Background documents to the Technology and Innovation Report 2023

Green Windows of Opportunity in the Global South

Rasmus Lema
UNU-MERIT, United Nations University
lema@merit.unu.edu

Roberta Rabellotti
University of Pavia
roberta.rabellotti@unipv.it

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Abstract

The green transformation has profound implications for the global economy and, hence, for the prospects for latecomer development. In this paper we review the insights derived from case studies of developing countries' green technology experience. We conduct a systematic literature review covering seven key technologies. This allows us to examine whether the green economy offers new opportunities for latecomer development and their ability to seize these opportunities. To understand how developing countries' capacities to exploit these opportunities differ across cases, we focus on sectoral systems and, particularly, on (a) preconditions allowing exploitation of these opportunities, and (b) strategic responses of public and private actors in this respect. We identify four different scenarios: (1) effective opportunity exploitation; (2) missed opportunities; (3) active approach; and (4) distant opportunities. We conclude by assessing the options for policy to support developing countries in their efforts to encourage green development strategies, focusing on both the provision and augmentation of opportunities and construction of the requisite sectoral production and innovation systems.

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For further information about this document, please contact Technology, Innovation and Knowledge Development Branch, UNCTAD, Palais des Nations, CH1211 Geneva 10, Switzerland, e-mail: stdev@unctad.org.

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Contents

1 Introduction

In a world that is transforming towards a greener global economy it is necessary to focus, particularly, on techno-economic developments aimed at innovations related to renewable energy and sustainable production and consumption. Innovation activities in these areas will contribute to economic diversification and creation of higher-wage jobs while also protecting the planet. The transformation to a greener economy will open 'Green Windows of Opportunity' (GWOs) which should allow developing countries to both catch up and forge ahead in green sectors and related value chains.

This paper discusses empirical insights from the case studies in the literature on developing countries' experience in key 'green economy' sectors, which includes those working on different types of sustainability-oriented technological changes. We review the existing empirical evidence on the essential roles in production, distribution, and use of renewables such as bioenergy, solar and wind energy, green hydrogen, and electric mobility.[1]

We address the following research questions: (a) Does the green economy offer opportunities for latecomer catch-up by developing countries? (b) What characterizes the capacity of developing countries to seize these opportunities? (c) What types of policy would support developing countries in their efforts to take advantage of GWOs?

We start with a wide literature survey, aimed at collecting information on the experiences of countries at different levels of development, in sustainability-oriented sectors. We customize the analytical framework proposed by Lema et al. (2020) to investigate GWOs in terms of their existence and characteristics, to gain insights into the preconditions for green innovation and the strategic responses of public and private actors in different sustainability-focused sectoral systems. Finally, we investigate the opportunities for catch up in green industries by developing countries and derive some lessons for policy.

The paper is organized as follows. Section 2 introduces the concept of GWOs, and their specificities and the analytical framework used to analyse their nature and the dynamics of their exploitation. Section 3 presents the methodology used for the literature survey and outlines the sectoral evidence

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[1] In this paper, we use the term 'green economy' to refer to the green sectors and industries which are the focus of this analysis. This includes industries engaged in activities that reduce both environmental impact and use of scarce natural resources. We focus on low carbon sectors that reduce dependence on fossil fuels and their adverse effects on climate change. Low-carbon developments are aimed at reducing emissions and avoiding dangerous climate changes while, simultaneously, achieving economic and social development (Lema et al., 2015). It is important to acknowledge the potential trade-offs between various environmental dimensions of green economy sectors such as use of rare-earth metals in wind turbines and electric vehicles (IEA, 2021) and waste from solar photovoltaic (PV) technology (HBR 2021).

on the presence and characteristics of GWOs, the necessary preconditions for their exploitation and the responses of different sectoral systems and different countries which are described in more detail in the Appendices. Section 4 draws on this empirical evidence to analyse the capabilities and actions required for developing countries to take advantage of GWOs, accounting for the differences across green technology types and across countries with different economic profiles. Section 5 summarizes the main findings, discusses the policy implications of our analyses, and suggests some directions for further research.

2 Latecomers' catch up and green windows of opportunity

2.1 The green transformation

The green economy is causing a major re-direction of techno-economic development. It involves profound shifts in technology and investment decisions, towards greener technologies and modes of production and guidance for continuing Information and Communication Technology (ICT) advances (Lema & Rabellotti, 2022). Although the green transformation is still nascent, it is already affecting key parameters for latecomer developments in the global economy.

