limitations described earlier, it should be emphasized that this study also has limitations due to the use of secondary data and a specific type of analysis of innovation performance in Brazil. Nonetheless, the findings of this study can still contribute to the field of innovation and stimulate further research and discussions on the topic.

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Looking beyond technology: Governance innovation to steer India's low-carbon transport transition

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Abstract

India's alternative fuels landscape has undergone substantial changes in the last two decades or so. Multiple objectives such as net-zero goal, controlling air pollution, developing industrial competence, and reducing import dependence have become integral part of the energy policy in the transport sector. For achieving these objectives, several alternatives such as electric vehicles, ethanol, bio-CNG, hydrogen, and methanol are being promoted through technology innovations, ambitious policy targets, and demonstration projects. However, simultaneous promotion of so many multiple fuels is historically unprecedented, presents some governance challenges, and therefore needs innovation in governance approach in addition to technological innovations. Technology and institutions need to co-evolve in a harmonious manner for a socio-technical transition. This study, however, points out that the current government's approach appears fragmented and suggests a governance framework for navigating a socio-technical transition involving multi-technology systems.

Keywords: alternative fuels, low-carbon transport, governance innovation, India

1. Introduction

Climate change crisis has been instrumental in shaping global energy policies. Novel technologies are currently being developed and deployed as a part of global energy transition to deal with it. Traditionally, for most countries, providing sufficient energy at affordable price had been the primary goal of energy policy. However, in the rapidly unfolding technological transition for a more sustainable environment, other policy objectives like reducing emissions, improving air quality, having a long-term sustainability vision, and developing industrial competence in the new green technologies get layered over the conventional objective of energy security. Weaving these multiple objectives into a unified coherent energy policy often becomes a significant challenge because different objectives are likely to be achieved at different time scales, require different technologies, different kind of policy support, and substantial funding. Often, some objectives conflict with each other, at least for the short to medium term.

India too is trying to achieve several objectives through its energy policy. Energy security has been its long-standing concern but has recently acquired urgency in the wake of rapidly rising oil import bill. Like energy security, air pollution is also a long-standing problem. Due to severity of the problem in cities like Delhi, the Supreme Court mandated the use of Compressed Natural Gas (CNG) in public transport in 2002 (Narain et al, 2005). Since then, CNG has become a prominent fuel technology for improving air quality in some regions. Since around 2008, renewable energy has been mainstreamed in India's energy policy due to climate change concerns. In 2010, the Government of India (GoI) adopted ambitious solar target of 20 GW by 2022 which has been augmented several times since then (PTI, 2020). Around the same time, GoI also launched its first policy program to promote electric vehicles (EVs), although compared to solar initiative, it was relatively subdued (Talwar, 2021). Finally, India also seeks to develop a robust industrial base in the novel green energy technologies. It could not develop a strong solar manufacturing base due to being a late entrant in the field (Behuria, 2020). However, the GoI believes that EVs and green hydrogen present an opportunity for India to develop industrial leadership in these fields provided it moves fast (Nouni et al., 2021).

To achieve these objectives, India has been promoting several fuels simultaneously. Consider the following excerpts:

'We are looking at this [energy transition] as a huge opportunity to become an EV hub. The aim is to bring the cost of EVs down by almost 40% through 'Make in India' mission by reducing imports'. - Mahendra Nath Pandey, Minister of Heavy Industries (Express News Service, 2022).

'The government is promoting ethanol manufacturing in a big way and assures that it will procure all ethanol produced in the country'. - Nitin Gadkari, Minister of Road Transport and Highways (Anon., 2021).

'It [bio-CNG] is the future as at present, around 12 million vehicles are already powered by natural gas throughout the world and more companies and municipalities are joining the CNG movement every day' - Nitin Gadkari, Minister of Road Transport and Highways (PTI, 2021).

'Ample availability of renewable energy power gives India an inherent advantage, it can be a global hub of green hydrogen' - Narendra Modi, Prime Minister (ENS Economic Burueau, 2023)

'The government is contemplating a `Methanol Economy Fund` to promote indigenously- produced methanol that could substitute 10 per cent of India`s crude oil imports by 2030'. - Nitin Gadkari, Minister of Road Transport and Highways (IANS, 2017).

The above excerpts highlight the GoI's simultaneous strong push to several alternative fuels. In situations, where policy has many goals and multiple technologies are at play, the governments are often advised to adopt a technology neutral approach and not pick winners. This can result in governments providing support to several technologies in order to avoid picking undeserving winners early on. However, with limited resources at hand, promoting multiple technologies is not considered to be a good long-term strategy as it can lead to financial stress (Azar et al., 2021). Further, a hands-off approach may lead to lock-in into a less sustainable technological option. Therefore, some scholars believe that technology neutral approach is not without flaws and must not be accepted unconditionally and applied universally (Haelg et al., 2018). Multi-technology simultaneous transitions, therefore, poses significant governance challenges which are likely to be exacerbated in developing nations with weak governance capacity, limited financial resources, and more acute dependence on fossil fuels.

In this study, a brief overview of five important low-carbon fuel technologies – EV, ethanol, bio-CNG, hydrogen, and methanol – is provided in section 3, after introduction (section 1) and theory and method (section 2). The fuel technologies are chosen based on their current or near-term market penetration, sustainability potential, and importance in government's energy transition plans. The selection was also based on consultation with the experts. As part of the overview, the study looks at the policy initiatives, underlying motivations, market potential, demonstration projects, and challenges. The governance implications of this multi-technology fuel landscape are discussed in section 4 which is followed by the final section, conclusion.

2. Theory and method

Initially, environmental governance approaches focused on specific issues like land development and pollution in a relatively fragmented way. Recently, however, governance approaches have begun paying attention to the relationship between social and technological to maintain socio-ecological systems (Voß and Bornemann, 2011). This approach views a successful socio-technical transition entails co-evolution in different realms – economic, social, political, and technological. Only when developments in the different domains reinforce each other, can a new technology be successfully integrated in the society (Kemp and Loorbach, 2006). More recently, in a reflexive turn, the governance itself has come to be seen as a challenge for sustainability and thus, the practices through which socio-technical transitions have to be achieved have become the object of study (Voß and Bornemann, 2011). This reflexive turn is therefore concerned with understanding various aspects governance like knowledge production, learning, and unintended consequences. A significant aspect of this reflexive governance approach is that it shuns the assumption of a single framing of a problem and one best solution to the problem that could be identified by an objective assessment. It instead integrates a plurality of perspectives and expectations in search for ways to achieve sustainability (Voss et al., 2006). The approach of transition management which constitutes long-term policy making incorporate the features of reflexive governance. Transition management is described as forward-looking, multi-actor governance aimed at long-term transformation that builds upon tools like knowledge integration, anticipation of long-term systemic effects, adaptivity of strategies and institutions, iterative participatory goal formulation and interactive strategy development (Kemp and Loorbach, 2006). It is a useful governance strategy in a situation where multiple technologies compete in the context of long-term societal transformation.

For the study, semi-structured interviews were conducted with government officials, technology experts, consultants, think-tank personnel, and academicians. The method of thematic analysis was used in analysing interview transcripts. Thematic analysis basically involves examining data for prevalence of themes and is a common method for analysing interview or newspaper data (Joffe, 2012). Thematic analysis identifies and enables the researcher to analyse recurring patterns of expressions in her data. But it often goes further and helps in interpreting different facets of the research topic in a general way (Braun and Clarke, 2006). Joffe (2011) argues that thematic analysis is a tool through which both manifest and underlying meaning of the data can be systematically analysed by capturing the nuances people bring to their expressions. Themes were inductively identified from the data.

3. Alternative fuels landscape in India

3.1 Electric vehicles

3.1.1 Policy initiatives and prospects

The first policy program to support EVs in India – Alternate Fuels for Surface Transportation Program (AFSTP) – was launched by the Ministry of New & Renewable Energy (MNRE) in 2010. Under AFSTP, INR 950 million was set aside for the period 2010-2012 for developing and promoting EVs (Talwar, 2021). The policy boosted the market of electric two-wheelers but sales declined sharply when policy was terminated in 2012 (Dutt, 2023). After that, the GoI introduced a more comprehensive National Electric Mobility Mission Plan (NEMMP) 2020 in 2013. The plan provided fiscal and monetary incentives and set a target of 6-7 million EV sales year on year from 2020 onwards (NEMMP, 2020). Recently, as part of NEMMP 2020, the government launched FAME (Faster Adoption and Manufacturing of Hybrid and Electric Vehicles) scheme. The first phase of the scheme lasted from 2015 to 2019 and the second phase begun in 2019 and will last till 2024 (FAME phase-I, 2015; FAME phase-II, 2019; Express news service, 2021).

Table 1– Allocations under FAME schemes (Parihar and Urele, 2021)

FAME-I scheme		FAME-II scheme	
Component	Allocated fund (INR crore)	Component	Allocated fund (INR crore)
Technology platform	190	Demand incentives	8956
Demand incentives	495	Charging infrastructure	1000
Charging infrastructure	30	Administrative expenditure	38
Pilot projects	70	Total for phase-II	9634
IEC/operations	10	Committed from phase-I	366
Total	795	Total	10000

EV industry is a globally developing industry in which all major economies want to develop technological competence faster than the others. A well-functioning self-sufficient EV supply chain would make countries less dependent on others for critical inputs. Therefore, the GoI launched National Mission on Transformative Mobility and Battery Storage in 2019 which is a phased manufacturing program to build domestic battery manufacturing capability¹. The initiative focuses on raw materials availability, electrochemistry

research, and manufacturing battery packs (Ministry of Heavy Industry and Public Enterprises, 2019). Niti Aayog has also initiated the National Programme on Advance Chemistry Cell (ACC) Battery Storage which incentivizes setting up large production units with a capacity of at least 5 GWh (Gode et al., 2021). Finally, recent changes in the FAME scheme mandates domestic content requirement for promoting domestic EV manufacturing. Many experts are optimistic about EV industry growth. A report by think tank CEEW estimates that a strong policy push can lead to EV sales between 14 and 26 million by 2030 (Singh et al., 2020). However, some experts are concerned that adopting ambitious targets can disrupt the automotive sector and result in job losses (Dua et al., 2021).

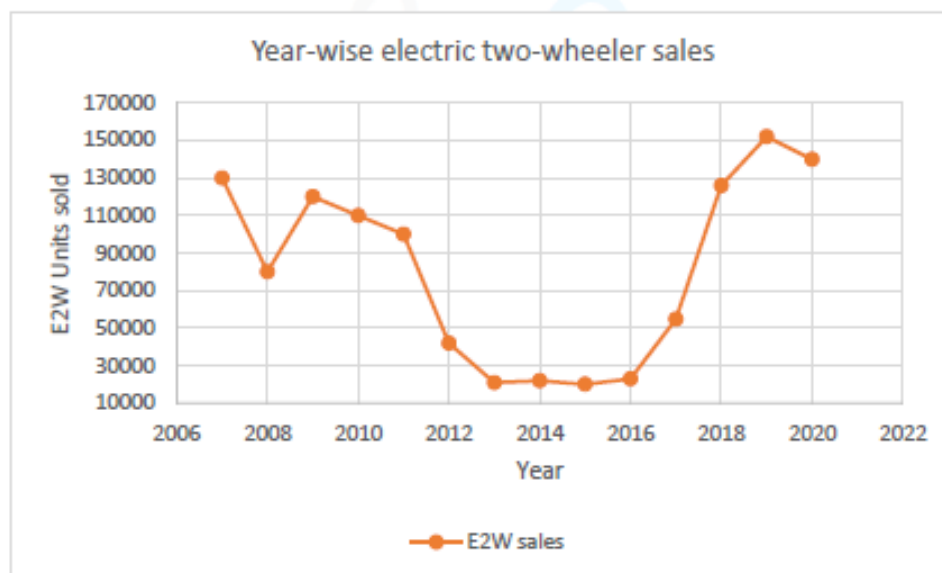
3.1.2 Current market, projects, and challenges

In India's automotive space, the electrification is expected to happen unevenly. Most of the electrification in India has happened in the two- and three-wheeler (including electric rickshaw) segments. Of the total EV sales, 79% is constituted by electric three-wheelers, 17% by electric two-wheelers, and merely 4% by electric four-wheelers (Parihar and Urele, 2021). The electric two-wheeler segment market has expanded because of low battery prices, government's policy push, and entry of vibrant start-ups like Ather (Dutt, 2023). In the higher weight category vehicle segments i.e. trucks and buses, the electrification is mostly happening in public and private demonstration projects and small-scale pilot projects. In the truck segment, for instance, private companies such as Olectra Greentech Ltd. and Infraprime Logistics Technologies have initiated some pilot projects for electric trucks (PTI, 2022; HT Brand Studio (2020). In the bus segment, the number of electric buses in India has increased from nil in 2017 to 4647 in 2022 due to the government's procurement policy strategy.

Accelerating EV transition would have to overcome three significant obstacles. First, India has to build a strong EV manufacturing capacity so that it does not lag behind like it did in the case of solar manufacturing (Behuria, 2020). This would require a strategic policy framework, raw materials availability, and sufficient finance. A report estimates that building manufacturing capacity targeting 50% to 100% localization would need between USD 6.1 billion and 12.3 billion (Singh et al., 2020). Also, the government has to secure supply of critical minerals such as lithium, nickel, graphite, and cobalt to build a complete supply chain and shield India from global fluctuations (ET Energy World, 2022; Parihar and Urele, 2021). Second, currently India has inadequate charging infrastructure which has to be expanded considerably to alleviate range anxiety of customers. According to an estimate, India would need close to 3,000,000 public charging stations by 2030 to support EV adoption targets set by Niti Aayog (Parihar and Urele, 2021). Further, due to unique factors like high

number of electric two- and three-wheelers, hot and humid environment, and poor quality of grid electricity, India would need its own context specific solutions and can't adopt other countries' strategies (Lakshmi, 2022). Third, India's current EV penetration is very low and thus the market has to grow substantially to support its domestic manufacturing ambitions and encourage entry of new players. For this, India needs to adopt stronger EV policies along the lines of EV mandates adopted by California and China. Lack of clear policies result in unwillingness of financial institutions to involve in extending debt to EVs and stifle the market (Singh et al., 2020).

Figure 1 – Electric two-wheeler sales in India. Source: Dutt (2023)



3.2 Ethanol

3.2.1 Policy initiatives and prospects

The earliest initiatives to promote biofuels like ethanol began from early 2000's because of the rising oil imports (Saravanan et al., 2018). In 2001, a small 5% ethanol blending pilot programme was started which was followed by a notification on India's first ethanol initiative – Ethanol Blending Programme (EBP) – by the Ministry of Petroleum and Natural Gas (MoPNG) in 2002. The notification mandated 5% ethanol blending from 2003 in certain states and union territories (Aradhey, 2011). In 2008, National Policy on Biofuels was adopted, which abandoned the mandatory aspect and adopted targets 5% blending by 2012, 10% by 2017, and 20% after 2017 (Chandel et al., 2017).

In the next iteration of biofuel policy, in 2018, – National Policy on Biofuel (NPB) 2018 – a target of 20% ethanol blending with petrol by 2030 was adopted (Das,

2020). Unlike earlier ethanol policies, NPB 2018 adopted a holistic perspective and in addition to reducing oil import dependence, also focuses on augmenting farmers' income, generate rural employment, and promote sustainability through judicious use of drylands (Das, 2020). It employed tax rebates, favourable depreciation on plant expense, and subsidized power and water supply to incentivize ethanol production. It also attempted to give a push to 2G ethanol that is produced from waste and doesn't conflict with food security. It adopted a Viability Gap Funding (VGF) scheme for infrastructure development under which a financial help of INR 50,000 million has been allocated for setting up of 2G bio refineries for 6 years (Zhou et al., 2021). However, NPB 2018 also allows ethanol production from edible feedstock like sugarcane juice, sugar beet, sweet sorghum, and starch containing materials like corn (Das, 2020).

Cutting down India's rising oil dependence is India's primary goal in promoting ethanol blended fuel. Estimates show that 10% ethanol blending that India achieved recently has enabled it to save INR 41,000 crore worth of fuel imports (Anon., 2022). Another significant benefit of promoting ethanol is that it can be helpful in boosting rural economy. India produces enormous quantities of agricultural waste which can be used for producing 2G ethanol. If such ethanol plants are set up, numerous rural job opportunities can be created in the areas of baling, hauling, transportation of biomass, and operation of plants (Singh et al., 2017). If India's vast biomass potential is tapped, 2G ethanol has considerable growth potential and can grow at a rate of 8.25 CAGR with a production capacity of around 5400 million litres by 2030².

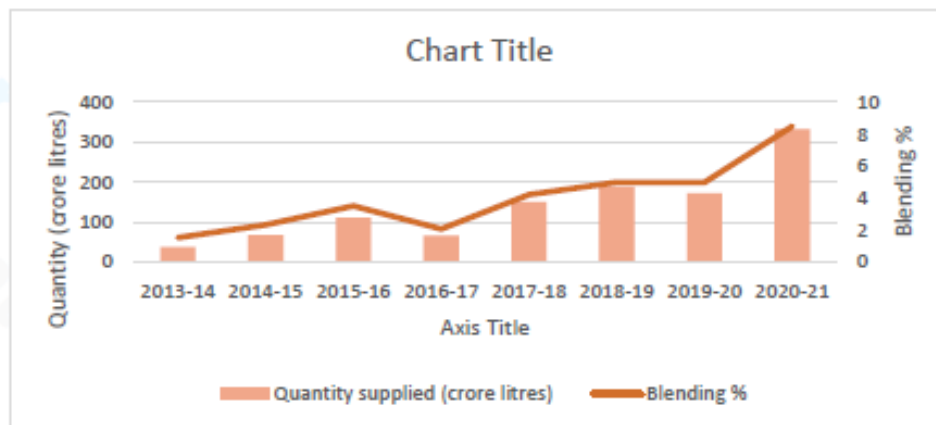
3.2.2 Current market, projects, and challenges

Most of the ethanol produced in India is utilized for production of potable liquor and the surplus is used for fuel blending by Oil Marketing Companies (Dey et al., 2023). Over the last two decades, but especially in the last 5-6 years, India's ethanol production capacity has increased. For instance, between 2010 and 2019, a 3700% increase in ethanol production for blending purposes was seen. Currently, the ethanol production capacity in India stands at 947 crore litres which includes 619 crore litres of molasses-based production and 328 crore litres of grain based production (Ministry of Consumer Affairs, Food & Public Distribution, 2022). Of this, close to 84% is derived from sugarcane, 10% is accounted for by Food Corporation of India's rice stocks, and 5 per cent from maize/damaged food grains (Saini et al., 2023). Thus, most of the ethanol produced in India is 1G as more sustainable 2G technology is relatively underdeveloped.

To develop 2G ethanol technology, the GoI has provided financial support for setting up of 12 commercial scale and 10 demonstration scale 2G ethanol

projects using lignocellulosic biomass and other renewable feed stocks for the period 2018–19 to 2023–24. An amount of USD 277.756 million has been set aside for the projects (Nouni et al., 2021). Some experts argue that with adequate financial and research support, 2G ethanol production can become an economically viable option while other point out that to decrease oil imports quickly, the government should optimize 1G production and not put undue focus on 2G technology (Roy and Chandra, 2019).

Figure 2: Ethanol production and blending



(Source: NITI Aayog and Ministry of Petroleum and Natural Gas (Sarwal et al., 2021))

Regardless of the production technology, the ethanol production in India faces several challenges. For 2G technology, the procurement window for agricultural waste feedstock is 15- 20 days which makes it difficult to establish a sustainable biomass supply chain. Also developing an agreement on the right remuneration to farmers for feedstock is a difficult issue too (Pandey et al., 2021). Sugarcane crop, which is a significant source of bioethanol feedstock, is a very water intensive crop. One litre of ethanol from sugarcane requires about 3,000 litres of water. As India attempts to increase its ethanol production, groundwater depletion may get worse. Increasing ethanol production may also interfere with India's food security. Completion of all the stages of sugarcane cultivation takes a long time rendering the land useless for cultivating other crops for about 4-6 years (Seth et al., 2021). Further, the government is also encouraging ethanol production from grains. Weather related contingencies still influence the quality and quantity of grain production and if more land is used towards meeting energy needs, food security may become a problem (Nouni et al., 2021).

3.3 Bio-CNG or compressed biogas (CBG)

3.3.1 Policy initiatives and prospects

Vehicular air pollution has been a major environmental concern in big cities like Delhi for a long time. To improve the air quality, Compressed Natural Gas (CNG) was introduced in early 2000's and has become an important part of the state's pollution control strategy since then (M.C. Mehta, v. Union of India, 1986). Also, the share of gas in India's energy mix is around 6.2%, which is low, and the government wants to increase it to 15% by 2030. A big part of this increase is expected to come from CNG deployment. However, increasing CNG production would adversely affect India's energy security as India imports around 50% of its gas. Further, CNG may be more sustainable as compared to gasoline and diesel but it is less green when compared to EVs. Bio-CNG can address the issues associated with CNG to some extent. Bio-CNG is biogas that is further compressed and purified to remove or reduce hydrogen sulphide (H₂S), carbon dioxide (CO₂), and water vapour thereby increasing the concentration of Methane (CH₄) from around 55% to more than 90%. The calorific value and other properties of bio-CNG is similar to CNG and therefore, it can easily replace CNG (Vijay et al., 2006). It is also more sustainable than CNG as it is produced from agricultural, cattle, and urban wastes (PTI 2022).

The bio-CNG potential in India is estimated at 62 million metric tonnes (MMT). Also, since its supply chain integrates rural and waste management sectors, it offers multi-sectoral benefits.

Therefore, the government launched the SATAT (Sustainable Alternative Towards Affordable Transportation) scheme in October 2018 to promote bio-CNG. SATAT policy plans to invest INR 2 trillion to set up 5000 bio-CNG plants across the country. This would result in production of 15 million metric tons of bio-CNG and 50 million metric tons of bio-manure as a by-product. Under the scheme, several incentives are provided such as assured offtake of the bio-CNG produced, long term agreements, priority sector lending, and financial assistance depending on the volume of bio-CNG produced with a cap of INR 100 million (Singhal et al., 2017).

3.3.2 Current market, projects, and challenges

CNG already has a good penetration in India and as bio-CNG can be used in CNG vehicles, it has the advantage of having a sizeable ready market and consumer familiarity. There are currently 17 bio-CNG plants operating in the country having an aggregate production capacity of 46,178 kg per day. Most of them are located in the western and northern parts of the country (Goyal, 2018). Governments trying to find a solution to the problem of rising waste are

exploring bio-CNG plants as an option. For instance, Delhi government recently announced that it will set up 10 new biogas plants (Manupriya, 2018). India also has Asia's largest bio-CNG plant in the Sangrur district of the Punjab state which produces a large quantity of agricultural waste. Following setting up of this plant, the Punjab government is planning to set up 42 more plants that would cumulatively produce 492.58 tonnes of bio-CNG per day (IANS, 2022). It is also reported that influential industrial houses such as Reliance Industries and Adani New Industries Limited (ANIL) are planning to invest INR 5-6 billion in setting up of bio-CNG plants (Kumar, 2022).

A key challenge in the development of bio-CNG (and CNG as well) is the lack of pipeline infrastructure. Gas pipeline infrastructure is inadequate and regionally skewed and its expansion would assure potential customers and boost demand (Corbeau, et al., 2018). Another obstacle is CNG's non-inclusion in the Goods and Services Tax (GST) regime which leads to considerable variation in the tax-rates in the CNG supply chain in different states³. Finally, the bio-CNG supply chain comprises different sectors like agriculture and urban waste and their co-ordination presents difficulties in efficient supply chain management. For instance, there is a lack of aggregation yards and formal aggregation models for collecting agricultural and livestock waste (Shrivastava, 2022). Similarly, many cities don't have adequate waste segregation facilities which are needed for bio-CNG plants' operation.

3.4 Hydrogen

3.4.1 Policy initiatives and prospects

There are different kinds of hydrogen fuel – grey, blue, and green. Grey hydrogen is produced from fossil fuels and is least sustainable form of hydrogen. Blue hydrogen is also produced from fossil fuels but the process is complemented by CO₂ capture and storage. Green hydrogen – which is the cleanest and most expensive of the three – is produced by water electrolysis running off renewable energy⁴. Ministry of New and Renewable Energy (MNRE) brought out India's first hydrogen and fuel cell roadmap called National Hydrogen Energy Roadmap (NHERM) in 2006 (Nouni et al., 2021). However, there has been a recent surge in the global attention to hydrogen. Therefore, the GoI launched a more holistic hydrogen initiative – National Hydrogen Mission – in 2022. The mission focuses on developing complete hydrogen value chain, catalyzing demonstration programs, development and deployment of hydrogen technologies, and addressing concerns pertaining to safety and standards (Qureshi et al., 2022). A national body called Indian National Hydrogen Energy Road Map (INHERM) has been set up to promote hydrogen utilization in the power and automotive sectors

(Qureshi et al., 2022). The government has also launched an ambitious 'hydrogen 2-1-2' initiative which aims to decrease the cost of hydrogen fuel by two times compared to gasoline, reducing the cost of hydrogen storage, distribution, and refuelling to less than \$1, and generate a favourable return on investment for hydrogen in less than two years (Jayakumar et al., 2022).

The green hydrogen push by the GoI is expected to accelerate green energy transition and develop India's industrial competence in a globally emerging novel technological field. Green hydrogen would help India in achieving its goals of energy independence by 2047 and net-zero by 2070. Its development can also help India becoming a hydrogen hub by capitalizing upon the falling costs of hydrogen technology through strategic investments in R&D at the right time. India already is one of the cheapest producers of solar energy which can be leveraged to power production of green hydrogen (Bhardwaj, 2021).

3.4.2 Current market, projects, and challenges

Hydrogen fuel is currently in the demonstration stage but can find commercial applications in the future in the heavy-duty buses and freight vehicles where EVs are at a disadvantage (Jayakumar et al., 2022). Several pilot projects have been initiated for testing hydrogen fuel's feasibility. Tata Motors in collaboration with Indian Oil Corporation Limited and Indian Space Research Organisation (ISRO) showcased India's first hydrogen fuel cell bus in 2018 and after evaluation of the trial run, Indian Oil Corporation Limited invited bids for 15 fuel cell buses in 2020 which was won by Tata Motors. The buses are expected to be on road in June 2024 (Express Drives Desk, 2018). Two hydrogen refueling stations have also been set up in Haryana at Gurugram and Faridabad by Indian Oil R&D Centre and National Institute of Solar Energy respectively (Jayakumar et al., 2022). Being a new and undeveloped technology, cost is the most significant barrier for hydrogen fuel. Green hydrogen production uses water electrolysis to produce hydrogen which is a very expensive process and until cost is considerably reduced, hydrogen take off is unlikely to happen. In addition to the cost, other factors like lack of hydrogen fuelling infrastructure, safety concerns, and delicate powertrain system of hydrogen vehicles also inhibits their uptake (Das, 2021).

3.5 Methanol

3.5.1 Policy initiatives and prospects

Methanol, also known as wood alcohol, is an alternative biofuel that can be blended with gasoline and used in ICE vehicles. It can be produced from a variety of sources like natural gas, coal, and biomass (Saraswat and Bansal, 2021). It is the latest addition in the policy basket for alternative fuels in India

and as such planning is still in the early stages with no clear policy roadmap. However, some recent high-level initiatives regarding methanol fuel development indicates the government's seriousness in developing it. In 2016, NITI Aayog organized an international conference on methanol economy to elicit perspectives from various stakeholders like industry, academia, policy makers, and government officials (Saraswat and Bansal, 2017). Following this, a taskforce called Methanol Economy taskforce was set up under which published a report in 2017 with the title 'India's Leapfrog to Methanol Economy'. The report highlighted methanol's potential in reducing oil and gas imports and argued for increasing use of methanol as transportation fuel, cooking fuel, and as diesel substitute in power generators used in telecom towers (Shih et al., 2018). In December 2017, NITI Aayog announced that is preparing a roadmap for India's methanol economy and plan to set up a Methanol Economy Fund of around INR 50 billion (Saraswat and Bansal, 2017). An important benefit of using methanol as an alternative fuel is that since it can be produced from coal gasification, it can allow for optimum usage of India's coal reserves. Coal usage for power generation is likely to decline in the future and India can divert its vast coal reserves for methanol generation. Moreover, coal gasification is combined with CCS technology produces very little emission and therefore can contribute to India's net zero goal (Saraswat and Bansal, 2021).

3.5.2 Current market, projects, and challenges

India has very low methanol production capacity. In 2020-21, its methanol production capacity was 234,000 metric tonnes (MT) or 0.23 million tonnes (Mt). In contrast, China blended around 21 million tonnes (Mt) of methanol with gasoline in 2016 (Saraswat and Bansal, 2021). At present, there are no commercial scale methanol plants in India but the government has set up some pilot projects. A technology demonstration public-private partnership project has been initiated between Indian Institute of Technology Delhi (IIT Delhi) and Thermax, an environmental solutions company. The aim of the project is to develop and refine indigenous technology for methanol production from high-ash Indian coal⁵. A pilot project to study the feasibility of 15% methanol blended petrol (M15) has been started in the state of Assam and would be extended to other areas if the outcomes are satisfactory (Nouni et al., 2021). The main challenge in developing methanol fuel in India is lack of a clear policy roadmap or mission. Some visions and goals have been stated but a detailed roadmap is yet to be articulated by the government. Another obstacle is uncertainty regarding production cost. While Saraswat and Bansal (2017) argue that methanol would be cheaper than ethanol and petrol even when subjected to comparable tax regimes and other costs, however, in absence of commercial scale production, an accurate picture can't be provided.

4. Discussion

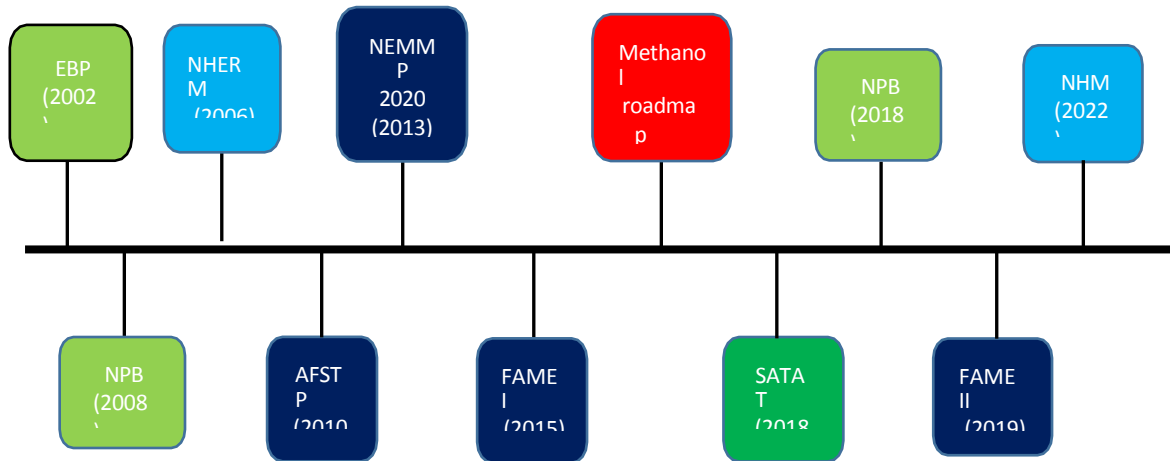
4.1 Governance challenges

The energy transition in India's transport sector is currently in a state of great flux. The government is battling on several fronts in trying to achieve multiple objectives and aggressively promoting many alternative fuels that are at different stages of maturity. Ethanol and methanol blending will help in reducing oil imports and save foreign exchange, bio-CNG deployment can be very effective in reducing vehicular air pollution in cities and reduce gas imports to some extent, and EVs and green hydrogen fuel are expected to support long term net-zero and industrial development goals. The progress on ethanol blending and EV penetration is taking place gradually, though the ambitious targets are likely to be missed. Bio-CNG has the advantage of a ready market but has not taken off as expected. Methanol and green hydrogen are at very early stages of development and would require sustained support for years to mature as viable fuels. These technological options, thus, are underpinned and justified by different values such as sustainability, technological feasibility, industrial competence etc. to different degrees and currently all desirable values don't converge into any single option. Such a complex situation involving multiple simultaneous transitions poses some intricate governance challenges.

Table 2: Summary table of India's alternative fuels landscape

Fuel/Tech nology	Policy goals and visions	Market status	Main objective(s)	Challenges	Magnitude of Investment
EV	Sales target of 30% for private cars, 70% for commercial vehicles, and 80% for two- and three-wheelers by 2030	Subsidy driven Little market penetration in two- and three-wheelers Procurement driven uptake in public sector city buses Pilot projects in other vehicle segments	Aligned with industrial policy goal of becoming EV hub Net-zero goal	Lack of battery manufacturing capacity Challenges of grid integration Upfront cost of Evs	US \$ 180 billion by 2030 to achieve policy targets ⁶
Bio-CNG	SATAT scheme envisages 5000 CBG plants with production capacity of 15 MMT of CBG and 50 MMT of bio-manure per annum by 2023-24	Ready market as a percentage of three-wheelers, buses, and cars run on natural gas Slow progress of SATAT scheme with only 38 commissioned plants	Cutting natural gas import dependence Addressing poor city air quality	Supply chain management issues pertaining to aggregating and segregating waste Lack of uptake of bio-manure Shortage of skilled professionals and lack of standards for the waste-to-energy segment Lack of inter-departmental co-ordination	INR 2 trillion to set up 5000 bio-CNG plants by 2024
Ethanol	Blending target of 20% by 2025	Blending target of 9.45% achieved recently Most bioethanol produced through 1g and 2g technology relatively underdeveloped	Cutting oil imports	Sugarcane farming for bioethanol production leads to groundwater depletion Using food grains can lead to food vs. fuel dilemma Lack of inter-departmental co-ordination	US \$ 5.5 billion to achieve 20% blending by 2025 ⁷
Green Hydroge n	National Green Hydrogen Mission envisages production of 5 MMT of green hydrogen per annum by 2030	Limited to pilot projects for buses and trucks	Aligned with industrial policy goal of becoming hydrogen hub Net-zero goal	Production processes still expensive Hydrogen production from coal is an emission intensive	INR 19,744 crore approved for National Green Hydrogen Mission ⁸
Methano l	No specific targets	Limited to f ew blending pilot projects	Cutting oil imports	Nascent technology so considerable ambiguities regarding cost and regulatory structure	Methanol Economy Fund of around INR 50 billion is planned

Figure 3: Timeline of major policy announcements of alternative fuels (Colour codes for text boxes – electric vehicle: dark blue, ethanol: light green, bio-CNG: green, hydrogen: light blue, and methanol: red)



4.1.1 Developing a strategic policy vision

In situations where multiple technologies are available as options, the question of technology neutral vs. technology specific support policies often arises. Conventionally, the popular opinion usually favours a technology neutral approach, offer a level playing field by setting minimum common technological standards, and allow the market factors to determine the rest. This approach is based on the argument that the state is often not in a good position to pick winners in the technological realm (Azar et al., 2011). In fact, the automobile lobby organization SIAM in its report has advised the Indian government to adopt a technology neutral approach and not try to pick winners (Anon. 2019). However, some scholars argue that in the context of sustainability transitions, the role of the state should not be limited to passively supporting technology but to adopt a more proactive approach. According to them, sustainability transition is inherently a political process and a hands-off approach may result in lock-in into a less sustainable option (Azar et al., 2011).

In the Indian context, the government so far has not adopted a strategic approach which has given mixed signals to the private sector, technology experts, and even the government officials themselves. For instance, on the one hand, the government has provided a strong push to electrification of public sector city buses indicating a clear preference to EV technology over its alternative – CNG buses. However, on the other hand, it has not adopted any official stronger EV policy targets like other countries have done in the form of EV mandates. EV mandates provide policy certainty to the investors and

entrepreneurs and considered very useful in holistically developing the ecosystem (Dua et al., 2021). Further, in the city of Indore, one of the most

successful bio-CNG plants in India is providing CNG fuel to city buses there (Perinchery, 2022). As the government expands bio-CNG and more cities install bio-CNG plants, buses could be an important consumer of this fuel. However, this is likely to conflict with the government's bus electrification drive. Similar kind of friction between natural gas and electrification is expected in the car segment and in the medium and heavy-duty vehicle segment. A strategic and comprehensive vision beyond the passive and hands-off technology neutral approach is thus required.

Table 3: Matrix table of policy objectives and alternative fuels

	Objective s	Reducing import dependence	Industrial competence	Short-term sustainability (air quality)	Long-term sustainability (net-zero goal)
Alternative fuel or powertrain					
Electric vehicles		*	***	*	***
Ethanol		***		***	
Bio-CNG		***		***	
Hydrogen		*	***		***
Methanol		***			

4.1.2 Articulating the role of gas

Related to the above point but drawing attention to its specific aspect is the complex issue of the role of gas in India's transport sector's energy transition. Overall, there seems to be a certain degree of ambiguity on it. A recent official document of the GoI – Long-Term Low Emission Development Strategy (LT-LEDS) – on India's long-term low carbon strategy identifies gas as a 'transition fuel', however the strategy of transitioning from it to other sustainable fuel options is not clear. The current penetration of CNG in India started in early 2000's with only public buses and three-wheelers but overtime infrastructure build up and low cost of CNG enabled it to expand to other vehicle segments as well (Anon, 2019). As the government further expands gas infrastructure in the country with the massive investments, the sunk investments is likely to aggravate our institutional and infrastructural lock-in into gas and accentuate its path-dependent character. Unfortunately, there is very little discussion on the possibility of gas lock-in, its implications for India's energy transition, and ways to address it in India's low-carbon transport policy discourse. A report by a

think tank, CEEW, did highlight gas lock-in and argued for capping gas penetration in India's energy mix at 18% (Malyan et al., 2021). However, lock-in by its very nature resists such an easy escape at a specified point.

4.1.3 Inter-sectoral co-ordination

Another significant challenge in developing alternative fuels and powertrains would be facilitating co-ordination between different actors from different sectors. The supply chains of many alternative fuels span across multiple sectors, government departments, and private players and co-ordinating activities of various actors from disparate sectors may not be easy but is imperative. For example, EVs' deployment and integration would depend on the co-operation from the electricity distribution companies. Many Indian electricity distribution companies are already under a substantial financial stress and therefore necessary improvements in the infrastructure and operations may not be easy. Similarly, effective management of Bio-CNG supply chain requires co-ordination among actors from different sectors like agriculture, urban waste management, and transport. Often, discord between different elements of supply chains disrupts the availability of feedstock and jeopardises the whole operation. In fact, the Indore bio- CNG plant is a success because the Indore municipality played a crucial role in developing and maintaining the supply chain.

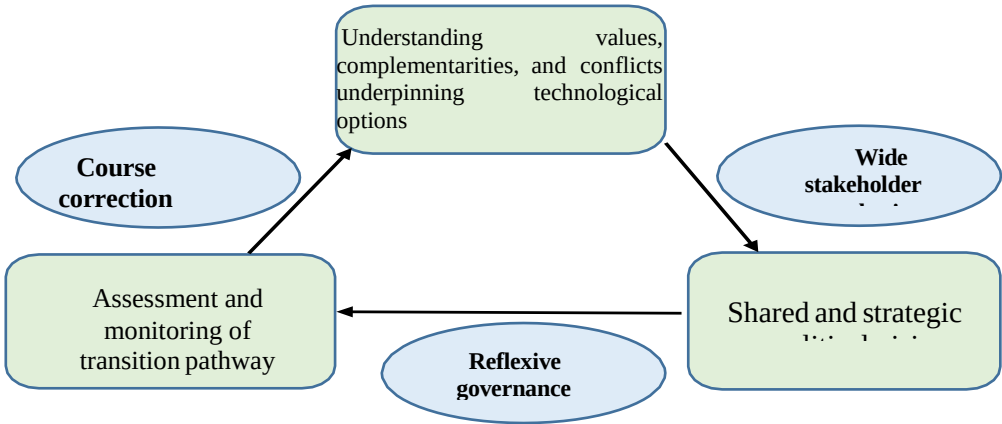
4.2 Rethinking governance

Governance challenges such as maintaining a strategic balance between technology neutrality and specificity, tackling a potential lock-in into a less sustainable technology, and developing productive interactions among supply chain actors from different sectors are not amenable to simple technical solutions. These challenges are inherently political. For instance, the entrenchment of natural gas vehicles in India's transport sector is the outcome of technological path dependence and is further intensified by organizational lobbying and inter-ministerial competition for policy influence. A shared political vision regarding the future of technology development arrived at through widespread stakeholder consultation is therefore crucial (Azar et al., 2011). Currently, much of the governance thinking seems to be done in fragmented and uncoordinated manner. Such a vision can't be developed easily as stakeholders' transition vision is underpinned by their diverging material interests and therefore may require negotiations and compromises.

Further, during the course of long-term transition, social, political, and economic contexts change which will in turn cause a concurrent shift in the values. Moreover, as technologies develop, the complementarities and trade-offs between them are also likely to change. Thus, in a rapidly evolving state, any

vision arrived at has to be periodically revisited and recalibrated. This would require incorporating reflexivity in the governance. In essence, this would require embracing the multi-dimensionality of problem framings and keeping the policy processes and goals open ended. Instead of providing one right solution to the problem, policy making in this case becomes a reiterative exercise of experimentation, learning, and knowledge integration (Voss et al., 2006).

Figure 4 – Iterative governance paradigm for development of India’s low-carbon transport



6. Conclusion

The government is trying to achieve multiple objectives like net-zero goal, reducing import dependence, developing industrial competence, and improving air quality through energy transition in the transport sector. Some of these objectives such as air quality control can be met in the short-term while others such as net-zero goal and developing industrial competence in a new technology requires a more long-term vision. The government has promoted multiple fuels over the years as no single fuel option can satisfy all the objectives in the short-term. Simultaneous promotion of multiple fuels has produced governance complexities regarding balancing policy neutrality with policy specificity, articulating the role of gas in India’s vehicle fuel transition, and creating inter-sectoral co-ordination. The study proposes a strategic governance framework based on understanding technology-value connection, experimentation, learning, and reflexivity. The framework doesn’t tell the policy makers what to do in the sense of providing a fixed solution to the problem but rather provides them a framework of how to think about long- term transition governance issues.

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Low-carbon technology: A study of solar PV (photovoltaic) from a perspective of technological innovation system in India

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Abstract:

The study attempts to analyse Indian solar PV (photovoltaic) technological innovation system and knowledge production in its innovation dynamics. The Indian PV industry has become one of the frontrunners in the renewable energy sector with consistently increasing the generation of power. The study relies on both primary and secondary data. It adopts technological innovation system framework to understand the crucial role, interplay of the various actors and institutions, the nature of the linkages and the knowledge production from various actors and to see the several key functions in the Indian PV technological innovation system (TIS). Analyzing these key functions will help in identifying the inducement and blocking mechanisms and to see the future directions pertaining to PV technological innovation system in the country. The study has found that entrepreneurs carry out many activities that perform a major impact. Processes related to knowledge development are found to be stable. At the same time, there is a large fluctuation in the processes related to market formation and guidance of the search. The number of research publications and patents has increased after the introduction of the National Solar Mission. Though the country is far behind others regarding investment in solar research and development (R&D). Inconsistent regulations, unpredictable behaviour of the government and the lack of a clear vision for the technology are the key barriers in the technological innovation system.

Keywords: Solar PV; Low-carbon Technology; Sustainable Development; Technological Innovation System; India.

Introduction

Low-carbon technology produces less pollution than traditional energy sources and it plays a crucial role in the transition to a low-carbon economy. Such technologies include Solar PV (Photovoltaic), wind turbines, biomass systems, carbon capture equipment, etc. Today, Solar PV (Photovoltaic) industry becomes one of the leaders of the renewable energy sector with consistently increasing the power generation. The study is motivated by the need to accelerate the supply of renewable energy with a special focus on solar energy with a vision of affordable and reliable clean energy because it addresses the issue of climate change and fostering sustainable development in India. The economy of the country is one of the fastest growing in the world. The consumption in the energy sector has increased rapidly in the country due to the rapidly growing population and growing economy. About 300 million people (nearly 24%) are not connected to the national electrical grid (World Bank Report, 2014). There is also a huge gap between the country's energy production and the energy consumption (Krishna, C., et al. 2015). According to Ministry of New and Renewable Energy (MNRE), solar energy promotes the ecologically sustainable growth and also addresses the country's energy security challenge among the various forms of renewable energy. Solar energy is the promising sectors which discourse the issues of climate change under National Action Plan on Climate Change in India (MNRE, 2019).

The main objectives of the study are to understand Indian Solar PV Technological Innovation System (TIS); to explore knowledge production and key policy implications towards the performance of the TIS in the country. Knowledge production refers to the research outcomes mainly research publications from the various R&D institutions, university, firms and so on. In this study, we adopt technological innovation systems (TIS) approach which is developed by Hekkert et al. (2007) and Bergek et al. (2008). A technological innovation system is defined as "a network of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology". It is made up of many elements such actors, technical and other types of competence, networks and institutions. The TIS perspective emphasizes systemic interdependencies between these elements, which give rise to various forms of synergies, such as collective assets on which the different actors can draw but which they could not produce if they worked in isolation. It has seven system functions such as entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resources formation and creation of legitimacy. The strength of this framework lies on the analysis of different structural components of the innovation system influence the development and diffusion of a specific technology. It provides insights to policymakers by identifying systemic weaknesses that hamper the development and diffusion of solar PV technology

in the country. This framework would help in exploring knowledge production and networks or linkages in the various key actors who shape solar PV technology in the country (refer table 1).

Table 1: Main key actors in Indian Solar PV innovation system

Main Actors	Descriptions
Solar Company	Domestic Manufactures (Cells, modules, balance of systems), Foreign-owned Manufactures, Project developers, Engineering, Procurement & Construction (EPC)
Regulatory Support	Apex Body and Regulatory Institutions, Policy Instruments
Government Research Institutes	Indian Institute of Technologies (IITs), central and state universities, Engineering Colleges, Other institutions offering courses on Renewable Energy. Council of Scientific and Industrial Research (CSIR), National Institute of Solar Energy (NISE), Solar Energy Corporation of India (SECI), etc.
Financial Institutions	Domestic Agencies and External sources
Industry Associations	Solar Energy Society of India (SESI), National Solar Energy Federation of India (NSEFI), Indian Solar Manufactures Association, Solar Power Developers Association, Solar Energy Trade Association in India etc.

Source: Own compilation; adapted from MNRE, 2019 and 2020

The remaining part of the paper has outline as follows. The following section will discuss a theoretical framework and literature review. A research methodology which is adopted for the study will be followed after this section. The next presents the analysis of Indian solar PV technological innovation system and overall findings. Finally, a concluding remark will be presented.

Theoretical framework and review of literature

Different scholars propound several definitions of innovation. Schumpeter (1934) defines innovation as “new combinations” of existing resources. It includes the introduction of new products, new methods of production, new sources of supply, exploitation of new markets and new ways to organize within firms (ibid)¹.

Nelson and Rosenberg (1993) argue innovation as the process by which firms master and put into practice product designs and manufacturing process that are new to them. Fagerberg, et al. (2005) also describe innovation is crucial for long-term economic growth and it tends to cluster in certain industries/sectors, which consequently grow more rapidly, implying structural changes in production and demand and, eventually, organizational and institutional change. On the same ground, the National Innovation Council (NIC) also defines innovation as new and unique applications of old technologies, using design to develop new products and services, new processes and structures to improve performance in diverse areas, organizational creativity, and public sector initiatives to enhance delivery of services. Further, Plessis (2007) also describes it as the creation of new knowledge and ideas to facilitate new business outcomes, aimed at improving internal business processes and structures and to create market-driven products and services. Moreover, innovation can also be seen as a multi-stage process whereby organizations transform ideas into new or improved products, services, or processes, to advance, compete and differentiate themselves successfully in their marketplace (Baregheh et al., 2009). It is also be seen that the concept of innovation is evolving or developing quickly, new concepts like open innovation (Chesbrough, 2003), responsible innovation (Stilgoe et al., 2013) and eco-innovation (Bossle et al., 2016) have emerged. It is understood that innovation is the ability to create and capture economic value from the invention and is now recognized as an important engine of economic growth.

In addition, Innovation system perspectives have implications in many different directions depending on the scope of the study. Innovation has been studied in various contexts in disciplines such as economics, science and technology studies (STS), management studies, commerce, social systems, etc. There is a wide range of approaches to theorising innovation perspective by a various scholar. The innovation systems approach analyses the flow of information and technology as well as the interactions and relationships between the actors involved, such as enterprises, research institutions and the government (Edquist, 2004).

Innovation Systems approach believes that complex interdependencies and interactions among the various actors need to carry out innovation. Over the years, different innovation systems approaches have emerged that were based on the different boundaries of the system such as National System of Innovation (Freeman, 1987; Lundvall, 1992 and Nelson, 1993), Regional System of Innovation (Cooke et al., 1997; Braczyk, Cooke and Heidenreich, 1998; Asheim et al., 2003 and Asheim, 1999), Sectoral System of Innovation (Breschi and Malerba, 1997; Malerba, 2002 and Malerba, 2004) and Technological Innovation System (Carlsson and Stankiewicz, 1991; Jacobsson and Johnson, 2000; Carlsson et al., 2002b; Carlsson and Jacobsson, 2004; Hekkert et al., 2007;

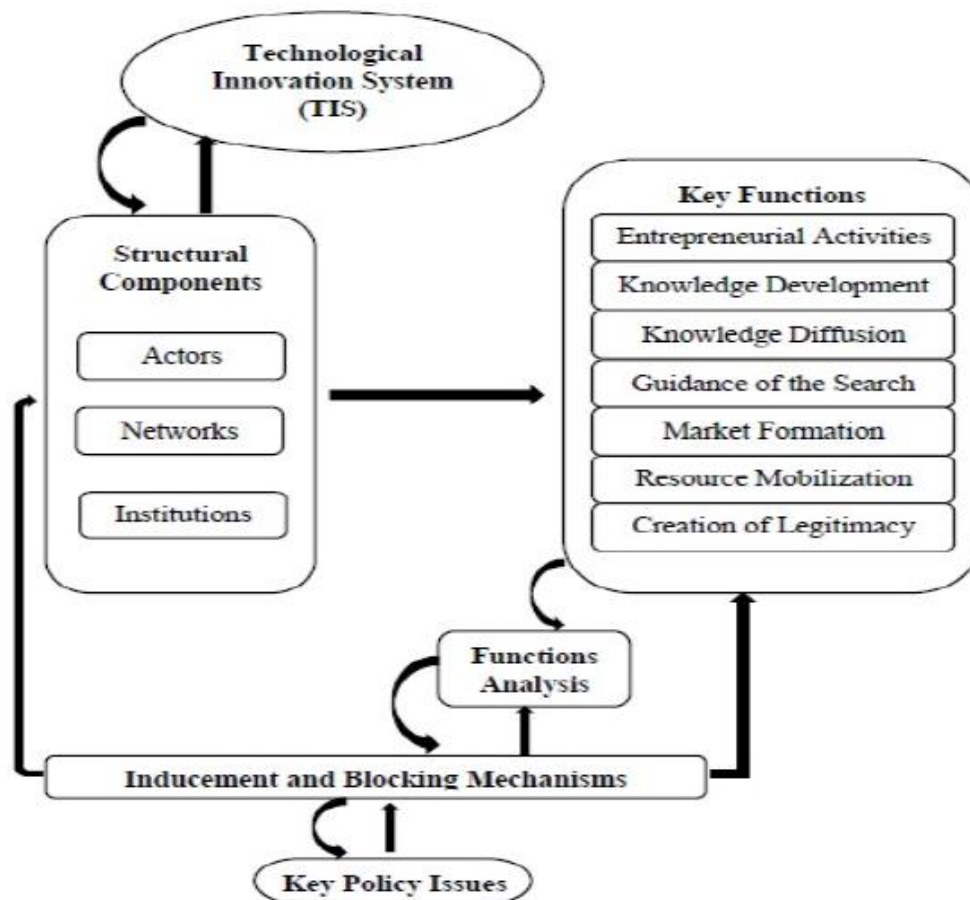
Negro et al., 2007; Bergek et al., 2008; Markard and Truffer, 2008; Hekkert and Negro 2008; Jacobsson 2008; Kamp 2008; Negro and Hekkert 2008; Coenen et al. 2010 and Bergek et al., 2015).

The Technological Innovation System (TIS) approach is technology specific in nature. It means that there are many technological systems in a country or region and that some actors are involved in several of them. Each of the technological systems is unique, and it varies in the ability to develop and diffuse new technology. This approach has structural components consist of actors, institutions, and the network of relations through which they are connected. It has seven system functions which are crucial in technological innovation systems. The TIS concept has emerged in the early nineties from a quickly expanding innovation system literature, which is rooted in evolutionary economics and industrial dynamics (Freeman, 1987; Lundvall, 1992; Nelson, 1993).

Carlsson and Stankiewicz (1991) defines TIS is “a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology” (Carlsson and Stankiewicz, 1991 p.93). Hekkert et al. (2007) also mentions it as “the network of actors, rules and material artefacts that influence the speed and direction of technological change in a particular technological area”. Its focusing area is to analyse the development of a particular technological field regarding the structures and processes that obstruct or support the development and diffusion of novel technologies. On the same ground, it is also defined as a set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field (Bergek et al., 2008; Markard and Truffer, 2008). The TIS perspective emphasizes systemic interdependencies between these elements, which give rise to various forms of synergies, such as collective assets on which the different actors can draw but which they could not produce if they worked in isolation (Bergek et al., 2015).

The main initial point of a technological innovation system is not so much a geographical area or an industrial sector, but a more specific technical knowledge field or a product and its applications. To analyse and evaluate the development of particular technological innovation regarding the structures and processes that support or hamper is the main purpose of TIS studies. Hence, this approach can be regarded as a more specific approach/micro oriented approach among the various innovation system approaches.

Figure 1: Technological Innovation System (TIS) Framework



Source: Own compilation adapted from Bergek et al. 2008 and Gosens, J. and Yu, L. (2013)

There are three structural components of TIS namely actors, networks and institutions. Firstly, actors include not only firms along the whole value chain, research institutes and universities but also public bodies, venture capitalists, organizations deciding on standards, other organizations such as industry associations and non-commercial organizations, etc. (Bergek et al., 2008). There are some methods to identify actors in a specific industry. Industry associations are a good source, as are exhibitions, company directories and catalogues. A patent analysis may disclose the volume and direction of technological activity in different organizations, among individuals. This can be help to identify firms, research organizations or individuals with a specific technological field. From bibliometric analysis² it will provide a list of the most active organizations in terms of publication and patenting. Such organizations will include not only universities but also institutes and firms. Finally, by taking interviewing or discussing with the experts from technology or firms or research institutions is a good way to explore more actors.

Secondly, network is an intermediate form between internal organisation within entities (such as firms) and markets. Its crucial function is to exchange the information (Carlsson and Stankiewicz, 1991). For instance, industry associations, research communities, user-supplier relations, policy networks, etc. are industrial networks. Carlsson et al., (2002); Jacobsson and Bergek, (2004); Negro, (2007) argue that networks are of critical importance for the development of a technological innovation system. Furthermore, networks can be transformed into development blocks, i.e. synergistic clusters of firm and technologies within an industry or a group of industries (Carlsson and Stankiewicz, 1991). It can be of different types. These can be of “learning networks” or “political networks”. In learning networks, they may include user-supplier networks, networks between related firms, networks between competitors or industry-university networks. Such networks mainly influences the transfer of tacit and knowledge production, innovation, management, which is explicit in nature. The networks also influences the hypothesis of what could be desire and what can be made possible, also closely relating to investment specific decisions. Whereas, political networks are kind of networks are mainly driven by political science literature. It argues that the architecture of the policy making happen when the ranges the actors sharing common beliefs, while competing with the influencing in line with their set of beliefs. The literature however looks it as a non-technology specific manner which reasonably considers that climate does not necessarily focus on TIS. For the new technology to gain foundation the technology specific networks need to engage themselves in broad political debate.

Lastly, institutions are at the central of innovation system concept (Edquist, 2001; Edquist and Johnson, 1997). North (1990) defines institutions are the rules of the game which exist into two forms; formal institutions and informal institutions. In formal institution, it can be laws and regulations whereas in case of informal institutions it can be like norms, values and routines. The author also further describes institutions as the humanly devised constraints that shape human interaction. Chang and Evens (2005) explain institutions are systematic patterns of shared expectations, taken for granted assumptions, accepted norms and routines of interaction that have robust effects on shaping the motivations and behaviour of sets of interconnected social actors. They need to be adjusted or aligned to new technology, if it is to diffuse (Freeman and Louca, 2002). It regulates interactions between actors and defines the value base of various segments of society. It also refers to cognition that influence firms’ or other actors’ decisions in the form of frames that structure learning processes.

On the other hand, Edquist (2001) asserts that institutions and organisations are the main machineries of innovation system. For our understanding, we are further focusing on the difference between these two. Organisations are the players or actors which are the formal structures with an explicit purpose and

they are consciously created (Edquist and Johnson, 1997). For instance, companies (suppliers or customers), universities, capital organizations, public innovation agencies, etc. are some important organisations. On the other hand, institutions are “the sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals, groups and organisations” (Edquist and Johnson, 1997). The nature of relation between organizations and institutions is a very complex form. Organizations are strongly influenced and shaped by institutions; it could be said to be ‘embedded’ in an institutional environment or set of rules, which include the legal system, norms, standards, etc. But institutions are also embedded in organizations (Edquist, 2001)³. For instance inside firms many institutions are developed. Some organizations directly create institutions for example organizations that create standards and public organizations that formulate and implement rules. North (1990) also explains how institutions and organizations are different. Organizations are the players in a society whereas institutions are considered as the rules of the game. The role of the rules is to explain the way that the game is played while organizations are groups of individuals who work toward a common goal and interests. Both institutions and organizations are the components of structural framework that supports human interaction.

The seven key functions of TIS such as entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resources formation and creation of legitimacy are derived from Bergek et al. (2008); Hekkert et al. (2007); Jacobsson and Johnson (2000). The functions are considered to be processes that are necessary for TIS build-up. Many authors argue that the functions are the main determinants of innovative performance for TIS (Bergek, 2002, Suurs et al., 2009; Bergek et al., 2015). They are system level variables. The following table 2 represents the summary of the key functions and their indicators.

Table 2: Summary of seven key functions and the indicators in TIS framework in our study

Key Functions	Summary	Indicators
Entrepreneurial Activities	This function performs innovative commercial and/or practice oriented experiments. Entrepreneurs are the vital actors of any innovation ecosystem.	Entry of solar PV industry. Commercial solar PV technology manufacturing and/or installing.
Knowledge Development	This function signifies the most important within the innovation system and it is always towards 'learning by doing' and 'learning by searching'.	Number of R&D research projects, trends in scientific publications and patents and number of research organizations.
Knowledge Diffusion	It emphasises on knowledge network, mainly assisting exchange of information about the technology.	Training programmes. Organizing international and national conferences/seminars/workshops/meetings. Demonstrations and exhibitions. Conducting awareness programmes.
Guidance of the Search	This function represents the selection processes necessary to facilitate a convergence in development.	Setting expectations on solar PV. Providing awards or showing interest. Setting targets and formulation of favourable regulations and policies.
Market Formation	This function signifies to assist the creation of markets, where a new technology has possibility to grow.	Introduction of tax regimes and standards. Public procurement and regulatory reform
Resource Mobilisation	Financial, material and human factors are necessary inputs for all innovation system developments.	Providing incentives/subsidies, human resources (scientists and research fellows), providing Funds/loans
Creation of Legitimacy	It addresses/finds resistance about the technology from established actors. The actors need to raise a political lobby that counteracts or supports PV technology.	Conducting advocacy activities (lobbying). Political debate in parliament and media.

Source: Compiled by author, adapted from Haung, P. et. al. (2016); Tigabu, A.D. et al. 2015; Wieczorek A. J. et. al. (2013); Gosens, J. and Lu, Y. (2013); Bergek et al. (2008); Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007 Negro et. al. (2007).

The concept of TIS is so popular today. Based on this framework there are many studies look at the dynamism of a specific technology field such as renewable energy technologies, solar, wind, biofuels, biomass, etc. For instance, Jacobsson and Bergek (2004) study on TIS dynamics around renewable energy technologies, in which an explicit distinction is made between the formative stage and the market expansion stage of a TIS. They have focused on trajectories of TISs in which the formative stage is characterised by the fluidity of technology in the sense of an absence of technological and institutional structures to support it. Another study, McDowall et al. (2013) discusses how policy instruments influence system functioning and addresses system weaknesses for the onshore wind innovation system in four countries i.e China, Germany, the USA and UK. The authors conclude with lessons for a low carbon instrument mix, e.g. the need to include systemic policy instruments alongside traditional demand pull and technology push. Suurs et al., (2010) also deliver a strategic insights for practitioners that aspire to support motors of innovation by conducting a research on 'automotive natural gas TIS' in the Netherlands. The study emphasises on the dynamics of build-up process by mapping the development of seven system functions of TIS. For our study, we are adopting the TIS framework developed by Hekkert et al. (2007) and Bergek et al. (2008). In this framework, the boundaries are not limited by geographical boundaries, as in national and regional innovation system perspectives. Contrasting to other perspectives also, it focuses on understanding the dynamics that block or induce the successful development of particular technologies.

Research methodology

The study has been undertaken first by reviewing the available literature related to renewable energy and in particular to solar energy. It is based on both quantitative and qualitative data. To achieve the desired outcome, several sources of primary and secondary data have been considered in the study. Some informal interviews have been taken to discuss key functions of Indian solar PV technological innovation system. Around 30 experts from various actors from PV innovation system (refer table 1) were interviewed in 2017. The experts' view on strength of each function was determined by rating scale (0-6 scales) and we finally incorporated the average value on each observation. Various annual reports from National Institute of Solar Energy (NISE), Solar Energy Cooperation of India (SECI), Ministry of New and Renewable Energy (MNRE), the Energy and Resource Institutions (TERI), Centre for Science and Environment (CSE) are also considered in our study. Moreover, to understand solar PV technological innovation system in the country we map different indicators that adopted from various literatures (refer the selected indicators in table 2). For production trends in scientific knowledge, we use the analysis of research publications with the help of Scopus⁴ online database. By analyzing the database, the productivity of research publications in different universities and

R&D institutions in the country are calculated and analyzed consequently. We have taken some specific keywords in the database. For instance, we use the keyword “(TITLE-ABS-KEY (multi-junction cells) AND PUBYEAR >2006 AND PUBYEAR<2017 AND (LIMIT-TO (AFFIL COUNTRY, "India"))) AND (LIMIT-TO (EXACT KEYWORD, "Multi-

Junction Solar Cells") OR LIMIT-TO (EXACT KEYWORD, "Multi-junction Solar Cells")))) to find out the number of publications in “multi-junction cells” from India during 2007 to 2016. For obtaining the granted patent number in Indian Patent Office⁵ (IPO) website, we use the patent search in double field search. We put keyword “solar energy” in the search field, then opt “OR” boolean operator. Then we have chosen inventor country as “IN” (stands for India) in the search bar. Similarly, we have also done the same procedure in case of wind energy. In case of granted patents in the United States Patent and Trademark Office (USPTO) database, first we select Cooperative Classification Codes (CPC) for related Solar PV technologies (see details in Appendix section). To find out the patent number, we put specific keyword for a particular technology. In case of the patents from Indian Patent Office (IPO), the number of the granted patent is retrieved by using the search engine “Indian Patent Office” supported by the Office of the Controller General of Patents, Designs & Trade (CGPDT), Ministry of Commerce and Industry, Government of India.

Analysis of Indian solar PV TIS

Entrepreneurial activities

Entrepreneurs are crucial for any well-functioning innovation system. Generally, their role is to turn the opportunities of knowledge development, market and network changes into action to take advantage of business opportunities. They transform opportunities to reckonable economic activity. This function tends to conduct technical experiments exploring uncertain regarding technologies, applications and markets, determining and crafting opportunities. A new entrant is the most important entrepreneurial activity for an emerging market. They have a chance to explore opportunity of new technologies. To map different natures of this function towards the number of new entrants and the extent of technologies used and nature of the new technologies engaged are needed to consider.

In India, the issue of oil crisis in the early 1970s provoked Indian scientists to develop solar PV technology and first indigenously develop solar cells⁶ and modules were developed by Central Electronics Limited (CEL) in 1977 (Bhatgava, 2004). About 70% of the production from the manufacturing capacity located in India is exported, mainly to such markets as Germany, Japan and USA. State owned enterprises such as Bharat Heavy Electrical Limited (BHEL)

and Central Electronics Limited (CEL) have been making solar panels and other equipment since 1970s, but their scale was limited to research and development and prototype level manufacturing till 1990s (Kharul, R., 2004). The first commercial scale manufacturing plant in the country was set up by Moser Baer in 2007 with 40MW manufacturing capacity (CSE, 2012). Nowadays, the vast majority of installed capacity is focused on thin films. A few Indian firms account for nearly 80 to 90 percent of the installed capacity, and this includes Moser Baer, Titan Solar, Indosolar, Tata Power Solar and the BHEL (Krishna, C., Sagar, A. D. and Spratt, S. 2015; MNRE, 2014).

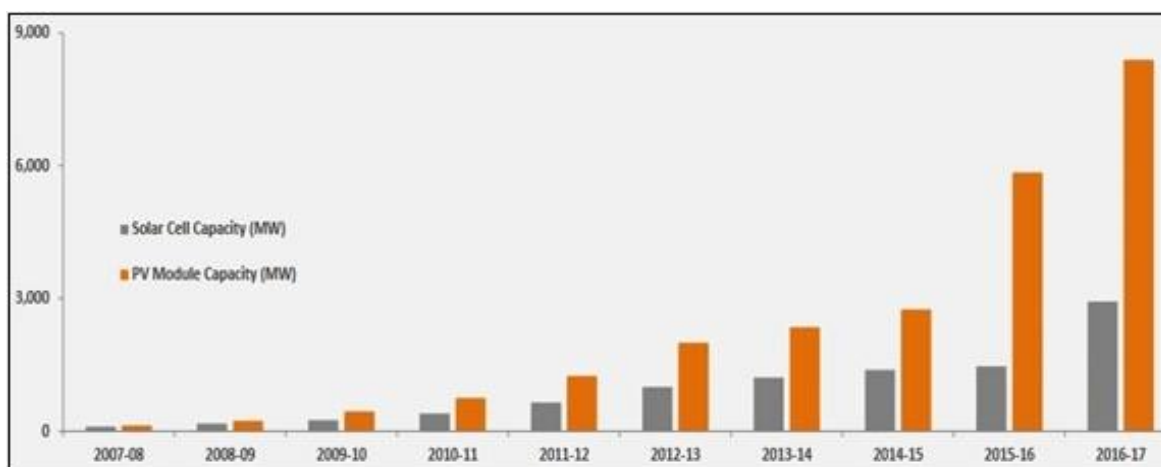
Currently, the country's total solar cell and module manufacturing capacity is estimated at 11.5 GW. Around 20 solar cell companies and 117 solar module companies listed with a total installed capacity of solar cells standing at 3164 MW and module capacity at 8398 MW respectively in 2017 (MNRE, 2018). The MNRE has released the list of domestic solar cell and module manufacturers with respective installed and operational manufacturing capacity (see table 3 and figure 2).

Table 3: Indian solar cell and module manufacturing capacity

Year	No. of Company		Cell		Module	
	Cell	Module	Installed (MW)	Operational (MW)	Installed (MW)	Operational (MW)
2017	20	117	3164	1667.05	8398	5506.55
2016	20	94	1753	1448.05	6913	5286.55
2015	16	93	1468	1123.05	5848	4307.55
2014	13	38	1216	240	2348	661

Source: Own compilation; based on various MNRE reports 2015 to 2019.

Figure 2: Indian solar cell and module manufacturing capacity, 2007-08 to 2016-17



Source: MercomIndia, 2017; MNRE, 2018

There are around 57 domestic EPC (Engineering, Procurement and Construction) companies in 2017 (MNRE, 2018). In case of the inverters, the country is mainly imported from German and USA based suppliers (Bridge to India, 2017). The following table represents the overall status of solar PV market in the country.

Table 4: Status of Indian solar PV market

Components	Status
Poly-silicon Feedstock	No manufacturing capability
Ingots and Wafers	Limited presence in the segment
Cells	Heavily dependent on imports
Module Inverters	Very heavily dependent on imports (90%). Higher costs compared to Chinese
Inverter	Market dominated by a few global players. Economies of scale required to build a production line
Battery	High dependence on imports
Transformers	Mature market
System Integration	Mature market

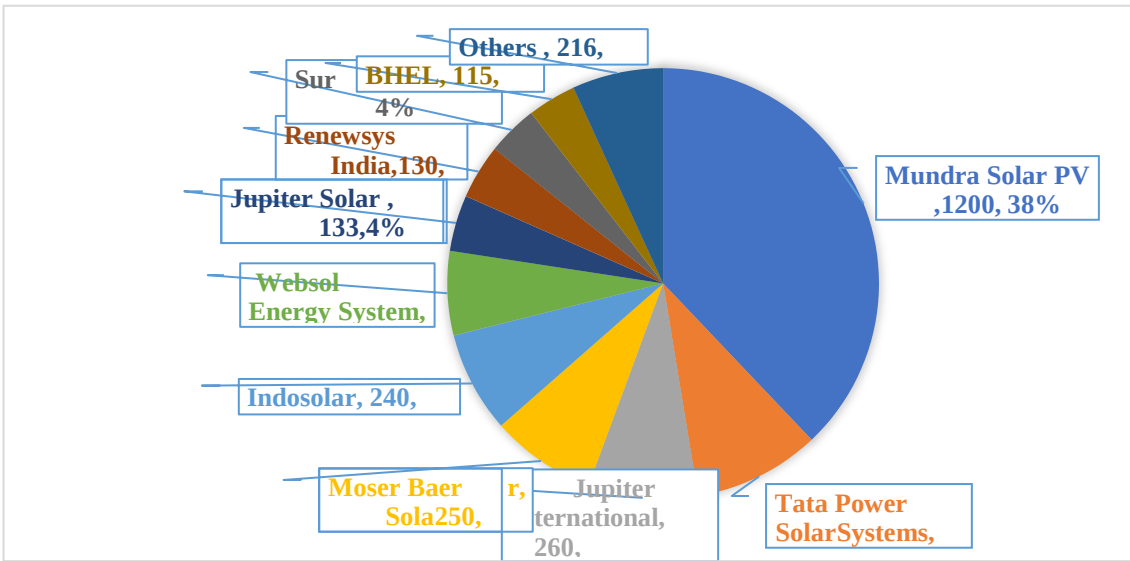
Source: World Bank (2016); MNRE, 2019

However, the country is a key emerging nation in terms of solar power (Fu, X. and Zhang, J. 2014). Around 75% of the cells are exported to international markets (Lema, R. and Lema, A. 2012). The Indian solar PV sector is a mix of three major approaches including patent licensing, joint ventures and acquisitions, and in-house R&D (Mallett et al. 2009), which matches the current development level of the technology and production capacity in the Indian solar PV sector. According to Fu, X. and Zhang, J. (2014) the biggest solar manufacturers in the country are Moser Baer Solar, Tata Power and HHV Solar. The Moser Baer Solar has long-term R&D plans, focusing on improving efficiencies and reducing cost through innovations. It has set strategic alliances with American solar technology companies focusing on distribution and production of solar technologies. It has its R&D facilities across the country and collaborative research programmes with internationally reputed research institutions and industrial players in India and abroad. Likewise, HHV Solar has also a mature R&D centre and overseas partnerships, while Tata power employed a conventional technology transfer mechanism by setting up a joint venture, Tata BP Solar, with BP Solar, one of the leading solar companies in the world (Fu, X. and Zhang, J., 2014).

Around 43% of the total module production in the country are from top 10 local manufacturers. The biggest local module manufacturers in the market share are

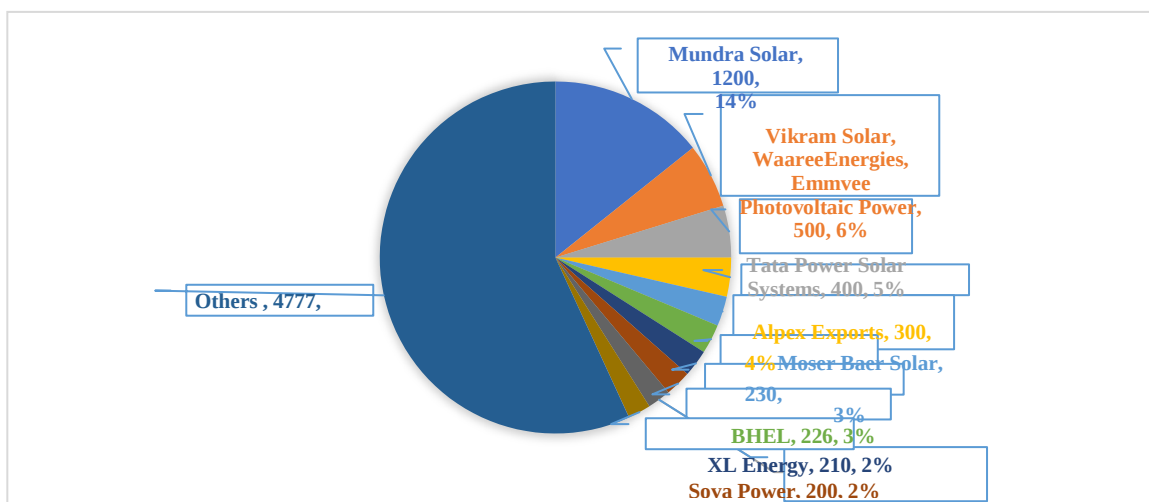
Mundra Solar (14%) and followed by Vikram Solar, Waaree Energies, Emmvee Photovoltaic Power and so on (see figure 3). The market share of Indian module manufactures is low. Most of this capacity is obsolete and uncompetitive. The country is importing around 84% of all module requirements from abroad, and the Chinese modules are highly demanded in the country (Bridge to India, 2017). There are three Chinese module companies among top 5 global module suppliers (see table 4). In case of the cell manufacture, Mundra Solar stands at the top and followed by Tata Power Solar System, Jupiter International, Moser Baer Solar, Indosolar and so on (see figure 4).

Figure 3: Top 10 Indian Solar Cell Manufacturers, 2017 (MW, %)



Source: MNRE 2018

Figure 4: Top 10 Indian Solar Module Manufacturers, 2017 (MW, %)



Source: MNRE 2018

Table 5: Top five imported foreign PV Firms in India and global PV module suppliers, 2017

Position	Imported Foreign PV Company in India (Origin Country)	Position	Global PV module Suppliers (Origin Country)
Rank 1	Trina Solar (China)	Rank 1	Jinko Solar (China)
Rank 2	Canadian Solar (Canada)	Rank 2	Trina Solar (China)
Rank 3	REC Solar (China)	Rank 3	Canadian Solar (Canada)
Rank 4	Jinko Solar (China)	Rank 4	JA Solar (China)
Rank 5	Ja Solar (China)	Rank 5	Hanwha Q Cells (South Korea)

Source: PV-tech, 2017. (Note; the ranking is based on shipment volumes in the particular year).

The following table 6 indicates the annual ranking of various Indian solar cell and module manufactures based on the manufacturer's share of total installed capacity.

Table 6: Annual ranking of solar cell and module manufactures in India (2016 to 2017)

Position	Cell Manufactures		Module Manufactures	
	Year 2017	Year 2016	Year 2017	Year 2016
Rank 1	Mundra Solar PV (Adani Group)	Tata Power Solar Systems	Mundra Solar (Adani Group)	Emmvee Photovoltaics
Rank 2	Tata Power Solar Systems	Jupiter Solar	Vikram Solar, Waaree Energies, Emmvee Photovoltaic Power	Vikram Solar
Rank 3	Jupiter International	Moser Baer Solar	Tata Power Solar Systems	Waaree Energies
Rank 4	Moser Baer Solar	Indosolar	Alpex Exports	Tata Power Solar Systems
Rank 5	Indosolar	Renewsys India	Moser Baer Solar	Alpex Exports
Rank 6	Webso l System Energy	Surana Solar	BHEL	Moser Baer Solar Limited
Rank 7	Jupiter Solar	Webso l System Energy	XL Energy	BHEL
Rank 8	Renewsys India	BHEL	Sova Power	XL Energy
Rank 9	Surana Solar	Premier Systems Solar	Renewsys India	Sova Power
Rank 10	BHEL	XL Energy	Lanco Solar	Renewsys India

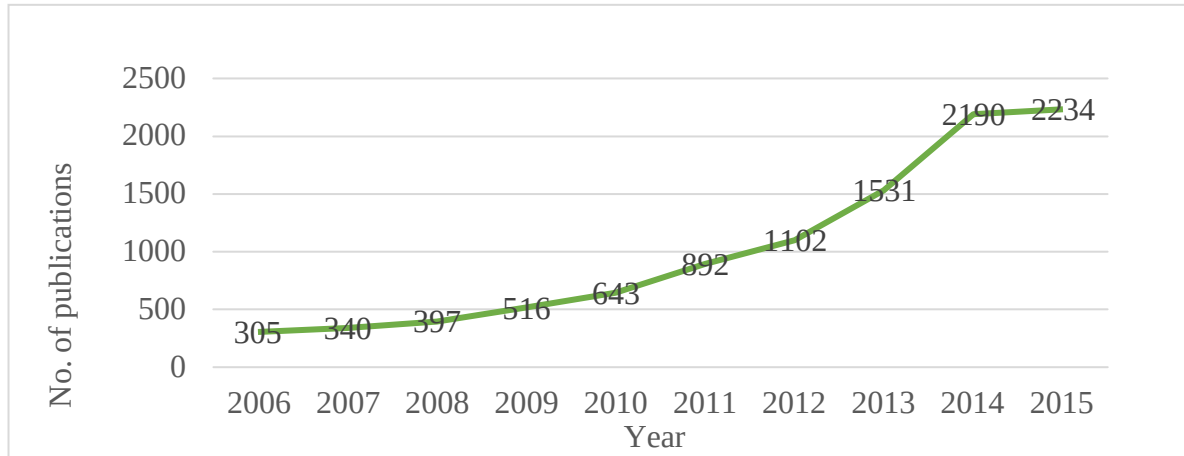
Source: Own compilation; adapted from MNRE Annual reports 2018 and 2019. (Note: this list is based on installed solar cell and module capacity during the respective year, and it is not based on other quality or process in PV value chain).

Knowledge development

Knowledge development is the heart of the innovation system. This function represents the crest and trough of the knowledge base of the solar PV TIS and how that changes over the period. It also captures knowledge about socio-economic and technological features of solar PV in the country. We are exploring the trends of scientific publications, number of patents, main research organisations and number of research and development projects towards solar PV.

To understand the scientific productivity of different R&D institutions and universities, we have analyzed Scopus online database. The following figure shows the number of publications related to solar PV.

Figure 6: Number of publications related to solar PV technology in India, (2006-2015)



Source: Researcher's data based on the Scopus database, 2017

The number of scientific publication in various solar PV technologies (for instance; Amorphous, Concentrating PV, Dye-sensitized cells, Mono crystalline, Multi-junction cells, Poly crystalline, Thin-film cell and so on) is indicated in the following table. The maximum number of the publications are found in thin-film, poly crystalline and dye-sensitized solar cells.

Table 7: Publication trends from India in various solar PV technologies (2007-2016)

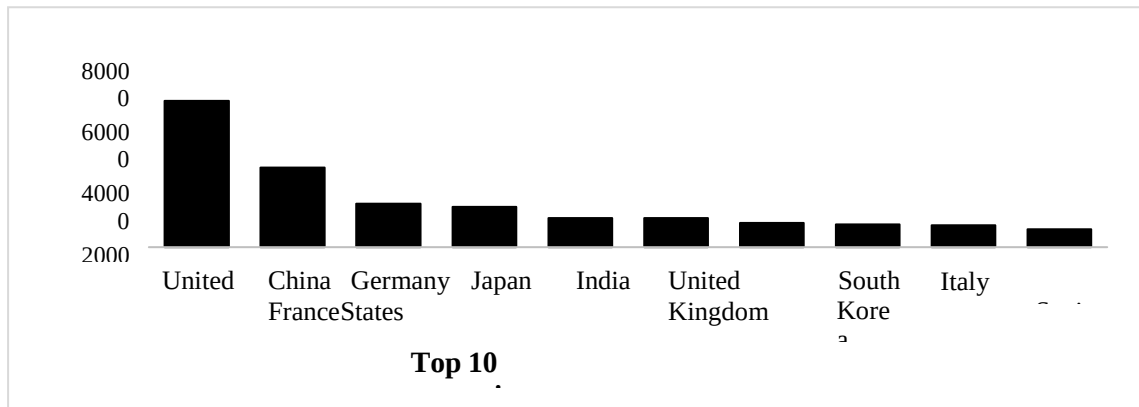
PV Technology	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Amorphous	57	81	117	120	139	92	118	108	152	165
Thin film cell	45	61	66	82	112	120	156	220	203	230
Concentrating PV	0	0	0	0	0	0	0	0	1	0
Dye-sensitized cell	5	13	18	29	65	71	95	153	170	169
Mono crystalline	4	7	9	6	6	10	8	8	13	15
Poly crystalline	1	8	80	148	154	168	170	185	198	206
Multi-junction cell	0	0	0	0	1	1	1	2	1	7

Source: Author's Compilation based on Scopus database, 2017

Globally, the country stands at the fifth position and covers about 5% of the total publications(refer figure 7). The total number publications till 2016 were 287853. Out of this, USA has published about 68,938 publications. The USA has published highest papers about 24% of total publications and then followed by

China 37,562 (13%), Germany 20,601 (7%), Japan 18,844 (6.5%) and followed by India 13,886 (5%).

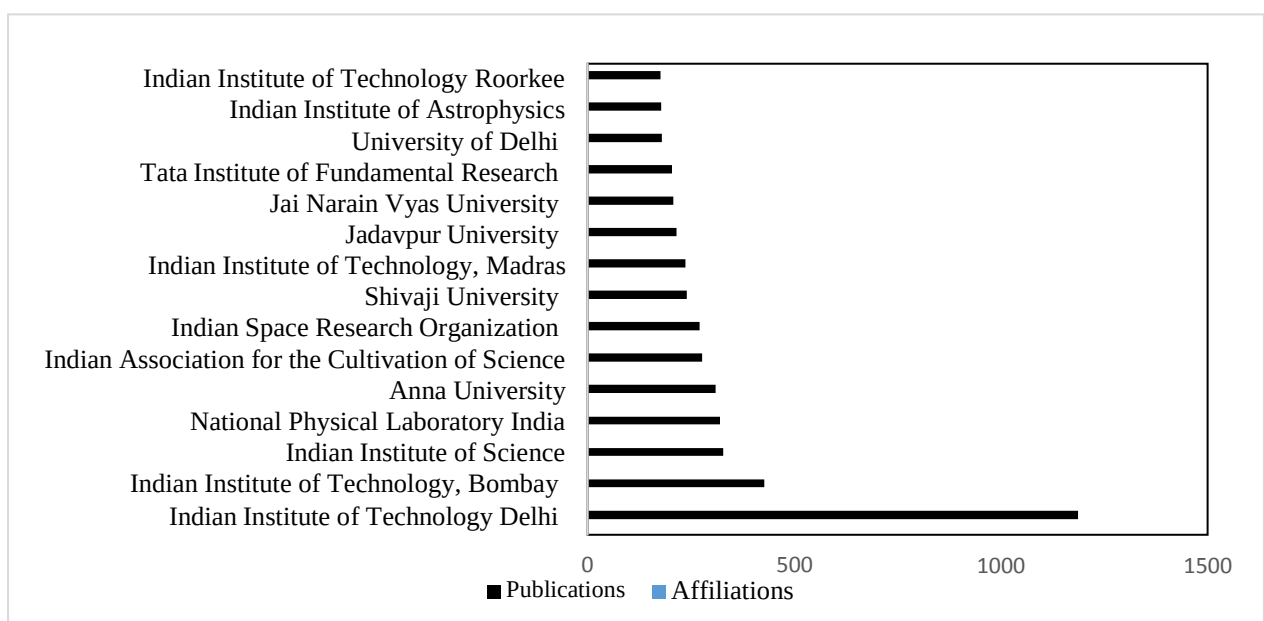
Figure 7: Publications related to solar PV by top 10 countries in the world



Source: Researcher's data based on the Scopus Database, 2017

The country also has a significant presence in productive R&D institutions and universities. The top 15 Institutions and universities are given with the publications in the following figure 8. IIT Delhi is on topmost with 1186 publications of the total publications (8.5%), followed by IIT Bombay 427 publications (3%), Indian Institute of Science 328 publications (2.4%) and others.

Figure 8: Publications by top 15 Affiliations in India



Source: Researcher's data based on the Scopus database, 2017

It is observed that among the top 15 affiliations major dominant institutions are from Indian Institute of Technologies and most of them are the public research and development institutions in the country.

In case of patents, about 19 granted patents have been registered until 2009 in the country (Goel, M., Maurya, V. and Desai, P. 2013). From Indian Patent Office (IPO) online database, it is also found that around 40 patents have been granted from the country until 2017. There are 101 granted patents⁷ from India until 2017 in various solar PV technologies in the United States Patent and Trademark Office (USPTO). The maximum number of patents are granted in the area of solar PV cells (23 patents). The main assignee of the patents in solar PV cells are Indian Institute of Technology (IIT), Council of Scientific and Industrial Research (CSIR), Yeda Research and Development Co., Ltd. and Applied Materials, Inc. The number of granted patents from the country in USPTO is shown in the following tables.

Table 8: Number of US granted patent from India in various solar PV technologies

Description	Granted patent	Description	Granted patent
Photovoltaic (PV) energy	5	Dye-sensitized solar cells	10
PV systems with concentrator	10	Solar cells from grp. II-VI material	0
Material technologies	0	Solar cells from grp. III-V material	2
CuInSe ₂ material PV cell	2	Microcrystalline silicon PV cells	0
Amorphous silicon PV cell	2	Polycrystalline silicon PV cells	0
Organic PV cells	23	Mono-crystalline silicon PV cells	1
Power conversion electric	1	Concerning power management	6
Grid-connected application	14	Maximum power point tracking	9

Source: Compiled by author based on USPTO database, see <http://patft.uspto.gov/netah/tml/PTO/search-adv.htm>

In case of research and development projects, various programmes are designed to improve efficiency, reliable and cost competitive performance of different PV technologies in the country. Solar Energy Corporation of India (SECI) and National Institute of Solar Energy (NISE) are main important government R&D institutions. These institutes help to set up a framework which would incubate an environment for accelerating R&D activities in the association with the goals of many ambitious missions. The NISE has been working on various aspects of solar resource utilization and technology development in collaboration with other research institutions, implementing agencies and industry in the country.⁸ It has developed a variety of technical

facilities for the technology evaluation and validation, testing and standardization, performance reliability, monitoring and data analysis (MNRE, 2018).

Under the R&D programme, the evaluation of various emerging technologies and standardizing the technologies for applications suitable for various field conditions is an important task. The NISE also assists other research organizations and industry in implementing innovative ideas and development of new products by offering its facility and expertise for developmental testing. Cooperation with institutions and industry, technology evaluation, testing and standardization; evaluation of technical, environmental, and economic performance; national referral test facility and developmental testing; coordination with Regional Test Centres (RTCs) and standards organizations are the main R& D programmes at the NISE. In addition to this, it has been working in close collaboration with the Bureau of Indian Standards (BIS) for bringing out national standards pertaining to the technology. It has also coordinates with the RTCs⁹ established in the country for the testing of PV devices and systems.

Knowledge diffusion

This function refers to the communication of knowledge between different actors in networks. We are focusing on activities of innovation system at diffusion of knowledge such as conducting training programmes, demonstration, exhibitions, conferences and creation of awareness. The NISE has taken up a project along with Indian Association for Cultivation of Science (IACS) and Central Electronics Ltd. (CEL) for the development of reference solar cells and modules, the procedures to be adopted for calibration of the reference products have been laid down. The spectral response system for solar cells and the solar cell tester have been installed and commissioned at IACS and CEL respectively. A big project in collaboration with National Renewable Energy Laboratory (NREL), USA and India Meteorological Department (IMD) 'Solar Resource Assessment based on Satellite Imagery' for Solar Resource Assessment has been taken up recently.

The NISE conducts various training programmes, seminars, workshops and other short (3 weeks) and long term (6 months) courses related to solar PV technology with the objective of disseminating the knowledge in the various field of solar PV. From 2008 onwards, a comprehensive '*Visitors Programme*' has initiated at the NISE with the aim of utilizing the facility and expertise developed for undertaking scientific projects, interactive research and training and human resource development. Every year NISE organizes around 18 training programmes related to solar energy. The institute has also been accredited as a training centre of conducting "*International Training Programmes*

on Solar Energy” under ITEC (The Indian Technical and Economic Cooperation) scheme of the Ministry of External Affairs. Moreover, Gujarat Institute of Solar Energy (GISE) located in Ahmedabad provides technical vocational training programs on solar PV technologies and has support to organizations and individuals who are looking for self-employment and want to make a career in solar energy field. The GISE is a notable institution in the country to promote solar power manufacturing, assembling and research and development facilities not only in the state but also in other parts of the country.

The Ministry of New and Renewable Energy has launched a National Solar Science Fellowship programme from the year 2011-12. The maximum number of fellowships is 10 and the tenure of the fellowship is three years. The total annual grant of the fellowship is Rs.32 lakh per person.¹⁰ The main aim of the fellowship programme is to provide a platform to the top quality scientists and engineers to use and expand the resources available at the identified schools or institutions in the country and abroad, and to address the complex problems of solar energy utilization for various end-use including power generations. IISc (Bangalore), TIFR (Mumbai), IACS (Kolkata), SEC (Gurgaon), NPL (Delhi), IITs, NITs, Jawaharlal Nehru Technology University (School of Energy), Devi Ahilya university (Centre of Energy Studies and Research), TERI University, School of Energy Studies (Jadhavpur University), School of Energy Studies (Anna University), Department of Energy (Tezpur University), Lucknow University (Department of Physics), University of Petroleum & Engineering (Dehradun), Energy Research Centre (Punjab University), CR University of Science & Technology, IP University (Delhi), H.N Bahuguna University (Uttarakhand), Mata Vaishno Devi University (Jammu) and Birla Institute of Technology & Science (Pilani) are the indicative list of institutions which can act as a host institution of the fellowship (MNRE, 2016).

Students and faculty of various colleges and universities visit the NISE for exposition to renewable energy technologies. The NISE hosts such visits not only for the students and faculty of educational institutions but also for industry partners, scientists from research organizations from different parts of the country and abroad, renewable energy agencies of the states, and officers and policy makers from various government departments.

A large number of international delegations from different countries have visited the NISE and participated in specially designed technical symposia. In 2010, there was an India- Japan Photovoltaic seminar in New Delhi in collaboration with New Energy and Industrial Technology development Organization (NEDO) of Government of Japan to discuss various issues related to PV technologies. The major events during 2008 to 2016 include a seminar to celebrate the year of physics, two tutorials on solar PV in Meerut and Kolkata, faculty improvement programme for engineering college held in Chennai, a

workshop on storage batteries, symposia for educational institutions, a meet of experts for PV roadmap of the country, a workshop on solar buildings and several expert group meetings on testing & standardization, photovoltaic systems, etc. The following table shows the list of training programmes under the MNRE support across the country.

Table 9: List of training programmes on solar PV under the MNRE support, (2015-2016)

Host Organisation, Location	Month, Year	Target groups	Participation Number
TERI, New Delhi	Oct, 2015	Distribution utilities, state nodal agencies and electricity regulatory commissions	35-40
Veermata Jijabai Technological Institute (VJTI), Mumbai	Oct, 2015	Financial institutions	20-25
KIIT University, Bhubaneswar	Dec, 2015	Distribution utilities, state nodal agencies and electricity regulatory commissions	35-40
Veermata Jijabai Technological Institute (VJTI), Mumbai	Dec, 2015	Channel partners, new entrepreneurs, manufacturers	80-100
TERI, Gwal Pahari Campus, Gurugram	Jan, 2016	Channel partners, new entrepreneurs, manufacturers	80-100
India Habitat Centre, Delhi	Jan, 2016	Financial institutions	20-25
Patna, Bihar	Feb, 2016	Distribution utilities, state nodal agencies and electricity regulatory commissions	35-40
TERI, Bengaluru	Feb, 2016	Channel partners, new entrepreneurs, manufacturers	35-40
Chennai*	Feb, 2016	Financial institutions	20-25
Bhopal*	Mar, 2016	Channel partners, new entrepreneurs, manufacturers	35-40
NISE, Gwal Pahari Campus, Gurugram	Apr, May, Jun, Jul, Aug, Sep 2017	Channel partners, new entrepreneurs, manufacturers	15-20

Source: Researcher's compilation; adapted from MNRE and TERI websites, here *means not available information about the host organisation.

[<http://mnre.gov.in/information/events/> and <http://www.teriin.org/events/trainings-solar-pv.php>]

The number of conferences related to solar PV has been increasing rapidly and becoming more international. After 2013, some of the notable conferences are 1st Renewable Energy Global Investment Promotion Meet & Expo (RE-INVEST) at New Delhi, 2015; Renewable Energy India Expo, Solar India Expo 2017 at Expo Centre, Greater Noida, UP; Renewable World, 2014, 2015 2016; HVI, 2014, 2015, 2016; Power-Gen India and Central Asia, 2014, 2015, 2016; Renewable World India 2016; Energy 2016; Solar Tech Expo India, 2015, 2016;

WRETC, 2014, 2015, 2016; RenewX at Hyderabad 2015, 2016, 2017, 2018 and Inter Solar Expo cum Conference at Mumbai, 2017. The main motto of these conferences is to create an important industry platform for manufacturers, suppliers, distributors, service providers and partners along the supply chain of global solar PV industry.

Guidance of the search

This function encompasses the creation of optimism and prospects towards the future of solar PV technology in India. At the same time, it also aims at reducing uncertainties and risks associated. In this function, we analyse by mapping specific targets set by governments or different stakeholders that raise expectations about the technological developments in the country. The Government of India has introduced a set of international and domestic initiatives to create the policy support needed to comprehend ambitious clean energy goals. In 2015, at the United Nations' Conference of Parties, the government had announced that the country would lead an International Solar Alliance of more than 120 solar rich countries to facilitate widespread deployment of solar power and development of the supporting ecosystem including knowledge exchange on manufacturing and skills. Some of the initiatives taken by the government are International Solar Alliance, the revised target of renewable energy by 2022, the formation of District Advisory Committees, Akshay Urja Shops and Akshay Urja Newsletter, Renewable Energy clubs, Rural Electrification programmes and so on. In line with the Paris Climate Agreement in 2015, the MNRE has announced the target of installing 175 GW capacity on renewable energy by 2022. Out of this, 100 GW is to come from the solar energy sector.

In 2010, the government announced National Solar Mission (NSM). It was a major initiative to promote ecologically sustainable growth while addressing India's energy security challenge. The goal is to make the nation one of the leaders in solar energy production in the world by 2022. Under this mission, there are three phases such as Phase-I (2010-2013), Phase-II (2013-17) and Phase-III (2017-2022) with different target achievements. The mission also has other additional goals such as promoting R&D, public domain information, develop trained human resource for the solar industry and expand the scope and

coverage of earlier incentives for industries to set up solar PV manufacturing in India. This mission has garnered much attention for various reasons. The mission has also inspired a full-fledged research on it. The NSM aims installations of 20,000 MW of grid-connected solar power generation, 2,000 MW of off-grid solar applications, 20 million sq. meters of solar thermal collector area for industrial applications and 20 million solar lighting systems for rural areas by the year 2022.¹¹ The mission's first phase has a target of 1100 MW of grid-connected, 200 MW of off-grid solar applications and 7 millions square meters of solar collectors.