At the heart of this megatrend are green sectors which have specificities that are influencing the nature of catch-up enabled by latecomer country developments. First, the embryonic green economy involves ferment, which, in turn, involves higher levels of experimentation and novelty and is offering some limited opportunities for path-following catch-up, based, mainly, on adoption of foreign technologies and the experience of other countries. Second, the green economy is driven fundamentally by social value and the provision of climate-related public goods. Some green sectors are seeing exceptional local, national, and international efforts, which are contributing to the creation and scaling up of new technologies in response to mounting environmental pressure and negative externalities. The essential green technologies are public goods in the context of climate change, meaning that their direct benefits are non-excludable. These features differentiate green from other sectors (such as automobiles, electronics and steel), typically studied in the catch-up literature (Chu, 2011; Hobday, 1995; Nolan & Yeung, 2001),and from emerging industries such as 3-D printing and artificial intelligence, in which market mechanisms play a dominant role (Lee et al., 2020). Third, the social objectives of the green transformation imply that more than previous techno-economic regimes, this regime is a case of directed development, supported by widespread government interventions. The levels of policy intervention, regulation and public financing in green sectors far exceed those typical of other industries such as those mentioned above, that is, steel and consumer electronics, for example.[2] In addition, in green sectors, such as renewable energy industries, direct public investments do not suffer from private investment crowding in/crowding out problems and, instead, generate positive externalities and market creation effects (Deleidi et al., 2020). Fourth, national environmental, energy and economic policies are influenced by global agendas, rules and mechanisms and, especially, those related to climate change (e.g., the Paris Agreement).

Given the above specificities of the green transformation and its key technologies, in what follows we propose an analytical framework to understand how latecomer catch-up might take place in green sectors and accounting for the specific nature of GWOs and the dynamics related to their exploitation.

2.2 The green window of opportunity analytical framework

In a recent article, Lema et al., (2020) proposed an analytical framework, resting on three pillars (and their interrelationships), to investigate latecomer catch up processes in green industries. Their framework is based on empirical evidence from several renewable energy industries in China, which, ten years ago, was a latecomer in green industries and since, has achieved remarkable green catch up (Ely et al ., 2019; Harrison et al., 2017). [3] The three framework components are:

- *the GWOs* arising from significant upheavals in public institutions and policy interventions, in technologies and markets;
- *sectoral systems,* including their preconditions, the strategies adopted by relevant institutions and strategic public and private actors and their interactions, needed to transform opportunities into reality;
- *catch up trajectories* originated by the interactions between GWOs, and the preconditions provided by and the activities in sectoral systems.

Figure 1 depicts this analytical framework and shows that the green transformation leads to new policy priorities, induces technological changes, and modifies market conditions. All these changes can lead to windows of opportunity, which, depending on their nature and the preconditions for their exploitation, influence catch-up trajectories in significant ways. In what follows we discuss the three pillars of this analytical framework. It should be noted that, while these elements are easy to separate analytically, they can be difficult to disentangle in practice because GWOs (unlike other opportunities

[2] The current ICT paradigm and the digital economy was spurred very much by public sector programmes and benefited from large investments in the military sector but was supported much less by deliberate public policies. To a large extent, the digital economy can be considered an unintentional by-product or positive externality of investments in the US military-industrial complex, even though the state also sought to commercialize the outcomes of these investments.