The phase-I is largely focused on grid-connected projects. To achieve 500 MW of solar PV, the government conducted two batches of reverse auctions. These bidding processes offer feed-in tariffs and long-term PPAs to the selected least-cost developers. The feed-in tariffs to developers are complemented by support to power utilities through the bundling of solar power with conventionally produced electricity, reducing the average per-unit cost of solar power. The NSM phase-I has divided into two batches, i.e. batch I & II. In Batch I, capacity addition of 150 MW of grid-connected solar PV plants was envisaged. Whereas in batch II, the remaining targeted capacity for Solar PV i.e. 350 MW is awarded. A Migration Scheme is launched to provide these projects to migrate from the respective existing arrangement to the one envisaged under the mission subject to the consent of distribution licensee, state government and willingness of developers.

Market formation

Market formation addresses the activities that induce or create of a niche for PV technology. It also enhances market development of the technology at the same time. In the Indian Solar PV technological innovation system, it is required to understand the sequence and function of the market formation. There are some regulation systems implemented by the government of India such as solar Renewable Purchase Obligations (RPOs), Renewable Energy Certificates (REC) and Feed-in Tariffs (FITs).

Solar RPOs are the minimum amount of solar energy that obligated entities; distribution licensees, open access and captive consumers; have to deliver or consume as a percentage of their total available electricity. They can meet this obligation by purchasing the required quantity of solar power directly from producers. Alternatively, they can buy solar Renewable Energy Certificates (RECs) to fulfill RPOs. If the required obligation is not met by the states, a penalty is levied. The RPO targets define how much electricity in the country is estimated to be produced from renewable energy sources. Many states are now establishing RPOs, which has stimulated development of a tradable REC program. Many states have with regulations under consideration with RPO

requirements ranging from 1% to 15% of total electricity generation across the country. Recently there is a prescription of solar-specific RPO announced after the amendment of the Tariff Policy. The solar specific RPO is increased from a minimum of 0.25 % in 2012 to 3 % by 2022 in different states. All the states have their State RPO target except Arunachal Pradesh and Sikkim. Manipur and Nagaland have 0.25 percent solar RPO targets in both 2012 and 2013. The MNRE has set RPO for every state to install solar power plants every year, according to the states requirements and its capacity of installation. Every year a RPO target is set for the individual states, which they need to achieve in that year.

However, every state has announced a solar specific percentage as a part of the overall Solar- RPO. These are currently in the range of 0.25% to 0.5% and expected to go up to 3% by 2022 as envisaged in the mission guidelines. These solar purchase obligations are complemented with solar RECs, which are announced by CERC on January 2010. Under the REC scheme, generators choose between selling the renewable electricity generated at a preferential tariff and selling the electricity generated separately from the environmental benefits.

Feed-in Tariff is a policy mechanism designed to accelerate investment in renewable energy technologies in the country. The FITs are based on the first estimates of the Central Electricity Regulatory Commission of the capital costs of the technologies, the cost of the debt and the expectations of market return. The tariffs for solar PV projects and solar thermal projects are fixed at Rs.17.90 /kWh and 15.40 /kWh till 2012. Under the NSM, the government promotes different types of solar energy projects. Due to the differences in the various solar PV technologies and also the differences in the development stages and their suitability in Indian conditions it is difficult to predict their cost and an appropriate feed-in tariff.

The MNRE has introduced different Generation Based Incentive (GBI) schemes for solar. Under this scheme, generation base incentive is provided to support small grid solar power projects connected to the distribution network at a voltage level below 33 kV. Indian Renewable Energy Development Agency (IREDA) has been designated as programme administrator for administering the generation of solar GBI. The agency has selected 78 projects with a total capacity of about 98 MW for which the ministry would provide GBI of Rs.12.41 per kWh to the state utilities when they directly purchase solar power from the project developers. The quantum of GBI to the utilities is kept fixed, as a difference of the CERC tariff for 2010-11 (Rs.17.91 per kWh) and a reference tariff of Rs.5.5 per kWh (MNRE). The local distribution utility would sign a PPA (Power Purchase agreement) with the project developer at a tariff decided by the respective SERC. The solar GBI would be payable to the state utilities for a period of 25 years. Project developer is required to be initially pre-registered with the state designated agency and after that register online with IREDA.

Resource mobilization

Resource mobilization is the process by which various resources need to be mobilized. These resources can be different types such as scientific, technical and financial. In this function, it is required to understand some extent to mobilise financial, human capital and complementary assets. Currently, there are more than 50 scientists at National Institute of Solar Energy (NISE) and Ministry of New and Renewable Energy who are engaging in research in various PV technologies. The government of India also allocates funds or provides other subsidies for various R&D activities in the country. Compare to another country in the world, India invests less money in the renewable energy sector. India invests Rs. 442.4 billion and covers only 2% of the global investment in the sector in recent year (MNRE, 2015 and Bloomberg New Energy Finance, 2015). China has become the leader in the global investment. Around Rs. 4532.4 billion and Rs. 2450 billion has been invested in China and USA respectively in the sector. It covers about 27% and 15% of the global investment.

Globally the investment in the renewable energy sector has increased steadily from USD 39.5 billion in 2004 to USD 285.9 billion in 2015¹². Steep cost reductions in solar PV and wind power make renewables attractive for new markets, particularly in developing countries where new electricity generation capacities are needed to satisfy increasing energy demand. Renewable energy investments in the developing countries like China, Brazil and India have been raised steadily over the past decade and overtook the total investment of OECD countries for the first time in 2015. The steady growth was to a large extent because renewables are now one of the lowest cost options for new power generation (REN21, 2017).

China is playing a dominant role which is increasing its investment by 17% to USD 102.9 billion, accounting for 36% of the global total (REN21, 2017). Overall, the developing countries like China, India and Brazil, committed a total of USD 156 billion (up 19% compared to 2014). The investment in the renewable energy sector has also increased significantly in the countries like India, South Africa, Mexico and Chile. Other developing countries like Morocco, Uruguay, Philippines, Pakistan, etc. have been investing more money than in the renewable energy sector from 2015 onwards. The renewable energy investment in the USA has been increased by 19% to USD 44.1 billion since 2011. The investment in the renewable energy has been weighted increasingly towards the wind and solar power among the various renewable energy sources (Bloomberg, 2016). Other technologies like small hydro energy, biomass energy, geothermal energy and waste to energy saw investment decline relative to 2014 (REN21, 2016). The renewable energy investment in the developed countries as a group declined by 8% in 2015, to USD 130 billion (Bloomberg New Energy Finance, 2015). The most significant decrease has seen in the European countries

regardless of the region's record year of financing for offshore wind energy. The government of India also allocates funds or provides other subsidies for various R&D activities in the country. The solar mission has launched with a preliminary budget allocation of Rs. 3.85 billion made in 2009. Compare to another country in the world, India invests less money in the renewable energy sector. India invests Rs. 442.4 billion and covers only 2% of the global investment in the sector in recent year (MNRE, 2015 and Bloomberg New Energy Finance, 2015). China has become the leader in the global investment. Around Rs. 4532.4 billion and Rs. 2450 billion has been invested in China and USA respectively in the sector. It covers about 27% and 15% of the global investment.

Currently, a total sum of INR 209.85 crores has been invested in the solar research and development from 2014 to 2017. Out of 89.35 crores, around 60 crores and 29.35 crores are allocated to various solar projects and the National Institute of Solar Energy (NISE) respectively (refer table 9).

Table 10: Solar R&D budget allocation and expenditure release (INR Crore), 2014 to 2017

Year	Budget Allocation		Total Allocated Budget	Expenditure Release		Total Expenditure
	Solar Projects	National Institute of Solar Energy (NISE)		Solar Projects	National Institute of Solar Energy (NISE)	
2014-15	44.80	40.00	84.80	44.80	49.36	94.16
2015-16	33.90	20.00	53.90	33.90	29.35	63.25
2016-17	60.00	29.35	89.35	45.44	07.00	52.44
Total	138.90	89.35	228.05	124.14	85.71	209.85

Source: Own compilation adapted from MNRE, 2018; Parliament of India (website)

In 2016-17, the total budget allocation and actual expenditure spent on solar energy sector are 89.35 INR Crore and 52.44 INR Crore respectively. It covers around 70% of the total budget allocation in the renewable energy sector and 56% of the total expenditure release. The share of the solar research and development budget allocation and actual expenditure spent from 2014 to 2017 are shown in the following table.

Table 11: Share of Solar R&D budget allocation and expenditure (INR Crore), 2014-17

Particular	Budget Allocation			Total Allocated Budget	Expenditure Release			Total Expenditure
	2014-15	2015-16	2016-17		2014-15	2015-16	2016-17	
Total RE	131.89	83.95	126.25	342.09	131.39	82.08	94.19	307.66
SE	84.80	53.90	89.35	228.05	94.16	63.25	52.44	209.85
Share by SE (%)	64	64	70	67	71	77	56	68

Source: Own compilation adapted from MNRE, 2018; Parliament of India (website). Here, RE and SE stand for renewable energy and solar energy respectively.

Creation of legitimacy

With regards to creation of legitimacy function, activities which legitimize the PV technology are considered here. It is a matter of defiance and social acceptance with significant institutions; the new technology and its promoter's needs to be considered suitable and necessary by related actors for resource mobilisation to happen, and the demand to be formed and the relevant new actors in the innovation system to gain a political stronghold.

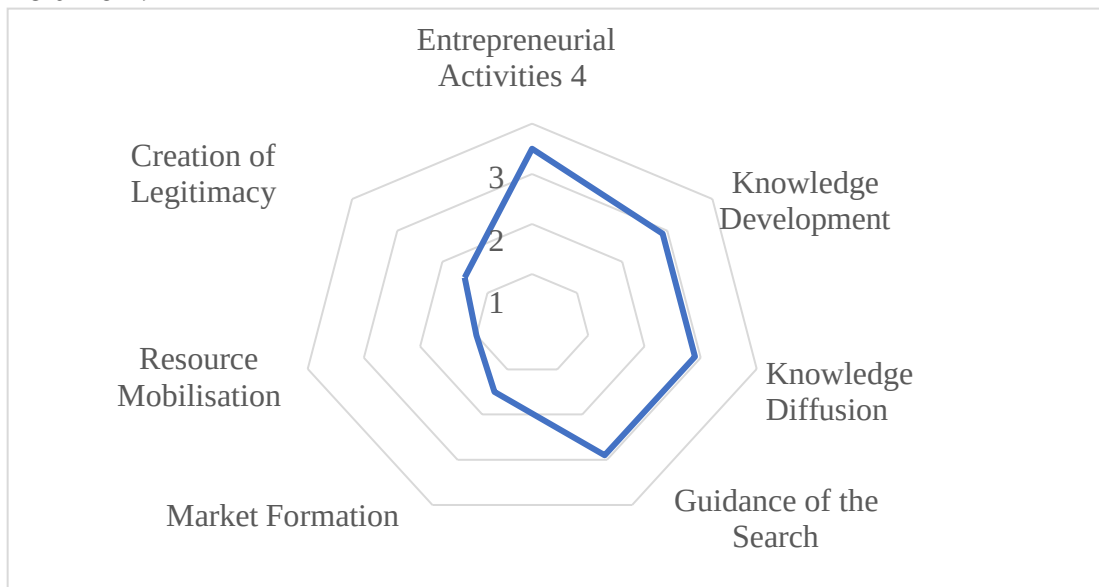
The Government has introduced a lobby for the PV technology by reforming the institutional and regulatory framework of its power sector. The MNRE is the results of reforms that ranged from unbundling of the State Electricity Boards, increased involvement of the private sector in a generation, transmission and distribution, to the liberal setting of electricity tariffs. The introduction of National Electrification Policy of 2005 and the Rural Electrification Policy of 2006 also contribute to the advocacy coalitions of the PV technology development. There are several institutions initiating information campaigns trying to popularize the use of PV systems. On the other hand, there is an issue about domestic content requirement (DCR) recently. To achieve solar capacity and cost targets the National Solar Mission auctions Power Purchase Agreements (PPAs) to solar developers and to ensure domestic solar manufacturing in the country the programme includes a DCR: developers must use solar cells and modules manufactured in India. However, the DCR makes an exception for solar PV developers using thin film technologies, which may be imported. The majority of solar developers in India currently use imported thin-film modules. In the mission's different phases DCR has sparked a major controversy recently. US have raised some questions over DRS's functioning and the import of thin films in India. US's primary concern is over the process and nature of thin films import in India from US itself, China and so on. So, few critical issues have come up in this regard. According to The Hindu, "the U.S. has taken India to WTO over the DCR under the National Solar Mission. The country is likely to argue

that the National Solar Mission is in the nature of government procurement; because the power is bought by a government owned company. India is not a signatory to the agreement on Government Procurement, hence, no violation. Secondly, India will argue that the DCR rules have truly caused no damage to any overseas manufacturers, because it is applied on a very small portion of the country's goals, the rules do not cover states' programmes." At the end The Hindu shares its own perspective "there are no quick and easy answers, but one way out could be to encourage Indian companies to acquire technologies abroad; for technology alone could be the answer to the advantage of scale that the American and Chinese companies have". So the bottom line the DCR is certainly going through some critical obstructions in the solar market. There are not immediate solutions so far from the Indian government.

Discussion and findings

After analysis the seven key functions of Indian solar photovoltaic technological innovation system, it found that entrepreneurial activities function embraces a fairly accumulated technological system that performs a dynamic result. The average rating strength of this function from various experts is 3.50 out of 7. In case of the functions related to knowledge development, knowledge diffusion and guidance of the search, the result is found to be stable. For these functions, the average strength of each function is 2.90 out of 7. At the same time, there is a less accumulated technological innovation system associated with the market formation and creation of legitimacy. These functions have an average of rating strength of 1.50 with fluctuation in the innovation system. The last function, resource mobilisation has the least accumulated technological innovation system with an average rating strength of one. The following figure 9 illustrates the assessment of the strengths of each functions. Inconsistent regulations, less interaction in networks, disconnected competitive entities, unpredictable behaviour of the government and the lack of funding are the key blocking mechanism of India's PV industry development.

Figure 9: Overall strength of seven functions of Indian Solar PV TIS, based on fieldwork



Source: Own compilation; based on experts' rating scale

Concluding remarks

The entrepreneurial activity for solar PV in India is increasing over a period of time. The country's total solar cell and module manufacturing capacity is increasing from 10 MW to 11.5GW in a decade. So far, 20 domestic solar cell and 117 module companies listed with a total installed capacity of 3164 MW and 8398 MW respectively in 2017. However, the project developers for Indian PV market is at nascent stage towards PV market formation and innovation network.

The Indian PV module manufacturers are also all new entrants with no prior experience in the sector. In regards with knowledge development, knowledge diffusion and guidance of the search, these three functions fall fairly under well accumulated technological innovation system. Though, the country stands at the fifth position in terms of the number of research publications it covers only less percentage of the global contribution. There is few granted patents in specific solar PV technologies. In addition to this, the networks and linkages are limited in number and those PV technologies which are flourishing lacks the experiences of learning by interaction.

Three functions market formation, resource mobilisation and creation of legitimacy fall under least accumulated technological innovation system. A number of institutional arrangements are strong enablers for PV in India, such as the National Solar Mission and its supporting policies and subsidies to stimulate R&D, market formation and investment. These targets, policies and subsidies

have led to a fast growing PV technology in India in which all relevant actors such as policy makers, manufacturers along the supply chain, project developers, utilities, research organizations and financing institutes play a significant role. These actors have worked together towards a sharp rise in PV implementation projects in India, a sharp decrease in the FIT and development of learning processes such as R&D, learning by doing and learning by using. Financial resources have also become available and knowledge is transferred from Western based companies and research organizations to the key actors of the technological innovation system. A key policy implication derived from the findings is that the development of an innovation system at its nursing stage is sensitive to conditions in its external context. It should be considered in designing policies, domestically and through global development assistance.

Appendix A

Classification into technology classes for solar PV technologies

Description	Cooperative Patent Classification (CPC) Codes
Photovoltaic (PV) energy, PV systems with concentrators, Material technologies, CuInSe ₂ material PV cells, Dye-sensitized solar cells, Solar cells from grp. II-VI materials, Solar cells from grp. III-V materials, Microcrystalline silicon PV cells, Polycrystalline silicon PV cells, Mono-crystalline silicon PV cells, Amorphous silicon PV cells, Organic PV cells, Power conversion electric/electronic, For grid-connected applications, Concerning power management inside the plant, Maximum power point tracking systems and thermal PV hybrids.	Y02E10/50, Y02E10/52, Y02E10/54, Y02E10/541, Y02E10/542, Y02E10/543, Y02E10/544, Y02E10/545, Y02E10/546, Y02E10/547, Y02E10/548, Y02E10/549, Y02E10/56, Y02E10/563, Y02E10/566, Y02E10/58 and Y02E10/60 respectively.

Source: USPTO website,

[See the link, <http://patft.uspto.gov/netahtml/PTO/help/helpflds.htm#CPC>]

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Notes

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- ¹ The author argues that innovation is the key driver to economic change and regional development of a nation as the setting up of a new production function that covers the case of a new commodity, as well as those of a new form of organization. He further mentions the distinction between an invention and innovation such as invention means a new product, process or improvement while innovation is a new product, process or improvement that has been commercialized.
 - ² The number of research publications, citation analysis, etc.
 - ³ Edquist, C. (2001). The systems of innovation approach and innovation policy: An account of the state of the art. DRUID Conference, theme; national system of innovation, institutions and public policies.
 - ⁴ Scopus is one of the largest online abstract and citation database of peer reviewed literature with smart tools that tract, analysis and visualize research which is covering more than 20,5000 titles from nearly 5,000 publishers.
 - ⁵ The Office of the Controller General of Patents, Designs & Trade (CGPDT), Ministry of Commerce and Industry, Government of India supports Indian Patent Office.
 - ⁶ Solar cell is the most important part of the PV technology and assists as the building block for solar modules, which collect solar radiation and convert it into electricity.
 - ⁷ The number of granted patents in particular description such as Photovoltaic (PV) energy, PV systems with concentrators, Material technologies, CuInSe₂ material PV cells, Dye-sensitized solar cells and so on are obtained by using Cooperative Patent Classification codes (See the details in Appendix section).
 - ⁸ Ministry of New and Renewable Energy, Government of India (MNRE), GOI see <http://www.mnre.gov.in/centers/about-sec-2/activities/>.
 - ⁹ The Regional Test centres (RTCs) are the organized test centres accredited by the Bureau of Indian Standards under Government of India.
 - ¹⁰ Ministry of New and Renewable Energy (MNRE), GoI. see <http://mnre.gov.in/file-manager/support-programme-scheme/national-solar-science-fellowship-programme.pdf>
 - ¹¹ Ministry of New and Renewable Energy, Strategic Report , See <http://www.mnre.gov.in/>
 - ¹² See, BNEF (Bloomberg New Energy Finance) Report, 2016. Since the investment data includes wind power projects of more than 1 MW, geothermal power projects, biomass projects, small hydro power projects, solar power projects, biofuel projects with an annual production capacity of 1 million litres or more, ocean energy projects.

Scarce energy and market abundance? Building project-based capability through renewable power generation

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Abstract

The renewable energy electrification value chain is developed across the globe, just as other clean-tech innovation systems, therefore knowledge bases, supporting sectors, and market structures vary by each process chain (Hipp & Binz, 2020). The latecomer countries of renewables and clean energy technologies in developing economies are the importers and users of the technologies, thus they are in the deployment chain and user chain. Recent studies indicate those latecomers in developing economies can “learn from importing” should we observe them by project bases in the deployment chain and user chain (Andersen and Lema, 2022). This study draws from project-based capabilities in Complex products and systems (CoPS). The study is interested in the process of building project capabilities through renewable energy electrification. What kind of project capabilities can be built from investing and developing power generation projects in different parts of the world using various technologies? What influences a firm’s decision to invest and develop a project with yet another technology and different locations which require the cost of learning versus sticking to the familiar technologies and known location to expand the business? This study aims to identify the process of building project capabilities through renewable deployment. The result is expected to add literature in core capabilities, its tension between business development and project capabilities. Take it a step further, the study attempts to discuss the role of state in this setting.

Keywords: Renewable energy; deployment chain; CoPS; Project-based capabilities; GCC

1. Introduction

Renewables and clean energy technologies are changing the landscape of the conventional energy market. Furthermore, the energy transition has brought “green windows of opportunity (Lema et al., 2020)” to developing economies, such as China and India. The renewable energy electrification value chain is developed across the globe, just as other clean-tech innovation systems, therefore knowledge bases, supporting sectors, and market structures vary by each process chain (Hipp & Binz, 2020). The latecomer countries of renewables and clean energy technologies in developing economies are the importers and users of the technologies, thus they are in the deployment chain and user chain. Recent studies indicate those latecomers in developing economies can “learn from importing” should we observe them by project bases in the deployment chain and user chain (Andersen and Lema, 2022).

Complex products and systems (CoPS) are services, products, and infrastructure that is low in volume, high in cost, and complex (Davies et al., 2011). The deployment of renewables is a highly client-driven, project-specific, capital-intensive service. The project-based organization is effective in producing CoPS depending on the organizational strategy and structure (Mike Hobday, 2000). The firm can build project capability through CoPS from none repeatable, customer-driven, various projects (Davies & Brady, 2000). This study is interested in the process of building project capabilities through renewable energy electrification. *What kind of project capabilities can be built from investing and developing power generation projects in different parts of the world using various technologies? What influences a firm's decision to invest and develop a project with yet another technology and different locations which require the cost of learning versus sticking to the familiar technologies and known location to expand the business?* Finally, those firms can be intermediaries for sustainability transition by transferring expertise and capabilities learned from international markets in the different locations. The large and well-established firms can bridge younger firms to international markets, in other words, contribute to market formation (Normann & Hanson, 2018; van der Loos et al., 2020). If so, *what role can state take in this situation?* This study aims to identify the process of building project capabilities through renewable deployment. The result is expected to add literature in core capabilities, its tension between business development and project capabilities. Take it a step further, the study attempts to discuss the role of state in this setting.

The study chose a single in-depth case study of the desalination and power generation firm in Saudi Arabia. Although it is a single-firm case study, the firm has experienced several projects that are all in different sizes, with diverse technologies, and in different locations around the world, to offer rich insights. Furthermore, Saudi Arabia is non-leader and latecomer country in renewable energy development, especially because it is one of the oil and gas producing

countries where the presence of incumbent industry and its infrastructure is strong. Section 2. reviews literature to identify framework of the research, then clarify research materials and method. Section 3. is to illustrate market condition of the region and the driver for the renewable energy deployment in Saudi Arabia. The purpose is to describe the regional market condition and the driver of renewable energy deployment in Saudi Arabia. It is important to address the environment as it affects firm's decision and behavior. Section 4. describes the firm's path to renewable power generation with important events contributed in building project capabilities in chronological order. Section. 5 summaries result as preliminary findings. Finally, Section 6. Expands the preliminary findings.

2. Research approach, materials, methodology

2.1 CoPS and project based capability

Complex products and systems (CoPS) are services, products, and infrastructure that is low in volume, high in cost, and complex (Davies et al., 2011). Structurally, the project-based organization structure is effective in producing CoPS than function-based organization structure (Mike Hobday, 2000). The firm can build project capability through CoPS from none repeatable, customer-driven, various projects (Davies & Brady, 2000). Suppose project-based organization structure is better suited for CoPS production, then the firm's system integration capability to vertically integrate and disintegrate or outsource becomes important to manage the production (Michael Hobday et al., 2005). Building long term capability through creating project specific solutions required by clients are observed from two perspectives; tension between business development and building project capabilities, and dilemma of truing project based capabilities into repeatable solutions (Denicol & Davies, 2022). Project-based firms can be either permanent or temporary organizations; temporary organizations are formed based on projects but discontinue upon completing of the project (Denicol et al., 2021). This study is interested in permanent type of project-based firm's capability in producing CoPS, especially how the firm build capability from non-repeatable solutions and development of customer centric, unique projects.

2.2 Sustainability transition and transition intermediaries

Since the early 2000s, sustainability transitions and intermediaries to accelerate transitions have been the subject of many studies. The systemic transition concept is developed from sectoral systems of innovation and addresses the co-evolution of society and technology (F. W. Geels, 2004). Geels' multi-level perspective (MLP) illustrates development of niche, emerging technology, and regime, incumbent technology, then landscapes to capture dynamic changes over time (Geels, 2005). The evaluation of early

transition phases, predevelopment of emerging technology to its stabilization process, can be evaluated by forecasting and backcasting to manage the transition (Rotmans & et al, 2001). Technological trajectory is determined by the selection environment and institutions which requires strategic niche management to nurture its formative stages (F. Geels & Raven, 2006; Kemp, 1994). Finally, function approach to technological innovation systems, its functions as system level variables and activities as factors influences performance of the systems (Bergek et al., 2008; Hekkert et al., 2007), can explain dynamic changes over time especially at the formative stages technological innovation systems experience (Suurs & Hekkert, 2009). To explore the relationship between intermediary firms and the role of state, review of more recent literature in the context of latecomer countries has revealed that two of the seven TIS functions are particularly important; 1. guidance of the search and influence on the direction of search, 2. market formation. First, guidance of the search/influence on the direction of search drives entry and rationalizes formation of the sector especially for the latecomer countries. The clear development agenda by government for energy security in wake of 2008 financial shock prompted Poland to build offshore wind industry (Sawulski et al., 2019), national target set by Kyoto protocol 2001 “Renewables Directive” in EU encouraged Portugal to diffuse wind power generation (Bento & Fontes, 2015), in some cases, policy driven market led two states to success in deployment of solar power (Quitow, 2015). Second, formation of market is critical for other functions of TIS yet likely to be lacking in the context of latecomer countries at formation stage. In absence of or weak domestic market, actors seek for markets in other subsystems of the same TIS. When the technology is standardized, other subsystems of the same TIS could become markets and spillover effects will be optimized across actors in the region (Binz et al., 2014). International competition works in favor of development of the technology if the country has existing capabilities (Sawulski et al., 2019). Intermediaries are particularly important in formation of market, both internationally and domestically. The well-established firm has access to informal and formal networks and various resources to explore international market (van der Loos et al., 2020). If the firm is closely related to existing activities in local market, it can enable supply industry emergence as seen in Norway’s case (Normann & Hanson, 2018). The large and established firms can create pathway for younger firms to access international markets (Normann & Hanson, 2018; van der Loos et al., 2020).

2.3 Materials and methodology

The data was mainly collected from secondary sources: company annual reports (2009-2022), company’s sustainability reports (2014-2020), investor reports, financial results, monthly newsletters, each individual project (72 including inactive, stalled, failed projects) information collected from company’s website and annual reports, governmental website, industry

association reports (2010-2022) and international organization data to cross reference. In addition, data from several interviews to the managements by various sectoral organizations (28) and an industry focused webinars (2) posted on YouTube which are transcribed by using Otter.ai software.

*To further the study, author is planning to interview company personnels before concluding the research.

The study chose a single in-depth case study of the desalination and power generation firm in Saudi Arabia. Although it is a single-firm case study, the firm has experienced several projects all in different sizes, diverse technologies, and different locations around the world to offer rich insights. Although at this point of progress, the study attempts to identify and measure following criteria based on previous literature review;

Project-based capabilities	Description	Measures
Client driven solution	Capabilities to manage, organize, and design customer-centric solutions	Project locations, varieties of technologies, tariff design
Develop system specification	Manage and coordinate production	Coordination with suppliers, partner companies, users, small firms
System integration	Vertical integration and disintegration or in- and outsourcing	Same sector and different process integration and disintegration or in- and outsourcing
Learning within and beyond projects	Promoting learning, new process of project excursions	# of projects, new business domain expansion

(Davies et al., 2011; Michael Hobday et al., 2005)

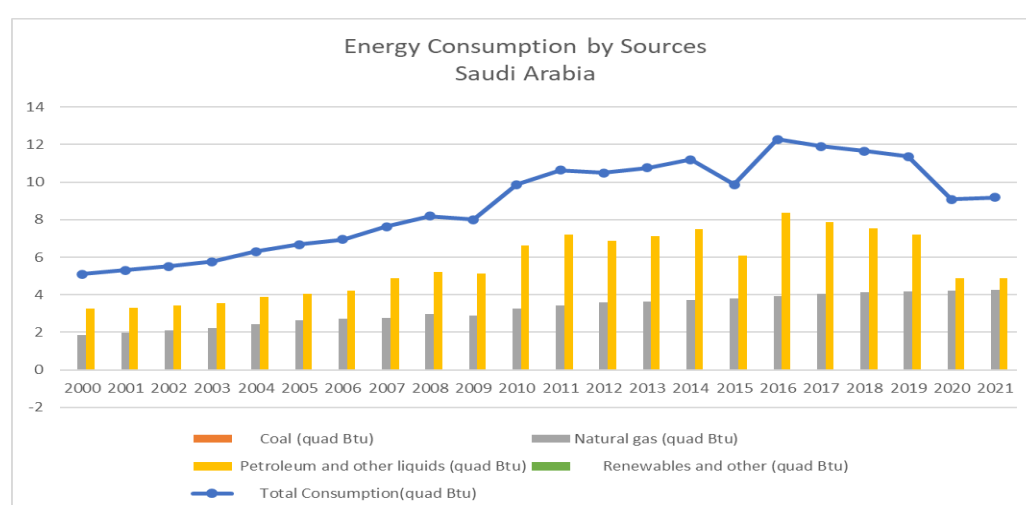
3. Market condition and the drivers

3.1 Regional market condition

The world's largest oil producing countries in the Arab Gulf region are encountering its own unique challenges in this energy transition. Located in Sun Belt area of the Middle East, the Gulf Cooperation Council (GCC) countries holds potential to be the all-round energy leader of the world by utilizing solar photovoltaic (Solar PV) and concentrated solar power (CSP), experimenting with green hydrogen production for domestic industry use as well as turning it to liquified ammonia to export overseas in the future. However, due to heavy energy subsidies and incumbent energy infrastructure, integrating renewables to current energy mix has been a challenging task for the GCC (Al-saidi, 2020; Malik et al., 2019). First, natural resource endowment allowed monarchical governments to offer generous social welfares to its citizens with minimal to no taxation to the society: energy subsidy is a part of

the social contract and domestic energy is priced significantly below market price (Krane, 2021). This domestic market condition makes other energy options economically unviable at both residential scale and utility scale deployment (Elshurafa&Matar, 2020). Second, deployment of renewables is capital intensive process. With combination of energy subsidies and existing energy infrastructure, there seems to be no “energy trilemma” for the oil and gas producing countries of the GCC, it makes economic sense to stay with incumbent energy infrastructure. On the other hand, paradoxically, this energy abundance accelerated domestic consumption which in turn became a liability that affects their energy security.

3.2The drivers of transition: Saudi arabia



Saudi Arabia’s Vision 2030 aims to be the world energy leader by diversifying from the current energy mix of 41.6% oil, 58.3% natural gas, and 0.1% renewables¹ to renewable power generation to 50% of its energy mix². The drivers for this energy transition are domestic consumption and their plan to export natural gas and other energy sources such as hydrogen (liquified ammonia). Saudi Arabia is the biggest oil producer in OPEC, also have the highest energy consumption in the region that is higher than global average (Frroukhi et al., 2016). The energy is a heavily subsidized which drives down the price of electricity generated by conventional energy and encourages wasteful behaviour by the consumers (Salam & Khan, 2018). Without diversifying energy mix, domestic consumption is eating away of what they could have sold in the market for revenue. Saudi Arabia is utilizing its natural gas reserves for domestic consumption and its production is slowly increasing in the past decades (Fig.1). However, Saudi Arabia's natural gas is associated with crude oil production which means that both productions are linked together; in other words, the country cannot secure gas production for domestic consumption without oil production, and since the amount of oil production is

controlled by OPEC+, it is difficult to increase production by their own decision alone for domestic consumption purpose (Kawamura 2017). Saudi Arabia also has non-associated gas fields yet to be exploited and plans to become the exporter of natural gas in the future. In order to explore untapped non-associated natural gas fields, which is capital intensive process, Saudi needs more investment of their own in addition to international investments to do so. Thus, Saudi Arabia needs to reduce domestic consumption of conventional energy, because it is mostly oil and associated natural gas, and increase their profits from export of oil and have other source of energy to secure energy for domestic consumption. This energy transition is crucial turning point to Saudi Arabia.

4. Building project based organization capabilities: Case study

This study conducted empirical analysis of Saudi Arabia based company, ACWA Power, and its path to build project organization capabilities through vertical integration and expansion to new business domains. Traditionally, water, power, transportation, constructions, hospitality, banking, telecommunications sectors are run by state or SOEs in the Gulf region just as the main economic sector of fossil fuel sector do. The renewable energy sector is a target sector for the growth and future employment of the nationals. In case of Saudi Arabia, renewables also a target sector for privatization. Currently, ACWA power of Saudi Arabia, Masdar of United Arab Emirates, and Nebras of Qatar is the leading government affiliated enterprises in renewables; assets on their portfolio are 42GW, 23GW, and 6.5GW including domestic and overseas projects (Sim 2022).

4.1 Formation period 2004 – 2007

ACWA Power Project was formed in 2004 as a joint venture of ACWA Holding and MADA Group for Industrial and Commercial Development³. ACWA Holding was represented by two well established firms, Abunayyan Trading Company and Abdulkadir Al Muhaidib & Sons Co⁴. The Abunayyan Trading Company was founded in Riyadh in 1960 and specialized in construction, operation and management, and contracting. Abdulkadir Al Muhaidib & Sons Co. was established in Dammam in 1940's and specialized in food, manufacturing, building materials, real estate, construction others*. On the other hand, MADA Group is an investment company owned by the Al-Rajhi Group to invest in specific targeted area*. ACWA power's business model is to develop, invest, operate, and optimize⁵. The company then acquired Shuaibah IWPP & Petro-Rabigh IWSPP, Shuqaiq IWPP and Marafiq (Jubail) IWPP in 2005-2006, Shuaibah expansion IWPP in 2007. Soon after the acquisition, ACWA Power Project established the First National Operation and Maintenance Company (NOMAC) with SOGEX-Oman to provide operation of maintenance for the plants*.

The first and the most important capability for project development of power sector is contracting and financing. Shuaibah IWPP was the largest desalination project at the time with the cost of 2.4 billion USD and capacity to produce 880,000 m³/day and 990MW. It was also the first independent water and power plant project in Saudi Arabia*. The project won several industry awards for the deal of the year for its innovative contract and financing*. This was the first deal which united Export Credit Agency (ECA) facility and Islamic banks in a single transaction*. The project was led by ACWA Power and Malaysian firms, especially Malaysian firms preferred working with Islamic tranches and Islamic finances (McLeod- Roberts, 2006). The key challenge was legal documentation; unlike other GCC countries where special commercial courts handle those documentations, Saudi Arabia operates under Sharia courts where enforceability of the project agreements and security on the collateral became problem for international investors (McLeod-Roberts, 2006). The significance was that the set of legal documentations the project achieved enough confidence for ECAs to invest and local banks entering longer term loans which made it possible by ECAs involvement (McLeod-Roberts, 2006). Next, Marafiq (Jubail) IWPP, another 3 billion USD giga project with 2,744 MW and 80,000 m³/day desalination capacity, also won several industry awards for deal of the year*. This project also was developed with multi stakeholders from Power and Water Utility Co for Jubail and Yanbu, Saudi's Sovereign Wealth Fund of Public Investment Fund, Saudi Electric Company, consortium of Suez, GIC, and ACWA Power. The project involved several international banks utilizing equity bridge loan (EBL) to offset risks. Finally, Shuqaiq IWPP project, 1.8 billion USD with 850 MW and 21,2000 m³/day desalination capacity, was financed 75% debt and 25% equity, which is higher equity than traditional 80/20 model.

These first mega IWPP projects uses varieties of technologies and combinations. In the GCC, three desalination technologies are used; multi effect distillation (MED), multistage flash (MSF), and reverse osmosis (RO) (Wogan et al. 2020). The evaporative technologies, MED and MSF, put energy to burn gas to run a power plant, turn the turbine to generate power, use the heat through combined cycle and generate steam and run a steam turbine (Engerati 2014). Whereas RO is a membrane technology to filter out the water. Technologies used in desalination and power generation are synergistic (Engerati, 2014) which enabled the firm to learn both desalination and power generation plant operation and management. During the formation period, the firm saw opportunities in renewable energies as cost of solar PV was coming down drastically. In 2007, China was committed to increase solar capacity to 1,800 MW by 2020 (National Development and Reform Commission) this meant China was ramping capacity to produce Polysilicon, wafer, c-Si Cell, and Module way faster than the rate of global installations (Metha, S., & Kann, S. 2012). ACWA presented their finding to the government and Saudi Electric

Company, however, they decided to prioritize economic growth over experimenting with renewables, showing no interest (CleanTech Business Club, 2022).

4.2 First expansion 2008 – 2011

With the initial success of five domestic mega IWPP projects, ACWA Power was formed with USD 800 million-dollar capital⁶. The company mission was “to be a world class company operating on a global platform, owning and operating power generation and desalinated water production plants” *. ACWA went on to the next domestic independent power project which achieved several important milestones for the development of power sector. Rabigh IPP was the first project with off taker was not supported by Ministry of Finance support and the largest tranche of Islamic debt of any IPP at the time*. ACWA also became the first firm to use Chinese EPC contractor in the GCC power project which contributed to reduce tariff difference by 31% from competitors’ bids*. This debt to equality ratio was 75/25 with some contingencies*.

At this period, ACWA expanded its operation to overseas, Oman and Jordan. Expansion to international markets requires capability to properly assess the market as well as know their own strength in that market. ACWA targeted markets with annual population growth, demography of the country, credit rating, social infrastructure, and human resources available (Project Finance International 2012). Several interviews to management⁷ have shown following criteria for the project selection:

- Demography of the country to determine future energy consumption and demand
- Credit conditions of the country to ensure financing
- Localization capability; human capital, industrialization capability, construction platform to minimize the cost
- Geographical location; land, location, future expansion to the *European market (green hydrogen)
- Rules and regulations, government policy; requires government commitment to energy policy

Oman fits the criteria; although Oman did not find and export oil and gas till 1967, and with much less production than other GCCs⁸, their economy and population has been developing at fast pace since 1970s. Barka 1 IWPP in Muskat, Oman was the first project developed under the privatization program of the country. The plant began commercial operations in June 2003 and ACWA acquired 58% of stake in August 2010. Barka 1 was 450 million USD

project with capacity of 427 MW and 91,000 3m/day. Next, ACWA targeted Jordan. Jordan was rated BB and Ba2 for sub-investment rating, the country has growing population of 2.5% per year and is located in unique geographical location with potential human resource base (Project Finance International, 2012). ACWA achieved acquisition of Central Electricity Generation Company (CEGCO) in June 2011. Jordan also privatized power sector in 2007 and ACWA had been watching its development for a while. CEGCO comprises of eight power plants and generated 52% of Jordan's power⁹. CEGCO portfolio included wind turbines, steam turbines, hydraulic turbines, gas turbines, and thermal all built in mid 1980s to 1990s. The operation and management capabilities and human resources that ACWA accumulated by prior mega IWPP projects enabled the firm to undertake technical due diligence, research, and site visits to make this transaction possible (Project Finance International, 2012).

Behind of those successful projects, there are unsuccessful bids. ACWA's bids for projects for IPPs in Riyadh, Saudi Arabia and Barka/Sohar, Oman did not succeed, but the management team reviewed to incorporate those experiences to improve next bids and project development¹⁰. ACWA submitted bid with Spanish firm, Iberdrola Renovables, for Shams 1 CSP IPP tendered by MASDAR in 2010 (Annual Report 2010). Although they were able to bid second lowest, they weren't able to secure the project. The bids submitted for Az-Zour IWPP, Kuwait, Hasiyan IPP, Dubai, and two IPPs in Jordan were not successful in 2011 which were lessons for the firm to refine the bids in the future (Annual Report 2011). Parallel to ACWA's effort, Saudi Arabia's late King Abdullah took initiative to found King Abdullah City for Atomic and Renewable Energy (K.A. CARE) in 2010. K.A. CARE is responsible for studying the possibility of introducing renewables and nuclear into the fuel mix, formulating policies and coming up with a procurement plan¹¹.

4.3 Building capabilities for new business domain: 2012-2015

After 8 years building project-based capabilities, ACWA is ready to explore new business domain specifically renewables. ACWA acquired its first PV plant in Bulgaria in 2011. Karadzhhalovo PV IPP has a smaller capacity of 60 MW. This acquisition was to build up their computing capacity and gain experience on the operation and maintenance (World Finance Videos 2013). NOMAC and U.S. based Sun Edison operated and managed the plant together. The plant was sold recently in September 2020 as ACWA focuses on larger projects¹².

The expansion to new domain of business made milestones in PV and CSP IPP projects. Morocco and South Africa saw the value in renewables. Developed economies have existing energy structures and the capability to afford fluctuating energy prices, whereas developing countries are in need of

developing or replacing their energy structure. Renewables are capital intensive but opex low, do not require fuel. Morocco and South Africa saw the value in long-term fixed cost of reliable energy for their growing need. NOORo I CSP IPP in Morocco (financial closure 2013), capacity of 160MW, was ACWA's next renewable project with Moroccan Agency for Solar Energy, MASEN. The project introduced the longest storage technology that enabled power to store up to 9 hours (Dolapho Aina 2017). Another milestone project is Bakpoort CSP IPP (financial closure 2013) in South Africa. This project was the first power sector investment in South Africa that ACWA worked on. Bakpoort CSP is also relatively smaller size project with capacity of 50 MW but with the used of molten salt heat storage, the plant was able to store energy for 9.3 hours to provide power for both base-load and off-peak demand (Bhula, 2020). ACWA was able to offer the lower tariff of \$0.17/kwh than their diesel operated plant of \$0.24/kwh (Project Finance International, 2013).

Interestingly, during this period, ACWA Power started to work on developing coal-fired plants in Emalahleni, South Africa (Khanyisa IPP, 2013), Hanoi, Vietnam (Nam Dinh 1 IPP, joint venture 2014), and Tete, Mozambique (Moatize IPP, concession agreement 2014). However, the latter two projects seem to be at stall, and Khanyisa IPP was failed due to ACWA not meeting environmental requirement set by the Pretoria High Court. ACWA submitted bids for 11 new projects in 2015 which is 4 times more than what they did in 11 years with typical success rate is 2 out of 3.

Noor Energy 1 CSP/PV IPP (financial closure 2019) project became the turning point in this regional market. Noor Energy 1, capacity of 700 MW CSP and 250 CSP, is located in Dubai, United Arab Emirates. It is a fourth phase of the famous Mohammed Bin Rashid Al Maktoum Solar Park. Dubai Electricity and Water Authority and ACWA led consortium achieved the lowest tariff, \$0.05845/kWh, which set a race to lower the price in the region (IRENA 2019, Voices of the Future 2022, Climate Investment Funds 2015).

"So in 2015 here in Dubai, we ended up tendering for 200 megawatt PV plant which is fairly well scaled. To that same approach, just drive the cost down. We ourselves were very surprised at the level of price that we were able to achieve when we submitted agenda because the product even though photovoltaic technology was driving costs down fast because the panel prices are coming down and so on until the technology was bringing down. At that time, the lowest known tariff was 8 cents. When we did math, we found it was 5.845. People said, man, this is too shocking, checked three times, okay sticking to our principles, we submitted the tender. Sure enough, we were the lowest we won the job. Everybody said this is nonsense. It's never going to happen. When it turns out, it's built and operating. We are making our money, everybody's happy. But that set the race immediately. It changed the mindset of the region." – then CEO.

4.4 Domestic market opening and alignment to national policy: 2016 and beyond

On January 2016, Mohammed bin Salman, then Deputy Crown Prince of Saudi Arabia launched long term national vision, Saudi Vision 2030. The Vision 2030 focuses on renewables development and subsequently value chain development¹³. Supported by PIF, National Renewable Energy Program (NREP) was established. The Renewable Energy Project Development Office (REPDO) was established at the same time to implement the programs. The government started subsidy reforms in water and power sector in 2016. Energy subsidy reform was passed in January 2016 and January 2018 (p.152, Krane 2021) and new tariffs were implemented for water and waste water services for consumers in the government, industry, and commercial sectors (U.S.-Saudi Business Council, 2021). Domestic market condition had improved as power generation from renewables and supply chain creation was incorporated into a long- term national vision. ACWA Power started to align to Vision 2030 goals and objectives¹⁴.

ACWA took on two major solar PV projects in 2018 and 2021; Sakaka PV IPP and Sudair PV IPP. Sakaka PV IPP, located in Al Jouf, Saudi Arabia, is the first utility-scale PV project in Saudi Arabia where the power station is connected to the national grid. The plant's capacity is 300MW and is expected to provide electricity to 75,000 households¹⁵. Sakaka PV achieved another lowest tariff of 0.0234/kWh which is getting closer if not lower than conventional power generation in Saudi Arabia¹⁶. The project is also subject to local content policy. Supply chain readiness study has found that Sakaka project's local content ratio was exceeding 30% (Alghamdi et al., 2022). ACWA Power recently announced its new business unit, ACWA Industrial Investment Company (AIICO) to work on local content development and industrialization in 2019. Next, ACWA-led consortium, including Saudi Aramco owned SAPCO and PIF owned Badeel, reached financial closure of Sudair PV project in 2021. The plant will be located in Sudair Industrial City, home for several industrial activities such as fabricated metal products, other non-metallic mineral products, rubber and plastic products, food products, chemicals and chemical products¹⁷. The plant is capable to generate 1,500MW for its off taker Saudi Aramco, and the largest PV project in Saudi Arabia.

There is notable project financing in more recent projects; DEWA V IPP in Dubai and Al Taweelah IWP in Abu Dhabi. DEWA V PV IPP (financial closure 2019) in Dubai, UAE, was another success in financing. The project tariff consisted of cost of plant construction (50%), financing cost including debt financing, equity, and profit for investors (30-35%), and operation and maintenance (15%) (Bonds&Loans 2016). The debt financing is 86% which is

higher than 80/20 standard with higher equity to lower the cost. This is the first project ACWA worked with Chinese government owned Silk Road Fund¹⁸. Al Taweelah IWP in Abu Dhabi, UAE, presented an opportunity for new way of financing challenging project. Al Taweelah IWP is partially powered by PV and uses reverse osmosis (RO) to desalinate water. The plant has capacity for 69 MW and 90,000m³/day. French ESG rating company, Viego Eiris provided credentials and management of the project finance loan confirming the project has met Green Loan principles, then French bank Natixis acted as arranger and investment agent under the Islamic Equity Bridge Loan for ACWA's equity portion¹⁹.

Finally, ACWA Power began its venture out to newer source of power generation by integrating various technologies. Jazan IGCC (financial closure 2021), located in Jazan Economic City, is a joint venture among Saudi Aramco Power Co, Air Products ME, Gas Industry Co, and ACWA Power*. Feedstock produced by the refinery will be fed to the plant, then the combined cycled power plant generates the power to the national grid. The project contract is Own-Operate-Transfer model*. The Red Sea Project (financial closure 2022) is a tourism project supported by renewable energy generation from solar PV (340 MW) with a battery energy storage system (BESS) *. This mega project is expected to generate 1,648MW and 18,315 m³/day desalinated water to the facility*. NEOM Green Hydrogen Project (expected financial closure 2023) is expected to produce green hydrogen from solar and wind energy generation*.

5. Preliminary result

Project-based capabilities	Description	Measures
Client driven solution	Capabilities to manage, organize, and design customer-centric solutions	Project locations, varieties of technologies, tariff design
Develop system specification	Manage and coordinate production	Coordination with suppliers, partner companies, users, small firms
System integration	Vertical integration and disintegration or in- and outsourcing	Same sector and different process integration and disintegration or in- and outsourcing
Learning within and beyond projects	Promoting learning, new process of project excursions	# of projects, new business domain expansion

Client driven solutions Since the start of operations, ACWA Power increase its presence in different parts of the world. Currently, ACWA Power has assets in 11 countries; Saudi Arabia, UAE, Oman, Bahrain, Jordan, Egypt, Morocco,

South Africa, Uzbekistan, Azerbaijan, and Turkey. Of those 11 countries, ACWA own and operate plants with several methods of power generation and desalination. The project development requires for the firm to deliver the technology of client's choice with the lowest possible cost. Managers of ACWA often emphasize of the firm for "technologically agnostic" and "build any technology a customer wants" at "humanly possible lowest cost. In order to design the tariff, the firm needs to study and assess factors influences the cost; local content, industrialization capability, construction platform, access to supply chain, purchasing power, human resource capability (Marcopolis Net 2015). The conditions, resources, and regulatory environment differs by the country of operations.

Development of system specification Though ACWA prefers to have larger stake on the projects, the most projects are developed in partnership with other investors and government counterparts. The project development start from forming a consortium, submitting bids, financial and contractual work, financial closure to begin of plant construction, then to operation and management. The process requires cooperation with other firms and financial institutions, as well as government offices. The firm works with several international EPC companies depending on the technologies used for the plants. The off takers and local suppliers are also "critical partners" delivering services. The good example is Shuaibah IWPP (Formation Period 2004 - 2007); navigating through Saudi Sharia Court contract requirement, the project financing with ECAs enabled Saudi local banks to enter the longer tenor contract which is not usual for their business bases and it has opened the door for international investors to desalination and power generation market in Saudi Arabia (McLeod-Roberts, 2006). DEWA project (2016 and beyond) was a fruit from working with Chinese investment fund for financing and closely working with Dubai government agency. "We (ACWA Power) do that by basically getting together multidisciplinary team, various specialists who come together and formulate the business case. To get the best partnership. The most value-adding partnership structure, competitive technology solution, procure lump sum turnkey construction contract, and the most competitive cost constitution and of course, structure debt and equity around it to deliver the most competitive tariff. The lowest competitive tariff solution is all based about staying engaged with different facets of the supply chain and cultivating with them a trust-based partnership so that all of them work towards a common goal of delivering the most competitive elements of the tariff solution." - CIO, 2015

System integration Since the early days, ACWA's business model is to "develop, invest, operate, and optimize" which enables the firm to capture ROI over the life cycle of the project. The firm established NOMAC, a company specializes in operation and management, and the most projects are operated by NOMAC or joint venture with local firms, international firms, and local

government agencies. NOMAC has its establishments in all countries that has ACWA owned plants, except for Jordan, where ACWA owns CEGCO to operate its plants. Along with ACWA Power project development, NOMAC gained experience in operating and maintaining both conventional and renewable energy generation and several methods of desalination.

Learning within and beyond projects ACWA Power started its business as desalination and power generation company in 2004. During the formation period, ACWA Power had experienced developing megaprojects (Shuaibah IWPP & Petro-Rabigh IWSPP, Shuqaiq IWPP and Marafiq (Jubail) IWPP in 2005-2006, Shuaibah expansion IWPP). The firm learned developing large-scale projects, financing and contracting those projects in domestic market, and operated and maintained all three methods of desalination (MED, MFD, RO) with the power generated by natural gas and oil (CCGT, steam). The next phase was expanding to international market, Oman and Jordan, where the firm learned to develop projects in different regulatory and contractual environment. Moving on to the new domain of business as renewable power generation, the firm acquired a small PV park in Bulgaria to gain experience in operation and management as well as computing capability. The firm started to submit bids for renewable projects in Dubai with Spanish renewable energy firm. Although earlier bids were not successful, the firm was able to learn from unsuccessful attempts. ACWA Power, without domestic market, then enter to markets in developing and emerging economies to develop renewable energy projects. As market condition improved in Saudi Arabia, the firm returned home to develop the first national grid connected solar PV IPP, Sakaka PV. Being “technologically agnostic” and “customer driven” project-based firm, ACWA is now expanding its business domain to Green Hydrogen production in NEOM, Saudi Arabia.

6. Discussion

This study aims to identify the process of building project capabilities through renewable deployment. The case study has shown us the pathway ACWA Power has taken and the process of learning and building on project-based capability the firm has had in the beginning. The firm’s business model of own and operate, not competing with market price, and staying technologically agnostic, which all are business development strategies, but also contributing the development of project-based capability. Not competing with market price and thoroughly pursuing the lowest possible cost prompt the firm to own and operate at the project sites.

Relationship between the state and ACWA Power has become closer over the years. Saudi Arabia’s largest sovereign wealth fund, Public Investment Fund (PIF) made direct investment to the firm through fully owned Sanabil Direct Investments Company in 2012 (Annual report, 2012). By January 2018, PIF

acquired a 15.2% of share in addition to 9.8 % of Sanabil Direct Investment Company's share, which increased total share of PIF to 25%. By 2019, International Finance Corporation (IFC) share of 4.302% was transferred to ACWA Power (Annual report, 2019). Before ACWA Power's IPO in Saudi stock exchange, PIF was expected to increase its share to 50%²⁰. Then CEO described, "PIF's acquisition of ACWA power allows the company to grow stronger. PIF is a heavyweight SWF with an enormous amount of network and relationships. This would push the business further in the world because it allows ACWA to improve its credit capacity and tap into PIF portfolio companies, not only financial but technical providers. PIF respects the balance that needs to be struck between allowing us to be truly regarded as private." (Bloomberg 2020). PIF share was increased upon IPO, but to 44.16% not 50% of the stake.

Renewable energy mix goal was set by the government, subsequence the government established agencies to implement the programs to achieve those energy mix goals, meaning infrastructure is financed by the government. The privatization program in 2002 aimed to handover project development and services functions to private sector, yet state is backing the private sector firm to the point of taking back its control. On the other hand, this may be seen as the government's way of giving the firm credibility to further its pathway of building capabilities. The government credibility enables the firm to attract foreign investors, at the same time, it attaches strings to the firm and may limit their freedom in conducting business. At the next phase of the study, role of state will be further considered.

[This study is still at the preliminary stage. To complete the study, author plans to conduct interviews to collect information from the firm, government, and industry personals.]

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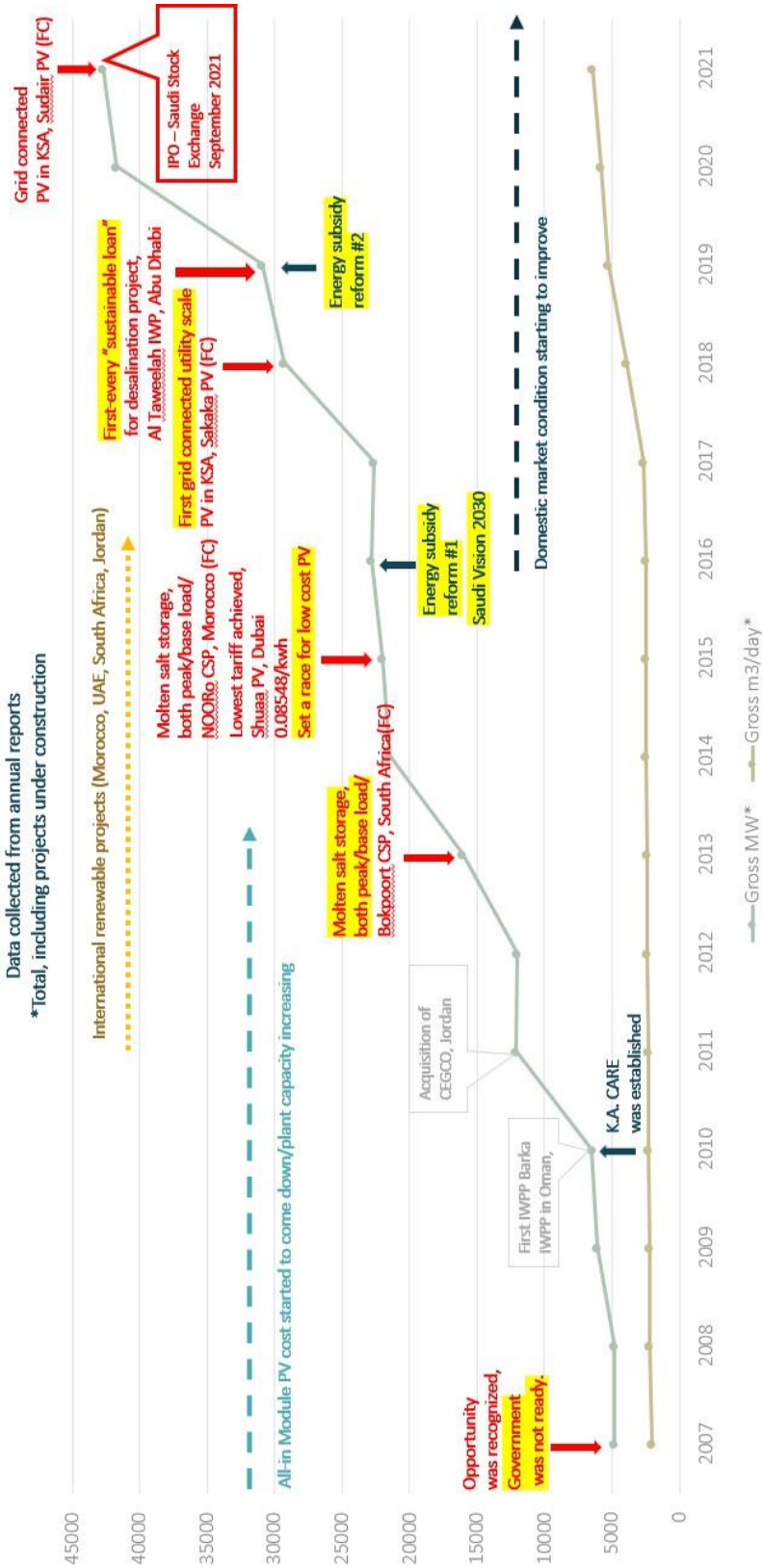
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ACWA Power Portfolio

Data collected from annual reports

*Total, including projects under construction



List of interviews (secondary source)

Date	Channel Name	Description	Interview title	Accessed
2013.05.03	Acuris	Specialist news, research, analysis, data, and events for financial professionals.	ACWA acquisition strategy to include Africa and Turkey	2023.03.24
2013.07.31	World Finance Videos	World Finance is a critically acclaimed bi-monthly magazine and website providing in-depth coverage and analysis of the financial industry and global economy.	Paddy Padmanathan on solar energy ACWA Power World Finance Videos	2023.03.21
2014.10.02	Engerati	YOUR SMART ENERGY NETWORK With 40,000+ engaged members and 80,000+ newsletter subscribers, Engerati is Europe's largest engaged community of utilities and power sector professionals. Supporting the next-generation utility. Electrification, decentralisation and digitisation are transforming traditional business models, blurring value-chain relationships and shifting regulatory landscapes.	Paddy Padmanathan, CEO, ACWA Power	2023.03.15
2014.02.20	World Finance Videos	World Finance is a critically acclaimed bi-monthly magazine and website providing in-depth coverage and analysis of the financial industry and global economy.	The privatisation of electricity in Saudi Arabia ACWA Power World Finance Videos	2023.03.18
2014.02.21	World Finance Videos	World Finance is a critically acclaimed bi-monthly magazine and website providing in-depth coverage and analysis of the financial industry and global economy.	Renewable energy in Saudi Arabia ACWA Power World Finance Videos	2023.03.18
2015.06.03	Climate Investment Funds	The \$11.1 billion Climate Investment Funds (CIF) is providing 72 developing and middle income countries with urgently needed resources to manage the challenges of climate change and reduce their greenhouse gas emissions. CIF is an enabler of pioneering climate-smart planning and climate action in low and	Paddy Padmanathan, CEO ACWA Power	2023.03.15

		middle-income economies, many of which are the least prepared yet the most prone to the challenges of climate change. CIF responds to the worldwide climate crisis with large-scale, low-cost, and long-term financial solutions to support countries achieve their climate objectives.		
2015.0 7.28	MarcoPolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	Saudi Arabia report: Solar energy future	2023.03.24
2015.0 7.28	MarcoPolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	Renewable energy projects in Saudi Arabia and the lowest feed in tariff for solar in UAE	2023.03.24
2015.0 7.28	MarcoPolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	ACWA Power strategy for 2015-2016	2023.03.24
2016.0 2.26	MarcoPolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	Fossil fuel vs renewables by Saudi Arabia's Acwa Power	2023.03.24
2016.0 09.29	Bonds & Loans	Bonds & Loans is the only 24/7 emerging market debt intelligence platform globally, where we leverage our extensive network of issuers and borrowers, investors, and senior DCM bankers to offer high quality, engaging and focused market intelligence, news, and multimedia content illuminating the key issues impacting emerging market debt.	Bonds & Loans Interview: Pascal Martese, ACWA Power	2023.03.24
2016.0 2.26	MarcoPolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business	ACWA Power strategy for 2016-2017	2023.03.24

		reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.		
2017.04.19	Dolapo Aina	This Youtube Channel covers the interviews(audio and video) and Travels of Dolapo Aina. A columnist, and communications strategist. Writing African Stories via Global Media Houses @Guardian Nigeria @Hostwriter Digital Diplomacy Techplomacy Diplomat without a passport http://bit.ly/DolapoTV	Dolapo Aina's The Interview Series With Paddy Padmanathan President of ACWA Power at COP22	2023.03.24
2017.06.16	CleanTech Business Club	CleanTech Business Club formerly known as Solar Business Club is a Private & Independent Human To Human (H2H) Leadership Club, that brings together Trusted Leaders of CleanTech & other Disruptive Technologies Industries with The Leaders of the Financial Community and Investors, Top Corporations, Energy Companies and Utilities as well as Political Decision-Makers and Public Opinion Influencers.	ACWA Power CEO Paddy Padmanathan - Short Term Goal: US\$ 70 Billion Platform	Need better sounds https://www.youtube.com/watch?
2019.04.30	ACWA Power	ACWA Power	New Market Investment Criteria: ACWA Power CEO & President Paddy Padmanathan	2023.03.18
2019.04.30	ACWA Power	ACWA Power	New Market Investment Criteria: Lucas Hautvast, VP Portfolio Management & Strategy	2023.03.15
2019.05.22	MEED Middle East Economic Digest	Established in 1957, MEED's media brand and publication has been integral to delivering business information and news, intelligence and analysis on the Middle East and Northern African economies and activities ever since.	"Ten Minutes into the Future of Energy" with Paddy Padmanathan, ACWA Power International	2023.03.18
2019.09.19	Regency Global	https://www.youtube.com/@regencyglobal2436/featured	SA INC EP4 ACWA Power 12minute	2023.03.24

2020.02.11	Bloomberg Television	The latest financial news and market analysis, direct from Bloomberg TV.	ACWA Power Will Be in 16 Countries by End of Year: CEO	2023.03.15
2021.04.22	ACWA Power	Webiner	ACWA Power Transition Talks Reimagining the future of water desalination.	2023.03.15
2021.06.24	Emerald	emerald is a globally recognized venture capital firm building a sustainable future at the crossroads of industry and technology. Founded in 2000, it is a pioneer in open innovation, providing multi-national corporations with rich deal flow and insight in the sectors and markets of tomorrow. Emerald has managed and advised assets of over €1 billion from its offices in Zurich, Toronto and Singapore. The firm is dedicated to tackling big challenges in climate change and sustainability via over 500 venture transactions and five third-party investment mandates, including loan guarantees to over 100 start-ups.	Paddy Padmanathan, ACWA Power - Is H2 production ready to scale? - Innovation Insights	2023.03.15
2021.10.23	Ministry of Economy and Finance of Uzbekistan	Minecofinuzb www.minecofin.uz	Tom Teerlynck Interview at the Uzbekistan Economic Forum 2021 mp4	2023.03.24
2022.08.2022	Voices of the Future	Voices of the Future is a series conceptualized by Tariq Qureishy that features conversations with prominent future-oriented thought leaders who are involved in helping to create a more positive, just, sustainable, regenerative, and enlightened society.	Paddy Padmanathan, CEO, ACWA Power - Future of Energy Industry - Full Interview	2023.03.21
2022.09.13	International Desalination Association	The IDA is a non-profit association that serves more than 2,600 core members in 60 countries and reaches an additional 4,000 affiliate members. IDA membership comprises scientists, end-users, engineers, consultants and researchers from	Global Water Community at IDA WC 2022 - Mr. Paddy Padmanathan, Vice Chairman	2023.03.18

	tion	governments, corporations and academia. An NGO of the United Nations, IDA is committed to outreach that informs the international community about advanced water treatment technology solutions and their critical role in providing new and sustainable sources of fresh water around the world.	and CEO of ACWA Power	
2022.1 1.14	CleanTech Business Club	CleanTech Business Club formerly known as Solar Business Club is a Private & Independent Human To Human (H2H) Leadership Club, that brings together Trusted Leaders of CleanTech & other Disruptive Technologies Industries with The Leaders of the Financial Community and Investors, Top Corporations, Energy Companies and Utilities as well as Political Decision-Makers and Public Opinion Influencers.	ACWA Power by 2030: 130GW+ RE portfolio & championing the green hydrogen growth - Paddy Padmanathan	2023.03.15
2022.1 1.15	Boston Consulting Group	Boston Consulting Group partners with leaders in business and society to tackle their most important challenges and capture their greatest opportunities. BCG was the pioneer in business strategy when it was founded in 1963. Today, we work closely with clients to embrace a transformational approach aimed at benefiting all stakeholders – empowering organizations to grow, build sustainable competitive advantage, and drive positive societal impact.	BCG at COP27 A New Era for Energy	2023.03.24
2022.1 2.20	Ministry of Economy and Finance of Uzbekistan	Minecofinuzb www.minecofin.uz	An interview with Clive Turton, Chief Investment Officer at ACWA Power	2023.03.24
2022.1 2.20	Arabian Business	Comprehensive Guide to Middle East Business and Industry News including, Banking & Finance, Construction, Energy, Media & Marketing, Real Estate, Transportation, Travel, Technology, Politics, Healthcare, Jobs and UAE guide.	AB In Focus: The Middle East's role as an energy transition hub	2023.03.24

List of interviews (secondary source)

Date	Channel Name	Description	Interview title	Accessed
2013.05.03	Acuris	Specialist news, research, analysis, data, and events for financial professionals.	ACWA acquisition strategy to include Africa and Turkey	2023.03.24
2013.07.31	World Finance Videos	World Finance is a critically acclaimed bi-monthly magazine and website providing in-depth coverage and analysis of the financial industry and global economy.	Paddy Padmanathan on solar energy ACWA Power World Finance Videos	2023.03.21
2014.10.02	Engerati	YOUR SMART ENERGY NETWORK With 40,000+ engaged members and 80,000+ newsletter subscribers, Engerati is Europe's largest engaged community of utilities and power sector professionals. Supporting the next-generation utility. Electrification, decentralisation and digitisation are transforming traditional business models, blurring value-chain relationships and shifting regulatory landscapes.	Paddy Padmanathan, CEO, ACWA Power	2023.03.15
2014.02.20	World Finance Videos	World Finance is a critically acclaimed bi-monthly magazine and website providing in-depth coverage and analysis of the financial industry and global economy.	The privatisation of electricity in Saudi Arabia ACWA Power World Finance Videos	2023.03.18
2014.02.21	World Finance Videos	World Finance is a critically acclaimed bi-monthly magazine and website providing in-depth coverage and analysis of the financial industry and global economy.	Renewable energy in Saudi Arabia ACWA Power World Finance Videos	2023.03.18
2015.06.03	Climate	The \$11.1 billion Climate Investment Funds (CIF) is	Paddy Padmanathan,	2023.03.15

	Investment Funds	providing 72 developing and middle income countries with urgently needed resources to manage the challenges of climate change and reduce their greenhouse gas emissions. CIF is an enabler of pioneering climate-smart planning and climate action in low and middle-income economies, many of which are the least prepared yet the most prone to the challenges of climate change. CIF responds to the worldwide climate crisis with large-scale, low-cost, and long-term financial solutions to support countries achieve their climate objectives.	CEO ACWA Power	
2015.07.28	Marcopolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	Saudi Arabia report: Solar energy future	2023.03.24
2015.07.28	Marcopolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	Renewable energy projects in Saudi Arabia and the lowest feed in tariff for solar in UAE	2023.03.24
2015.07.28	Marcopolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector	ACWA Power strategy for 2015-2016	2023.03.24

		analysis, information on companies, leaders, etc.		
2016.0 2.26	Marcopolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	Fossil fuel vs renewables by Saudi Arabia's Acwa Power	2023.03.24
2016.0 09.29	Bonds & Loans	Bonds & Loans is the only 24/7 emerging market debt intelligence platform globally, where we leverage our extensive network of issuers and borrowers, investors, and senior DCM bankers to offer high quality, engaging and focused market intelligence, news, and multimedia content illuminating the key issues impacting emerging market debt.	Bonds & Loans Interview: Pascal Martese, ACWA Power	2023.03.24
2016.0 2.26	Marcopolis Net	MarcoPolis is an international online publishing company specialized in producing executive interactive business reviews by country, featuring various content, such as interviews, videos, stories, sector analysis, information on companies, leaders, etc.	ACWA Power strategy for 2016-2017	2023.03.24
2017.0 4.19	Dolapo Aina	This Youtube Channel covers the interviews(audio and video) and Travels of Dolapo Aina. A columnist, and communications strategist. Writing African Stories via Global Media Houses @GuardianNigeria @Hostwriter Digital Diplomacy Techplomacy Diplomat without a passport http://bit.ly/DolapoTV	Dolapo Aina's The Interview Series With Paddy Padmanathan President of ACWA Power at COP22	2023.03.24
2017.0	CleanT	CleanTech Business Club	ACWA Power	Need

6.16	ech Business Club	formerly known as Solar Business Club is a Private & Independent Human To Human (H2H) Leadership Club, that brings together Trusted Leaders of CleanTech & other Disruptive Technologies Industries with The Leaders of the Financial Community and Investors, Top Corporations, Energy Companies and Utilities as well as Political Decision-Makers and Public Opinion Influencers.	CEO Paddy Padmanathan - Short Term Goal: US\$ 70 Billion Platform	better sounds https://www.youtube.com/watch?
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2019.04.30	ACWA Power	ACWA Power	New Market Investment Criteria: Lucas Hautvast, VP Portfolio Management & Strategy	2023.03.15
2019.05.22	MEED Middle East Economic Digest	Established in 1957, MEED's media brand and publication has been integral to delivering business information and news, intelligence and analysis on the Middle East and Northern African economies and activities ever since.	"Ten Minutes into the Future of Energy" with Paddy Padmanathan, ACWA Power International	2023.03.18
2019.09.19	Regency Global	https://www.youtube.com/@regencyglobal2436/featured	SA INC EP4 ACWA Power 12minute	2023.03.24
2020.02.11	Bloomberg Television	The latest financial news and market analysis, direct from Bloomberg TV.	ACWA Power Will Be in 16 Countries by End of Year: CEO	2023.03.15
2021.0	ACWA	Webiner	ACWA Power	2023.03.

4.22	Power		Transition Talks Reimagining the future of water desalination.	15
2021.06.24	Emerald	Emerald is a globally recognized venture capital firm building a sustainable future at the crossroads of industry and technology. Founded in 2000, it is a pioneer in open innovation, providing multi-national corporations with rich deal flow and insight in the sectors and markets of tomorrow. Emerald has managed and advised assets of over €1 billion from its offices in Zurich, Toronto and Singapore. The firm is dedicated to tackling big challenges in climate change and sustainability via over 500 venture transactions and five third-party investment mandates, including loan guarantees to over 100 start-ups.	Paddy Padmanathan, ACWA Power - Is H2 production ready to scale? - Innovation Insights	2023.03.15
2021.10.23	Ministry of Economy and Finance of Uzbekistan	Minecofinuzb www.minecofin.uz	Tom Teerlynck Interview at the Uzbekistan Economic Forum 2021 mp4	2023.03.24
2022.08.2022	Voices of the Future	Voices of the Future is a series conceptualized by Tariq Qureishy that features conversations with prominent future-oriented thought leaders who are involved in helping to create a more positive, just, sustainable, regenerative, and enlightened society.	Paddy Padmanathan, CEO, ACWA Power - Future of Energy Industry - Full Interview	2023.03.21
2022.09.13	International	The IDA is a non-profit association that serves more than		2023.03.18

	Desalination Association	2,600 core members in 60 countries and reaches an additional 4,000 affiliate members. IDA membership comprises scientists, end-users, engineers, consultants and researchers from governments, corporations and academia. An NGO of the United Nations, IDA is committed to outreach that informs the international community about advanced water treatment technology solutions and their critical role in providing new and sustainable sources of fresh water around the world.	Global Water Community at IDA WC 2022 - Mr. Paddy Padmanathan, Vice Chairman and CEO of ACWA Power	
2022.1 1.14	CleanTech Business Club	CleanTech Business Club formerly known as Solar Business Club is a Private & Independent Human To Human (H2H) Leadership Club, that brings together Trusted Leaders of CleanTech & other Disruptive Technologies Industries with The Leaders of the Financial Community and Investors, Top Corporations, Energy Companies and Utilities as well as Political Decision-Makers and Public Opinion Influencers.	ACWA Power by 2030: 130GW+ RE portfolio & championing the green hydrogen growth - Paddy Padmanathan	2023.03.15
2022.1 1.15	Boston Consulting Group	Boston Consulting Group partners with leaders in business and society to tackle their most important challenges and capture their greatest opportunities. BCG was the pioneer in business strategy when it was founded in 1963. Today, we work closely with clients to embrace a transformational approach aimed at benefiting all stakeholders – empowering organizations to grow, build sustainable	BCG at COP27 A New Era for Energy	2023.03.24

		competitive advantage, and drive positive societal impact.		
2022.1 2.20	Ministry of Economy and Finance of Uzbekistan	Minecofin.uzb www.minecofin.uz	An interview with Clive Turton, Chief Investment Officer at ACWA Power	2023.03.24
2022.1 2.20	Arabian Business	Comprehensive Guide to Middle East Business and Industry News including, Banking & Finance, Construction, Energy, Media & Marketing, Real Estate, Transportation, Travel, Technology, Politics, Healthcare, Jobs and UAE guide.	AB In Focus: The Middle East's role as an energy transition hub	2023.03.24

Project Name	Facilities	Technology	International / Domestic	Location	Specific location	Off taker	Owner (Mat Wer)	Des ali F uel	Project Cost (US \$ M n)	AC Of Wfta A ke Co ntr	Other Investors	EP C	O & M	Project start date	Project Company	Project Page	Additional Information
Shuaibah IWPP	Three combined water and power groups, each with a steam turbine/generator	Domestic	Saudi Arabia	120 km south of Jeddah, Western Saudi Arabia	Water & Electricity Company	90%	88%	Arabian Light Crude	2,304,500	30% P A-B O O 20 years	PI F, S E C , K h a n a h, T N B, M a k of	Si e m e n s (P o w e r), D o o s a n H e a v y (D e s a l i n a t e d W	N O M A C F C)	2005 (Dec. 1)	Shuaibah Water & Electricity Company ("SWE C")	http://www.shuaibah-3-iwp-replaces-shuaibah-iwpp-0fczxlsz	*https://www.pfie.com/story/3636099/shuaibah-3-iwp-replaces-shuaibah-iwpp-0fczxlsz

		r train and four multis tag e flash water desal ination units.										f at er)						%20Po w er%20a nnounc ed%20f inancial %20clo se,Wa ter%20 and%2 0Electri city%20 Holdin g%20C o.
M ar af i q (J u b ai l) I W P P	I W P P	G & St eam T ur bi ne s- C C G T, M ul ti- Ef fe	Do me sti c	Sa udi i Ar abi a	Ju ba il, N or th Ea st er n Sa u di Ar ab ia	T a w re d (a su bs id ia ry of M ar afi q)	2, 7 4	80 0	N a t u r a l G a s	3, 0 8 3	20 0 %	P W - B O T 20 ye ar s	Po we r & W ate r U ti lit y Co for Ju bai l an d Ya nb u, PI	G E, H oi I, S i D E C on so rti du m	JO M (J oi nt ve C) 200 7 (Ju n.F C)*	2 0 2 0 4	Jub ail http://www.arabianbusiness.com/industries/energy/marafiq-project-reaches-financial-close-58473	*https://www.arabianbusiness.com/industries/energy/marafiq-project-reaches-financial-close-58473

		ct Des ali na ti on (ME D)									F, SE C and co ns ort iu m of Su ez, GI C and A C W A Po we r		M A C)					
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Bar ka 1	I W P P	Ga s & Ste am Tur bin es - CC GT, Mu lti- Sta ge Fla	Int er nat ional	O ma n 60 k m no rth of M us cat , O ma	O ma n Po we r an d Wa ter Pro cur em ent	42 7 00 0	91, 00 0	N a t u r al G as	41 5 1 %	41 9 1 %	P W PA - BO O 18. 7 ye ars	In str at a, M ult ite ch, 35 % pu bli c -	A na sal & Hi ta ch i Zo se n	N O M A C (A ug 3 Q 1 Ac qu isit io n)*	20 10 0 (A ug 3 Q 1	2 0 0 0 3 Q 1	AC W A Po we r Bar ka SA OG ("B ark a")	http://acwpower.com/ar/newsroom/releases/latest-news/aicw-power-international-	*https://

		sh (M SF)			n	Co mp an y						M us cat St oc k M ar ke t						iwp p/ barka-1- iwpp- transact ion-in- oman/
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CE G C O	I P P	Co nv en	Int er nat	Jor dan			27		D ei se							201 1 (Ac qui			

- Amman South IPP		tional						l							sition)			
CEGC O-Hussein Thermal IPP	IPP	Thermal	International	Jordan			198	Nuclear Fuel Oil and Diesel							2011 (Acquisition)		http://www.cwa.gov.jo/new/s/cwa-power-signs-25-year-ppa-for-the-485-mw-hussein-cigt-ipp/	PPA was signed 2016, turning thermal plant to CCGT

Hajr (Qurayyah) IPP	IPP	Combustion	Domestic	Saudi Arabia	Eastern Province, Saudi Arabia	Saudi Electricity Company	3,927	N/A	Natural Gas	2,717	22.49%	A-BO 20 years	SE, Samsung C&T, MENA Infrastructure	Samsung C&T	NO MC (NFC) * 1	2012	2015	Hajr Electricity Production Company ("Hajr EP CO")	http://www.cwa.gov.sa/hajr-ipp/	*https://www.meed.com/quraayyah-power-plant-reaches-financial-close/*https://www.acwapower.com/new-s/acs-499-of-samsung-cts-share-in-hajr-electricity-production-company/
Kirikkale CC GT	IPP	CCGT	International	Turkey	Kirikkale, Turkey	Merchant market	950	N/A	Natural Gas	930	69.0%	Merchant market		Samsung C&T	NO MC (DJV) *	2012	2017	ACWA Güç Elektrik İletime ve Yönetimi	http://www.cwa.gov.sa/hajr-ipp/	*https://disclosures.ifc.org/project-detail/ESRS/35395/acw

N O R o I C S P	I P	So lar PV	Int er nat ional	Mo roc co	O ua rz az ate , A ga dir di str ict, M or oc co	Mo roc can Ag enc y for Sol ar Ene rgy ("MA SE N")	16 0	N A	N A	84 1	73 1	P - B O T 25 ye ar s	PA M as e n (M or o cc o , A ri es , T S k, A S R A	Sp ai n's TS El ect ro ni ca y El ect ric id ad , Ac cio na Inf ra str uc tu re s, Ac ci on a In ge ni eri a an d Se ne r In ge	N O M A C FC)	201 3 pr. FC)	2 0 1 6 Q 3	AC W A Po we r Ou arz aza te ("A PO ")	http://www.wa-cwa.com/en/projects/no-oro-i-csp-ipp/	*http://www.cspfocuss.cn/en/detail_161.htm

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Kh an yis a IPP	I P P	Co al- fir ed PP	Int er nat ion al	So ut h Af ric a	E m ala hl en i, So ut h Af ric a											2013(?)	N A			The project failed due to not meetin g their climate change require ment and not meetin g deadlin e.
Na m Din h	I P P	Co al- fir ed	Int er nat ion	Vie tna m	Ha noi , Vie		1, 2 0 0	N A	C o al							2014 (Q 3.				The project seemed to be

1 IPP	PP	al		tna m											JV)				stalled.
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Bar ka 1 Ex pa nsi on Ph ase II IW P	I W P	S W R O	Int er nat ion al	O ma n	Bar ka, O ma n	O ma n Po we r an d Wa ter Pro cur em ent Co mp an y		56 .8 m 3 / d a y, S W R O		U S 41- D.9 71 % M n	W PA BO O- 4.2 5 ye ar s	In str at a, M ult ite ch, 35 % pu bli c - M us cat st oc k mar ke t	O s m of lo w , A us tr al ia	N O 201 5 (?) C O m a n		2 0 1 6 Q 1	http://www.cwawater.com/en/projects/barka-1-expansion-phase-ii-iwp/	*https:	

S al al a h 2- Gre e n fi el d P r o j e c t	I P P	C C G T	Int er nat ional	O ma n	Ra ysu t, O ma n	O ma n Po we r an d Wa ter Pro cur em ent Co mp an y	44 5	N A	N a t u r a l G a s	45 0	27 %	PP A- BO O- 15 ye ars	Mit sui (45 %), DI DI C (10 %)	SE PC III	D h 201 5 (A ug. FC) *	2 0 1 8 Q 1	Dh ofa r Ge ner ati ng Co m pa ny ("S ala lah 2")	http://www.mee.gov.cn/omn/finance/close/https://www.nomac.com/energy/our-operations/nomac-global/y/salalah-2-ipp-greenfield-project/	
Sh ua a En erg y 1	I P P	So lar PV	Int er nat ional	U AE (D ub ai)	Du bai, UA E	DE W A	20 0	N A	N A	32 6	24 9 %	PP A- BO O 25 ye ars	DE W A (51 %) K El ec tr on ic a y El ec tri ci da	S pa in' O M A C K El ec tr on ic a y El ec tri ci da	N 201 5 (Jul .FC) *	2 0 1 7 Q 1	Shu aa Ene rgy 1 P.S .C ("D E W A P V")	http://www.wa.gov.sa/article/130803	*https://saudi-gazette.com.sa/article/130803

Petro-Rabigh I WSP	IP	Steam Turbines	Domestic	Saudi Arabia	Rabigh, Western Saudi Arabia	Petro-Rabigh Petrochemical complex	360	13.9	Heavy Fuel	1991	90%	WEC - BOT 25 years	Marubeni, JGC Corporation, ITOCHU Corp, Petro Rabigh	MHI	Rabigh Project (NOMAC)	2015	2018	Rabigh Aramco Water and Electricity Company ("RAWEC")	https://www.acwapower.com/en/project/petro-rabigh-i-wspp/	* https://www.meed.com/power-closes-rawec-refinancing-facility * https://www.kinneyrecruiting.com/london/legal-news/chadbourne-advises-on-the-us776-million-financing-of-the-rabigh-independent-water-steam-and-power-plant-expansion/
NOOR II CSP	IP	Concentrated Solar Power using parabolic troughs and molten salt thermal energy storage (7 hours)	International	Morocco	Ouarzazate, Agadir district, Morocco	Moroccan Agency for Solar Energy ("MASEN")	200	N/A	N/A	1975	100%	PASA - BOT 25 years	SENER	SENER	NOMAC Masen 25%	2015	2018	ACWA Power Ouarzazate II ("AOP2")	https://www.acwapower.com/en/project/noor-ii-csp-ipp/	* https://www.acwapower.com/news/acwa-power-and-masen-achieve-financial-close-of-noor-ii-and-noor-iii-projects-corresponding-to-phase-2-of-the-noor-solar-complex-in-ouarzazate-morocco/
NOOR III CSP	IP	Solar technology and	International	Morocco	Ouarzazate, Agadir	Moroccan Agency for	150	N/A	N/A	1982	75%	PASA - BOT 25 years	SENER	SENER	NOMAC 75%	2015	2018	ACWA Power Ouarzazate	https://www.acwapower.com/en/project/noor-iii-csp-ipp/	https://www.acwapower.com/news/acwa-power-and-masen-achieve-financial-close-of-noor-ii-

P		mol ten salt ther mal ener gy stor age (7 hou rs)			r dis tric t, Mo roc co	Solar Ener gy ("M ASE N")					O T 25 y e ar s			% Ma sen 25 %	)*	4	azat e III ("A PO 3")	project s /noor o-iii- csp- ipp/	and-nooro-iii- projects- corresponding -to-phase-2-of- the-nooro- solar-complex- in-ouarzazate- morocco/
K h a l l a d i W i n d F a r m	IP P	Wi nd (V es ta s tu rbi ne s)	Inte rnat ional	Mo roc co	30 km Eas t of Tan gie rs, No rth of Mo roc co	Ind ustr ial com pan ies (cap tive PP As)	120	N A	N A	1 7 5	2 6 0 1 %	P A- B O 20 ye ar s	Arg an Infr astr uctu re Fund 25% / SA HA M 24%	Vest as, Sta m, Ceg elec & A.G .T.T.	N O 201 5 0 (N 1 ov. 8 FC Q) *	2 0 1 Kha llad i ("K hall adi")	https:// acwa power. c om/en /projec ts/khal l adi- wind- ipp/	* https://ww w.ebrd.com/ work-with- us/projects/p sd/khalladi- wind- farm.html	
Zar aq IPP	IP P	Co m bi ne d c y cl e g as	Inte rnat ional	Jor dan	Cit y of Zar qa Ind ust rial Zo ne, the Ha she mit e Kin gdo m of Jor dan	Nat iona l Elec tric Po wer Co mp any (NE PC O)	485	N A	N a t u r a l g a s	4 8 9 0 %	6 0 0 %	P A- B O 25 ye ar s	Sh ando ng Ele ctric Co por ation III (SE PC III)	CE G C O (IT p.F C) *	201 5 0 (Se p.F C) Q 3	Ma hat at Al Zar qa Le Ta wle ed Al Tak ah Al Kah rab aiey ah PSC ("Za rqa")	https:// www .acwap o wer.co m/en/ project s /zarqa -ipp/	* https://ww w.power- technology.c om/marketd ata/zarqa- combined- cycle-power- plant- jordan/	
Bar ka 1 Ex pa nsi on Ph ase I IW P	I W P	RO	Inte rnat ional	O man	Bar ka, Oman	Om an Pow er and Wat er Proc ure men t	N A	45 .5 m 3 / da y / S	U S 4 1 5 3 %	1 9 0 8 %	W P A- B O 35% Pub lic - Mus cat Stoc	Inst rata, Mul titec h, 35% Pub lic - Mus cat Stoc	Ab ei ns a, Sp ai n	N O 201 5 (?) 1 4 Q 2	2 0 1 Kha llad i ("K hall adi")	https:// www .acwap o wer.co m/en/ project s /barka -1- expansi			

						Com pany		W R O			s	k Mar ket					on- iwp/		
Hassyan IPP	IPP	Steam turbines	International	UAE (Dubai)	Dubai, UAE	DEWA	2,400	N/A	Clean Coal (and Natural Gas)	3,262,935,700	2016	DEWA (51%), HEI (14.7%) & Silk Road Fund (7.35%)	GE and Harbin Electric International Company Ltd (HEI)	NO	2016	2016	Hassyan Energy Phase I P.S. C ("Hassyan")	https://www.acwapower.com/en/project/hassyan-ipp/	*https://www.acwapower.com/news/hassyan-energy-phase-1-reaches-financial-close-on-dewas-24-gw-hassyan-clean-coal-project-with-signing-of-us-247-billion-financing/ *first ultra-super critical coal development
Ibri IPP	IPP	CCGT	International	Oman	Ibri, Oman	Oman Power and Water Procurement Company	1,509	N/A	Natural Gas	942,015,000	2016	Mitsui (50.1%), DIDI C (5%)	SEP CO III & Power China	Dhofa O&M Co (Subcontracted to NO MAC)	2016	2016	Ad-Dhahirah Generation Company SA OC ("Ibri")	https://www.acwapower.com/en/project/ibri-ipp/	*https://www.meed.com/oman-power-project-reaches-financial-close/
Sohar 3	IPP	CCGT	International	Oman	Sohar, Oman	Oman Power & Water Procurement Company			Natural Gas	942,015,000	2016	Mitsui (50.1%), DIDI C (5%)	SEP CO III & Power China	Dhofa O&M Co (Subcontracted to NO MAC)	2016	2016	Shinas Generation Company SA OC ("Sohar")	https://www.acwapower.com/en/project/sohar-3-ipp/	*https://www.meed.com/oman-power-project-reaches-financial-close/
Risha PV	IPP	Solar PV	International	Jordan	Risha, Jordan	National Electric Power	50	N/A		658,100	2016		Stirling & Wils	CEGC	2016	2016	Risha for Solar Power Project	https://www.acwapower.com/en/project/	*https://www.acwapower.com/news/acwa-power-commences-commercial-operations-at-

						Co mp any (NE PC O)					20 ye ar s		on		)*	4	ects PSC ("Ri sha")	s /risha- pv- ipp/ 	risha-pv-in- jordan/
S h u a i b a h 2 (S T P C)	I W P	SW RO	Do mes tic	Sa udi Ara bi a	Shu ai ba h, Sa u di A ra bi a	Shu aiba h Wat er and Elec trici ty Co mp any	N A	25 0	Co n v e n t i o n al	3 0 8 0 %	1 0 0 %	W P A - B O O - 2 5 Y R		Abe ima Fisia	NO MA C*	20 17 (F C)	2 Tw o Wat er Dev elop me nt Proj ect Co mp any ("SE PCO 2")	https:// /acwa power. com/en /projec ts/shu aibah- 2-iwp- stpc/ 	* https:// ww w.nomac.com /en/our- operations/no mac-globally- old/shuaibah- two-iwp-stpc/
Ma fra q PV IPP	IP P	Sol ar PV	Inte rnat ional	Jor dan	50k m nort h- east of Am man, Jord an		150	N A	N A							20 17 (M ar. FC)			https:// www. acwapower.co m/news/acwa - power- mafra-q-signs- financial- agreements- for-603-mwp- solar-pv-ipp- in-jordan/
Al Maf raq Solar PV Park	IP P	Sol ar PV	Inte rnat ional	Jor dan	the Kin g Hus sein Bin Tal al Dev elo pm ent Are a, Maf raq, Jord an	Nat iona l Elec tric Po wer Co mp any (NE PC O)	60	N A	N A	7 1	5 1 %	P P A B O O 20 ye ar s		ET Solu tion s	CE G C O (IT SA wit h N O M AC)	20 17 (M ar. FC)	Sun rise Sol ar En erg y PS C ("M afraq")	https:// /www _acwap _ower.co m/en/ project s/ _mafr aq-pv- ipp/ 	* https:// ww w.power- technology.co m/marketdat a/al-mafraq- solar-pv- park-jordan/ * http://acwag uc.com.tr/2- acwa-power- mafra-q-signs- financial- agreements- for-60- 3-mwp-solar- pv-ipp-in- jordan
						Mas						P		Chi nt			AC WA Po wer Bouj	https://	* https:// www .globaldata.co m/store/repor t/masen-noor-

No or PV 1	IP	PV	International	Morocco	Morocco	en (Moroccan Agency for Sustainable Energy)	135	NA	NA	2010	75.00%	PAT - 2015 R		Group, Sterling & Wilson and Shapoorji Pallonji	NO M AC / Ing ete am	2017 (M ay. FC Q)*	2018 AC WA Po wer Laa you ne ("La ayo une ") / AC WA Po wer Oua rzaz ate IV ("A PO 4")	/acwa power. c om/en /projec ts/noor _pv- 1/	pv1- photovoltaic- solar- energy- generation- 170-mw- morocco/ *https://www .acwapower.co m/media/338 987/noor-pv- 5218- compressed.p df https://www. meed.com/exc lusive-acwa- power- reaches- financial-close- on-morocco solar-project/
Dai rut IPP	IP	Conventional	International	Egypt	Al Hanadi , Esna , Egy pt	Egyptian Electricity Trans mission Com pany	2,250	NA	Conventio al	2013	40%	PPA - 2010	PIF 25% Hassan Alla m: 10% GE: 10% China Silk Road: 15%	Consortium of GE & SE PC OI II	Consortium of GE & SE PC OI II	2018 (ex pected)		https://www. power- technology.co m/news/acw a-power- plant- in- egypt/	
Be nba n PV (1-3)	IP	Solar PV	International	Egypt	Aswan Province in Benban, Egy pt	Egyptian Electricity Transm ission Co mp any (EE TC)	120	NA	NA	2015	25%*	PPA - 2015 R	EBRD 75%, ICBC 25%*	Chint Solar (Z hei jan g)	NO M AC (Ja n. FC Q)*	2018 (Ja n. FC Q)*	2019 AC WA Benban One for Enegy ("Be nba n")	https://www .acwapo wer.co m/en/ project s /benb an-pv- ipp/	*https://ww w.africa- energy.com/li ve- data/article/e gypt-acwa- power- reaches- financial- close-benban- solar-pv- projects *https://ww w.pv- magazine.com /2018/01/08/ acwa-power-

W A V PV	P	ar PV	rnat ional	E (D ub ai)	ai, UA E	WA		A	A	6	4	A				19	0	U	.acwap	us/media-
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																ar.	3	A	wer.co	atest-
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																)	1	ne	project	/dewa-acwa-
																		rg	s	power-and-
																		y	/dewa	silk- road-
																		3	-v-pv/	fund-reach-
																				financial-
																				closing-on-
																				950mw-4th-
																				phase
No or Ene rgy 1	IP	CSP with To we & Tr ough	Inte rnat ional	UA E (D ub ai)	Dub ai, UA E	DE WA	95 0 (7 00 CS P+ 25 0P V)	N	N	4	2	A	PP	ICB	Sh ang hai Ele ctri c is the eng inee ring , pro cure ment and con struc tion (EP C)	NO	20	2	DE WA CSP The AC WA	*http://noore
																MA	19	0	https://	energy.ae/
																			/acwa	*https://www
																			power.	.nsenergybusi
																			om/en	ness.com/proj
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																				/news/fin-
																				close-
																				achieved-on-
																				950-mw-noor-
																				1-solar-
																				project-in-
																				dubai-647652/
Al Ta we ela h	I W P	Rev ers e Os mos is (R O) an	Inte rnat ional	U A E (A bu D h a bi	Abu Dha bi, UA E	The Emi rate s Wat er and Elec tricit y	69	90	N	8	4	W	MU BAD	Abe	NO	20	2		https://	*https://ww
																			/acwa	w.waterworld.
																			power.	com/drinking
																			om/en	-
																			/proje	water/treatme
																			cts/al-	nt/article/141
																			taweel	69801/taweel
																			ah-	ah-iwp-
																				obtains-the-
																				first-ever-
																				sustainable-
																				loan-
																				qualification-

Ibri 2 PV * GRID *	IP	Solar PV	International	Oman	Ibri, Oman	Oman Power and Water Procurement Company	500	NA	NA	395	50%	Pf Investment Corporation (40%), Alternative Energy Projects Co. (10%)	Purchasing Engineering Corporation (HDEC)*	NO	2020	2020	2020	Shams Ad-Dhahira Generation Company*	https://www.acwapower.com/news/financial-closure-achieved-for-the-largest-solar-photovoltaic-power-plant-in-oman/ https://www.acwapower.com/en/projects/ibri-ii-solar-power-project/	* https://www.acwapower.com/news/financial-closure-achieved-for-the-largest-solar-photovoltaic-power-plant-in-oman/ * https://www.nsenergybusiness.com/projects/ibri-ii-solar-power-project/