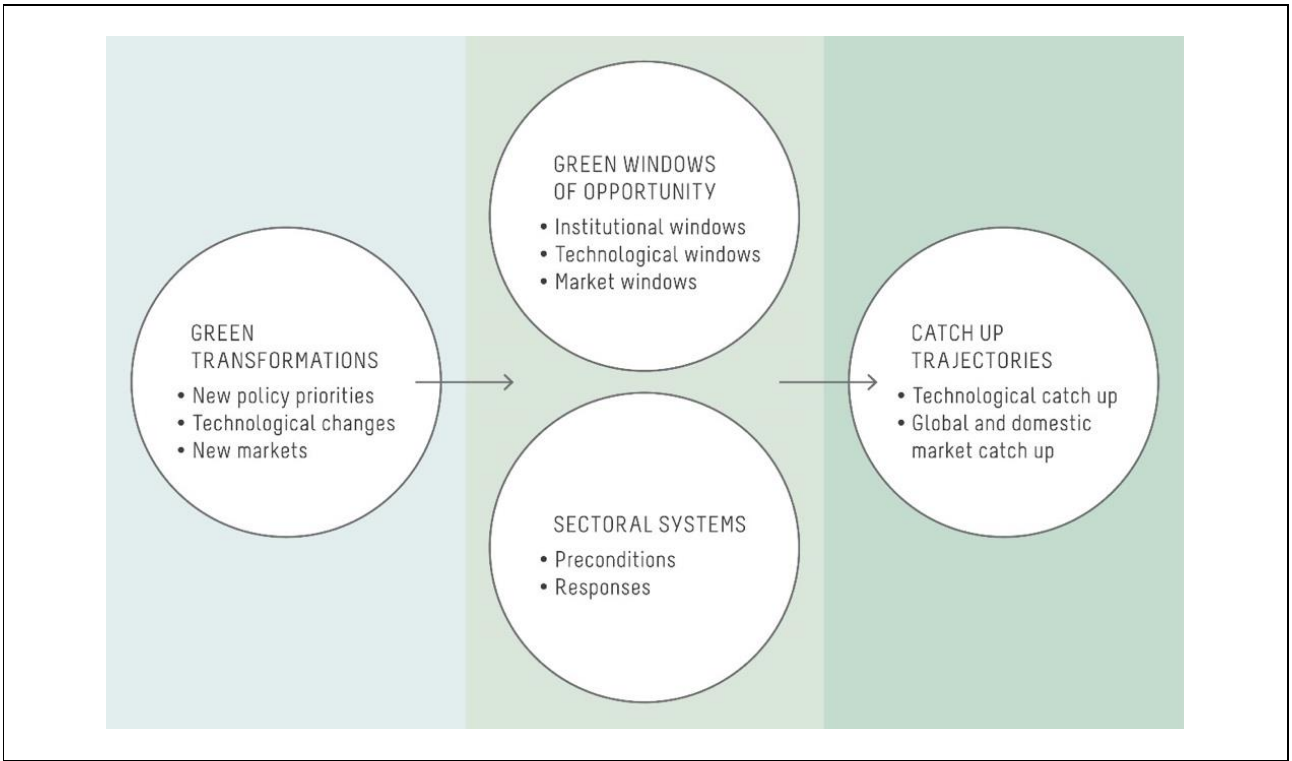
[3] The case studies on Chinese catch up trajectories in renewable energy industries include: biomass (Hansen & Hansen, 2020), hydro energy (Zhou et al., 2020), solar photovoltaics (Binz et al., 2020), concentrated solar power (Gosens et al., 2020) and wind energy (Dai et al., 2020).

for latecomer development, such as those related to the digital economy), tend to be characterized by endogeneity.

Green windows of opportunity

GWOs are defined as favourable, but time-bounded conditions for latecomer green developments, arising from changes in public institutions and policy interventions, markets and technologies associated with the green transformation. Due to the sectoral specificities of the green technologies discussed earlier, the role played by public policies, their directionality and the externalities generated, alongside the greater risks and uncertainties associated with the development and commercialization of these technologies, the nature and dynamics of GWOs differ from the windows of opportunity in other sectors, proposed originally by Perez and Soete (1988) and investigated more recently by Lee and Malerba (2017), in sectors ranging from steel (Lee & Ki, 2017), to cameras (Kang & Song, 2017), to aircraft (Vértesy, 2017), to wine (Morrison & Rabellotti, 2017).

Figure 1: Analytical framework



Source: Adapted from Lema et al. (2020)

The emergence and opening of GWOs are often due to government actions and are mainly institutional. Although GWOs are also influenced by demand conditions and technological changes, they are frequently driven by public actions and related adjustments to the institutional framework.

Examples of institutional drivers in China, include implementation of the renewable energy law in 2006, which promoted the initial development of the biomass industry (Hansen & Hansen, 2020), and sector-focused 'missions' such as the Rooftop Subsidy and the Golden Sun Demonstration Programs, implemented in the solar sector (Iizuka, 2015). Accordingly and in contrast to most work on windows of opportunity in the context of catch up, which tend to focus on external technology (Wu & Zhang, 2010) or market changes (Morrison & Rabellotti, 2017), GWOs are mainly endogenous to the country, although also intersecting and interacting with the external environment and with emergent external windows.

The creation of a domestic market is another crucial element of institutional windows of opportunity. In this respect, green sectors differ from many 'non-green' consumer or capital goods sectors where government-led demand creation is the exception rather than the rule. Examples of demand-pull policies are feed-in tariffs, aimed at creating competitive parity between green energies and fossil fuels by subsidizing demand. In the Chinese case, public procurement policies and local content requirements are common as are demonstration projects such as the Ride the Wind and Golden Sun programmes - especially in the formative stages of sector development (see the Appendices).