Jubail 3A	IPP	Reverse Osmosis	Domestic	Saudi Arabia	Jubail, KS A	Saudi Water Partnership Company (SWPC)	NA	600		658	40.20%	WPABOOR-25YR	Consortium of Sepco 3 (China), Power China and Spain's Abengoa	NO	2020	2022	Jazlaha Water Desalination Company	https://www.acwa.com/en/projects/3a-iwp/	*https://energy-utilities.com/acwa-reaches-financial-closure-for-650m-news084715.html https://www.saudi-gulfprojects.com/2020/09/acwa-power-announces-the-financial-closure-of-jubail-3a-iwp/
Kom Ombo PV	IPP	Solar PV	International	Egypt	Kom Ombo, Egypt	Egyptian Electricity Transmission and Distribution Company (EETC) Power*	200	NA	NA	165	100%	PPABOOR-25YR	Stirling and Wilson*		2021	2023	(Apr. FC)	https://www.power-technology.com/projects/kom-omb-solar-pv-park-egypt/	*https://www.power-technology.com/arketdata/kom-omb-solar-pv-park-egypt/
Sudair	IPP	Solar PV technology	Domestic	Saudi Arabia	Sudair Ind		1500	NA	NA	924	35	PPA			2021		Sudair	https://www.apower.com/news/acw-a-	*https://www.acw

PV	P	usi ng bi- faci al pan els wit h trac kin g tech nol ogy , and an aut om ate d rob otic clea nin g solu tion	stic	Ara bia	ustr ial Cit y, Sau di Ara bia						%	- B O O - 2 5 Y R							(Au g. FC) *		r O ne R en e w ab le E ne rg y C o m p an y	acwa po wer. com /en/ proje cts /su dair -pv- ipp /	power- announce s- financial- close-for- 1500-mw- sudair- solar- plant- and- aramco- joining- the- consortiu m-under- pif- renewabl es- program/
Sir dar ya CC GT	I P P	CC GT	Int ern atio nal	Uz bek ista n	Shi rin Cit y, Sir dar ya reg ion , Uz bek ista n	JSC Na tio nal Ele ctric Grids of Uz bek ista n	15 00	N A	N a t u r a l g a s	75 0	5 1 %	P A - B O O T- 2 5 Y R						202 1 (FC)*	20 24	A C W A Po we r Sir da rya LL C	https ://w ww. acwa po wer. com /en/ proje cts /sir dar ya- ccgt /	*https://e nergy- utilities.co m/acwa- power- s-1bn- uzbekista n-power- project- reaches- news1115 63.html *https:// www.nse nergybusi ness.com /new s/acwa- power- sirdarya- ccgt- power- plant- uzbekista	

																			n-silk-road-fund/
Redstone CSP * GRI D *	IPP	CSP with Thermal Storage	International	Southern Africa	Northern Cape Province, South Africa	Eskom Holdings	100	NA	NA	724	49% PA - BOO 20 years				NO MAC	2021 (May. FC) *	2023 Q4	ACWA Power Solar Reserve Rostonsolarthermal Power Plant (RF) Proprietary Limited	https://www.trinityllp.com/redstone-csp-financial-close/*
Jazan IGCC * GRI D *	IPP	Integrated Gasification, Comb	Domestic	Saudi Arabia	Jazan Economic City, Saudi	Saudi Aramco	Power: 3,800 MW (Gross)	NA	Crude oil	7,200	25 years - On-Operate	Saudi Aramco Power Co. (20%) • Air Products				2021 (Oct. FC) *	NEW		https://www.acwapower.com/news/announce-the-financial-close-for-12-billion-

		ined Cycle			Ara bia		s s) , Ste am : 5 8 5, 0 0 0 T ons / hou r, Hy dro gen : 18 4, 00 0 n M 3 / hou r						e- Tr a ns fe r (O O T) m o de l	ME (46%) • AC WA Pow er (25%) • Gas Indu stry Co. (Air Prod ucts Qud ra) (9%)							cts / jaz an- igcc/ asugasic ationpow er-joint- venture- at-jazan- saudi- arabia/ *https://j igpc.com /home-1
Dz hank el dy Wind Farm	IPP	On shore Wind	Intern ational	Uzbek istan	Dzhank eldy, Bukhara Region, Uzbekis tan	JS C Natio nal Elec tric Grid of Uz	500	NA	NA	658	100%	25- year PPA B				NOMAC	2022 (Aug. Signed)*	NEW Power Bas in W	FE "AC WA Pow er Bas in W	https://www.adb.org/sites/default/files/project-document/56086/56086-001-erp-en.pdf	

						be kis tan (NE GU)						O O (T)						in d " L L C	anke ldy- wind : ipp/	
Nu k us W in d Fa r m	I P P	On sho re Wi nd	Int ern atio nal	Uz bek ista n	Nu ku s, Ka rak alp aks tan reg ion , Uzb ekis tan	JS C Na tio nal Ele ctri c Gri d of Uz be kis tan (NE GU)	10 0	N A	N A	10 8	1 0 0 %	2 5 - ye ar P P A				202 2 (Fal l. FC) *	N E W Po we r Wi nd Ka rat au FE LL C	A C ://w ww. acwa po wer. com /en/ proje cts /nu kus- win d- ipp/	* https:// www.acw apower.c om/news /acw a- power- signs- agreemen t-for- 100mw- uzbekista n-wind- power- project/	
T h e R e d S e a P r o j e c t	I W P	PV, BES S, Inte rnal Co mb usti on Eng ine, RO, MS W	Do me stic	Sau di Ara bia	Red Sea co ast bet we en the loc ali ties of U ml uj and Al Waj h	Th e Red Sea Util ities Co mp any	1, 64 8	18, 315			5 0 %	2 5 - ye ar U C A				202 2 (Fe b. FC) *	N E W FI Q R E D SE A F O R E N E R G Y CO M PA NY	M A R A ://w ww. acwa po wer. com /en/ proje cts /the -red- sea- proje ct/	* https:// www.acw apower.co m/news/ acw a- power- led- consortiu m- achieves- financial- close-for- the-us159- billion- red-sea- project/	
Lay la Sol ar	I P P	Sol ar PV	Do me stic	Sau di Ara bia	Afl aj gov ern orat e, Sa ud i Po w	Sa ud i Po w	91	N A	N A	10 5	4 0. 1 0	3 0 -				N O M A	20 22 (Ju n. En	20 24 *	La yla Sol ar En po	* https:// www.ara bnews.co m/node/ 20968 41/busine

PV					Riyadh province, Saudi Arabia	er Procurement Company					%	e ar PPA		C	Si gn ed)*	er gy Co m pa ny	wer. com /en/ projects /lay la- solar- pv- ipp/	ss- economy *https:// www.nomac.com/en/our-operation s/nomac-globally/layla-solar-pv-ipp/
Ar Ras s	I P	PV Power Plant, bi-facial modules with tracking technology	Do me stic	Sau di Ara bia	Ar Ras s Po we r Pro cur em ent Com pa ny (SP PC)	70 0	N A	N A	45 0	4 0 1 0 %	P A B O 2 5 y ea rs	Water and Electricity Holding Company (Bad el) 20%, the State Power Investment Corporation from China a 39.9 %			20 22 (M ar. Si gn ed)*	N E W	Ar Ras s Sol ar En er gy Co m pa ny	https ://w ww. acwa po wer. com /ne ws/ acwa po wer- inks- purchase- agree men t- for- 700-mw- ar-rass- solar-pv- project-in- saud i- arabi a/
Bas h Wi nd Farm	I P	On shore Wi nd	Int ern atio nal	Uz bek istan	Bas h, Bu kh ara Re gio n, JS C Na tio nal Ele ctri c	50 0	N A	N A	69 0	1 0 0 %	2 5 - y e a r P			N O M A C	20 22 (M ar. Si gn ed)*	N E W	FE "A C W A Po wer	*https:// www.adb .org/sites /default/ files/p roject- document s/56085/5

					Uz be kis tan	Gri d of Uz be kis tan (NE GU)					P A B O O (T)				)*	B as h W in d " L L C	projec ts / ba sh- win d- ipp / L	6085-001- esia- en.pdf		
Su ez Wi nd En erg y - 1.1 G W	I P P	Wi nd	Int ern atio nal	Eg ypt	Sue z Gul f and Ga bal El Zei t, Ras Gh arib , Egy pt	Egy ptia n Ele ctri city Tra ns mis sion Com pany (EE TC) Pow er	1, 10 0	N A	N A	15 00	P P A - B O O - 2 5 Y R				202 2 (No v. Mo U signed)*	20 26	S u e z W i n d E n e r g y	https :// ww w.ac wap o wer. com /en/ projec ts / su ez- win d- ener gy- 11- gw/ gulf-area/	*https:// www.acw apower.co m/news/ the- sovereign- fund-of- egypt- joins- acwa- power as--co- investor- of-11-gw- wind- energy- project-in- the--suez- gulf-area/	
Ar Ras s PV	I P P	Sol ar PV	Do me stic	Sau di Arabia	Qas sim Pro vinc e	Sau di Po wer Pro cur ement Com pany (SP PC)	70 0	N A	N A	45 00	4 0 0 %	P P A B O O 2 5 y ears	Wat er and Elec tricit y Hold ing Com pan y (Bad eel) 20% , the Stat e Pow er Inve stme nt Cor pora			202 2 (Se p. FC) *	N E W	Ar Ra ss Sol ar En er gy Co m pa ny	https ://w ww. acwa po wer. com /en/ projec ts / ar- rass -pv- ipp / /	*https:// www.acw apower.co m/news/ acw a- power- links- power- purchase- agreement for- 700-mw- ar-rass- solar-pv- project-in- saudi- arabia/

		ES			istan	Uz be kis tan (N EG U)	0 M W B E S S											/kar akal paks tan- win d ipp/	%20Powe r%20is %20prou d%20to,K ungrad% 20wind% 20far m%20in% 20Karakal pakistan.& text=The %20 project%2 0is%20ex pected%2 0to,be%20 full y%20com missioned %20in%20 2027.	
Rab igh 2 IPP	I P P	3 Po we r Blo cks - Gas Tu rbines	Do me stic	Sau di Ara bia	Rab igh , We stern Sa udi Arabi a	Sau di El ectric ity Co m pany	2, 06 0	N A	N a t u r a l G a s	1, 56 1	5 0 %	P A - B O O 2 0 y ea rs	SCT (12.5 %), SEC (50%)	Sa ms un g C & T Co rp or ati on		Acq uisi tion s	20 18 Q 1	Al- Mo urj an for Ele ctri cit y Pro du cti on Co mp an y ("M EP C O")	https ://w ww. acwa po wer. com /en/ proje cts /ra big h-2- ipp /	
Rab igh 3 IWP	I W P	Rev er se os mos is (R O	Do me stic	Sau di Ara bia	Rab igh , We stern Sa udi		N A	600	S W R O	68 7	7 0 0 %	P W P A - B O O -				Acq uisi tion s	20 21 Q 4	Ra bi gh T hr ee C o m	https ://w ww. acwa po wer. com /en/ proje	

		)			Arabi a							25 Y R						pa ny	cts /ra big h-3- iwp /	
Sh uai ba h Ex pa nsi on IW P	I W P	Rev er se O s mos is (R O)	Do me stic	Sau di Ara bia	120 km sou th of Jed dah , We ster n Sau di Ara bia	W at er & E lec tri ci ty C om p a n y	N A	150		23 3 3	3 0 0 %	W P A - B O O 2 0 y e a r s	PIF, SE C, Kh aza na h, TN B, Ma lak off	Sie me ns Ak tie ng ese llsc haf t an d Do osa n He av y In du stri es Co nst ruc tio n	A L I M T I A Z N O M A		20 09 Q 4	S h u ai b a h E x p a n s i o n P ro je ct C o m p a n y ("S E P C O")	https://www.iwglo.com/articles/106254/acwa-powers-project-backed-bond-saudi-arabia	
Sal ala h IW P	I W P	Rev er se O s mos is	Int ern atio nal	Om an	Dh of ar re gi o n, O m a n	O ma n Po wer & Wa ter Pro cur em ent		114 m ³ /da y		U S D 16 0 M n	5 0 1 %	W P A - B O O - 2 0 Y					20 21 Q 1	Dh of ar re gi o n C o m p a n y SA OC	https://www.iwglo.com/articles/106254/acwa-powers-project-backed-bond-saudi-arabia	

						Co mp an y					R						(S ala lah IWP")	/sala lah- iwp/	
Bo w ar eg e D es ali na tio n Ba rg es	I W P	RO	Do me stic	Sau di Ara bia	Ya n b u, S a u d i A ra bi a	SW CC	N A	25, 000	Di es el	99	6 4. 8 5 %	W P A - B O O	Raka a Sau di Pow er and Wat er Co mpa ny	W E TI C O	N O M A C		20 08 Q 2		chro me- extension: //efaidn bmnnnib pcajpcglcl efind mkaj/htt ps://ww w.acwapo wer.com/ media /338963/ bowarege -iwp- compress ed.pdf
Qur ayy ah IPP	I P P	Co mb ine d cyc le (G as & Ste am)	Do me stic	Sau di Ara bia	Eas ter n Pro vince , S a u d i A r a b i a		3, 92 7		N a t u r a l G a s			B O O (2 0 y e a r s) P P A		Sa ms un g C &T / Sie me ns Ma jor Su bc ont rac to r	N O M A C 1 0 0 % (N o mi te Su bc on tra ct or: Sie m en s L T S A)		20 14 Q 2		

Notes

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- ¹ Data Source: IEA Electricity Information 2022 <https://www.iea.org/data-and-statistics/data-product/electricity-information>, Saudi energy mix in 2020.
- ² <https://www.vision2030.gov.sa/v2030/a-sustainable-saudi-vision/>
- ³ According to the company's website, Nov. 2013, accessed Mar. 2023
- * Annual Report 2009
- ⁴
- ⁵ Company overview: <https://acwapower.com/en/investor-relations/overview/>
- ⁶ Company history: <https://acwapower.com/en/about-us/company-history/>
- * Annual Report 2009
- ⁷ Interview lists available in Appendix
- ⁸ <https://www.worldbank.org/en/country/gcc/publication/economic-brief-oman-july->
- ⁹ Annual Report 2011
- ¹⁰ Annual Report 2010
- ¹¹ King Abdullah City for Atomic and Renewable Energy (K.A. CARE): <https://www.energy.gov.sa/en/pages/fq.aspx>
- ¹² ACWA Power sells its stake in a 60MW photovoltaic power plant in Bulgaria: <https://www.acwapower.com/news/acwa-power-sells-its-stake-in-a-60-mw-photovoltaic-power-plant-in-bulgaria/>
- ¹³ Saudi Vision 2030 https://www.vision2030.gov.sa/media/rc0b5oy1/saudi_vision203.pdf
- ¹⁴ Annual report emphasis on alignment to Vision 2030 in 2016 onward.
- ¹⁵ Project details provided from ACWA portfolio.
- ¹⁶ Though this is difficult to clarify because there is no real market price in Saudi Arabia.
- ¹⁷ Chap.2, The economics of Renewable Energy in The Gulf edited by Akhonbay, 2019. The industrial sector is the largest consumer of energy. It makes sense to replace, generate, and self-consume renewables for the industrial sector.
- ¹⁸ Government of Dubai announced the financial closing of the project in 2019.
- ¹⁹ ACWA Newsroom announcement in 2020 <https://www.acwapower.com/news/taweelah-iwp-obtains-the-first-ever-sustainable-loan-qualification-for-a-desalination-project/>
- * Project details provided from ACWA portfolio.
- ²⁰ <https://www.acwapower.com/news/the-public-investment-fund-announces-increase-in-stake-in-acwa-power/>

Mapping the spatial variation of path dependencies in global regimes – A novel scheme of analysis and illustration in the water sector

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Abstract:

A core argument in the geography of sustainability transitions literature is that regime- and innovation system structures vary across space. Yet, current studies provide very limited analytical tools to empirically study their variation. This paper develops a theoretically informed analytical framework for assessing and mapping the spatial variation of path dependencies in global socio-technical regimes. It provides a first set of proxy indicators for measuring the variance in regime strength across spatial contexts, allowing for a rough characterization of where path dependencies in infrastructure sectors are stronger or weaker. Based on the identification of path dependence in three dimensions (technology/materiality, actor networks and institutions), it outlines the ideal-type path dependencies to be expected depending on a given place's embeddedness in global regime structures. The framework is applied to a case study in the urban water management (UWM) sector which demonstrates the general utility and relevance of the approach. In depth empirical illustrations of the UWM sector in the Netherlands, Israel, Kenya and India show how path dependencies in a specific country may change over time due to a combination of endogenous and exogenous factors. The study has strong policy implications, as the concrete actions to support transformative change differ strongly depending on the strength and nature of path dependencies, making one-size-fits-all approaches for destabilizing or circumventing global regime structures elusive.

Keywords: global regimes, spatial variation, geography of sustainability transitions, infrastructure, urban water management

1. Introduction

To achieve the ambitious goals of the UN's 2030 agenda, transforming key infrastructure sectors like energy, water, transport or housing will be of key importance. Infrastructure sectors are responsible for a majority of global greenhouse gas emissions (estimated at 79% of total emissions) (Thacker et al., 2021), making them a key target for radical innovation and transformation. Numerous experiments with transformative infrastructure solutions are currently underway in different parts of the world. However, while some of them are successful in their local contexts, they have proven very difficult to scale. Rather than transformative change, the dominant pattern in most infrastructure sectors is thus one of stability and incremental innovation (Geels and Turnheim, 2022).

A key reason for this observation are the persistent path dependencies and lock-ins that exist in many infrastructure sectors (Markard, 2011). Nevertheless, we still have a rather rudimentary understanding of the nature of these path dependencies, how they vary between sectors and across space and how they can be actively mitigated (Fuenfschilling and Binz, 2018; Miörner et al., 2022a). One key research gap in this realm relates to creating a deeper understanding of the spatial variation of path dependencies in different sectors. Elucidating this variation could provide crucial insights on where transformative change could be initiated most easily and effectively. It is therefore adamant to examine in more depth how sectoral structures - and the path dependencies they give rise to - vary across cities, regions and countries worldwide.

When it comes to understanding the transformation of infrastructure sectors, *transition studies* (Markard et al., 2012; Truffer et al., 2015; Loorbach et al., 2017) offer powerful conceptualisations for analysing sector structures and their inherent path dependencies (Miörner et al., 2021). A key concept in this literature is the 'socio-technical regime', referring to configurations of actors, institutions and technologies that have developed over extended periods of time and aligned into solutions 'that work' (Kemp et al., 1998; Markard et al., 2009). Typical examples of deeply entrenched regimes are fossil-fuel based power systems, car-based urban mobility or industrial agriculture. Key factors inducing path dependencies in these regimes range from economic and technological factors such as sunk costs and technical interdependencies to social and cognitive factors including entrenched use patterns or regulations (Unruh, 2000; Kemp et al., 1998).

Recent research has demonstrated that path dependencies do not only stem from local contexts, but also from globalized sector structures (Fuenfschilling and Binz, 2018). So far, transition studies have assumed that the path dependencies emanating from regimes have a more or less homogenous influence across space. Only few studies have begun to explore 'global' socio-technical regimes

more systematically and looked into whether and why regime structures differs between places and sectors (Klitkou et al., 2015; Tilsted and Bauer, 2021; Miörner et al., 2022a; Simoens et al., 2022). Nevertheless, the current understanding mostly attributes spatial variation in sectoral path dependencies to the uniqueness of particular places, rather than trying to understand how the influence of a global regime varies across space and how that spatial variation manifests in a multidimensional way.

This paper therefore aims to develop a theoretically informed framework for mapping and analysing the spatial variability of regime structures in order to derive a better understanding of the spatial variations in the strength of path dependencies. To this end, this paper draws on, and contributes to, recent work in the geography of sustainability transitions (GeoST) literature. Our framework is operationalized with a range of indicators, which consider path dependencies in three fundamental dimensions of regimes, namely the material/technological-, actor network-, and institutional dimension. We illustrate and validate our framework by mapping the spatial variation of the socio-technical regime in the global water sector, which represents an emblematic case of a sector with a particularly strong global regime structure and deep lock-ins in many countries (Lieberherr and Fuenfschilling, 2016).

The next section will introduce the literature on the geography of sustainability transitions and motivate the three basic conceptual dimensions of path dependencies in global regimes. Based on the conceptual elaboration, we then construct a typology of regime strength in different territorial contexts. This is followed by a discussion on case selection rationale and methodology in section 3, and an illustration of the applicability and analytical utility of our framework in section 4. To this end, we analyse the spatial variability of the global regime in the water sector and use four countries (India, Israel, Kenya and the Netherlands) as in-depth examples for demonstrating how spatial variability in regime strength translates into real-world transformation potentials. We discuss our findings as well as broader implications for the analysis of other sectors in section 5, before discussing our main contributions to the literature and policymaking and practice in section 6.

2. Conceptual framework

The literature on sustainability transitions provides valuable insights when it comes to analysing established socio-technical structures as barriers to the fundamental transformation of unsustainable modes of production and consumption (Truffer et al., 2015; Markard et al., 2012). The literature has its roots within the field of innovation studies (Geels, 2019), where the concept of the ‘technological regime’ was first introduced by Nelson and Winter (1982) to understand how successful technological designs become locked-in to certain development trajectories (David, 1985). Later, Rip and Kemp (1998) emphasised

the embeddedness of technology in societal structures and established a socio-technical systems perspective which portrayed (infrastructure) solutions as “configurations that work”, including not only technological components but also people, processes, and artefacts (Rip and Kemp, 1998, p. 387). Contemporary work in transition studies accordingly often conceptualises sectors as socio-technical systems consisting of configurations of more or less aligned actors, institutions and technologies (Markard et al., 2012; Miörner et al., 2021).

Socio-technical systems are typically characterized by a high degree of stability and a tendency to favour incremental rather than disruptive innovation (Fuenfschilling and Truffer, 2014; Markard et al., 2012). Yet, for a long time, space was neglected in research on sustainability transitions and a failure to account for the globalized nature of the economy left many barriers to sustainability transitions unexplained (Coenen et al., 2012; Truffer and Coenen, 2012; Hansen and Coenen, 2015; Binz et al., 2020). An emerging literature dealing with the geography of sustainability transitions targets this drawback. The GeoST literature explicitly addresses the simultaneously localized and global nature of technology development, the international diffusion of innovations and institutions, and why sustainability challenges faced by regions and cities around the world tend to be similar, despite strong variation in their geo-physical, economic and cultural preconditions (Fuenfschilling and Binz, 2018; Coenen et al., 2012; Binz and Truffer, 2017). Over the last decade, the GeoST literature has been prolific when it comes to explaining the spatial heterogeneity of transitions dynamics, the territorial embeddedness of socio-technical regimes and niches, and the multi-scalar nature of sustainability transitions (Murphy, 2015; Miörner and Binz, 2021).

In our quest to understand the spatial variation of path dependencies, we draw on one of the most fundamental concepts in transitions research, namely the ‘socio-technical regime’, and anchor our conceptual elaboration in recent contributions to GeoST. By teasing out different dimensions of global regimes, we argue that the observed spatial variability in sectoral path dependencies can be attributed to differences in how deeply institutionalized and materialized these dimensions are and how they have diffused and manifest differently across space.

2.1 Global socio-technical regimes

A fundamental claim in transition studies is that sectoral path dependence can be attributed to socio-technical regimes, which reflect the deeply institutionalized formal and informal rules that stabilize development trajectories in a given sector (Kemp et al., 1998; Markard and Truffer, 2008; Geels, 2019). As these rules have co-evolved with a particular technology, they have a highly stabilizing effect on the socio-technical system resulting in path

dependencies and lock-ins (Geels, 2019). Regimes are typically focused on one, or a few, socio-technical configurations, defined as well-aligned sets of actors, technologies and institutions, that together provide a societal function such as water, energy or transport (Geels, 2002). Once a particular socio-technical configuration has become deeply institutionalized in a sector, it is taken for granted by actors who consequently reproduce, maintain, and incrementally improve it rather than introducing or adopting radical alternatives (Fuenfschilling, 2019; Geels and Schot, 2007).

Regimes reproduce stability by exerting mimetic pressures, legal and normative sanctions, and by shaping the legitimacy of established and emerging socio-technical configurations. The stability generated by socio-technical regimes often extends beyond regional and national contexts. Despite very different regional conditions, infrastructure solutions tend to look similar in different parts of the world (Nilsson, 2016; Brook, 2013). Recent contributions have argued that in many sectors, this is due to the existence of ‘global regimes’ (Fuenfschilling and Binz, 2018). Global regimes are defined as *“the dominant institutional rationality in a socio-technical system, which depicts a structural pattern between actors, institutions and technologies that has reached validity beyond specific territorial contexts, and which is diffused through internationalized networks”* (Fuenfschilling and Binz, 2018, p. 739). A global regime thus corresponds to a highly institutionalized socio-technical configuration of actors, technologies and institutions that serves as a globally legitimate ‘template’ (Miörner and Binz, 2021) for establishing infrastructure solutions. Global regime rationalities diffuse across different parts of the world through, for example, international corporate networks and investment flows (Tilsted and Bauer, 2021; Lesch, 2021), standards for technology, processes and management models (Miörner and Binz, 2021), as well as institutional, educational and professional mimicry (Fuenfschilling and Binz, 2018). Diffusion processes result in local routines, practices, standards, and technological choices being increasingly aligned to the global regime (Miörner and Binz, 2021).

The urban water management (UWM) sector provides an emblematic example of a sector with a strong global socio-technical regime (see e.g. Lieberherr and Fuenfschilling, 2016; Fuenfschilling and Binz, 2018). UWM solutions look strikingly similar around the world, with large-scale, pipe-based, water-intensive infrastructure solutions being implemented even in areas of water scarcity, such as China, Africa, and the Arabian Peninsula (Fuenfschilling and Binz, 2018; Nilsson, 2016). However, even in this sector with a strong global regime, some regions and countries are able to deviate from the global ‘gold standard’. In some places, radically different alternatives, such as high-quality on-site sanitation approaches, small-scale water recycling systems or nature-based solutions have been successfully institutionalized (Hacker and Binz, 2021; Gleick, 2003; Hoffmann et al., 2020). While these solutions have not yet seriously challenged the centralized approach globally, they have become

integral part of the sanitation system in territorially delimited contexts, such as cities in India (Reymond et al., 2020) and the US (Hacker and Binz, 2022), or informal settlements around the world (Van Welie et al., 2018).

Seeking to explain this pattern, scholars have explored the role of place-specific conditions that enable radical innovation to emerge (Coenen et al., 2015; Hansen and Coenen, 2015). Studies have focused on 1) the unique characteristics of certain cities, regions and countries, 2) the activities of local actors in experimenting with novel context-specific solutions, and 3) the technological and organizational outcomes of such development processes (Truffer et al., 2015; Simmie, 2012; Steen and Hansen, 2018). The core argument in this strand of literature is that under specific context-specific conditions, alternative solutions can develop *despite* the lock-in effects of established (global, national, regional) regimes. It then follows that endogenous innovation capacity, the capacity to anchor resources from other regions (Miörner and Trippl, 2019; Trippl et al., 2018), or strategies aimed at shielding a region from global regime pressure (Miörner and Binz, 2021) are key determinants of whether, where and how transformative innovation occurs.

Thus, even if we assume that the regime in a particular sector is globalized, variations in local preconditions ought to give rise to differences in the isomorphic pressure, or 'spatial reach', of the regime. In other words, the extent to which a global regime has materialized into physical infrastructure, the extent to which global regime actors are present, and the extent to which global institutions have been adopted or copied locally, may vary between spatial contexts and explain where deviant action is more or less likely. For example, a lack of financial resources may prevent the construction of large-scale infrastructure, protectionist economic policy may inhibit global actors from entering a specific national context, or a peripheral geographic location may result in countries and places being 'forced' to diverge from the global regime.

This does not mean that the global regime has no influence in such contexts. On the contrary, the 'go to' solution offered by the global regime may still play an immense role in defining legitimate trajectories and shaping the envisioned 'end goal' for actors engaged in infrastructure development. Its influence, however, may range from this (cognitive, normative) structuring effect to more direct effects of the global regime having been translated into material infrastructure (technology), international networks of regime proponents (actors), and standards, norms and policies (institutions). In this paper, we argue that the degree to which these three dimensions have developed differently across spatial contexts are relevant indicators for the strength of a global regime in particular places.

2.2 Key dimensions of global path dependency

Concepts drawing on a socio-technical system perspective (i.e. Technological Innovation Systems, the Multi-Level Perspective, Strategic Niche Management literature, etc.) largely concur that the basic elements of those complex systems consist of technologies and material artefacts; actors and their networks; and institutions (Kemp et al., 1998; Geels and Turnheim, 2022; Markard and Truffer, 2008). The path dependencies that emanate from (global) regimes can accordingly be distinguished along these three dimensions. In the remainder, we will first define each of these three dimensions in detail and then develop a typology of how they may interact in different spatial contexts, resulting in stronger or weaker regime influence.

Technology refers to “entities, both material and non-material, created by the application of mental and physical effort in order to achieve some value” (Bain, 1937). Technology embodies knowledge, values and beliefs and can take both non-physical/abstract (e.g., blueprints, models, processes) and material (products, tools, machines) forms. In infrastructure sectors, the most apparent manifestation of technology is its materialization in physical infrastructure in the built environment, such as grids, power plants, treatment facilities or road networks. One of the most striking features in infrastructure sectors is that low, sometimes virtually non-existent, spatial variation exists in the core technologies and their design and implementation across different countries and regions, despite substantial differences in geophysical and institutional preconditions (Brook, 2013).

The existence of material infrastructure that reflect the dominant rationality of the regime creates network effects and increase the costs associated with adopting a new technology, by the need of complementary investments and learning that negatively influence the diffusion of innovations not in line with the regime (Hall, 2004). Having adopted a regime technology thus severely limits the opportunities for local innovation processes, as well as the adoption of innovation developed elsewhere (Geels, 2019). Consequently, if the dominant institutional rationality of the regime has become embodied in material infrastructure, the regime’s influence is arguably higher than if the corresponding infrastructure has not (yet) been constructed.

Actors are typically defined at the level of organizations that are involved in provision of societal functions. They include, but are not limited to, firms, universities, governments and their agencies, end users, utilities, and various intermediaries, such as industry- or cluster organisations, and NGOs (Rip and Kemp, 1998; Geels, 2002; Bergek et al., 2008; Kanda et al., 2020; Kivimaa et al., 2019; Bergek, 2020). Understanding the networks that span between these actors, especially the ones that have an interest in reproducing regime solutions, such as MNCs, big consultancy firms, utility companies, etc., is crucially

important to understand how global regimes evolve, get reproduced and diffused across the world (Lesch, 2021; Miörner et al., 2022a). However, networks between global regime actors do not extend uniformly across space. For example, corporate networks tend to be spatially concentrated in a selection of countries (Lesch, 2021; Yang and Dong, 2016; Tilsted and Bauer, 2021). Hence, we argue that global regime influence is higher in spatial context that are (relationally) 'within reach' of global regime actors, in terms of their linkages with local (subsidiary or partner) actors, or through investment flows and/or influence over local decision makers.

Institutions, finally, refer to the regulative, normative and cultural-cognitive 'rules of the game' in a sector (Scott, 2008) that are manifest as laws, policies, norms, values, etc. in different contexts and at different spatial scales (Zukauskaitė et al., 2017; Bathelt and Glückler, 2013). Institutions shape local selection environments and may be more or less aligned with the dominant rationality of the global regime. Institutions have a strong structuring effect on technology choices and innovation activities in a particular national or regional context, even when physical infrastructure and/or actors that are aligned with the global regime are not present (Fuenfschilling, 2019). Under conditions of high uncertainty, actors tend to engage in routinized and imitating behaviour (DiMaggio and Powell, 1983), looking for templates in other places (or at the global level) to copy from, leading to a harmonization of laws, regulations, norms or behaviours, across territorial contexts. We argue that the adoption of standards, laws, policies and other institutions that reflect the global regime increases its strength and mimetic pressure in a given spatial context, independent of the degree to which other regime dimensions have materialized locally.

2.3 Towards a typology of regime strength in different territorial contexts

The elaborations above imply that regime strength in a given territorial context can be proxied by the strength of path dependencies in the three foundational dimensions. One key distinction to be made upfront is between territorial contexts where the dominant regime technology is already materialized in physical infrastructures (e.g., high-income countries with well-established energy, water or transport networks (Tab. 1) and those contexts where infrastructure is missing or depending on solutions that deviate from the regime (e.g., some low- and middle-income countries (Tab. 2). In the remainder, we will first discuss the former, which tend to have higher path dependencies, and then cover the latter, which – at least in principle – offer more inroads for divergent action. While we will analyse global regime strength at a country level, our framework could in principle be applied to any other spatial scale, as well as for understanding differences within territorial contexts (e.g., the rural/urban divide, East/West Europe, etc.).

Table 1 accordingly outlines four country profiles that exist in cases where infrastructure has already been built up. As material path-dependencies are given in these cases, we distinguish four ideal-types based on the presence of regime actors and their networks (actor dimension) and their alignment with institutions in the global regime (institutional dimension). Quadrant 1 then describes countries with the strongest conceivable path dependencies, while Quadrant 4 describes the lowest possible path dependency for places with existing regime infrastructure. Quadrants 2 and 3 lie in between.

Table 1: Typology of countries with well-developed physical infrastructure

Presence of regime actors	Institutional alignment with global regime	
	High	Low
High	1. Regime leader	2. Transitioning regime leader
Low	3. Regime steward	4. Transitioning regime steward

Source: own elaboration.

Quadrant 1 relates to countries in which the global regime rationality is strongly manifested in all three dimensions. These are typically countries that pioneered the development of regime solutions, giving actors, technologies and institutions a lot of time to co-evolve and align. These *regime leaders* (Quadrant 1, Tab. 1) are thus deeply entrenched in the dominant regime structure, in terms of an extensive use of the core technologies, a high presence of regime actors, and institutions that strongly favour the regime. Quite often, local firms, consultants and intermediaries have turned into global lead actors in the respective sector and thus have a strong stake in reproducing the regime trajectory. The transition potential in such countries is arguably very low.

Quadrant 2 refers to countries where regime actors are present, but where some local actors (e.g. governments, authorities, or civil society groups) have developed an awareness of the inadequacies or weaknesses of the global regime solution. In such '*transitioning regime leader*' contexts (Quadrant 2, Tab. 1), physical infrastructures and actor networks are regime-dominated, but institutional structures have started to diverge from the status quo, not seldom motivated by visions of (and experiments with) radically alternative niche solutions. In parallel to active experimentation with alternatives, cracks within the regime might also support deviant action. This may happen when the high investment needs of ageing infrastructure systems become visible, or exogenous developments (e.g., environmental catastrophes, climate change, etc.) reveal the inherent limitations of the current regime solution.

A third type are *regime stewards* (Quadrant 3, Tab. 1). This ideal type refers to contexts that are not deeply embedded in the actor networks of the global regime, but which still largely emulate the dominant global regime rationality. These countries have, early or more recently, successfully developed their

infrastructure systems without involving global actors in local infrastructure development. This is typically achieved by copy-pasting a global regime template, in terms of dominant technologies and institutional set-ups, yet by drawing heavily on local actors. Institutions, in terms of laws, standards and regulations, but also norms and visions, are thus aligned solidly with the dominant regime, while actors are more 'domestic'. Despite the absence of global regime actors, they thus feature relatively strong path dependencies.

Fourth and finally, there are contexts where physical infrastructure has been implemented, but where global regime actors are not present and the institutional alignment with the regime is weak or quickly dwindling. The most salient example here are countries with high re-investment needs in conventional physical infrastructure, but limited political will to do so, as is the case, for example, in some states of the former Soviet Union or the US. The transformative potential in such *transitioning regime stewards* (Quadrant 4, Tab. 1) is arguably the highest among all contexts with pre-existing infrastructure, as the limitations of global regime solutions are highly visible and niche actors enjoy little competition with global regime actors. However, the lock-in effects of sunk investments and cognitive lock-ins resulting from a history of having benefited from regime technologies should still not be underestimated. In order to fully exploit endogenous innovation capabilities, such countries would arguably still have to create protective spaces that allow nurturing alternative infrastructure solutions and gradually realigning their institutional environments to allow for transformative innovation.

Table 2, in contrast, describes the types of path dependencies to be expected in contexts where physical infrastructures have not yet been successfully developed or are virtually non-existent, cover only parts of the country (e.g., urban centres), and/or are implemented based on technologies that diverge from the global regime. Interestingly, the literature shows that in many low- and middle-income countries, despite the absence of material and technological lock-ins, key decision makers are still highly committed to implementing 'conventional' global regime solutions (Nilsson, 2016; Fuenfschilling and Binz, 2018). The concrete types of 'regime' actors also differ slightly in these settings. In addition to private actors such as MNCs or engineering consultants, also development agencies, development banks and NGOs often play a key role in infrastructure development (Bardouille, 2012; Blowfield and Dolan, 2014). While these actors are highly diverse in scale and scope, they also tend to diffuse the status quo rather than promoting highly innovative and transformative solutions (Nilsson, 2016; Gambrell et al., 2020). As in the four types discussed above, path dependencies may be explained with the presence of global regime actors and/or institutional mimetic pressures. Here as well, four ideal-type situations may be distinguished.

Table 2: Typology of countries without physical infrastructure (own elaboration)

Presence of regime actors	Institutional alignment with global regime	
	High	Low
High	5. <i>Regime follower</i>	6. <i>Regime distractor</i>
Low	7. <i>Regime aspirant</i>	8. <i>Regime dissident</i>

Source: own elaboration.

First, *regime followers* (Quadrant 5, Tab. 2) are actively seeking to attract global regime actors to solve their infrastructure problems and have institutions that strongly favour the rationality of the global regime. It is thus unlikely that these countries will diverge from global ‘best practices’, despite potential mismatches between dominant regime solutions and place-specific conditions. Various low- and middle-income countries around the world try to solve their local problems by turning to external actors and their global templates. Yet, many of them also fail to fully harness the potential of prevailing global solutions and are left with “ever-developing” infrastructure systems that do not seem to deliver on their promises (Nilsson 2016; Gambrill et al. 2020).

Regime distractor Quadrant 6 (Tab. 2), describes a variation of the previous type, in which global regime actors are present, but the institutional context, in terms of policy priorities and directionality, is not strongly aligned with the global regime. The local presence of global regime actors per se does not point to a strong transformative potential. Yet, if the mismatch between local needs and conventional solutions becomes obvious (Miörner et al., 2022a) and the institutional framework is actively promoting experimentation with alternative designs, regime actors may be pushed into more actively exploring alternative configurations and thereby reorient their main investment and R&D strategies (Sotarauta et al., 2021). Regime distractor contexts may also provide testbeds for divergent solutions developed elsewhere and induce learning effects for the further diffusion of niche technologies.

Third, countries can also be characterised by an absence of both regime actors and physical infrastructure, but still strive to eventually go for the global regime solution. In such *regime aspirant* contexts (Quadrant 7, Tab. 2), key stakeholders (e.g. public utilities or governments) may have strong faith in the superiority of the regime solution without relying on global regime actors for supplying knowledge and implementation support. This puts them in a peculiar situation, being institutionally aligned with the regime and thus on a path dependent trajectory, while lacking the resources, endogenous capabilities, and/or international linkages to implement conventional infrastructure. In other words, the institutional set-up defines a narrow technological trajectory (which may or may not be suitable given place-specific conditions), but networks and means to realise it are lacking, leading to highly fragmented coverage and failing systems

without working alternatives. Many low- and middle-income economies tend to be trapped in this situation for extended periods of time (Nilsson, 2016).

The eighth and final type in our typology are *regime dissidents* (Quadrant 8, Tab. 2). They are characterized by an institutional environment which is not aligned with the global regime, combined with weak presence of global regime actors. These contexts arguably contain the lowest conceivable path dependencies, which makes them very interesting from a transition point-of-view, as they provide significant degrees of 'structural freedom' (Pike et al., 2016) for experimenting with solutions that diverge from the global regime. Regime dissidents are typically low- and middle-income countries, possibly with high rates of rural-urban migration. Despite not being institutionally or technologically locked-in to regime structures, they however often also lack technological, institutional and organizational capabilities for developing transformative innovations. For implementing innovative infrastructure solutions, they thus tend to depend on strong policy support and/or linkages to actors in niches in other parts of the world.

The above discussion shows that spatial contexts differ substantively in the degrees of global path dependencies and in the opportunities to diverge from them. In the remainder, we will operationalize the above typology and apply it to the global water sector to further illustrate and substantiate our main conceptual points.

3. Case selection, methodology, data

In this section, we first present our case selection rationale and a set of indicators for measuring and mapping regime strength in the technology, actors, and institutional dimensions. We then introduce the data and indicators used to map the spatial variability of the global regime in urban water management (UWM).

3.1 Case selection: Global regime of the water- and sanitation sector

Previous studies have shown that the global water- and sanitation sector exhibits a particularly strong global socio-technical regime (Lieberherr and Fuenfschilling, 2016; Fuenfschilling and Binz, 2018; Miörner et al., 2021). Across the world, UWM is characterized by a strikingly narrow set of physical infrastructure, technologies, actor roles and professional identities, organizational set-ups and core values. UWM solutions typically revolve around large-scale, investment-intensive infrastructure, piped networks and centralized treatment facilities operated by utility companies (Larsen et al., 2016). Over the last 100 years, the conventional UWM approach has become taken-for-granted across countries and contexts with substantially different local and regional preconditions (Nilsson, 2016; Gambrill et al., 2020).

At the same time, the ‘centralized’ UWM paradigm has also failed to deliver on its promises in many contexts, especially in many low- and middle-income countries or in developed economies with strong water scarcity problems. Alternative solutions, such as off-grid, small-scale and hybrid water reuse systems, are thus increasingly promoted as a more flexible, adaptable and potentially sustainable approach than centralized systems (Hoffmann et al., 2020). ‘Pockets’ of transformative innovation thus exist in contexts as diverse as California, India, Kenya or Australia. In some countries, de-centralized UWM solutions are even getting legitimized in parallel with conventional ones, thus inducing polycentric or splintered regime structures (Heiberg et al., 2020) (van Welie et al. 2018). The sector thus features a strong global regime and considerable spatial variation and divergent action in parallel. As such, the global UWM sector represents a ‘critical case’ (Flyvbjerg, 2006) for testing the applicability of our framework – if the framework can capture spatial variation of global path dependencies in a sector with very high degrees of path dependencies and spatial variation, it illustrates the potential of this type of analysis also in other infrastructure sectors.

3.2 Indicators: Methodology and data

Below, we present our methodological approach for assessing the strength of the global regime using our three analytical dimensions from section 2. We first discuss our approach to operationalization in general and then explain which concrete data sources and indicators were used to analyse the spatial variability of the global UWM regime. Details on the derivation of the indicators and the data on which the case study is based can be found in Appendix A.

3.2.1 Technological dimension

The technological dimension of a regime is most evident in the physical infrastructure and technologies that are used to provide societal functions. As discussed above, many infrastructure sectors rely on particularly long-lived and capital-intensive assets and technologies that hinder transformative change (Markard, 2011).

To assess the extent to which a spatial context is covered by infrastructures and technologies associated with the global regime, it is first necessary to identify the *material basis* on which a sector relies to provide its societal function. For example, transport services are provided, among others, through car- based mobility, which relies on built infrastructure such as road networks, highways, gas stations and specific technologies such as cars, traffic control devices and navigation aids. The second step is then identifying appropriate indicators for the *coverage* with these infrastructural and technological elements in a given spatial context. Using the example of car-based mobility, the length of the road network, the stock of road vehicles, and new registrations of passenger cars

might be suitable indicators.

In UWM, grid infrastructure is the core element of the global regime, with investments in pipes and sewers accounting for 70-80% of the infrastructure costs and thus the sector's core lock-in effects (Hoffmann et al., 2020). Connection rates to piped water supply and sanitation networks are therefore a suitable proxy indicator for this type of path dependency. In this paper, we rely on data from the WHO/UNICEF Joint Monitoring Project on water supply, sanitation and hygiene (World Health Organization, 2021) for assessing this indicator. The latest data are available for 2020 and cover 198 countries (water supply), and 196 countries (sewerage connections), respectively.

3.2.2 Actor dimension

When assessing the spatial variability of the global regime in the actor dimension, our interest lies in identifying (networks of) actors that are involved in the provision of societal functions through 'regime' infrastructures and technologies. This means tracing the networks of incumbent actors that have the highest stakes in reproducing and diffusing the sector's core technologies and infrastructure designs.

As a first step, it is therefore essential to identify (a selection of) *key actors* involved in the dissemination of regime solutions within a sector, e.g., based on a literature review, interviews with sector experts or a stakeholder analysis. Stakeholder identification should lead to a list of core incumbents, such as (multinational) companies, consultants, investors, donors, associations, or even universities. The second step is then to define indicators that make it possible to examine their *spatial reach* in terms of their physical presence (e.g., through subsidiaries, representation in decision-making bodies, etc.) or their intangible influence (e.g., through development assistance, advisory activities, etc.). Among other approaches, relational methodologies such as social network analysis (Wasserman and Faust, 1994) or socio-technical configuration analysis (Mörner et al., 2022b) can be particularly useful for this purpose.

Considering that MNCs, transnational investment flows and engineering consultants play a very important role in the UWM sector (Swyngedouw et al., 2002), we decided to use corporate actors and the spatial reach of their subsidiary network as a key proxy indicator here. Based on a purposive sampling approach (Etikan et al., 2016), we used two lists compiled by experts and two stock indices to generate a list of 54 MNCs that jointly represent the water sector's key regime incumbents¹. We then extracted data for the majority-owned subsidiaries of these 54 companies from the Orbis database (September 2022), resulting in a sample of 12,425 subsidiaries located in 122 countries. In the results section, we present the corporate network of the UWM sector's key MNCs and assess its spatial distribution in terms of the number of subsidiaries

per 100,000 inhabitants in a given country.

This analysis was complemented with an examination of international aid flows in terms of bilateral official development assistance (ODA), since in low- and middle-income countries, MNCs are often not present and thus not the only and/or most important actors influencing infrastructure development. Donors and development banks (like the World Bank, Asian Development Bank, Water Aid, Bill and Melinda Gates Foundation etc.) play a much more important role here. For a long time, these actors have actively promoted the conventional, capital-intensive UWM infrastructure models of the Global North, thus diffusing the global regime across the Global South (Nilsson, 2016; Lesch et al., 2022). Donor interventions, just like MNC involvement, may therefore hinder radical innovation (Wieczorek, 2018). As a proxy for donor interventions, we used data for the average amount of bilateral aid per year from 2011 to 2020 from the OECD's International Development Statistics database (OECD, 2022), which contains data for 144 countries.

3.2.3 Institutional dimension

Measuring spatial variability in the institutional dimension, finally, is most challenging, as institutions are multi-layered and include both formal and informal regulatory, normative, and cognitive elements. If the rules, norms and beliefs associated with the global regime are deeply institutionalized in a spatial context, local actors will follow the regime's trajectory, even if it has not (yet) built physical infrastructure or attracted global regime actors. Transformative change can therefore only be expected if the dominant global rationality is not present or institutional arrangements exist that fundamentally challenge the global regime (Kern, 2011).

Different methodological inroads exist for conducting institutional analysis. For example, formal institutions can be assessed based on an identification of policies, laws, regulations, and norms that are associated with the global regime and a subsequent examination of their diffusion across spatial contexts. In relation to car-based mobility, one might examine, for instance, the introduction of fossil fuel subsidies in the automotive sector (e.g., diesel subsidy) or automobile use in general (e.g., commuter subsidies). In contrast, the scope of informal institutions such as norms, habits, and customs can be investigated using discourse analysis methods, as language is not only crucial for the construction of reality, but also constrained by existing institutions (Kern, 2011; Fuenfschilling and Truffer, 2014; Yuana et al., 2020). In this regard, discourse network analysis (Leifeld, 2013) or socio-technical configuration analysis (Heiberg et al., 2022; Miörner et al., 2022a) provide useful inroads for analysing how institutional structures associated with different technologies vary across spatial contexts.

In the water sector, institutions are diverse and include formal regulations (e.g., environmental standards), cultural/normative norms (e.g., associations between the flushing toilet and the concept of modernity, and the “yuck factor” associated with water reuse) and cognitive frames (e.g., engineering curricula) (Hoffmann et al., 2020; Nilsson, 2016). Given that the water sector typically relies on an entrenched combination of these “taken-for-granted” institutions, we decided to trace this dimension with two distinct proxy indicators.

First, we draw on the approach and data of Heiberg et al. (2021) who examined how organizations evaluate traditional and alternative UWM technologies and related infrastructural and institutional elements in newspaper articles. The authors extracted 563 articles from over 180 English-speaking newspapers from LexisNexis in the period 2011 - 2018, and coded statements, which endorse or challenge the dominant regime solutions in UWM. Using the data of Heiberg et al. (2021), we here focused on the target audience of each coded newspaper article and counted the absolute number of narrative events that legitimize or de-legitimize traditional vs. alternative UWM infrastructure solutions in a country. We calculated the share of narratives endorsing traditional UWM infrastructures and used it as an indicator of global regime strength in countries with sufficient data (≥ 10 narrative events per country), which led to a coverage of 18 countries.

This exploration of discursive activities was complemented with an examination of countries' engagements in the development of technical standards for conventional and onsite/decentralized UWM technologies. Technology standardization is a good proxy for normative institutional dynamics, as standards guide the development of sectors by defining the most legitimate technologies and future problem-solving routines (Miörner and Binz, 2021; Smink et al., 2015). The process of standardization is not only technical (Smink et al., 2015), but also highly political, as it maintains, creates, or disrupts a sector's core technological trajectories and institutional logics (Lawrence and Suddaby, 2006; Fuenfschilling, 2019).

In this paper, we assess whether countries were predominantly involved in the elaboration of global ISO standards for onsite/decentralized UWM technologies, conventional UWM technologies, or both. We focused on a subset of ISO committees (one technical committee, two sub-committees and two project committees, for more details see the Appendix) concerned with standard-development for UWM systems, i.e., centralized/decentralized drinking water, wastewater, stormwater and urban water reuse systems and related services. We then examined country membership in these committees using information available at the website of the International Standardisation Organisation and American National Standards Institute.² We then assigned the 42 standards developed in these committees to either conventional, regime-related UWM technologies (37) or onsite/decentralized

UWM technologies (5). Based on the information on the participation of country representatives in the elaboration of the 42 standards, we developed an indicator, which demonstrates whether countries participated more strongly in the elaboration of conventional or onsite/decentralized UWM technologies. A normalized indicator was then constructed for assessing countries' focus in technology standardization processes (see Appendix A). Negative values indicate a tendency to engage more with alternative UWM technology standards, while positive values indicate that countries are more active in standardizing conventional regime solutions. In sum, we obtain results for 85 countries from this indicator.

4. Results

Table 3 gives an overview of the descriptive statistics for each of our indicators. In the remainder we will first explore and globally map the indicators for those three dimensions in more detail. We then use four country examples (Netherlands, Israel, India and Kenya) to illustrate in depth how the three dimensions jointly condition global regime influence in a given country.

Table 3: Descriptive statistics for the indicators assessing the spatial variability of the global regime.

	n	Min	Max	Median	Ø
Technology dimension					
Share of Population with Piped Water Supply (2020) ^a	198	0.04	1	0.89	0.75
Share of Population With Sewer Connections (2020) ^a	196	0.10	1	0.42	0.44
Actor dimension					
Average Bilateral Development Aid to the Water Sector Per Capita in \$US (2018) (2011 – 2020) ^b	144	0.00	175.88	1.33	6.50
Number of MNC subsidiaries per 100,000 Inhabitants ^c	122	0.00	12.85	0.08	0.71
Institutional dimension					
Share of Narrative Events (≥ 10) Favorable towards centralized UWM (2011 – 2018) ^d	18	0.1	1	0.62	0.63
Participation in Water-Related ISO-Committees (2022) ^e	85	-0.44	0.4	0	-0.03

Sources: a) WHO Joint Monitoring Project on Water Supply, Sanitation and Hygiene – World Health Organisation (2022); b) OECD (2022); c) ORBIS; d) coded newspaper articles derived from NexisUni, based on the data and classification of Heiberg et al. (2020). e) International Standardization Organisation & American National Standard Institute.

4.1 Global regime variation

4.1.1 Technology dimension

Figure 1 shows how piped water coverage ranges from 4.35 percent in Liberia to 100 percent in 54 countries. While near full coverage (>80%) is achieved in several world regions, particularly in Northern America and Europe, much lower coverage levels are observed in West, East and Central Africa, as well as South- and Southeast Asia. 17 countries largely lack any piped water- and sanitation infrastructure (connection rates as low as 0.1%). With a few exceptions (such as Botswana and Thailand), piped water coverage generally correlates with percentage of a country's population connected to a sewerage system (Figure 2).

Figure 1: Access to piped water supply, share of population. Source: own design based on data from the WHO Joint Monitoring Project on Water Supply, Sanitation and Hygiene (2020). Map data: Department of Human Geography, Lund University.

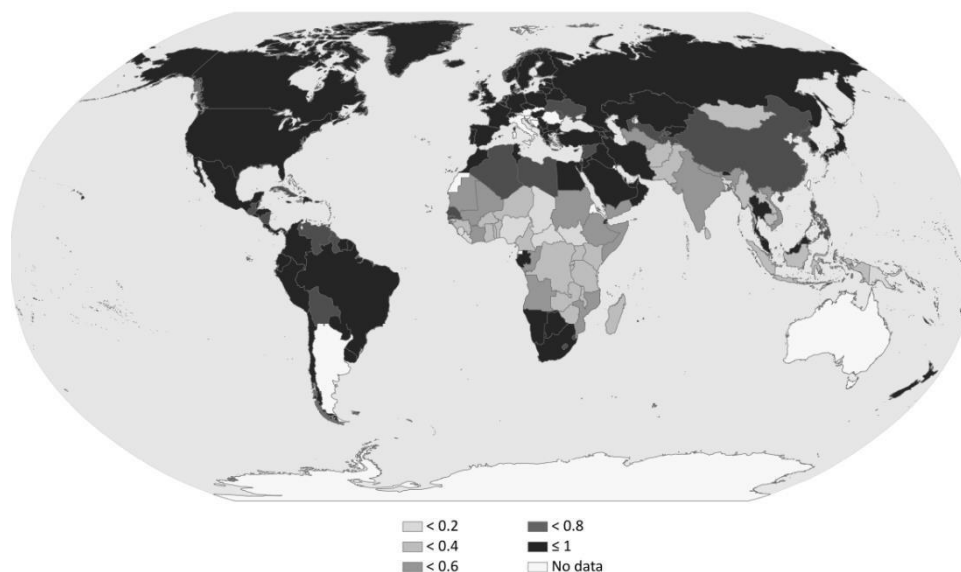
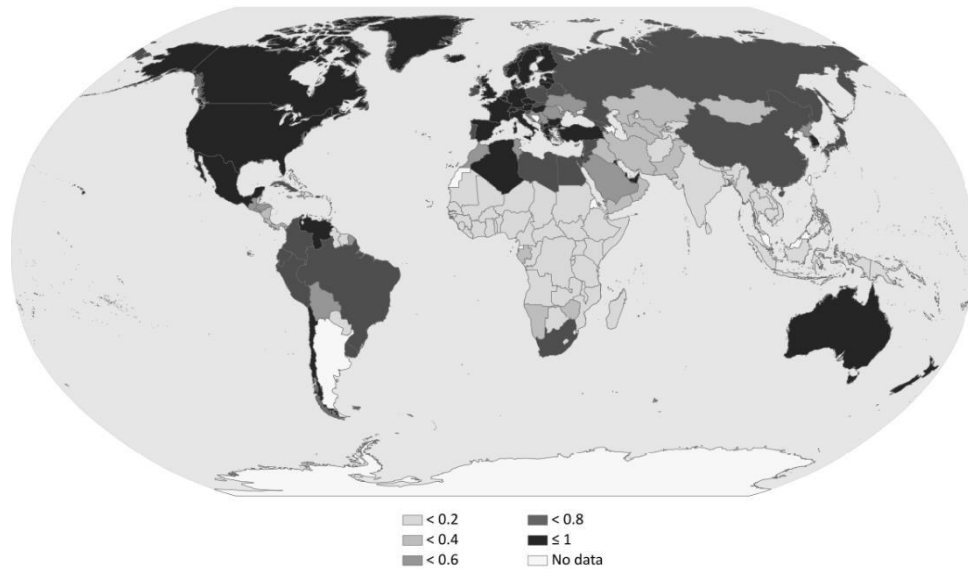


Figure 2: Access to sewerage connections, share of population. Source: own design based on data from the WHO Joint Monitoring Project on Water Supply, Sanitation and Hygiene (2020). Map data: Department of Human Geography, Lund University.



4.1.2 Actor dimension

Figure 3 illustrates the global network of major MNCs and their subsidiaries in the water sector. Overall, it shows that the corporate network of the global regime spans 122 countries, with corporate presence varying widely from one (e.g., Bangladesh) to 2931 (US) subsidiaries in a country, which corresponds to a range of 0.0005 to 12.85 subsidiaries per 100,000 inhabitants. This shows the pervasiveness of the global regime in the water sector and the wide spatial reach of its core actors.

Figure 3 furthermore illustrates which companies from which countries are most influential in diffusing regime rationalities across the globe. Considering the *out-degree* of different countries, i.e., the number of subsidiaries established abroad by MNCs of the respective countries, German (2560), French (2352), US (2428) and Spanish MNCs (1870) appear to be most influential in diffusing global regime solutions. These countries are also highly integrated into the corporate network when looking at the number of subsidiaries in each country, i.e., the so-called *in-degree*. Most of the subsidiaries of the companies in our sample are located in the US (2931), Germany (1837), Spain (936), and the UK (916). However, countries where no major water multinational are headquartered are also closely integrated into the water sector's corporate network. These include Australia (*in-degree* of 416), the Netherlands (291) and Poland (257). In addition,

Chinese multinationals are increasingly active in diffusing global regime solutions, not the least in East Asia and Australia.

According to the discussion in section 3.2.2, MNC networks should be complemented with an indicator for donor involvement, to also cover the influence of regime actors in low- and middle-income countries in Latin America, Africa and Asia. Figure 4 shows that 144 countries, some of which are not part of the corporate networks, may be influenced by the global regime through donor involvement. In general, countries are either hosting subsidiaries or receiving aid, but some countries - especially the BRICS countries, apart from Russia - are characterized by the presence of both MNCs and development banks, thus getting 'double' outside influence from MNCs and donors.

Figure 3: Corporate network in the water sector. Figure shows the corporate network of the MNCs by illustrating the headquarter-subsidary links between countries. The figure also shows the outdegree, i.e., the yellow node, to illustrate how many subsidiaries the MNCs of a country have established elsewhere, and the indegree, i.e., the size of the red node, indicates how many subsidiaries have been established by foreign actors in a country. Source: own design based on data from ORBIS, indicators calculated by the authors. Map data: Department of Human Geography, Lund University.

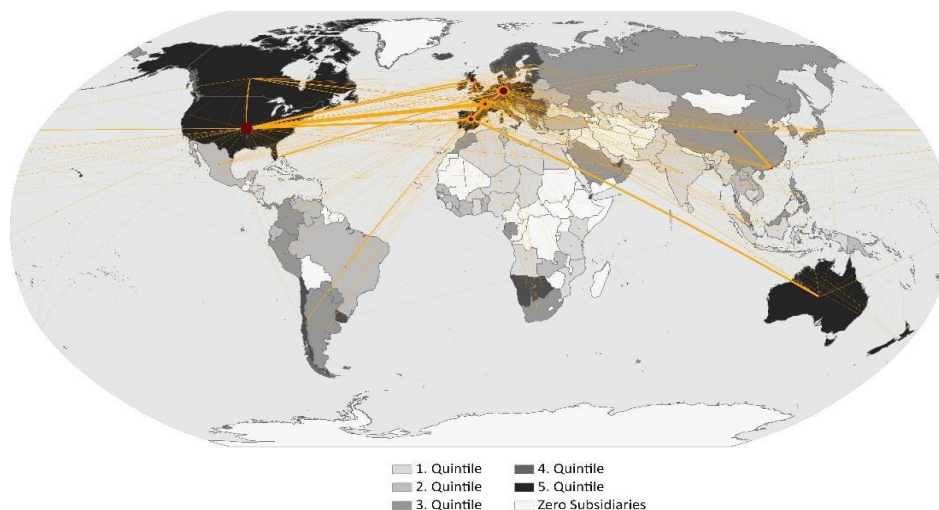
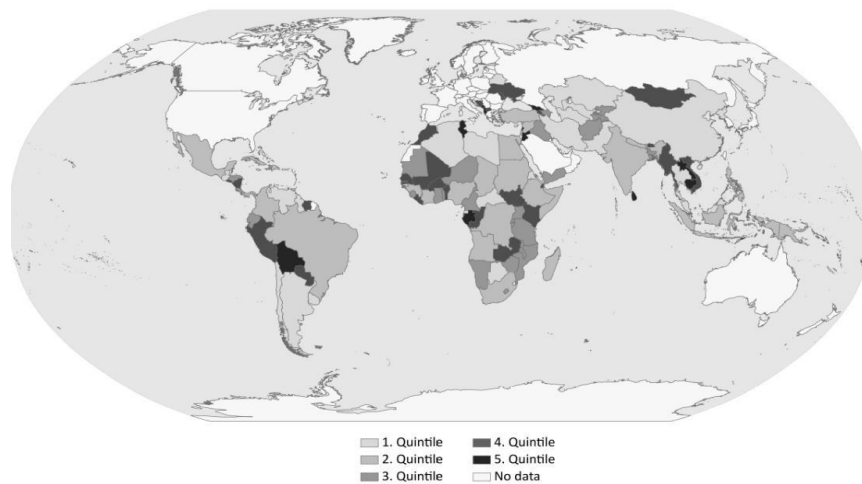


Figure 4: Average bilateral development aid to the water sector. Figure shows the average bilateral development assistance to the water sector received by countries per capita from 2011 to 2020. The classification of the data illustrates the distribution of financial assistance in terms of quintiles. Source: own design based on data from OECD.stat. Map data: Department of Human Geography, Lund University.



4.1.3 Institutional dimension

Figure 5 illustrates the UWM-related discourse captured for 18 countries, demonstrating that the share of narratives supporting conventional UWM solutions differs strongly between countries. Interestingly, in some countries that are quite locked into the global regime in the actor and technology dimension, the discourse is characterized by a substantial share of narratives favouring modular UWM, including the Netherlands (36%), the US (41%) and Canada (43%). Equal and slightly higher shares of favourable narrative towards modular UWM are also registered for countries with a lower level of material infrastructure, as can be seen in the example of India (48%) and Kenya (43%).

Complementing Figure 5, Figure 6 shows that 30 of the 85 countries examined were strongly involved in developing standards that deviate from the global regime configuration. These are primarily low- and middle-income countries in Southern Africa and Southern and Eastern Asia. However, some countries in the Global North, such as Italy and Switzerland, also appear to be actively involved in setting global standards that diverge from the regime. In contrast, 35 countries are mostly focused on developing conventional UWM standards, including many high-income countries such as Sweden and Israel, but also low-income countries such as Zimbabwe. Finally, a group of 20 countries are involved in standardizing both onsite/decentralized and conventional UWM

solutions. This group includes pioneers in the water sector such as France, Germany, and Japan, as well as countries without extensive physical infrastructure such as Kenya and India.

This section has given a bird's view of the spatial variability of the global regime in the water sector in our three analytical dimensions. In a next step we will explore in more depth, how the interplay of these three dimensions leads to different forms of path dependencies in countries that represent the ideal-types of our analytical framework. To that end, we will discuss in depth the indicators and sector development dynamics in four illustrative cases, namely the Netherlands, Israel, Kenya and India.

Figure 5: Share of discourse endorsing centralized UWM infrastructure. Figure illustrates the share of narrative events published in English-language media between 2011 and 2018 that favor centralized UWM solutions. Source: own design based on coded newspaper articles derived from NexisUni, based on the data and classification of Heiberg et al. (2020).

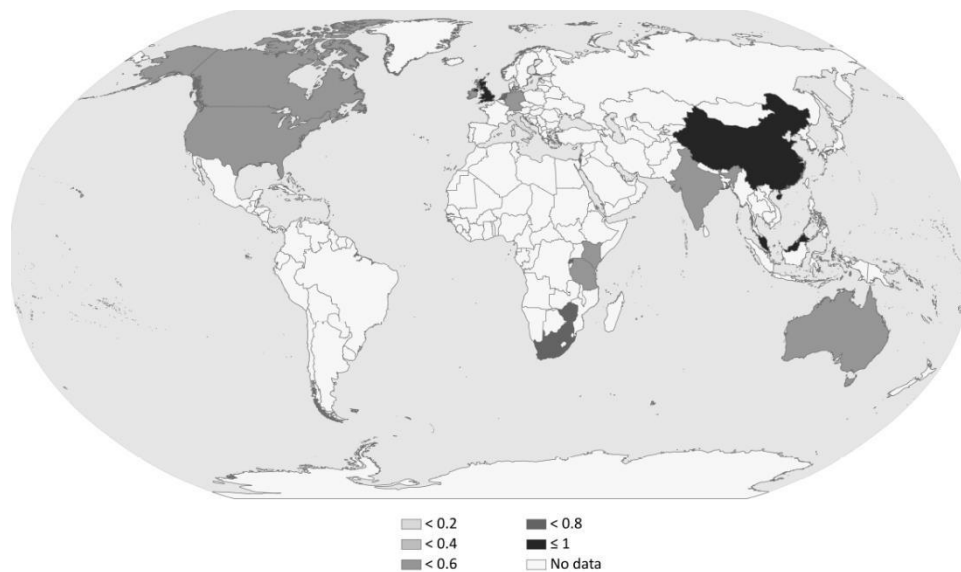
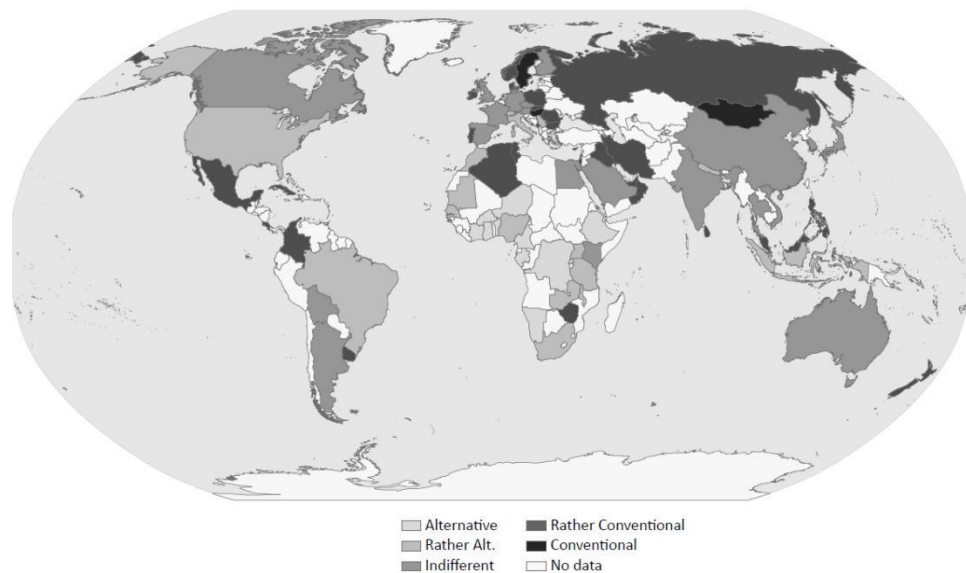


Figure 6: Tendency to engage in ISO committees elaborating alternative or conventional UWM standards. Figure shows whether countries were involved in the development of alternative or conventional UWM technology standards through their participation in the respective ISO committees. Source: own design based on data from the International Standards Organization and American National Standards Institute websites, December 2022.



4.2 Assessing ideal-type countries' path dependencies in more depth

For each of the four countries we first assess regime strength based on a classification of our indicators according to a five-point scale, with one indicating weak and five indicating strong global regime influence in the respective dimension. Classifying the data for each indicator into the same number of classes allows not only for a systematic comparison of the data across dimensions, but also for plotting overall regime strength using radar plots (detailed information about the classification of the data can be found in Appendix A). We furthermore supplement our country characterization with evidence from academic and secondary literature to triangulate our proxy indicators to ensure an adequate picture.

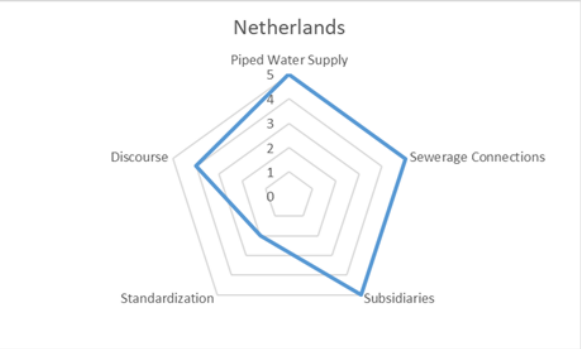
4.2.1 Countries with material infrastructure

Regime leader: the Netherlands

The Netherlands is an emblematic example of a global *regime leader* in UWM (see Tab. 4). The regime is very strong in the technological and actor dimensions; 100% of the population has access to piped water and sewerage systems, and subsidiaries of foreign MNCs are widely present in the country. While drinking

water pipes were already in place in the Netherlands in the 19th century, public health considerations led to the gradual introduction of sewerage infrastructure in the first half of the 20th century (Geels, 2002; Ampe et al., 2021). As a result, regime technologies, actors, and institutions had a long time to co-evolve and align with each other, which led to the development of strong and multinational regime incumbents. Today, the Dutch UWM sector forms a key part of the global UWM regime.

Table 4: Global regime strength in the Netherlands.

Indicator	Value	Score	
Share of Population with Piped Water Supply	1	5	
Share of Population with Sewer Connections	1	5	
Average Bilateral Development Aid to the Water Sector Per Capita in \$US	N/A	N/A	
Number of Subsidiaries per 100,000 Inhabitants	1.69	5	
Share of Narrative Events (10) Favorable towards centralized UWM	0.64	4	
Tendency to participate in ISO committees developing standards for conventional water technologies	-0.23	2	

Source: own elaboration based on the data presented in section 3.

Yet, in contrast to the technological and actor dimensions, regime strength is less pronounced in the institutional dimension, with alternative, on-site UWM technologies being favourably framed in 36% of the analyzed media discourse. Dutch actors also engage more strongly in the development of ISO standards for onsite/decentralized UWM technologies than for conventional solutions. This is in line with the findings of Ampe et al. (2021) who note that in the 1990s, an awareness of the inadequacies of large-scale centralized wastewater treatment plants emerged in the Netherlands, resulting in the development of a movement advocating for alternative small-scale wastewater treatment and reuse projects. As such, even though the physical infrastructure and actor networks are still dominated by the rationalities of the global regime, the institutional structures, core discourses, and standardization activities are

beginning to diverge from the status quo, pointing in the direction of the Netherlands becoming a *transitioning regime leader*.

Secondary literature reveals that scientists increasingly engage in research on decentralized water treatment systems, and enter the UWM sector with commercial spin-offs (Ampe et al., 2021). The National Institute for Applied Water Research also increasingly looks for ways to make the Dutch water sector more resilient to climate change (Heiberg and Truffer, 2022), resulting in the development of innovative decentralized sanitation system, e.g. in Sneek (Ampe et al., 2021; Heiberg and Truffer, 2022). Since then, many other small-scale treatment projects have been implemented (e.g., in Amsterdam and Rotterdam) (UNESCO and UNESCO i-WSSM, 2020) and national policies such as the "Circular Economy in the Netherlands by 2050" strategy support these approaches (UNESCO and UNESCO i- WSSM, 2020).

Regime steward: Israel

The UWM sector in Israel superficially resembles the Dutch case, but also differs from it in key respects. It is also characterised by a predominance of the global regime in its material infrastructure, with 100% of the population connected to piped water supply and sewerage systems. The absence of MNC subsidiaries, however, suggests that Israel is not deeply embedded in global actor networks, and we thus categorise the country as a '*regime steward*' (Tab. 5). Secondary sources suggest that this is largely due to Israel's endogenous efforts to meet the water needs of a rapidly growing nation, while suffering from severe water scarcity (Teschner et al., 2012). A strong agricultural lobby and the pursuit of a modern, Western lifestyle led Israel to emulate templates from Western Europe when building up its centralized UWM infrastructure. This process was however led by local actors (Teschner et al., 2012; Teschner and Negev, 2013). Ever-present water scarcity and geo-political complexities further pushed the creation of centralized, national water management institutions and technologies, as a key building block of the Israeli state (Teschner et al., 2012), which may explain the country's endogenous development trajectory in the UWM sector.

Table 5: Global regime strength in Israel.

Indicator	Value	Score	
Share of Population with Piped Water Supply	1	5	
Share of Population with Sewer Connections	1	5	
Average Bilateral Development Aid to the Water Sector Per Capita in \$US	-	-	
Number of Subsidiaries per 100,000 Inhabitants	0	-	
Share of Narrative Events (10) Favorable towards centralized UWM	0.7	4	
Tendency to participate only in ISO committees developing standards for conventional water technologies	0.4	5	

Source: own elaboration based on the data presented in section 3.

The institutional indicator corroborates the above arguments. While Israel engages almost exclusively in developing ISO-standards for conventional UWM technologies, 30% of the analysed narratives favored modular UWM. Also here, Israel's constant battle with water scarcity might provide an explanation (Teschner et al., 2012), as it triggered the development of a range of regime- and niche- related local water innovations (Philippe et al., 2017). The competence of local firms range from centralized solutions such as seawater desalination and large-scale water reuse (Teschner et al., 2012) to pioneering on-site, modular UWM. A closer look at the narratives in newspaper articles, however, reveals that the local on-site UWM industry is highly export-oriented, suggesting that it is not (yet) in a position to challenge deeply institutionalized regime solutions at the national level (Heiberg et al., 2021).

The case of Israel thus nicely illustrates that a lack of international linkages and pressure to develop context-sensitive solutions can lead to local innovation dynamics that benefit transitions away from the global regime, again pointing to the opportunity to become a *transitioning regime steward*. Yet, the case also illustrates how the global regime rationality can exert influence even without direct connections through corporate linkages. Due to the strong material path dependencies in the form of centralized infrastructures, the Israeli UWM sector is "trapped" in the development path of the global regime, and accordingly

struggles to adapt, reform, and cope with changing water supply and demand conditions (Teschner et al., 2012).

4.2.2 Countries with limited material infrastructure

Regime follower: Kenya

Kenya is emblematic for a country with low coverage of global regime technology, with 33% of the population having access to piped water supply and only 6% having a sewerage connection, according to the WHO/UNICEF Joint Monitoring Project data. With a rather strong influence from global actor networks, high levels of ODA and local narratives advocating conventional UWM solutions, Kenya illustrates the ideal-type of a *regime follower* (Tab. 6).

Table 6: Global regime strength in Kenya.

Indicator	Value	Score	
Share of Population with Piped Water Supply	0.33	2	
Share of Population with Sewer Connections	0.06	1	
Average Bilateral Development Aid to the Water Sector Per Capita in \$US	2.26	4	
Number of Subsidiaries per 100,000 Inhabitants	0.01	1	
Share of Narrative Events (10) Favorable towards centralized UWM	0.57	3	
Tendency to participate only in ISO committees developing standards for conventional water technologies	0	3	

Source: own elaboration based on the data presented in section 3.

Explanations for this pattern can be traced back to the colonial history of Kenya, with influence of British engineers who exported European UWM solutions to the country, catering to the needs of the colonial project (Nilsson, 2016). This resulted in a segregated UWM system that served only a very small part of the population (Blomkvist and Nilsson, 2017). After independence, the most influential actors in shaping Kenya's UWM infrastructure, both the central government and external donors, continued along the trajectory of the global regime, despite frictions with local contexts, leaving Kenya with an “ever-developing” infrastructure system (Nilsson, 2016; Van Welie et al., 2018). Despite significant inefficiencies in Kenya’s centralized UWM infrastructure, regional water boards and utilities continue to get primarily involved in centralized UWM (Van Welie et al., 2018; WSUP, 2017), while various

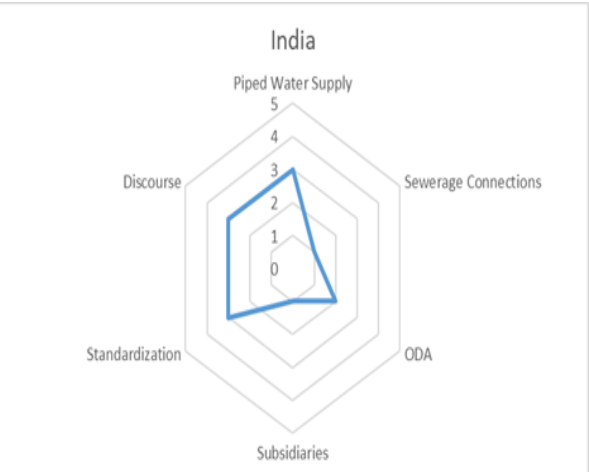
institutional constraints prevent the formalization of already widespread on-site UWM solutions such as grey- and wastewater reuse at the household level (UNESCO and UNESCO i-WSSM, 2020).

Kenya exemplifies how an integration into the international actor network of the global regime can push low- and middle-income countries into an infrastructure paradigm that is not fully adapted to local conditions (Van Welie et al., 2018; Miörner et al., 2022a). At the same time, however, it is possible to imagine that the country's embeddedness in international actor structures may provide opportunities for transitions. If Kenya transformed its policy priorities to exploring alternative UWM solutions, or if international donors realigned their UWM agenda, international linkages might be conducive for the acceleration of transitions. Kenya's recent commitments to developing standards for onsite UWM solutions, policies encouraging the adoption of low-cost technologies (2016-2018 Kenya Environment and Sanitation Policy), and the emergence of social enterprises focused on container-based sanitation services appear promising (WSUP, 2017). The international development community is also increasingly endorsing a new UWM paradigm called Citywide-Inclusive Sanitation, which explicitly promotes a range of UWM solutions, including onsite and sewerred, centralized, and decentralized technologies (Gambrill et al., 2020; Lesch et al., 2022). If these developments at the national and international levels result in institutional change and new investment priorities in the UWM sector, Kenya could indeed become a *regime distractor* that actively puts niche innovation on the agenda of international actors.

Regime dissident: India

India features some of the most promising structural conditions for diverging from global regime rationalities. Albeit having slightly higher connection rates than Kenya (44% water supply, 13% sewerage), the Indian UWM sector features lower path dependencies in the other dimensions of our framework. In the actor-dimension, India both lacks a strong presence of foreign water MNCs and receives a comparatively low amount of bilateral ODA. In the institutional dimension, evidence is somewhat mixed, with the discourse being fragmented into two camps of almost equal size, one advocating centralized UWM and the other advocating on-site/decentralized UWM (Tab. 7). India is thus one of the few countries worldwide, that has adopted a dual frame of reference when it comes to UWM solutions, giving legitimacy to both centralized and on-site approaches.

Table 7: Global regime strength in India.

Indicator	Value	Score	
Share of Population with Piped Water Supply	0.44	3	
Share of Population with Sewer Connections	0.13	1	
Average Bilateral Development Aid to the Water Sector Per Capita in \$US	0.30	2	
Number of Subsidiaries per 100,000 Inhabitants	0.01	1	
Share of Narrative Events (10) Favorable towards centralized UWM	0.52	3	
Tendency to participate only in ISO committees developing standards for conventional water technologies	0	3	

Source: own elaboration based on the data presented in section 3.

Secondary evidence suggests that the development trajectory of the UWM sector in India was initially quite similar to Kenya's, with British engineers implementing a centralized water and sanitation system that predominantly served the British colonizers (Chaplin, 1999). This inequality got transposed after independence, as available financial resources were monopolized by the middle and upper classes, which, combined with the Indian government's policies, led to the neglect of alternative approaches to UWM in most of the 20th century (Chaplin, 1999). Until the last decade, major donor projects and national policies also focused mainly on building up large-scale UWM infrastructure (Klinger et al., 2020; CSE, 2014). Yet, due to high rates of urbanization, poor management of existing UWM infrastructures, and climate change, parts of the country suffer from extreme water stress and inadequate sanitation infrastructure, which led to high transformation pressures (Schellenberg et al., 2020), renewed policy action and resulting windows of transformative opportunity (Mörner et al., 2022a).

Recent developments show that India's low degree of path dependency from global regime structure (in the technological- and actor-dimensions) coupled with an endogenous emergence of on-site solutions (Heiberg et al., 2020), have allowed the country to increasingly diverge from global regime pressures. At an aggregate scale, the country no longer has a clear aspiration to adhere to conventional UWM solutions and has indeed become one of the most advanced

contexts for implementing decentralized UWM solutions (Ulrich et al., 2021). Many of the on-site water reuse plants already installed in the country still fall short of their potential, largely due to a lack of skills and knowledge among planners and operators and an inconsistent regulatory framework (Reymond et al., 2020; Ulrich et al., 2021; Klinger et al., 2020). Yet, their quick diffusion also points to the country's shift from a *regime aspirant* to a *regime dissident* over the past years.

5. Discussion and conclusion

This paper aimed at developing a theoretically informed analytical framework for assessing and empirically mapping the spatial variation of path dependencies in global socio-technical regimes. Our conceptual elaborations and empirical illustration in the UWM sector have shown the general utility and relevance of this approach. While the literature on the geography of sustainability transitions has long promoted assessing spatial variations of regime and innovation system structures as a key research agenda (Coenen et al., 2012; Hansen and Coenen, 2015; Binz et al., 2020), it has provided surprisingly limited tools to empirically assess and globally map them. The analytical approach and set of indicators applied here is certainly not exhaustive, but should be seen as a first proposal on how to improve our capacity to map spatial variability in socio-technical regime strength in more depth.

Overall, our approach makes three key contributions to existing literature. First and foremost, it provides a novel analytical framework for globally mapping the variance of path dependencies of regime strength. This approach thus allows for an – admittedly still rather rough – characterization of where in the world path dependencies that hinder transitions are stronger or weaker. Other studies could use a similar approach to assess the path dependencies in related (network-based) infrastructure sectors like energy or transport. Our framework is analytically generalizable in terms of the three basic dimensions outlined in our conceptual model (technology/materiality, actor networks and institutions). The concrete system architecture and dynamics resulting from the interplay of these elements might look quite different in other sectors, meaning that the concrete indicators used to assess global regime influence would have to be adapted accordingly.

A second, more conceptual contribution relates to our two four-field tables which outline the ideal-typical path dependencies to be expected in different spatial contexts depending on their embeddedness in the global regime. The main contribution of these tables is that they allow for assessing the structural preconditions of a given place for transitioning away from the global regime in detail. It allowed us to show how the initial conditions of actors in countries such as the Netherlands, Kenya and India differ quite fundamentally from each other not just in terms of the uniqueness of their local cultural and geo-physical

preconditions, but also in their relationship to guiding actors and institutions at a global sector level. The concrete action taken to support transformative change in each of these eight contexts thus strongly differ from each other, making a one-size-fits-all approach to transition governance elusive.

A third contribution which we could only sketch out in the empirical illustration relates to our framework's capacity to developing a dynamic perspective on a given spatial context's (country, region, city) position in our typology and explaining the factors that make them move from one quadrant to the other. In our empirical illustrations, we highlighted how shifts happened primarily on the institutional axis. It would be an interesting analytical endeavour to analyze in more depth how and why given cities, regions or countries move through our ideal-types also in the technology and actor dimensions and thereby increase or decrease their transformative potential. For example, aging UWM infrastructures in countries that were regime leaders in the 20th century may, if not maintained, lead to partial breakdowns of physical infrastructure and thus a shift in the technological/material dimension. For example, over the coming two decades the cumulative investment need in water and wastewater infrastructure in the US has been estimated to be 2.2 trillion USD higher than the projected capital investments at the current rate (ASCE, 2020).

Another maybe even more generative analytical inroad would be conceptualizing global 'sequences' of transition dynamics that move or co-evolve between places with different transformative potential. In the UWM sector, one could imagine that sector transformation initially emerge and scale in contexts like India or Kenya that are somewhat decoupled from global regime structures, rather than the technologically most advanced, but also most locked-in countries like the Netherlands or Israel. How a transition would then get transposed from there also into other, more locked in contexts and how the 'division of labor' in a truly global sector transformation might look like in different sectors is an open and highly interesting research agenda to be explored in the future.

Our results finally also have relevant policy implications, not the least for stakeholders in quickly developing middle-income countries. In the UWM and similar sectors, high-income economies with fully developed infrastructure systems have a clear disadvantage for inducing transformative change. Middle-income countries without a strong embedding in the global regime, but still a relatively high level of organizational, financial and technological capabilities (like India and Vietnam, among others) arguably contain highly promising preconditions for inducing radical innovation. A clear opportunity for (policy-induced) divergence from global regimes exists in those contexts. Leapfrogging into highly novel infrastructure designs arguably is an under-valued, but highly attractive option for these countries, as it might provide local firms,

governments and intermediaries with unique first-mover advantages in sectors that have very high projected investment needs globally. For transition studies, this in turn implies that much more effort should be put in understanding transition dynamics in these contexts, rather than in the deeply locked-in Western countries that will inevitably be latecomers in future infrastructure transformation trajectories.

Last but not least, some limitations exist in our analytical approach that would also warrant targeted future research. First we applied our framework only to the country level, but it should quite obviously also be applied to regions (e.g. states in the USA or India), different cities (within or between countries) and be used to further conceptualize and theorize regional differences in regime strength. Second, applications to other sectors would need a deep reflection on what key proxy indicators could be for each of our three foundational dimensions. Third, one would have to explore in more depth not just the presence or absence of regime actors and concepts in a given place, but also the mechanisms and content of what gets transposed across space. Finally, one could elaborate more deeply on the policy implications for places that correspond to the ideal-types in our framework. What sort of path breaking or transformative innovation policies (Schot and Steinmueller, 2016; Yap et al., 2022; Edler and James, 2015; Kivimaa and Kern, 2016; Grillitsch et al., 2019) could be employed in countries with strong material path dependencies and what policy approaches would allow low- and middle income countries to remain shielded from global regime pressures?

6. Bibliography

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Appendix A - Derivation of the indicators

Technological dimension

Data on the proportion of the population with access to piped water and sanitation were taken from the WHO-UNICEF Joint Monitoring Program (JMP) database. The JMP database contains more than 5,000 national databases that are used to produce estimates of water, sanitation, and hygiene coverage in more than 200 countries, territories, and areas. The JMP database allows analysis of water supply and sanitation by type of facility, so we obtained specific estimates for households with piped water supply and households connected to sewerage systems. The most recent data were available as of 2020 and included 198 countries and territories in the piped water supply category and 196 countries in the sewerage connection category. Classification using a five-point scale followed a simple division of 100 percent into five classes, where, for example, a coverage rate of up to 20 percent corresponds to a score of one, indicating low strength of the global regime. In contrast, a coverage rate of over 80 percent corresponds to a score of five, indicating high global regime strength in the country.

Actor dimension

Corporate presence indicator

To examine the corporate network of the global water sector, we first used a purposive sampling approach to create a list of MNCs representative of the global water sector (Etikan et al. 2016). For this purpose, we used two rankings, the “GWI – The world’s top 50 water businesses” (2021b) and “GWI – The world’s top 50 private water operators” (2021a), and two stock indices, the “S&P Global Water Index” (2022) and “Société Générale Index World Water” (2022), as a basis. To create a representative list, we first checked the lists for common entries. To this list, we then added companies that have established at least one subsidiary abroad and are extensively involved in the water sector (either in the supply of equipment, consulting, construction, or operation and maintenance of UWM infrastructure). This resulted in a list of 54 companies headquartered in 18 countries.

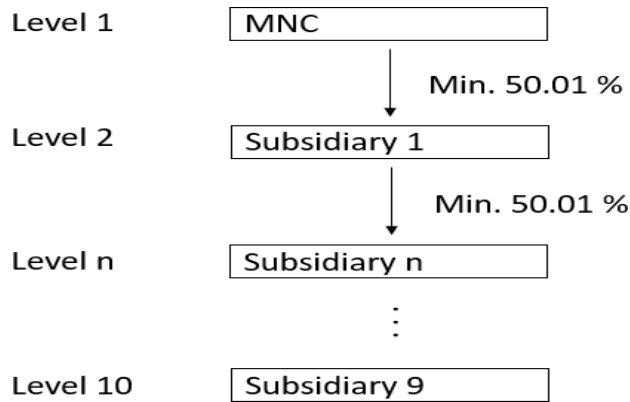
Table A1: Water MNCs included in the analysis. Headquarter countries are indicated in parentheses.

A.O. Smith (US)	Ebara (Japan)	Metawater (Japan)
ABB (Switzerland)	Eranove (France)	Metro Pacific Investment (Philippines)
Acciona Aqua (Spain)	Evoqua Water Technologies (US)	Mott MacDonald (UK)
Acea (Italy)	FCC (Spain)	Mueller Water Products (US)
ACS (Spain)	Franklin Electric (US)	Orbia (Mexico)
ACWA Power (Saudi Arabia)	Genuit (UK)	Pentair (Ireland)
Advanced Drainage Systems (US)	Georg Fischer (Switzerland)	Rethmann (Germany)
AECOM (US)	Grundfos (Denmark)	Saur (France)
Anglian Water Group (UK)	GS Inima (Spain)	Sempcorb Industries (Singapore)
Beijing Capital Eco-Environment Protection (China)	Guangdong Investment (Hong Kong)	Severn Trent (UK)
Beijing Enterprise Water Group (Hong Kong)	Hitachi Zosen (Japan)	SNF (France)
Black & Veatch (US)	Interpump (Italy)	Stantech (Canada)
Cecep Guozhen Environmental Protection (China)	Jacobs (US)	Tetra Tech (US)
China Everbright Water (Hong Kong)	Kemira OYJ (Finland)	VA Tech Wabag (India)
China Lesso Group (China)	KSB (Germany)	Veolia (France)
China Water Affairs (China)	Kubota (Japan)	Watts Water Technologies (US)
Danaher (US)	Kurita (Japan)	Xylem (US)
DuPont (US)	Manila Water (Philippines)	Yunnan Water (China)

Source: own compilation based on GWI (2021a, 2021b).

In a second step, we extracted information on the subsidiaries of these 54 companies from the Orbis database in September 2022. As illustrated in Figure A1, we included all subsidiaries in our analysis that are majority-owned across ten levels of ownership.

Figure A1: Sampling of subsidiaries. Source: own elaboration



In a third step, we cleaned the list of subsidiaries for duplicates, entries with data older than 2020, and those without location information, resulting in a sample of 12,425 subsidiaries. Since ORBIS typically provides location information for subsidiaries at least at the country level, we screened the data to find out how many subsidiaries the 54 MNCs established in each country. Overall, we find that the MNCs established subsidiaries in 122 countries. To obtain comparable results, we present the number of subsidiaries in a country per 100,000 inhabitants. In addition, we use two indicators from social network analysis (Wasserman and Faust, 1994) to show which countries have established the most subsidiaries via their MNCs (*outdegree* - yellow node) and which countries host the most subsidiaries of the MNCs (*indegree* - red node). To present the number of subsidiaries in a country per 100,000 inhabitants on a five-point scale, we considered the distribution of the data and sorted them by quintiles. This results in the distribution shown in Table A2.

Table A2: Five-Point Scale for the indicator Number of Subsidiaries per 100,000 Inhabitants.

Quintile	Data Range
1	0.0091 – 0.01541
2	0.01542 – 0.505
3	0.0515 – 0.1968
4	0.2015 – 0.7077
5	0.8042 – 12.8467

Source: own elaboration based on data from ORBIS.

Aid indicator

The aid indicator is based on the OECD.Stat database, more precisely on the database "Geobook: ODA by Sector - Bilateral Commitments by Donor and Recipient". The database contains information on the target countries and the sectoral distribution of bilateral official development assistance (ODA) of the DAC countries.³ From the database, we retrieved information on the amount of bilateral ODA provided by DAC countries to the water supply and sanitation sector of a number of countries. The data provided by the OECD covers the period from 2011 to 2020 and are reported as the absolute amount of ODA in US\$ received by a given country's water supply and sanitation sector in a given year. For our purposes, we present the data as the average amount of ODA to the water supply and sanitation sector received by a country per year and per capita, covering the entire period from 2011 to 2020.

To present the average amount of ODA to the water and sanitation sector that a country receives per year and per capita on a five-point scale, we considered the distribution of the data and sorted them by quintiles. This results in the distribution shown in Table A3.

Table A3: Five-point scale for the indicator Average Amount of ODA to the Water and Sanitation Sector per Year and per Capita in U.S. dollars (2018) over the Period 2011 - 2020.

Quintile	Data Range
1	0.0036 – 0.2930
2	0.3028 – 0.7227
3	0.7646 – 1.9404
4	1.9857 – 4.8592
5	4.9022 – 175.8789

Source: own elaboration based on data from OECD.stat

Institutional dimension

Discourse indicator

For our discourse indicator, we draw on the data and approach of Heiberg et al. (2021). The authors devised a spatially referenced database of narratives that (de-)legitimize centralized (conventional) and modular (alternative) UWM infrastructure by first accessing a selection of over 180 English-speaking newspapers as well as selected global expert journals via LexisNexis.⁴ Using a sophisticated keyword search, the outlets were filtered for articles published between 2011 and 2018 that addressed solutions to water problems. Heiberg et

al. (2021) classified 563 articles as relevant for analysis. As Heiberg et al. (2021) intended to provide insight into positive or obstructive narratives around particular UWM technologies or institutions in the media, Heiberg et al. (2021) classified a number of UWM technologies and institutions into centralized (traditional) and modular (alternative) UWM solutions. Individual narratives in the articles were coded subsequently with a binary qualifier variable indicating whether a statement legitimized or de-legitimized a corresponding centralized or modular technology or institution. In addition, Heiberg et al. (2021) used a set of three types of spatial variables to assess the geographic patterns behind the registered narratives.

Of these three variables, we focused on the audience location of a narrative (i.e., usually the country where the outlet is published) to assess the discourse on UWM infrastructure within a country. Following Heiberg et al. (2021), we constructed a share indicating the proportion of narratives within a given country (country of audience location) that are supportive of centralized UWM technologies/institutions.

Favorable narrative share towards centralized technologies in country i

$$x_{c_i}^{favorable} = \frac{\sum N_{Lcen_i} + \sum N_{DLmod_i}}{\sum N_i}$$

where $x_{c_i}^{favorable}$ denotes the audience-based favorable narrative share in country i , which is given by the sum of all legitimizing narratives toward modular technologies N_{Lcen_i} and all de-legitimising narratives toward modular technologies N_{DLmod_i} divided by the sum of all narratives N_i in the respective country i .

Since we only include countries with more than 10 registered narratives in our analysis, we include 18 countries for which 1297 narratives were registered. Of these, 828 were narratives that legitimized centralized (traditional) UWM solutions and 469 were narratives that legitimized modular (alternative) solutions. For an overview of the resulting positive proportion of narratives toward centralized technology, see Table A4.

Table A4: Narrative events concerning centralized UWM technologies and institutions 2011 - 2018.

Country	All narratives	Favorable narratives	Share of favorable narratives in %
US	305	180	0.5902
India	279	144	0.5161
South Africa	129	92	0.7132
Singapore	125	109	0.8720
United Kingdom	86	69	0.8023
Israel	79	55	0.6962
Australia	49	24	0.4898
Canada	46	26	0.5652
Zimbabwe	34	27	0.7941
Ireland	29	13	0.4483
Malaysia	25	21	0.8400
Rwanda	25	18	0.7200
Kenya	21	12	0.5714
China	17	17	1.0000
Germany	14	6	0.4286
United Republic of Tanzania	13	7	0.5385
Netherlands	11	7	0.6364
Italy	10	1	0.1000
Total	1297	828	

Source: own elaboration based on data from Heiberg et al. (2021).

Classification using a five-point scale followed a simple division of 100 percent into five classes, where, for example, a favorable narrative share towards centralized UWM solutions of up to 20 percent corresponds to a score of one, indicating low strength of the global regime. In contrast, a favorable narrative share towards centralized UWM solutions of over 80 percent corresponds to a score of five, indicating high global regime strength in the country.

Standardization indicator

The standardization indicator shows whether countries are predominantly involved in the development of ISO standards for conventional UWM technologies, for onsite/decentralized UWM technologies, or for both. The

indicator is based on an examination of country participation in ISO technical committees, their subcommittees, or project committees, since this is where international standards are developed. To assess the standardization of UWM technologies, we first searched the ISO committees for technical committees, subcommittees, and project committees that develop standards for UWM solutions in the areas of drinking water, wastewater, stormwater, urban water reuse systems, and services. This resulted in a list of five committees for which we retrieved membership information (members and observers were both considered participants) and information on what type of standards were developed in these committees from the International Standards Organization website and, in one case, from the American National Standards Institute website. In addition, we divided the total of 42 standards developed in the five committees into two categories, conventional UWM technologies and onsite/decentralized UWM technologies. Table A5 provides an overview of the committees, the members of the committees, and the standards developed in the committees.

Table A5: ISO committees included in the analysis.

Committee	Name	Members	Observers	ISO Standards	Conventional ISO Standards	Decentralized/onsite ISO Standards
ISO/TC 224	Drinking water, wastewater and stormwater systems and services	36	32	23	21	2 (ISO 24521, ISO 24525)
ISO/TC 282/SC 2	Water reuse in urban areas	23	26	7	6	1 (ISO 23056)
ISO/TC 282/SC 3	Risk and performance evaluation of water reuse	16	6	10	10	-
ISO/PC 305	Sustainable non-sewered sanitation systems	34	12	1	-	1 (ISO 30500)
ISO/PC 318	Community scale resource oriented sanitation treatment systems	29	19	1	-	1 (ISO 31800)
Total				42	37	5

Source: own elaboration.

Using the information on committee membership, we then calculated shares indicating country participation in the development of conventional (P_c) and onsite/decentralized ISO standards (P_d). As illustrated in Table A7, example

country A has participated in the development of 21 out of 27 conventional ISO standards and in 4 out of 5 onsite/decentralized standards through its membership in three committees (ISO/TC 224, ISO/PC 305, ISO/PC 318), resulting in shares of 57 percent and 80 percent, respectively.

Table A6: Participation of country A in the development of ISO standards concerning conventional and onsite/decentralized technologies.

Quintile	Data Range	Label
1	-0.4378 – -0.4	Alternative
2	-0.2703 – -0.2	Rather Alternative
3	-0.1297 – 0.1297	Indifferent
4	0.1676 – 0.2	Rather Conventional
5	0.4	Conventional

Source: own elaboration.

Subtracting P_d from P_c then yields an indicator that indicates in relative and normalized terms, whether a country was more likely to participate in the development of conventional or onsite/decentralized ISO standards on UWM technology. While a negative result indicates a tendency to be (rather) involved in the development of alternative UWM technology standards, positive results indicate that countries are (rather) actively developing centralized UWM technology standards. In our example, a result of -0.23 indicates that country A is more engaged in developing onsite/decentralized standards.

Table A8: Five-point scale for the indicator measuring the tendency of countries to engage rather in the elaboration of centralized ISO UWM standards or onsite/decentralized ISO UWM standards.

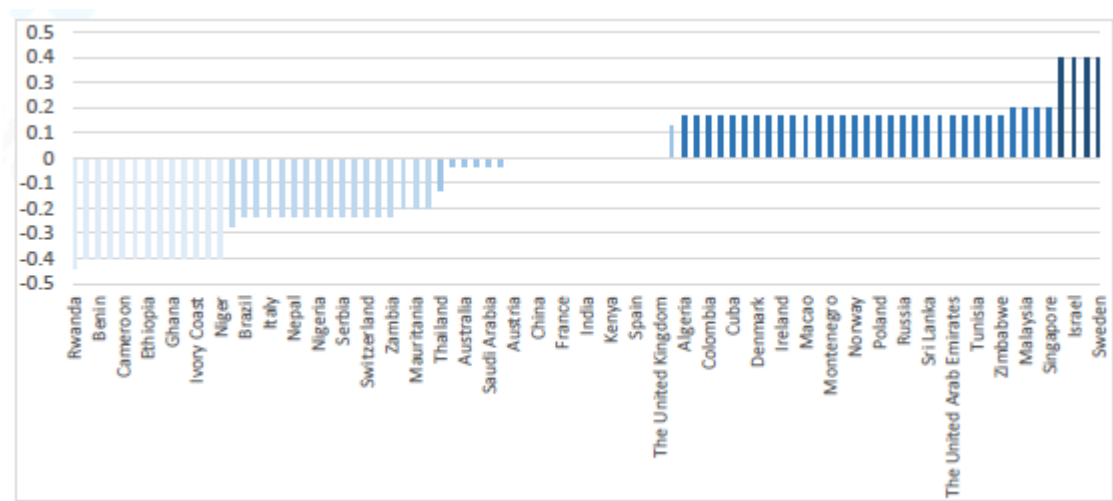
Committee	ISO Standards	Conventional ISO Standards	Onsite/decentralized ISO Standards
Total	42	37	5
Country A Participation			
ISO/TC 224	23	21	2
ISO/PC 305	1	-	1
ISO/PC 318	1	-	1
Country A Participation Share	$25/42 = 0.5952$	$21/37 = 0.5676$	$4/5 = 0.8$

Source: own elaboration.

By doing so we obtain results for 85 countries, whose distribution is illustrated in Figure A1. To represent the tendency of countries to participate in either centralized or on-site/decentralized ISO UWM standards development on a five-point scale, we looked at the distribution of the data and manually

classified the data into five categories. This resulted in the classification shown in Table A7.

Figure A1: Distribution of the Standardization Indicator.



Appendix B

Table B1: Final dataset.

	Technological Dimension				Actor Dimension				Institutional Dimension			
Country	Proportion of population with piped water supply (2020)	Scale	Proportion of population with sewer connections (2020)	Scale	Subsidies per 100,000 inhabitants	Scale	Average bilateral ODA (2011 - 2020) per capita	Scale	Proportion of discourse favoring centralized technologies (2011 - 2018)	Scale	Participation in water-related ISO-committees	Scale
Afghanistan	22.3786	2	3.1513	1	0.0000	na	1.7909	3	na	na	na	na
Albania	80.6785	5	79.4682	4	0.0000	na	13.5475	5	na	na	na	na
Algeria	71.8563	4	88.1897	5	0.0091	1	0.0691	1	na	na	0.1676	4
American Samoa	100.0000	5	48.6600	3	0.0000	na	na	na	na	na	na	na
Andorra	100.0000	5	100.0000	5	1.2942	5	na	na	na	na	na	na
Angola	42.4483	3	12.9801	1	0.0030	1	0.5294	2	na	na	na	na
Anguilla	na	na	na	na	0.0000	na	0.1333	1	na	na	na	na
Antigua and Barbuda	na	na	na	na	1.0212	5	1.1539	3	na	na	na	na
Argentina	na	na	na	na	0.0620	3	0.0067	1	na	na	-0.0324	3
Armenia	100.0000	5	71.4730	4	0.0000	na	4.8592	4	na	na	na	na
Aruba	na	na	na	na	0.0000	na	na	na	na	na	na	na
Australia	na	na	88.5000	5	1.6314	5	na	na	0.4900	3	-0.0324	3
Austria	na	na	92.5744	5	1.1214	5	na	na	na	na	0.0000	3
Azerbaijan	90.9918	5	na	na	0.0000	na	1.8898	3	na	na	na	na
Bahamas	na	na	na	na	0.0000	na	na	na	na	na	na	na
Bahrain	na	na	91.2582	5	0.2351	4	na	na	na	na	na	na
Bangladesh	15.3545	1	9.3489	1	0.0006	1	0.8531	3	na	na	0.4000	5
Barbados	98.7821	5	3.3453	1	0.3480	4	na	na	na	na	na	na
Belarus	96.2713	5	73.8716	4	0.0423	2	0.0641	1	na	na	na	na
Belgium	100.0000	5	89.0993	5	0.9836	5	na	na	na	na	na	na
Belize	87.1285	5	8.6618	1	0.0000	na	0.2766	1	na	na	na	na
Benin	36.7410	2	0.1000	1	0.0412	2	2.4974	4	na	na	0.4000	5

Bermuda	100.0000	5	5.0000	1	12.8467	5	na	na	na	na	na	na
Bhutan	100.0000	5	17.5055	1	0.0000	na	2.2783	4	na	na	na	na
Bolivia (Plurinational State of)	68.6105	4	50.2447	3	0.0000	na	5.0646	5	na	na	0.1297	3
Bosnia and Herzegovina	na	na	na	na	0.0305	2	3.1133	4	na	na	na	na
Botswana	90.5851	5	1.4049	1	0.4252	4	0.0740	1	na	na	na	na
Brazil	98.3380	5	69.1937	4	0.0414	2	0.5269	2	na	na	-0.2324	2
British Virgin Islands	na	na	na	na	0.0000	na	na	na	na	na	na	na
Brunei Darussalam	100.0000	5	na	na	0.0000	na	na	na	na	na	na	na
Bulgaria	100.0000	5	86.2704	5	0.3310	4	na	na	na	na	0.1676	4
Burkina Faso	28.1390	2	0.1000	1	0.0096	1	2.3363	4	na	na	-0.4000	1
Burundi	38.2420	2	0.1000	1	0.0000	na	1.1442	3	na	na	na	na
Cabo Verde	89.7551	5	27.9798	2	0.0000	na	49.7637	5	na	na	na	na
Cambodia	31.9227	2	16.5356	1	0.0120	1	5.1197	5	na	na	na	na
Cameroon	36.0818	2	1.1017	1	0.0000	na	1.5913	3	na	na	-0.4000	1
Canada	100.0000	5	81.4554	5	1.0095	5	na	na	0.5700	3	0.0000	3
Caribbean Netherlands	na	na	na	na	0.0000	na	na	na	na	na	na	na
Cayman Islands	na	na	na	na	0.0000	na	na	na	na	na	na	na
Central African Republic	14.0062	1	0.1000	1	0.0000	na	0.1068	1	na	na	na	na
Chad	19.7877	1	0.1000	1	0.0061	1	0.4365	2	na	na	na	Na
Channel Islands	na	na	na	na	0.0000	na	na	na	na	na	na	na
Chile	100.0000	5	88.8651	5	0.4865	4	0.0374	1	na	na	na	na
China	79.9025	4	67.0316	4	0.0505	2	0.0758	1	1.0000	5	0.0000	3
China,	100.000	5	93.0083	5	3.4014	5	na	na	na	na	na	na

Hong Kong SAR	0											
China, Macao SAR	100.0000	5	100.0000	5	0.0000	na	na	na	na	na	0.1676	4
Colombia	88.6235	5	78.0540	4	0.0845	3	0.5417	2	na	na	0.1676	4
Comoros	na	na	na	na	0.0000	na	2.9738	4	na	na	na	na
Congo	52.7537	3	1.2913	1	0.0000	na	3.3338	4	na	na	na	na
Cook Islands	89.0438	5	na	na	0.0000	na	131.6898	5	na	na	na	na
Costa Rica	100.0000	5	20.9878	2	0.0000	na	1.9081	3	na	na	0.1676	4
Côte d'Ivoire	41.6483	3	6.7089	1	0.0417	2	0.3170	2	na	na	-0.4000	1
Croatia	na	na	58.0768	3	0.1462	3	na	na	na	na	na	na
Cuba	79.5705	4	61.0541	4	0.0000	na	0.5351	2	na	na	0.1676	4
Curaçao	na	na	na	na	0.0000	na	na	na	na	na	na	na
Cyprus	100.0000	5	54.7728	3	0.3313	4	na	na	na	na	0.1676	4
Czech Republic	100.0000	5	85.9408	5	0.9805	5	na	na	na	na	0.0000	3
Democratic People's Republic of Korea	64.8664	4	42.1506	3	0.0000	na	0.0341	1	na	na	na	na
Democratic Republic of the Congo	35.0150	2	0.1000	1	0.0000	na	0.4649	2	na	na	-0.4000	1
Denmark	100.0000	5	92.2608	5	1.0186	5	na	na	na	na	0.1676	4
Djibouti	83.1294	5	5.1521	1	0.3036	4	4.7500	4	na	na	na	na
Dominica	na	na	na	na	0.0000	na	0.4306	2	na	na	na	na
Dominican Republic	80.8591	5	16.0226	1	0.0553	3	0.6150	2	na	na	na	na
Ecuador	90.8072	5	66.5015	4	0.0170	2	1.9404	3	na	na	na	na
Egypt	100.0000	5	74.4585	4	0.0117	1	0.5447	2	na	na	-0.0324	3
El Salvador	91.4823	5	42.5140	3	0.0154	2	1.9936	4	na	na	na	na
Equatorial Guinea	na	na	na	na	0.0713	3	0.0036	1	na	na	na	na
Eritrea	na	na	na	na	0.0000	na	0.1145	1	na	na	na	na
Estonia	93.4619	5	86.1400	5	0.3769	4	na	na	na	na	na	na
Eswatini	60.5099	4	9.5170	1	0.0000	na	0.2198	1	na	na	na	na
Ethiopia	41.3480	3	0.1000	1	0.0000	na	0.7144	2	na	na	-0.4000	1

Faeroe Islands	100.0000	5	na	na	0.0000	na	na	na	na	na	na	na
Falkland Islands (Malvinas)	90.6179	5	100.0000	5	0.0000	na	na	na	na	na	na	na
Fiji	83.4579	5	20.8676	2	0.1116	3	2.2143	4	na	na	na	na
Finland	100.0000	5	84.5667	5	0.2166	4	na	na	na	na	0.0000	3
France	100.0000	5	81.9741	5	1.0341	5	na	na	na	na	0.0000	3
French Guiana	87.5380	5	46.4298	3	0.0000	na	na	na	na	na	na	na
French Polynesia	100.0000	5	18.6017	1	0.0000	na	na	na	na	na	na	na
Gabon	81.5930	5	33.9268	2	0.0899	3	6.6122	5	na	na	-0.4000	1
Gambia	76.8841	4	1.6298	1	0.0000	na	1.5625	3	na	na	na	na
Georgia	82.4664	5	60.6184	4	0.0000	na	12.6244	5	na	na	na	na
Germany	100.0000	5	95.9857	5	2.1925	5	na	na	0.4300	3	0.0000	3
Ghana	34.7032	2	3.1233	1	0.0129	1	1.6790	3	na	na	-0.4000	1
Gibraltar	100.0000	5	100.0000	5	11.8726	5	na	na	na	na	na	na
Greece	100.0000	5	85.3020	5	0.0576	3	na	na	na	na	na	na
Greenland	100.0000	5	92.2608	5	0.0000	na	na	na	na	na	na	na
Grenada	na	na	na	na	0.0000	na	3.5550	4	na	na	na	na
Guadeloupe	100.0000	5	39.6302	2	0.0000	na	na	na	na	na	na	na
Guam	na	na	na	na	0.0000	na	na	na	na	na	na	na
Guatemala	77.1047	4	43.8453	3	0.0000	na	0.2930	1	na	na	na	na
Guinea	24.5316	2	2.1136	1	0.0228	2	0.5751	2	na	na	na	na
Guinea-Bissau	34.6336	2	1.1499	1	0.0000	na	0.4273	2	na	na	na	na
Guyana	65.4320	4	2.1623	1	0.0000	na	0.2377	1	na	na	na	na
Haiti	19.0910	1	0.1000	1	0.0000	na	1.1626	3	na	na	-0.4000	1
Holy See	na	na	na	na	0.0000	na	na	na	na	na	na	na
Honduras	91.5403	5	41.4139	3	0.0101	1	0.8568	3	na	na	na	na
Hungary	100.0000	5	83.8263	5	0.4244	4	na	na	na	na	0.4000	5
Iceland	100.0000	5	94.1112	5	0.2930	4	na	na	na	na	na	na
India	43.6930	3	12.5821	1	0.0084	1	0.3028	2	0.5200	3	0.0000	3
Indonesia	34.5458	2	11.2634	1	0.0051	1	0.5475	2	na	na	-0.2324	2

Iran (Islamic Republic of)	98.6375	5	35.9983	2	0.0000	na	0.0178	1	na	na	0.2000	4
Iraq	83.4730	5	30.1827	2	0.0000	na	1.5194	3	na	na	0.1676	4
Ireland	97.3901	5	66.7102	4	1.4784	5	na	na	0.4900	3	0.1676	4
Isle of Man	98.1500	5	na	na	0.0000	na	na	na	na	na	na	na
Israel	100.0000	5	100.0000	5	0.0000	na	na	na	0.7000	4	0.4000	5
Italy	na	na	96.8366	5	0.3341	4	na	na	0.1000	1	-0.2324	2
Jamaica	83.1764	5	22.8682	2	0.0000	na	0.1006	1	na	na	na	na
Japan	98.0517	5	79.1226	4	0.0996	3	na	na	na	na	0.0000	3
Jordan	89.2584	5	66.9332	4	0.0196	2	31.9808	5	na	na	na	na
Kazakhstan	80.9325	5	37.3856	2	0.0107	1	0.0096	1	na	na	na	na
Kenya	32.6747	2	5.6418	1	0.0074	1	2.2647	4	0.5700	3	0.0000	3
Kiribati	38.8377	2	11.2124	1	0.0000	na	27.8703	5	na	na	na	na
Kuwait	na	na	100.0000	5	0.0000	na	na	na	na	na	na	na
Kyrgyzstan	93.6000	5	15.5061	1	0.0000	na	0.9207	3	na	na	na	na
Lao People's Democratic Republic	31.2592	2	1.1234	1	0.0275	2	5.8816	5	na	na	na	na
Latvia	93.9756	5	85.4450	5	0.3181	4	na	na	na	na	na	na
Lebanon	89.2351	5	77.8895	4	0.0000	na	6.3656	5	na	na	na	na
Lesotho	68.7073	4	1.2176	1	0.0000	na	0.9383	3	na	na	na	na
Liberia	4.3462	1	0.1000	1	0.0198	2	2.3631	4	na	na	na	na
Libya	77.9569	4	69.3123	4	0.0146	1	0.0725	1	na	na	na	na
Liechtenstein	100.0000	5	98.7000	5	0.0000	na	na	na	na	na	na	na
Lithuania	95.8608	5	93.4463	5	0.4041	4	na	na	na	na	na	na
Luxembourg	100.0000	5	98.3393	5	11.9813	5	na	na	na	na	0.1676	4
Madagascar	34.8753	2	1.1721	1	0.0000	na	0.4387	2	na	na	na	na
Malawi	21.6818	2	1.7445	1	0.0000	na	0.7646	3	na	na	-0.2000	2
Malaysia	95.3219	5	na	na	0.1298	3	0.0433	1	0.8400	5	0.2000	4
Maldives	51.1269	3	65.7808	4	0.0000	na	0.2386	1	na	na	na	na
Mali	49.5535	3	1.2696	1	0.0000	na	3.3958	4	na	na	na	na
Malta	100.000	5	98.4375	5	0.4530	4	na	na	na	na	na	na

	0											
Marshall Islands	30.9291	2	38.4101	2	0.0000	na	49.5320	5	na	na	na	na
Martinique	100.0000	5	46.4825	3	0.0000	na	na	na	na	na	na	na
Mauritania	52.9814	3	2.7591	1	0.0000	na	1.2117	3	na	na	-0.2000	2
Mauritius	100.0000	5	na	na	0.7077	4	6.4760	5	na	na	na	na
Mayotte	92.6734	5	57.9849	3	0.0000	na	na	na	na	na	na	na
Mexico	97.6783	5	81.0015	5	0.0504	2	0.4216	2	na	na	0.1676	4
Micronesia (Federated States of)	na	na	na	na	0.0000	na	9.7634	5	na	na	na	na
Monaco	100.0000	5	100.0000	5	7.6445	5	na	na	na	na	na	Na
Mongolia	25.0210	2	24.8817	2	0.0000	na	3.6479	4	na	na	0.4000	5
Montenegro	89.4380	5	44.6886	3	0.1592	3	20.4661	5	na	na	0.1676	4
Montserrat	98.0775	5	20.0891	2	0.0000	na	0.4001	2	na	na	na	na
Morocco	80.2195	5	58.5264	3	0.0515	3	3.5662	4	na	na	-0.2324	2
Mozambique	40.6802	3	1.0737	1	0.0064	1	1.8691	3	na	na	na	na
Myanmar	33.1139	2	0.1000	1	0.0055	1	2.1870	4	na	na	na	na
Namibia	81.2916	5	34.9718	2	0.1968	3	0.7863	3	na	na	-0.4000	1
Nauru	na	na	na	na	0.0000	na	24.7369	5	na	na	na	na
Nepal	49.9366	3	4.9541	1	0.0000	na	0.7227	2	na	na	-0.2324	2
Netherlands	100.0000	5	100.0000	5	1.6983	5	na	na	0.6400	4	-0.2324	2
New Caledonia	98.6106	5	na	na	0.0000	na	na	na	na	na	na	na
New Zealand	100.0000	5	85.2242	5	1.1613	5	na	na	na	na	0.1676	4
Nicaragua	69.7411	4	24.6587	2	0.0151	1	2.8083	4	na	na	na	na
Niger	39.9105	2	0.1000	1	0.0041	1	1.2113	3	na	na	-0.4000	1
Nigeria	10.1419	1	8.9736	1	0.0005	1	0.3249	2	na	na	-0.2324	2
Niue	97.0109	5	na	na	0.0000	na	32.7565	5	na	na	na	na
North Macedonia	92.1341	5	80.8072	5	0.0480	2	4.1653	4	na	na	na	na
Northern	89.6609	5	54.2754	3	0.0000	na	na	na	na	na	na	na

Mariana Islands												
Norway	100.0000	5	84.6581	5	0.5165	4	na	na	na	na	0.1676	4
Oman	95.5092	5	21.4242	2	0.1762	3	na	na	na	na	0.1676	4
Pakistan	25.9071	2	27.2772	2	0.0018	1	0.1834	1	na	na	na	na
Palau	85.5025	5	71.0614	4	0.0000	na	175.8789	5	na	na	na	na
Panama	93.0506	5	34.1607	2	0.1622	3	0.4855	2	na	na	na	na
Papua New Guinea	18.1205	1	7.0983	1	0.0224	2	0.4237	2	na	na	na	na
Paraguay	100.0000	5	8.4065	1	0.0841	3	2.4604	4	na	na	na	na
Peru	90.3600	5	73.5743	4	0.0758	3	1.9857	4	na	na	na	na
Philippines	65.6445	4	6.9644	1	0.0684	3	0.3978	2	na	na	0.1676	4
Poland	89.2771	5	64.3624	4	0.6791	4	na	na	na	na	0.1676	4
Portugal	100.0000	5	65.0495	4	0.8042	5	na	na	na	na	0.2000	4
Puerto Rico	100.0000	5	100.0000	5	0.0000	na	na	na	na	na	na	na
Qatar	100.0000	5	97.2000	5	0.0347	2	na	na	na	na	na	na
Republic of Korea	100.0000	5	100.0000	5	0.0644	3	na	na	na	na	0.0000	3
Republic of Moldova	72.2829	4	33.9649	2	0.0744	3	2.9514	4	na	na	na	na
Réunion	100.0000	5	51.3924	3	0.0000	na	na	na	na	na	na	na
Romania	na	na	54.8396	3	0.2339	4	na	na	na	na	0.1676	4
Russian Federation	93.7827	5	76.6734	4	0.0754	3	na	na	na	na	0.1676	4
Rwanda	38.3587	2	1.2181	1	0.0000	na	1.0700	3	0.7200	4	-0.4379	1
Saint Barthélemy	100.0000	5	5.7129	1	0.0000	na	na	na	na	na	na	na
Saint Helena	98.2000	5	52.1000	3	0.0000	na	na	na	na	na	na	na
Saint Kitts and Nevis	na	na	na	na	0.0000	na	0.0376	1	na	na	na	na
Saint Lucia	96.7077	5	5.0398	1	0.0000	na	0.3376	2	na	na	na	na
Saint Martin	100.0000	5	60.1760	4	0.0000	na	na	na	na	na	na	na

(French part)												
Saint Pierre and Miquelon	90.5000	5	na	na	0.0000	na	na	na	na	na	na	na
Saint Vincent and the Grenadines	na	na	na	na	0.0000	na	0.1352	1	na	na	na	na
Samoa	84.0701	5	0.1000	1	0.0000	na	13.1445	5	na	na	na	na
San Marino	100.0000	5	85.0000	5	0.0000	na	na	na	na	na	na	na
Sao Tome and Principe	96.9833	5	17.1628	1	0.0000	na	5.2518	5	na	na	na	na
Saudi Arabia	84.2447	5	59.1136	3	0.0546	3	na	na	na	na	-0.0324	3
Senegal	75.0479	4	8.0620	1	0.0179	2	3.5958	4	na	na	-0.2324	2
Serbia	94.2618	5	57.1295	3	0.1831	3	na	na	na	na	-0.2324	2
Seychelles	na	na	16.7652	1	0.0000	na	14.0329	5	na	na	na	na
Sierra Leone	20.9166	2	0.1000	1	0.0125	1	1.4088	3	na	na	na	na
Singapore	100.0000	5	100.0000	5	2.8887	5	na	na	0.8700	5	0.2000	4
Sint Maarten (Dutch part)	na	na	na	na	0.0000	na	na	na	na	na	na	na
Slovakia	na	na	69.3258	4	0.8975	5	na	na	na	na	0.1675	4
Slovenia	na	na	72.1895	4	0.3848	4	na	na	na	na	na	na
Solomon Islands	45.6602	3	7.1578	1	0.0000	na	4.3021	4	na	na	na	na
Somalia	46.9826	3	6.0820	1	0.0000	na	0.4156	2	na	na	na	na
South Africa	90.7705	5	60.6198	4	0.0523	3	0.3788	2	0.7100	4	-0.2324	2
South Sudan	4.4362	1	0.1000	1	0.0000	na	3.5254	4	na	na	na	na
Spain	100.0000	5	95.2478	5	2.0019	5	na	na	na	na	0.0000	3
Sri Lanka	39.4450	2	1.7797	1	0.0140	1	4.9022	5	na	na	0.1676	4
State of Palestine	54.2752	3	53.2457	3	0.0000	na	18.1669	5	na	na	na	na
Sudan	46.0687	3	1.0324	1	0.0000	na	0.5143	2	na	na	na	na

Suriname	80.2754	5	2.3208	1	0.0000	na	2.4155	4	na	na	na	na
Sweden	87.7008	5	88.1723	5	0.5842	4	na	na	na	na	0.4000	5
Switzerland	100.0000	5	100.0000	5	1.3403	5	na	na	na	na	-0.2324	2
Syrian Arab Republic	70.6773	4	75.8446	4	0.0000	na	0.5629	2	na	na	na	na
Tajikistan	64.9914	4	16.2411	1	0.0000	na	1.4281	3	na	na	na	na
Thailand	80.8482	5	13.6537	1	0.0401	2	0.0548	1	na	na	-0.1297	3
Timor-Leste	65.6146	4	11.4063	1	0.0000	na	5.0522	5	na	na	na	na
Togo	25.0764	2	0.1000	1	0.0242	2	1.4826	3	na	na	na	na
Tokelau	95.2445	5	na	na	0.0000	na	na	na	na	na	na	na
Tonga	100.0000	5	2.8734	1	0.0000	na	11.9966	5	na	na	na	na
Trinidad and Tobago	92.6341	5	20.1130	2	0.2144	4	na	na	na	na	0.1676	4
Tunisia	92.5120	5	59.9477	3	0.0423	2	16.5370	5	na	na	0.1676	4
Turkey	95.2364	5	88.7350	5	0.0344	2	0.3297	2	na	na	na	na
Turkmenistan	51.8731	3	28.5205	2	0.0000	na	0.0050	1	na	na	na	na
Turks and Caicos Islands	na	na	na	na	0.0000	na	na	na	na	na	na	na
Tuvalu	na	na	na	na	0.0000	na	58.0902	5	na	na	na	na
Uganda	22.7595	2	0.1000	1	0.0000	na	1.6312	3	na	na	-0.2324	2
Ukraine	63.7663	4	51.3354	3	0.0297	2	2.3465	4	na	na	na	na
United Arab Emirates	100.0000	5	97.0853	5	0.3741	4	na	na	na	na	0.1676	4
United Kingdom	100.0000	5	97.7864	5	1.3493	5	na	na	0.8000	5	0.0000	3
United Republic of Tanzania	37.6404	2	0.1000	1	0.0017	1	1.6812	3	0.5400	3	-0.2000	2
United States of America	98.7644	5	84.5338	5	0.8855	5	na	na	0.5900	3	-0.2703	2
United States Virgin Islands	46.6839	3	41.6213	3	0.0000	na	na	na	na	na	na	na

Uruguay	100.0000	5	61.3255	4	0.2015	4	0.0400	1	na	na	0.1676	4
Uzbekistan	70.1869	4	26.5117	2	0.0090	1	0.2060	1	na	na	na	na
Vanuatu	47.5857	3	3.3060	1	0.0000	na	8.4617	5	na	na	na	na
Venezuela (Bolivarian Republic of)	79.2028	4	89.6522	5	0.0246	2	0.0088	1	na	na	na	na
Viet Nam	48.4453	3	1.2558	1	0.0154	1	2.2235	4	na	na	-0.0324	3
Wallis and Futuna Islands	98.8639	5	na	na	0.0000	na	22.5858	5	na	na	na	na
Western Sahara	na	na	na	na	0.0000	na	na	na	na	na	na	na
Yemen	55.9444	3	30.4483	2	0.0000	na	0.8030	3	na	na	na	na
Zambia	32.0771	2	8.0961	1	0.0163	2	4.0792	4	na	na	-0.2324	2
Zimbabwe	27.4758	2	26.0058	2	0.0000	na	1.2533	3	0.7900	4	0.1676	4

Notes

- ¹ GWI – The world's top 50 water businesses (2021b), GWI – The world's top 50 private water operators (2021a), S&P Global Water Index (2022), Société Générale Index World Water (2022).
- ² We focused on ISO/TC 224, ISO/TC 282/SC 2, ISO/TC 282/SC 3, ISO/PC 305 and ISO/PC 318.
- ³ DAC countries refers to the members of the Development Assistance Committee. As of November 2022 there are 31 members within DAC.
- ⁴ The full list of newspapers screened is provided by Heiberg et al. (2021).

The green and circular policy making process – Trends and perspectives from key stakeholders in the global south

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Abstract

While most green policy papers analyze policy impacts, this paper highlights trends and perspectives of the process of green policymaking focusing on the Global South. The paper applies an evolutionary economic theoretical perspective in seeking to investigate changes in the institutional conditions for global greening over time and space. The paper brings the results of a survey undertaking in 2020-2023 among key green policymakers and influential stakeholders from the Global South, all working professionally on or having a strong influence on green policymaking and green governance. The paper seeks to trace the main green policy learnings and key recent tendencies and perspectives from these 86 experts and practitioners from nine different Global South countries. Main findings are that the green policy agenda is quite recent compared to Global North countries, but it is sharply on the rise. Environmental targets are highly prioritized even compared to economic priorities. Circular economy perspectives are on the rise but generally represent a novel agenda policy wise. Global South green policy making is generally self-assessed to be less impactful and effective than in the high-income countries and the weaknesses in implementation are particularly pointed to in our survey. The challenges to effective green policymaking are perceived as considerable. Overall, green policy making in the Global South still has distinct features reflecting the short time span of policy learning and green societal transformation.

Keywords: Green policy making, environmental policy, green economy, circular economy, eco-innovation, green growth, green catching-up, evolutionary economics.

1. Introduction

Policy papers on environmental sustainability are plentiful as environmental regulation historically has been seen as a core driver of eco-innovation and societal greening (Ashford & Heaton, 1979; Borsatto & Bazani, 2021; Cohen & Tubb, 2018; Hemmelskamp, 1997; Jaffe & Stavins, 1995; Kemp, 2000; Majone, 1976; Norberg-Bohm, 1999; Pickman, 1998; Porter & van der Linde, 1995; Sonnenfeld & Huber, 2008; Andersen, 2023). This literature, however, mainly analyzes impacts of environmental policymaking or specific policy measures as perceived by those affected by the policy, i.e. companies, consumers and households, or by undertaken correlation analyses. Accordingly, only few papers deal with the actual actors or processes of green policy making, especially in the Global South see though e.g. (Shi et al., 2008; Skytte, 1999; Xue et al., 2010). This paper feeds into this research gap.

The paper applies an evolutionary economic theoretical perspective in emphasizing the key role of institutional change for economic development (Freeman & Soete, 1997). From this perspective, and noticeably within the sub-framework of regional and national innovation systems (Cooke et al., 1997; Freeman, 1988; Lundvall, 1992; Nelson, 1993) we are interested in contributing to a better understanding of the co-evolutionary processes of institutional, scientific, economic and technological greening of the economy over time and space (Altenburg & Pegels, 2017; Andersen, 2009; Andersen & Foxon, 2009; Weber et al., 2005). In this paper we zoom in on the green policy making process and its evolution over time, which we see as setting the core framework conditions for eco-innovation. Our overall research question is to investigate the state and nature of green policy making in the current critical stage of intensifying global greening where Global South countries are stepping up their green policies markedly. The paper seeks more specifically to highlight trends, perceptions, effectiveness, and challenges of green policymaking in the Global South as perceived by policymakers themselves. We bring the results of a survey undertaking yearly in the years 2020-2023 among key policymakers and related core stakeholders from the Global South, with a main emphasis on Africa. The survey participants are all working professionally on green policymaking, green governance or green business development. While the survey is relatively small, the participants are all very influential in the actual green policymaking process in their home countries as will be explained further in the section on methodology.

We see our analysis as feeding into the green catching-up literature (Corrocher et al., 2021; Dai et al., 2021; Landini et al., 2021; Pegels & Altenburg, 2020) and other related concepts in the evolutionary economics literature directed at global

economic development, such as first mover advantages, learning curves, and techno-economic paradigms (Freeman & Soete, 1997; Herman, 2021; Perez, 2009).

We presume that the Global South Countries are less economically developed and are late entrants in the greening process as compared to the Global North; the latter we accordingly perceive as being early green entrants and more economically developed. We recognize off course that this is a very crude assumption, as there is considerable variety in the green performance and history of different both Global North and Global south countries (OECD, 2020; Schröder et al., 2019; United Nations, 2011). However, we believe with the current relatively small sample, can make a first analysis using such a crude distinction, to bring a picture of some main trends where finer analyses must await the growth of the sample. We hence see the paper as a contribution to the analysis of the degree and nature of the uneven global greening over time and space (Andersen, 1999). The focus here is strictly on the institutional change part, narrowed to the core policy making process as seen from the policymakers' perspective. The broader discussion of green catching-up trends and dynamics more generally we leave for another paper. To our knowledge there are no other papers with a focus on green policymaking and policy learning in the green catching-up literature, which is typically focused only on economic parameters while neglecting institutional and co- evolutionary change.

Given that industrialization is sought accelerated strongly across Global South countries in these years as a core means of economic development and that many of the most polluting industries to a high degree have moved to the Global South, the degree and strength of green policymaking in the Global South is of immense importance for climate change and wider environmental degradation (de Jong et al., 2012; Herman, 2021; Mani & Wheeler, 1998). Some argue that if the green and circular productive systems fail to spread to the Global South, it is likely that the impacts of increasing urbanization and industrialization in these countries will more than offset the gains that could arise from the most efficient circular productive systems implemented in the Global North in the next decades (Korhonen et al., 2018).

The paper is structured as follows: In section 2, we discuss some of the most relevant concepts and ideas regarding green policymaking and its relationship with economic development. Section 3 describes the methodology, while the core section 4 presents and discusses the results of the survey. The concluding remarks are made thereafter.

2. Green policymaking, institutional change and economic development

The relationship between environmental degradation and economic development is at the core of the green agenda and remains disputed. The mainstream economic hypothesis of an environmental Kuznets curve suggests an inverted U-shaped relationship between economic growth and environmental impacts, as countries that reach higher per capita income levels would achieve the financial and technological capabilities to solve environmental issues effectively (Arshad Ansari et al., 2020; Dinda, 2004). However, empirical evidence suggests that, contrary to that hypothesis, the green economy is not an automatic result of economic development but depends to a high degree on the use of green policymaking and other institutional instruments (Pegels & Altenburg, 2020). It is therefore of great interest to highlight the degree and nature of the green policymaking process in Global South countries and relating this to their current stage of economic development.

The relationship between green policymaking, eco-innovation, greening of societies and economic development has been a dominating focus of environmental policy research particularly from the more mainstream economic perspectives. Dominating this discussion is the debate around the so-called Porter hypothesis and its variants (Ambec et al., 2013; Cohen & Tubb, 2018; Jaffe & Palmer, 1997; Porter & van der Linde, 1995). The starting assumption is that companies only go green (eco-innovate) when forced by environmental regulation; the stricter the environmental regulation, the more eco-innovation. The Porter hypothesis suggests further that well-designed environmental regulations may have a positive impact on firms' innovation outputs as these regulations push firms to develop eco-innovations before their competitors that are not subject to the same policies (the "weak" version), and subsequently also impact positively the firms' competitiveness and overall performance – the "strong" version (Porter & van der Linde, 1995). Therefore, firms subject to new, more strict environmental regulation might experience early mover competitive advantages from being ahead on the learning curves and acquiring capabilities in those green technologies before their competitors (Pegels & Altenburg, 2020).

However, neglected by this discussion is the fact that these 'stick' policy measures over the years have been complemented by a range of 'carrot' policy measures incentivizing eco-innovation and green business development (Andersen, 2023), important for the rise of green business models and the evolving greening of the economic process (Andersen, 1999; 2023). Hence since companies in Global North countries have been subjected to stricter environmental regulations as well as incentivizing green policies much longer than Global South countries, they are generally presumed to be greener; there is also considerable evidence to support this (Andersen et al., 2021; Camilleri, 2020;

Chen et al., 2018; Mealy & Teytelboym, 2020; Panarello & Gatto, 2023; Pegels & Altenburg, 2020). This discussion on the greening of industries and the economy should not, however, be confused with a discussion on the climate footprint or other environmental footprints of respectfully Global North and Global South countries where Global North countries generally have a much higher environmental footprint due to the higher consumption levels (Cranston & Hammond, 2010). The greening of the economic process, we presume, is a necessary requirement for the greening of companies, innovation and society in the long term, not a guarantee for obtaining environmental sustainability, see also (Andersen, 2008; Andersen 2023).

Conversely, the “pollution haven hypothesis” (PHH) states that, given the increasing economic globalization and the role of global value chains in international production arrangements, more stringent environmental policymaking and other green policies might cause the more polluting industries to shift their activities towards countries and regions with less stringent environmental regulations in the Global South (Dechezleprêtre & Sato, 2017). This undermines the efforts to reduce pollution on a global level while generating incentives for Global South countries to maintain weak environmental regulation and low abatement costs for those industries as a way to attract capital and increase employment levels, accepting the environmental costs as a necessary evil in exchange for economic growth (Dechezleprêtre & Sato, 2017). As for the Porter hypothesis, empirical evidence shows mixed results, some supporting and some contradicting the PHH (Gill et al., 2018; Yang et al., 2018). Some research point to the fact that companies are greening their strategies and innovation more pervasively and globally within their industries (Faria & Andersen, 2017b). Also, the global multinational companies, being very brand sensitive, are generally among the green frontier companies, taking their strategies and eco-innovations globally (OECD, 2023).

Our starting assumption in this paper is that environmental policies historically has had and still have a core albeit very changing role for the greening of companies and eco-innovation more generally over time and space. We analyze policies not as an object (a specific program or instrument) but rather as a broad integrated co-evolutionary process of economic, institutional and societal development, taking place at many levels within national and regional innovation systems and in part at global levels. The greening process is intrinsically dynamic as even the definitions of what can be considered green and green policymaking change over time (Jiao & Boons, 2014). In this sense our evolutionary perspective and claim is rather that the economic process itself can go green and that indeed this has taken place to a fairly high degree in the early mover (Global North) countries through a series of co-evolutionary transformations and policies (Andersen, 1999, 2008, 2010; Faria & Andersen,

2017). This means we can describe the greening co-evolutionary process – in short- as shifting importantly from a primarily regulation driven environmental enforcement process (the environment as a burden) to an increasingly market driven process (the environment as a business opportunity), albeit continuously supported by appropriate green framework conditions of a very varied character. Environmental policy making has mainly taken off the last 50-60 years since the launch of the environmental ministries and -agencies in the beginning of the 1970s in the developed countries (mainly US and Western Europe), while the Global South countries more late has moved into green policy and green economic development (Andersen, 1999; 2023; Andersen et al., 2021; Landini et al., 2021; Lema et al., 2021; Mathews, 2017; Mealy & Teytelboym, 2020). We seek boldly to characterize some features of the current stage of green policymaking in Global South countries, knowing well that this is a very large research question in need of further research. We acknowledge that policies co-evolve with and come to form an integrated part of modern mixed economies as part of economic development, though taking on different forms and in different regional and institutional contexts, with distinct differences in the Global North or South (Aryal et al., 2021; Herman, 2021).

We refer to green policymaking as not only environmental regulations but also other policy measures such as financial and information instruments, educational programs, national action plans and more in any political sphere, none the least into green industrial policymaking important for the greening of industry and promotion of eco-innovation (Borel-Saladin & Turok, 2013). The literature on green policymaking and its effects on economic activities is still much focused on the Global North and industrialized countries (Pegels & Altenburg, 2020).

We embrace a rather broad green agenda, partly as greening is understood in multiple ways, partly to trace how the green agenda evolves over time in policymaking, though we are restricted by our limited surveys. We include and address noticeably both a ‘green economy’ and a ‘circular economy’ perspective. We define the green economy in evolutionary terms as the integration of environmental parameters into the economic process (Andersen, 2008, 2010); i.e. environmental parameters have become an important part of economic development through the pursuit of green business development and ‘green growth’ (Andersen, 2008; Capasso et al., 2019; Halle, 2016; OECD, 2011). The circular economy we define as the integrating of circular principles of maximizing the regeneration and retention of resources in the economic process (Andersen, 2023). More generally, the circular economy is usually defined as the shift from a linear take-make-waste economy to a regenerative, restorative, near zero waste economy (Andersen, 2023; del Río et al., 2021; Deutz, 2020; Kirchherr et al., 2017, 2023). The circular economy agenda is generally seen as an

alternative to predominant linear approaches in green policymaking, where some degree of waste creation is accepted and focus therefore is on waste and pollution management, in contrast to the circular ambitious attempt of designing/innovating out any type of waste (Patwa et al., 2021; Andersen, 2023).

The circular economy is a recent sub-policy agenda of the broader green agenda, which is gaining much policy momentum recently globally, forwarded by very strong recent circular policies in particularly the EU (D'Amato et al., 2017; Ko et al., 2022; UNEP, 2023).

The circular economy is an advanced and very demanding green agenda (de Jesus & Mendonça, 2018; Ghisellini et al., 2016; Kalmykova et al., 2018; Korhonen et al., 2018; Patwa et al., 2021). Transforming from a linear to a circular economy requires substantial changes in companies' and consumers' behavior as well as institutional change, i.e. the development of novel design criteria, novel ways of organizing circular production, novel waste and other infrastructures and product and resource traceability and more (Acerbi & Taisch, 2020; Cantú et al., 2021; Francesco La Russa et al., 2022; Lewandowski et al., 2016; Prieto-Sandoval et al., 2018; Andersen, 2023). This is not an easy task, given that the path dependent nature of technologies and institutions restrict systemic and radical changes (Dosi, 1982). Theoretically, global South Countries may gain circular leapfrogging advantages by investing early in circular rather than end-of-pipe infrastructures and solutions (Andersen et al., 2021; Lema & Rabellotti, 2023), a research question still limited researched (Gedam et al., 2021; Geng & Doberstein, 2008; Jabbour et al., 2020; Patwa et al., 2021; Zeng et al., 2021). The question touched upon in this paper is to what degree Global South countries' policies are pursuing such radical endeavors. The question on industrial circular trends and -leapfrogging opportunities forms the core in a related research project, 'GeckoCir', undertaken currently by the authors in Kenya¹ Preliminary results show that Kenyan manufacturing companies are still in an early stage of circular business development but their circular interest is high and the circular framework conditions are improving dramatically in recent years (Andersen et al. 2021). Our respondents, even though professionals in the green area, are not necessarily able to distinguish sharply between green and circular (before taking the course); we try to discuss this more specifically during the survey analyses in the paper. We interpret this paper more as a green policy and institutional trend analysis than a circular paper per se.

3. Methodology

The paper seeks to highlight trends, processes, impacts and challenges of green policymaking in the Global South as perceived by policymakers. We bring the results of a recent survey undertaken four times in the years 2020-2023 among in

total 86 policymakers and key stakeholders from nine different Global South countries, though with an overweight on African countries.

The survey participants are all working professionally on green policymaking, green governance or green business development, many in influential positions in their home countries. However, the survey has its distinct features as it builds on a sample of course participants. The participants have all taken part in an intensive 3-4 week course in Denmark for professionals on 'The Green and Circular economy- Dynamics and Governance', funded by the Danish Development Agency 'Danida'. The course forms part of the green capacity development program of Danida directed at the Danish environmental partner countries in the Global South. The authors are respectively course leader and teacher at this course, which has taken place yearly since 2017 at the University of Copenhagen.

The survey was undertaken during the course so all participants have responded. All participants are carefully selected by the Danish green development program meaning that they carry key responsibilities for the green policymaking or green agenda in their home countries. The participants are all directly involved in or responsible for green policymaking in their home countries, the others are influential green practitioners or stakeholders in their home countries, e.g. from utilities or branch associations involved in policy lobbying, see the sample overview Table 1 below. One of the courses was a so-called Leadership course for the top-managers, which is shorter (10 days) than the usual course with highly influential policymakers and lobbyists. It is important to emphasize that the actual politicians are not part of the respondents.

The course is a 3-4 week intensive course with ca. 25 participants each year meaning that the respondents are not anonymous but people well-known to the authors, people we have interacted with during intensive learning sessions and whose backgrounds we know in detail. The survey was carried out at the very onset of the course. This means the actual course has not influenced on the survey results. We intend in the future to survey the ex-participants from all the courses from time to time, both to assess the effect of the courses on their green perceptions and insights that we know from personal experiences are substantial, but also to study the long-term changes in the green policy making process in the Global South.

The respondents come from countries where Danida runs an environmental program; that is four African countries, three Asian and two from Latin America, see Table 1 below. The countries may vary somewhat from year to years as Danida changes their priorities, decided by the Danish Ministry of Environment and the Danish Ministry of Foreign Affairs. These nine countries are all relatively well-functioning emerging economies, so they do not represent

the least developed Global South countries. African countries dominate, however, especially Kenya, which is the least developed continent; other Global South areas have a smaller representation rate and this should be taken as a limitation when generalizing the conclusions to all Global South countries.

Table 1 - Description of the sample:

Regions		Sector	
Africa	58	Business	12
<i>Egypt</i>	12	<i>Business Association</i>	6
<i>Ghana</i>	10	<i>Company</i>	5
<i>Kenya</i>	32	<i>Consultant</i>	1
<i>South Africa</i>	4	Public sector	67
Asia	23	<i>National authority</i>	38
<i>China</i>	5	<i>Local or Regional authority</i>	20
<i>India</i>	5	<i>Utility</i>	5
<i>Indonesia</i>	13	<i>Government Training Institute</i>	4
South America	5	Other (NGO, University)	7
<i>Argentina</i>	3		
<i>Colombia</i>	2		
Education level		Gender	
High school	1	Female	34
Technical training	1	Male	52
Bachelor's degree	29		
Master's or MBA degree	44		
Doctorate degree	11		
		Age Group	
		Younger than 40	43
		41-60	43
		60 or older	0

The respondents are well educated, including 11 with a PhD, they are middle aged rather than young reflecting that many of them are in a position of power. There are slightly less women than men, but there is, interestingly, quite a high amount of women occupying high and top positions in green policymaking in these countries. The respondents work predominantly in the ministries, and mainly the ministries of environment, but also ministries of industry, treasury and planning are represented. Local and regional authorities are also well represented including some from utilities. Finally, there is quite a number from business associations and influential big and small companies as well as some other key stakeholders, including a training facility for government officials in Kenya. Overall, the sample represents a broad group of expert stakeholders with very high influence on the green strategizing and policy making in their home countries. The countries represent Global South countries who are experiencing a relatively good economic and institutional development. We recognize that the sample is relatively small and somewhat skewed with an

overrepresentation of Africa and especially Kenya- we expect it will grow over the years and become more even. We believe none the less the insights and positions of the respondents represent a very interesting window into the policy making process undergoing currently in different Global South Countries distributed on three continents.

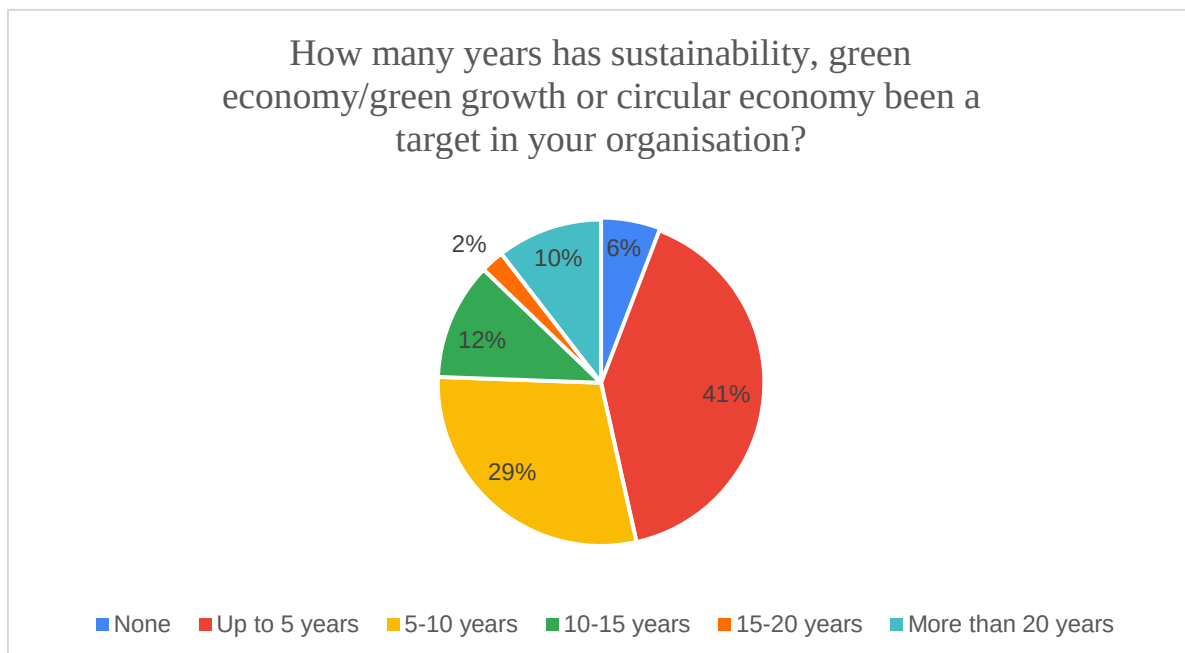
4. Analytical findings

In this section, our empirical survey results are brought focusing on the following four main themes: a) Changes in green policy priority over time, b) Changes in rationality in green policymaking (green economy and circular economy perceptions, c) Assessments of the efficiency of the green policy making and d) Challenges to the green policy making.

4.1 Time and priority of green policymaking in the global south

A core research question is to what degree and since when green policy making is being prioritized among the involved countries. Figure 1 highlights the emergence in time of green targets among the participants' organizations; since they predominantly come from policymaking organizations – or organizations which influence strongly on the green policy making- we see this as a measure of the integration of green policy targets in the policy makingprocess.

Figure 1. The timing of green policy targets

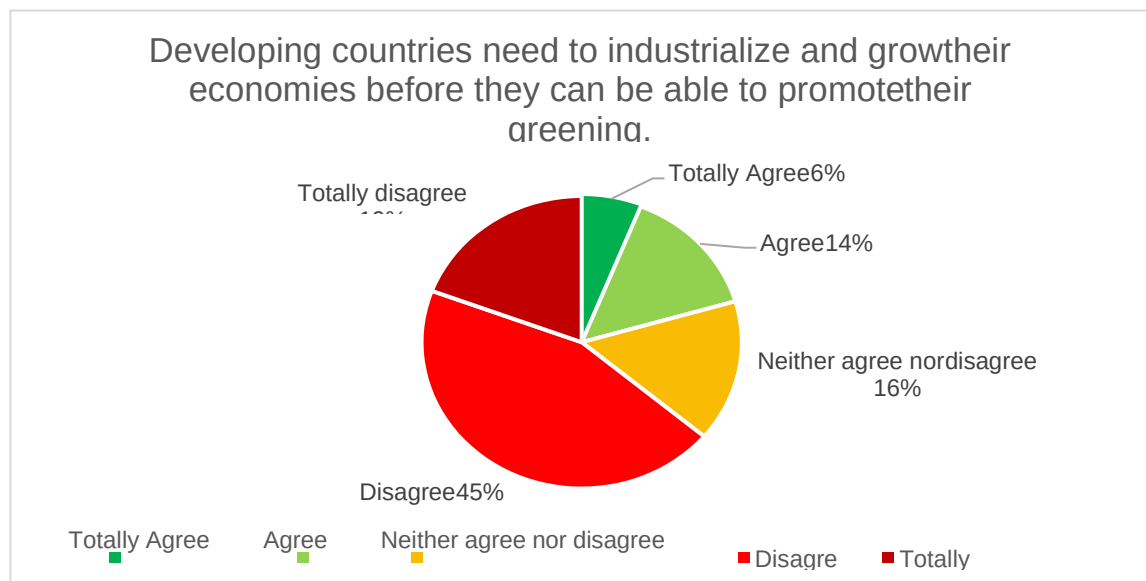


A significant finding from figure 1 is the very recent nature of the green target setting in the selected countries. As much as little below half (41%) say green targets have only been set within the last 5 years, further 29% say within the last 10 years. This means that 70% states green targets have mainly been prioritized only within this very recent period of the last 10 years. Only 10% experienced green targets for more than 20 years. Compared to the Global North timing, where the green policy agenda emerged strongly already in the 1970s and 1980s (Hunold & Dryzek, 2005; Mani & Wheeler, 1998; Meyer, 2021), there is a significant time gap of more than 40 years. The figure, however, clearly illustrates the rapid widespread increase in green policy target setting in recent years among the analyzed Global South countries.

4.2 Perspectives in green policy making and their evolution

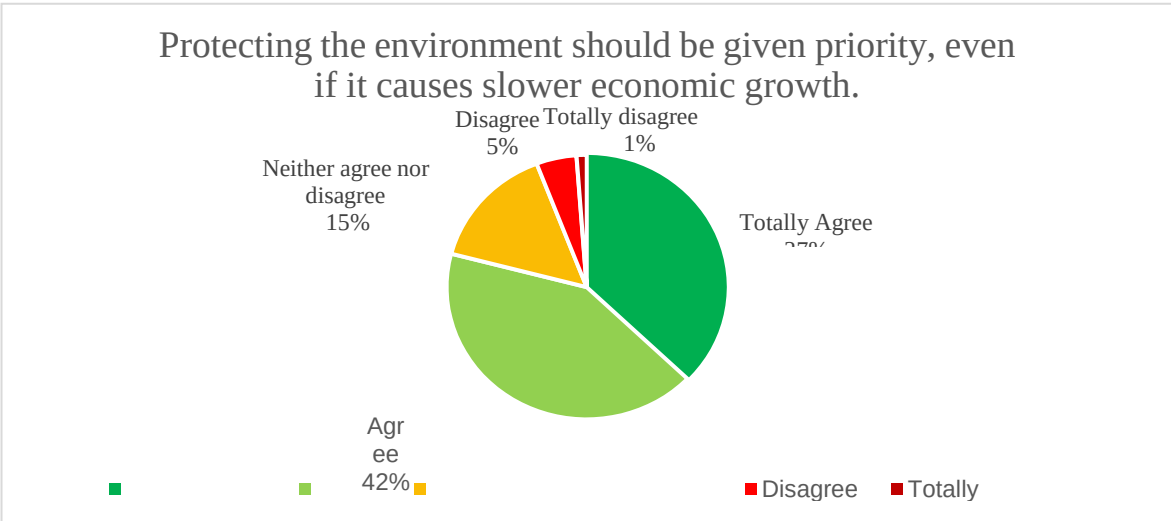
This section briefly discusses core changes in rationality in the green policymaking process focusing on the key environment-economy dichotomy perception. Figure 2 and Figure 3 below together highlights perceptions of 'green growth', i.e. alignments of economic and environmental targets. Figure 2 shows that two thirds (64%) believe in integrated green growth, i.e. that they can grow their economies while simultaneously promoting their green policies, whereas nearly a quarter (20%) believe economic development needs to be achieved first. 16% are undecided, illustrating that this is a difficult topic to address. It is significant that one fifth (and considerably more if we include the 16% undecided) sees greening as a burden to business and economic development. In contrast, surveys from the Global North conclude that respondents widely see greening as a business opportunity and a necessary license to operate (Bassi & Dias, 2019; Bassi & Guidolin, 2021; Marin et al., 2015).

Figure 2. Green growth perceptions and economy–environment trade-off



The related Figure 3 below shows that there is high willingness to prioritize environmental targets over economic targets. An overwhelming 79% agree or totally agree that this should be the case, with 15% of the respondents indecisive and only 6% disagreeing.

Figure 3. Green growth perceptions and economy-environment priorities



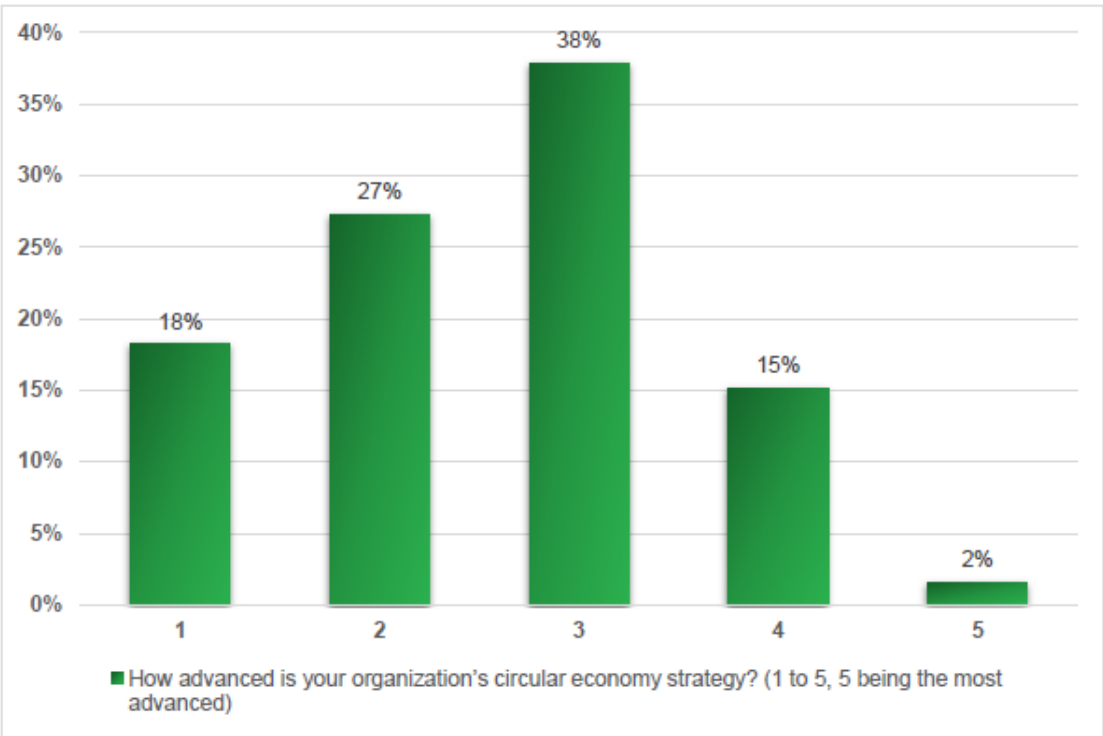
Overall, environmental targets are seen as highly prioritized among these policymaking stakeholders, demonstrating that there is a real sense of urgency and strong political priority of greening. This latter finding may, though, be biased by the fact that the survey participants are all working with environmental issues and policymaking, other policymakers in these countries are likely to answer differently. Hence we stress that all conclusions in the paper only refer to those actively involved in or influencing importantly on green policymaking in their countries.

Figure 2 and 3 are in part showing diverging results, illustrating the perceived difficulty and complexity of this subject. Together they show that there is still a relatively high expectation that the effect on economic development from stronger green policies in their countries will be detrimental.

4.3 Circularity perceptions

When it comes to the emergence of circular economy strategies, Figure 4 below shows that these are well on their way in Global South Countries. However, the assessment is that about 40% are at a medium level of development, while the other 45% assess the circular strategies still to be at a low (scoring 1) or relatively low (scoring 2) level of development yet. Only 2% believe that their organization is on a very high level of circular economy strategizing.

Figure 4. Circular Economy Strategizing

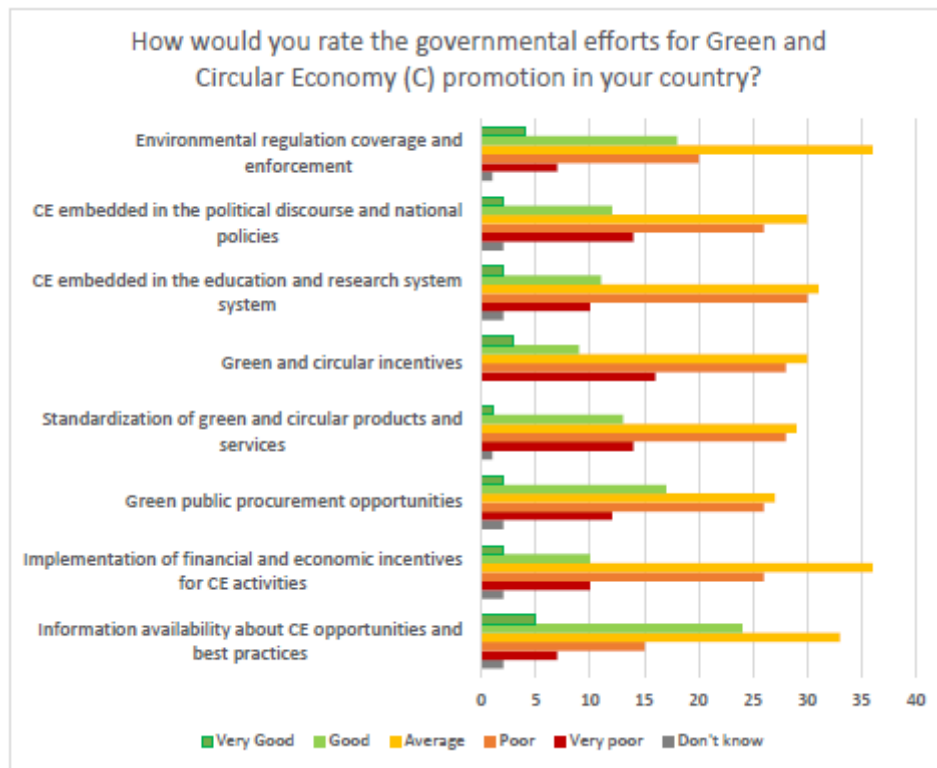


4.4 Assessment of the green and circular policy effort, measures and impact

This section highlights the perceived effectiveness of green policymaking in Global South countries by the respondents. Some of the themes will be highlighted further in the succeeding section on policy barriers.

In Figure 5 below, eight different types of green policy measures are rated on a scale from very poor to very good.

Figure 5. Rating the green and circular policy effort nationally



CE= circular economy

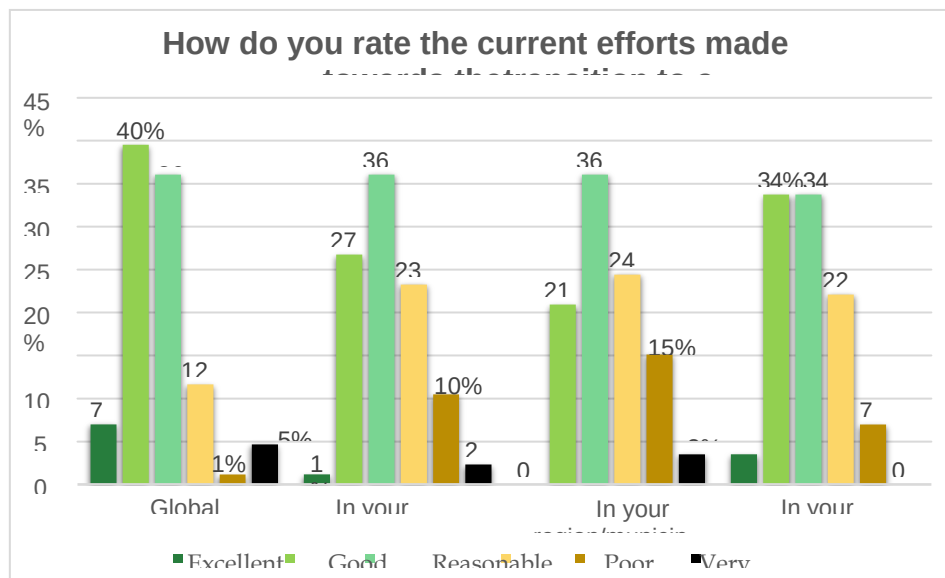
What stands out is that while a 'medium' performance is dominating across all seven parameters, a 'poor' performance scores very high in all, and the highest in two measures. Also alarming is the fact that a 'very poor' performance is found in all seven areas, with scores between 8-19%. On the other side the 'very good' score is generally very low, between 1-6% only. The 'good' score is also relatively low with scores between 10-14%, and additionally one on respectively 20%, 21% and 28%. The negative side is, in other words, dominating in the impact assessment. The measures asked to are both the hard environmental regulation and several soft, more economic and information measures such as information tools, public purchasing underlying standards, and 'carrot' measures (positive incentives for green and circular innovations), some of the targeted the advanced circular economy agenda directly. It is noticeably that 'green and circular incentives' (the 'carrot' approach) scores most very poor and poor ratings, while regulation scores the best ratings, reflecting that these countries rely to a high degree on environmental greening and enforcement in their greening process.

The embeddedness of the circular economy discourse in policy making broadly and in the research and education system receives nearly similar poor

assessments followed closely by Standardization and public green purchasing. In other words, the more economic instruments and the positive incentive side - economic and other rewards (carrot rather than stick) is not sodeveloped.

In Figure 6 below the participants were asked to rate the effort to transform to a circular economy in respectively their own workplace, their municipality/region, their nation and globally. This question seeks in other words to identify their assessments of the green transformation at different systemic levels but also to compare their own situation with that of other nations and regions.

Figure 6. Global, national, local and organizational assessment

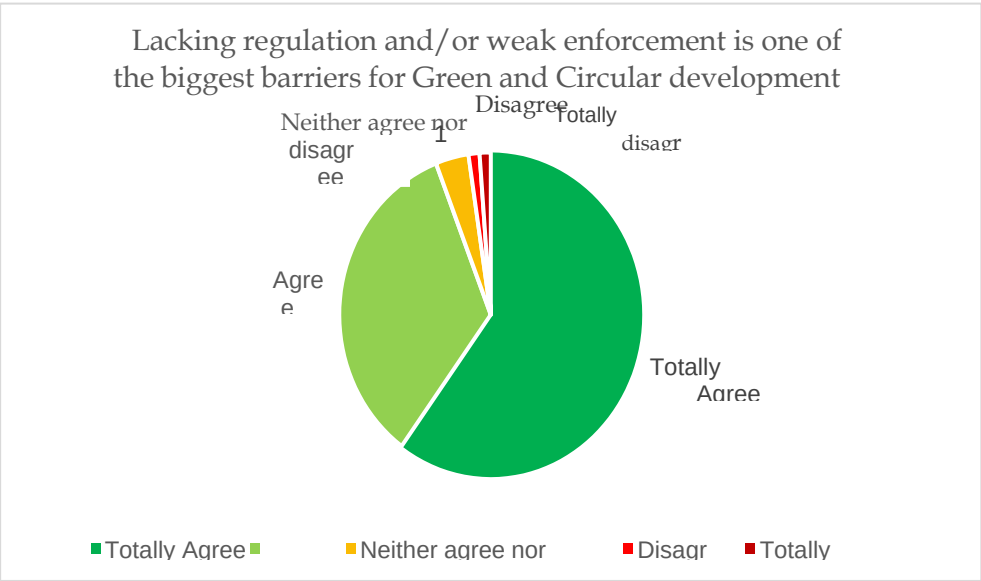


While they generally assess a 'reasonable' performance in all these (34-36%), they see a 'good' effort considerably higher globally (40%) than in their own countries (27%) and somewhat lower yet regionally (21%). This may be interpreted in the way that they see the global South to be behind the Global North when it comes to circular policy making efforts, (given the fact that the Global South representatives comes from all global South regions (Africa, Asia, Central and South America)). Interestingly, they assess their own workplace as performing better than nationally and regionally (34% Good and 3% Excellent), with only the global levels scoring more on excellent (7%). 'Poor' and 'very poor' ratings are also relatively high nationally and interestingly a bit worse regionally; workplace performing again a bit better. This overall reflects the rather novel stage of circular policy making in many Global South countries (with exceptions which are difficult to capture in the current small survey). Also globally there are some "Poor" ratings, but representing a much lower percentage (12% Poor, only 1% Very poor).

4.5. Challenges for effective green policymaking in the global south

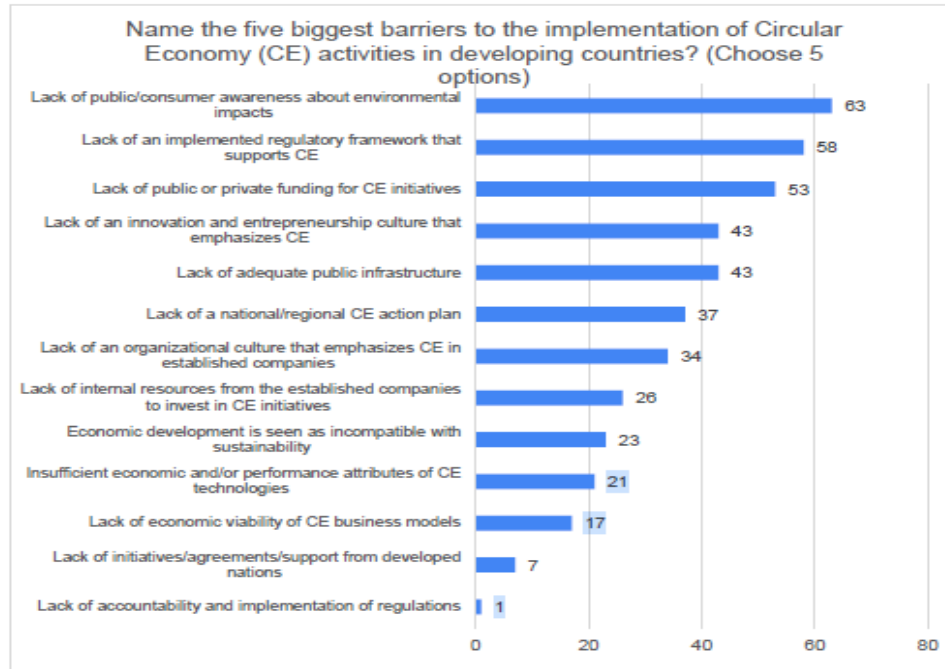
In this last section we highlight the barriers to effective green policy making further. From Figure 7 below it is apparent that that lacking regulation and/or weak enforcement is considered a major barrier for green and circular development, with 94% agreeing or totally agreeing with this affirmation.

Figure 7. Environmental regulation and environmental enforcement effectiveness



When it comes to identifying the biggest barriers for a transformation to a circular economy more specifically in the Global South, the main barriers are highlighted in Figure 8 below,

Figure 8. Barriers for the implementation of circular economy in the Global South



The three biggest barriers are identified as a lack of: 1) Green consumerism-citizens are not seen as a driver, on the contrary; from the courses we know that participants generally have little faith that this situation can be changed. 2) A circular economy supporting implemented policy framework; it is here the word *implementation* that matters; it is a very clear experience from the courses, that participants perceive their green regulations as good but it is the implementation that is seen as a major problem. 3) Public/private funding for circular economy initiatives. From the courses we hear frequent evidence of lacking R&D and other programs to support green and circular innovation.

The middle ranked barriers are:

4) Lack of innovation and entrepreneurship culture related to CE; we may, following input on the courses, interpret this as a generally low focus on innovation more generally.

5) Adequate infrastructures, illustrating challenges in building up public green institutions; e.g. the informal sector (the 'waste pickers') is according to the participants responsible for a high degree, in some countries most, of the waste collection and sorting of the waste going to recycling. 6) national/regional circular economy action plan, i.e. quite a number of the countries do still not have a national or regional circular economy action plan (but this is also the case with many Global North Countries). Related to this is 6) lack of a circular culture in

companies and a 7) internal resources within companies. Insufficient technologies and viability of circular business models are also pointed to as somewhat minor challenges; finally, support from the Global North is only seen as a small barrier; indeed a high amount of the green policies in the participating policies are directly or indirectly supported by development programs from the Global North.

A somewhat relevant analysis to compare with from the Global North is a relatively recent study by Kirchherr et al. (2018) who conducted an analysis based on desk research, semi-structured interviews and a survey to circular economy experts and stakeholders from businesses and governments in the European Union on the barriers to CE development in the region, classifying them into 'cultural', 'regulatory', 'market' and 'technological' barriers. The authors conclude that cultural barriers, especially "Lacking consumer interest and awareness" and 'Hesitant company culture' are the main barriers to CE implementation in the EU. Droege et al. (2021) studied challenges to assessing CE implementation by the Portuguese public sector using semi-structured interviews with 21 CE and assessment experts finding there to be strong cultural barriers. They noted an absence of awareness for assessing CE as well as a lack of leadership commitment to that purpose. Our survey similarly points to the lack of consumer awareness and business awareness as main barriers to CE implementation in the Global South; however, regulatory and governmental-related barriers as well as lacking public and private resources have a more prominent role in the latter. This may reflect the general problems in the Global South with green policy implementation, but also the more recent stage of circular economy policies in some Global South Countries as compared to the Global North.

5. Conclusion

We have in this paper sought to make a first analysis of the current status and trends of green policymaking in selected countries of the Global South based on our special 'Danida course' sample of respondents representing important green policymakers. We have fundamentally sought to shed light on the institutional aspects of the uneven global greening processes and dynamics. We see this as feeding into evolutionary economic research on co-evolutionary economic change. Rather than the traditional economic or technological perspective in the green catching-up literature, we seek to shed light specifically on green institutional change – the core green policymaking process and its transformation over time- and its relationship to economic development.

While we recognize the small size of our sample and the somewhat skewed composition with African and mainly Kenyan overweight, we none the less argue that our analysis has some important explanatory value for the Global

South as such, given the very high influence of our respondents in the policymaking process in their home countries. We also acknowledge that more detailed studies are needed on regional differences, e.g. between Asia, Africa and Latin America, and correlating answers with GDPs. We intend to do this once the sample grows bigger in the coming years. We also intend to combine these findings with our supplementary business and policy research in Kenya in the ongoing GeckoCir research project in Kenya, in order to shed in-depth light on the co-evolutionary economic, institutional and technological dynamics of the greening of national innovation systems in different regions of the Global South.

Generalizing the main findings of the current survey we find that a strong green agenda is quite recent in the Global South, having been prioritized only the last 5-10 years, compared to a timespan of 50-60 years of strong green policy making in the first mover Global North countries. Some elements of green policy leapfrogging may be identified, as circular economy perspectives are being introduced relatively early in the green policy learning process as an important policy target and seems to be rapidly progressing. The environment is, however, still to quite a high degree considered a threat to business and economic development. Green consumerism is also seen as very poorly developed and so are green and circular business strategies and cultures, hence overall the greening of the economic process is not so far. Despite this we find that environmental targets are highly prioritized even compared to economic priorities, illustrating the urgency felt in these countries to take environmental action. Green policymaking is clearly seen as a very important, albeit we recognize that our 'green' respondents are biased and are likely to prioritize green issues more than a more representative sample of respondents. Given that these are the actual people developing the green policies in their countries, their opinions are naturally of key importance.

Another main finding is that the effectiveness and impact of green policymaking in the Global South is relatively poor, and perceived as considerably lower than global levels. Overall, the green policy making in the Global South is sharply on the rise, with an impressive degree of priority but also many severe policy challenges, not just in the well-known weak enforcement of environmental regulation but also in the more mature and more market oriented preventive policy measures such as providing positive incentives for green business development and green and circular innovation and supporting green public purchasing. In short, environmental regulation and whip like policy measures is still a central policy measure, while incentivizing green policy measures ('carrots') are still quite weak which appears to be a main distinct feature of Global South green policymaking in its current stage. Given the key role of policymaking –widely understood - for the greening process these findings have

serious implications for the making of strategies and policy measures in Global South countries. We conclude that the greenpolicy learning in the Global South is still in an emerging stage of development characterized by many challenges albeit in rapid transformation providing an important window of opportunity for improving the policymaking processes.

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Note

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Choice of bio-inputs versus chemical inputs by farm householdstowards green agriculture: Evidence from India

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Abstract

This paper has compared the use of bio-fertilisers and manures with respect to synthetic fertilisers and pesticides in order to address sustainability issue in Indian agriculture. The paper also examines the potential of bio-fertilisers, manures and bio-pesticides on farm output. Using the 77th round of NSSO data, the paper found that farming households are more relying on chemical fertilisers than bio-fertilisers. Farm households from backward states are more relying on chemical inputs compared to developed states. The estimated output function result shows that the expenditure on seeds have the maximum influence over the output followed by labour than other inputs. The estimated result also shows that bio-inputs have potential to increase productivity.

Key Words: Green Agriculture, Bio-inputs, Chemical Inputs

Introduction

Green growth and green economy have been considered as a practical tool for achieving the objective of sustainable development. In India, green revolution has undoubtedly increased the agricultural productivity which has helped to meet the food demands of growing population. Since then, the use of chemical pesticides and fertilisers have played a vital role in boosting up the agricultural production. At the same time, the use of inorganic fertiliser has deteriorated the soil conditions and increased the concern of farm sustainability. Along with soil quality the toxic effects of chemical fertiliser and pesticides has affected the plant, animal as well as human being. This has emerged the importance of eco-friendly

agricultural system that will help in providing healthy food and long-term soil-environmental sustainability. To reduce the toxic effects of chemical fertilisers and pesticides on both human and plant life, organic or sustainable or eco-friendly agricultural practice has been developed. Hence environmentally friendly green agriculture has become major concern globally to meet the growing demand for organic food and maintaining sustainability of soil health. In fact, a study has found that there is almost a gap between ten million tons of plant nutrients between removal of crops and supply through chemical fertilisers. Both the cost and environmental impact of chemical fertilisers proves that for farmers bio-fertilisers as the viable option to increase agricultural productivity. Bio-fertilisers and bio-pesticides play a crucial role in maintaining microorganisms of soil and protecting the plant.

Against this backdrop, the present study first attempts to analyse the use of bio-fertiliser and bio-pesticides contrast to chemical inputs like fertilisers and pesticides. Second impact of using bio-fertiliser and pesticides on farmers' productivity.

Review of literature

The history of using chemical fertiliser and pesticides in India is not very long. India has witnessed almost 60 years of history in using synthetic fertiliser and pesticides as the use has been intensified only after green revolution. There are studies which has discussed the potential of bio-fertilisers in increasing agricultural productivity and addressing sustainability issues in agricultural sector (Suhag, 2016; Atieno et.al, 2020). Atieno et al (2020) raised their concern on deleterious effects of chemical inputs on pollution both soil and water, soil fertility, human life, flora and fauna. At the same time studies also discusses the impact of chemical fertilisers on environment and ecosystem (Chandini et. al, 2019; Shiwakoti et. al, 2019). Shiwakoti et al.(2019) in their study focused on how long-term tillage and nitrogen fertilization is expected to alter micronutrients over time.

Basically bio-fertiliser is considered as organic product that contains some particular microorganisms. Atieno et al (2020) in their study in Great Mekong Region (GMR) focused on how countries on Bahadur et al (2014) in their study discussed importance and application of potassic biofertilizers and the study mentioned that biofertilizers are considered as one of the best modern tools for sustainable agriculture. Mishra and Dash (2014) in their field-based study found that compared to chemical fertiliser, use of bio-fertiliser leads to higher yield and higher benefit to cost ratio. Other than that, the number of tillers, plant height and profit to farmers are also higher that proves better sustainable economic development for the farmers. Kumar et al (2017) in their study highlighted the vital role of biofertilizers in maintaining long term soil fertility and sustainability. The study mentioned that bio-fertilizers fixes atmospheric

di- nitrogen, mobilizes fixed macro and micro nutrients in the soil into forms available to plants. In a similar line Mishra et al (2013) in their paper reviewed role of bio-fertiliser in organic agriculture and found that bio-fertilisers are essential components of organic farming that play a vital role in maintaining long term soil fertility and sustainability. Sharma and Chetani (2017) in their study reviewed the effect of organic and chemical fertilisers on plants and the study suggests that use of organic fertilisers and amendments are eco-friendly compared to synthetic fertilisers that causes environmental pollution and soil deterioration. A recent study by Paul et al (2023) discusses sustainability transition for Indian agriculture. The study focused transition to sustainability through a framework that includes scale, affordability and sustainable inputs.

Most of the exiting study discusses the potential and future prospective of bio-fertilisers on agricultural productivity. Studies that are empirically verified the perspective of bio-fertilisers are limited. The present study is an attempt to fill this gap and understand the perspective of bio-fertilisers and manures in farm productivity.

Data and methodology

The paper has used the recent unit level data of National Sample Survey (NSS) on Situation assessment survey of agricultural Households. NSS in its 77th round has collected micro information on different aspects of farming. The data was collected during the period 2018- 2019. It has captured the information for two cropping season – Khariff and Rabi seasons. Khariff season has mostly captured information on various indicators during July to December 2018. This is basically monsoon season in India whereas Rabi season captures information during January to June 2019 – post monsoon season. Here the unit of analysis is farm households and the total number of households are 58040. The sample households are drawn from all over India.

The study deployed descriptive approach to dissect the variables in interest. It includes comparison across states in using bio-fertilisers, manures and chemical fertilisers. Other than that, the study makes use of regression analysis in measuring the productivity of farmers.

Model specification

With the help of ordinal least square regression model, the effect of expenditure on chemical fertilisers vis-à-vis bio-fertilisers has been described farm output. It is hypothesised that bio- fertilisers have positive impact on farm output. Mathematically, the relation can be expressed as:

$$\log Y_i = \beta_1 + \beta_2 \ln land + \beta_3 \ln labour + \beta_4 \ln Biofertiliser + \beta_5 \ln Manure$$

$$+ \beta_6 \ln \text{BioPesticides} + \beta_7 \ln \text{Chemical Pesticides} \\ + \beta_8 \ln \text{Chemical Fertiliser} + \beta_9 \ln \text{Irrigation} + \beta_{10} \ln \text{Seed} + U_i$$

Here Y_i represents the farm output. The variable is entered in logarithm form. The variable land indicates total area of land that a household possesses. All other variables basically represent expenditure on different inputs like expenditure on labour, biofertilizer, manure, bio-pesticides, chemical pesticides, chemical fertilisers, irrigation and seeds. Except land all other independent variables are entered in logarithm form.

Hypothesis and variable construction

The variables are chosen to identify the effect of different inputs on farm output.

Land: The variable land is deployed to understand the impact of holding size on farm output. The variable is entered in logarithm form and it is hypothesised that the increase in size of holding will increase farm output.

Labour: Labour acts as a crucial input in the production process. To measure the effect of labour in the agricultural output, our study has taken expenditure on labour. Our data set has information on expenditure on human labour. The expenditure on human labour is given as paid out expenses and imputed expenses. For calculation, we have added both the components and found out the total expenditure on labour. We hypothesise that the expenditure on labour has positive impact on farm output. The variable is entered in logarithm form.

Bio-Fertiliser: The major variable in the analysis is bio-fertiliser. For bio-fertiliser paid out expenses are considered. The variable entered in continuous and logarithm form. The study hypothesises that bio-fertilisers have positive influence in

Chemical Fertilisers: For chemical fertilisers also, we have taken paid out expenses of farm households and the study assumes that use of chemical fertiliser will increase the agricultural output.

Manure: Manure is considered as organic matter, if added to the soil, that will increase the soil fertility. Manure is completely environmentally friendly. Hence, for maintaining soil fertility, manure is one of the crucial inputs. Our data has given paid out expenses and imputed expenses of the farm households. We have added both the expenses to find out the total expenditure on manure. The variable is a continuous one and entered in logarithm form.

Bio-pesticides: Pesticides are used to protect the plant. Bio-pesticides are derived from natural materials like animals, plant, bacteria and certain minerals. It does not contain any chemical substances and hence is considered as environment

friendly. The study includes expenditure on bio-pesticides by farm households. For bio-pesticides also, the data has given both paid out expenses and imputed expenses. We have taken the total of paid out and imputed expenses.

Chemical Pesticides: Chemical pesticides contain chemical substances and used to protect plant from pests, insects and weeds. As the percentage of households relying on chemical fertiliser is higher, the study includes chemical fertiliser as one of the independent variables to measure the production function.

Irrigation: Indian agriculture is mostly rainfed and proper irrigation facilities will definitely have positive impact on farm output. For irrigation, our data set provides both paid out expenses and imputed expenses. The study includes total expenditure done by farm households on irrigation.

Seed: Green revolution signifies how the high yielding varieties of seeds boost up the rice and wheat production in India. Hence use of seed plays a vital role in agricultural production. The study has taken expenditure on seeds by farm households. Both paid out expenses and imputed expenses are included in the variable.

The notation and expected signs are presented in table 1.

Table 1. Hypothesis and variables			
Variables	Notation	Description	Expected sign
Dependent Variable			
Output	Ln Output	Continuous variable which explains total agricultural output of farm households	
Independent Variables			
Land	Land	The variable is entered as continuous variable with total area of land in acre	+
Labour	Ln Labour	The variable is entered as continuous variable and logarithm value of expenditure on labour	+
Bio-fertiliser	Ln bio- fertiliser	The variable is entered as continuous variable with households' expenditure on bio-fertiliser	+
Manures	Ln Manure	The variable is a continuous one which explains farm households' expenditure on manure	+
Bio-Pesticides	Ln Bio-Pesticides	The variable is entered in logarithm form that includes household's expenditure on bio-pesticides	+
Chemical Pesticides	Ln Chemical Pesticides	The variable explains households' expenditure on chemical pesticides and is entered in logarithm form	+
Chemical Fertiliser	Ln Chemical fertiliser	The variable explains use of chemical fertilisers for crop production	+
Irrigation	Ln Irrigation	This variable explains whether the households' expenditure on irrigation affects positively on farm output or not	+
Seeds	Ln Seed	The variable explains expenditure on seeds for different crops	+

Results and discussion

A comparative analysis on use of bio-fertilisers, manures vis-à-vis chemical fertiliser is presented in table 2. As discussed, fertilisers are considered as vital inputs in farming and usually farmers rely on two types of fertilisers – bio fertiliser and chemical fertiliser. Table 1 discusses the state wise position in using both types of fertilisers. That apart, the study also takes into account the use of manures as it is an organic matter and if added to the soil that will increase the productivity.

Table 2: State wise Use of Bio-Fertiliser, Manures and Chemical-Fertiliser			
States	Bio-Fertiliser	Manures	Chemical-Fertiliser
Andhra Pradesh	3.27	16.12	50.23
Arunachal Pradesh	1.34	7.29	7.89
Assam	6.87	9.78	51.19
Bihar	7.92	14.42	71.53
Chhattisgarh	6.46	15.82	66.36
Goa	7.00	13.00	48.00
Gujarat	20.63	14.99	64.38
Haryana	15.81	9.39	59.78
Himachal Pradesh	4.51	11.27	62.80
Jammu & Kashmir	6.57	20.69	66.17
Jharkhand	3.50	12.40	70.42
Karnataka	9.18	26.73	67.35
Kerala	23.15	37.19	46.57
Madhya Pradesh	8.98	10.24	64.22
Maharashtra	9.83	12.50	65.04
Manipur	2.86	5.46	57.39
Meghalaya	5.64	34.62	35.26
Mizoram	0.40	5.93	1.98
Nagaland	0.00	0.42	0.42
Odisha	3.66	24.84	75.36
Punjab	16.93	10.45	63.94
Rajasthan	12.38	12.48	47.89
Sikkim	1.89	3.36	5.25
Tamil Nadu	15.86	22.21	42.65
Telangana	7.01	23.46	73.94
Tripura	22.54	17.37	66.19
Uttar Pradesh	14.73	7.15	69.57
Uttaranchal	2.75	11.31	39.45
West Bengal	15.10	20.24	71.40
All India	10.63	15.08	60.31
<i>Source: NSSO Unit level Data, 2018-19 Figures are in percentage</i>			

At all India level farming households are mostly using chemical fertilisers as 60.31 per cent of households are relying on chemical fertiliser. Only 10.63 per

cent of households are using bio-fertilisers. Among all states Kerala stands first in using bio fertilisers with 23.15 per cent of farm households spending on bio-fertilisers followed by Tripura with 22.54 per cent and Gujarat with 20.63 per cent of farm households using bio-fertilisers as inputs. Other than these three states, five states Haryana (15.81%), Punjab (16.93%), Rajasthan (12.38%), Tamil Nadu (15.86%) and Uttar Pradesh (14.73%) are higher than the national average. Coming to use of manure, farm households from Kerala 37.19 % stands first in the row followed by Meghalaya (34.62%) and Karnataka (26.73%). Other than these three states Odisha (24.82%), Telangana (23.46%), Tamil Nadu (22.21%) and Jammu & Kashmir (20.69%) are using manures higher than national average as inputs in agricultural production. Compared to these green inputs, the percentage of households using chemical fertilisers is significantly higher and farm households from backward states like Odisha, Bihar, Telangana, West Bengal are more inclined towards chemical fertiliser. Odisha with more than 75 per cent of farm households (75.36%) occupies first place in using chemical fertiliser backed by Telangana (73.94%) and Bihar (72.53%). This could be due to the fact that illiteracy among farm households regarding the negative impact of chemical fertiliser.

Table 3: State wise Use of Bio-Pesticides and Chemical-Pesticides		
States	Bio-pesticides	Chemical-pesticides
Andhra Pradesh	2.40	40.78
Arunachal Pradesh	4.02	3.13
Assam	6.83	30.48
Bihar	9.33	34.85
Chhattisgarh	5.22	31.15
Goa	9.00	12.00
Gujarat	8.65	26.83
Haryana	8.10	44.17
Himachal Pradesh	4.83	21.90
Jammu & Kashmir	14.25	22.92
Jharkhand	3.30	13.21
Karnataka	8.29	23.91
Kerala	6.85	10.84
Madhya Pradesh	4.06	35.94
Maharashtra	7.76	42.02
Manipur	8.95	43.51
Meghalaya	15.38	7.31
Mizoram	3.16	1.98
Nagaland	0.21	0.00
Odisha	4.94	51.71
Punjab	9.52	51.73
Rajasthan	2.76	14.37
Sikkim	0.84	4.62
Tamil Nadu	8.35	20.31

Telangana	3.78	65.28
Tripura	15.85	41.19
Uttar Pradesh	14.58	49.07
Uttaranchal	6.27	17.89
West Bengal	4.10	56.17
All India	7.59	34.91
<i>Source: NSSO Unit level Data, 2018-19</i>		

Table 3 presents a comparative analysis in using bio-pesticides and chemical pesticides for plant protection among the farm households. At all India level 7.59% of households are spending on bio-pesticides for plant protection. Tripura (15.85%) stands first among all states in using bio-pesticides backed by Meghalaya (15.38) and Uttar Pradesh (14.58%). Farm households from Tamil Nadu (8.35%), Punjab (9.52%), Manipur (8.95%), Maharashtra (7.76%), Karnataka (8.29%), Jammu & Kashmir (14.25%), Haryana (8.10%), Gujarat (8.65%), Goa (9.00%) and Bihar (9.33%) are using bio-pesticides higher than national average. Coming to chemical fertilisers, at all India level 34.91 percentage of households are spending on chemical fertiliser. 65.28 percentage of farm households from Telangana are occupying first position in using chemical fertiliser followed by West Bengal (56.17%) and Punjab (51.73%).

Regression analysis

Table 4 presents the estimated output function which is regressed with land, labour and other inputs like seeds, chemical fertilisers, bio-fertilisers, manures, chemical, bio-pesticides and irrigation.

Table 4: Estimated Output Function			
Independent Variable	Dependent Variable: LnOutput		
	Coefficient	Robust StandardError	P Value
Constant	.201	.005	.000
Land	.0205	.002	.000
Labour	.2775	.005	.000
Bio-fertiliser	.0355	.002	.000
Manure	.0357	.002	.000
Bio-pesticides	.0399	.003	.000
Chemical Pesticides	.0311	.002	.000
Chemical Fertiliser	.0889	.003	.000
Irrigation	.0492	.001	.000
Seed	.4930	.006	.000
No of Observations	57,978		
R Square	.88		

Agricultural output depends a number of variables like land labour and other inputs like seeds, fertiliser, and irrigation. When it comes to make a choice between the bio inputs like fertilisers and pesticides, farmers would compare the benefits, at least the short run. Farmers may not be able to realise the long-term benefits of bio inputs. The positive externalities of the use of bio inputs would go beyond the individual farmer who is using. Therefore, it is important to know the return from each agricultural input. Table 4 presents the results of OLS regression analysis. We have considered all possible inputs in the agriculture to explain the agricultural production function. We notice that the expenditure on seeds have the maximum influence over the output followed by labour. We can infer that farmers who spend more money on high quality seeds receive high return. This gives an important lesson to the farmers. Instead of being too much obsessed to load extra doses of chemical fertilisers, farmers should give top priority on seed choice and invest maximum money for buying the best variety of seeds to improve the yield. When it comes to choose between the chemical fertilisers and bio fertilisers the former gives higher returns as compared to the bio-fertiliser and manure. However, between bio pesticide and chemical pesticides, bio pesticides seem to have higher returns. After seeds and labour employment, chemical fertiliser and Irrigation have the maximum contribution to the output. While choosing between chemical pesticide and bio pesticides, bio pesticides seem to have better contribution as compared to chemical pesticides.

Concluding observations

The study was an attempt to understand the potential of bio-fertilisers, bio-pesticides and manures to increase farm productivity along with other inputs. Studies have already witnessed the potential of chemical fertilisers and pesticides in farm productivity. Though the potential of bio-fertilisers and pesticides are discussed in existing studies, this paper is an attempt to measure it empirically. The study found that bio-fertilisers and manures have lower return than chemical fertiliser. This results again proves the potential of chemical fertiliser as it was found in earlier literature. However, the potential of bio-fertilisers can not be denied at all. Bio-fertilisers have positive impact on agricultural productivity. Compared to chemical pesticides, bio-pesticides have higher return.

No doubt bio-fertilisers have potential to increase the agricultural productivity though not like chemical fertilisers which act as fast food for agricultural production. The major concern is not relying on bio-fertilisers and pesticides for farm output. This is basically low adoption rate or diffusion of bio-fertilisers across regions and over the time. The knowledge creation and diffusion among farmers could be possible when proper policy and institutional interventions are made. In India the role of government agencies and agricultural universities in adopting any agricultural technology is comparatively less compared to

other progressive farmers, information and communication technologies (Das, 2010; Das, 2013; Das, 2014; Das, 2018). Without understanding the heterogeneity that exist among farmers and differential farm characteristics, it is not possible to replace bio-fertilisers in the place of chemical fertilisers. The institution intervention needs to analyse the micro dimensions to replace bio-fertilisers and move towards sustainable agriculture.

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