Note, also, that increases in market demand can be domestic or global. For developing countries, which often have small domestic markets, this is an important aspect. However, given the limited tradability of many green energy products, unless the domestic lead firms have the capacity needed for foreign direct investments, domestic market creation is often more important than the creation of an external market.

Institutional windows can also induce technical change in the form of mission-guided public R&D programmes, such as the offshore wind demonstration projects in China which have supported the sector to a certain extent (Dai et al., 2020) or the concentrated solar power industry, developed through government funding of research organizations' technology development activities (Gosens et al., 2020).

In addition, markets, and technology interact. Market investments in the form of green subsidies in the absence of corresponding investments in technical change, can cause a 'market trap'; latecomers may become the market leaders, but remain in technology follower positions. Conversely, if the induced technical change is not matched by (domestic or external) market demand, strong technological capabilities may remain dormant (Hain et al., 2020).

To conclude, in green industries, institutional-cum-demand windows are more frequent than opportunities emerging primarily from technology breakthroughs, especially in sectors focused on the production of energy generation technologies and, not least, in more mature technological settings, such as the case of solar PV and in the context of the large internal market in China. In the succeeding sections, we discuss the degree to which this applies, also, to the case of countries with small domestic markets that might benefit from newly emerging technological advances.

Sectoral system: preconditions and responses

Figure 1 suggests that catch-up trajectories depend significantly on the preconditions in and responses of firms and supporting institutions such as universities, research centres and standards organizations, to GWOs.

Perez and Soete (1988) conditioned the catch up capacity of lagging countries on the availability of a reasonable level of productive capacity and a sufficient endowment of qualified human resources. Countries' preconditions enable effective responses to emerging windows of opportunity. These preconditions include the existence of public institutions and companies with a certain level of absorptive capacity, which allows them to recognize an opportunity (Vértesy, 2017). In general, the ability to exploit windows of opportunity in specific industries depends on the firm's existing accumulated capabilities in the same or closely related sectors and on the development of the sectoral innovation system in which it is embedded which influences its strategies (Lee & Malerba, 2017).

The response to a GWO is influenced by the techno-economic specificities of the country's green sectors, which will differ in their technological maturity and tradability.[4] Firms can implement various strategic initiatives to exploit GWOs, which will require different capabilities and actors for different types of green industries and the associated catching up trajectories. However, some responses are common to most green sectors. In the case of mature sectors where it is relatively easy for firms to acquire world-class technologies, market success depends more on capital investment and the development of organizational capabilities. For example, the 2006 renewable energy law in China, facilitated entrepreneurial activity in the biomass and wind sectors, based on licensing core technologies and production plant designs, mainly from European firms (Dai et al., 2020; Hansen & Hansen, 2020). Similarly, solar PV production capability, although initially a response to external demand, has depended on the acquisition of technologies in the international market, to manufacture solar panels according to the globally dominant design (Binz et al., 2020)

It is clear, also, that certain firms are better able to exploit windows of opportunity and frequently become national champions. Examples in the Chinese case include Dragon Power to produce biomass, Suntec for solar PV and Goldwind for wind technologies. All have played a crucial role in

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[4] See Section 3 for a discussion of tradability and maturity among sectors.

building knowledge linkages within the global economy, moving from initial licensing and more conventional technology transfer, to mechanisms such as outward foreign direct investments in technology lead markets and ties to foreign universities (Fu & Zhang, 2011; Lema & Lema, 2012). For example, Dragon Power's acquisition of a Danish company was crucial for its leadership in the international biomass sector (Hansen & Hansen, 2020), while Goldwin's and Envisions' R&D subsidiaries in Europe have established relations with foreign universities and have benefited from the recruitment of very experienced engineers (Haakonsson et al., 2020).

In the formation and strengthening of the sectoral innovation system, the diffusion of innovation from first-mover leading firms to followers is especially important in the domestic sector. Hansen and Hansen (2020) show that a single Chinese producer fully exploited the initial window of opportunity, but policies related to the formation of supplier relationships and university-industry links and a rather weak intellectual property regime, allowed knowledge to spill over from the leading company to other domestic firms in related industries and diffused these technological capabilities to a multiplicity of actors. This increased the number of firms that benefited from that window of opportunity and caused a change in global market leadership from Western producers to Chinese firms.

Sectoral innovation systems are reinforced by intense interactions among lead firms, suppliers, technology providers and financial institutions (Fu, 2015). Stronger linkages within the sectoral innovation system contribute to technological deepening during the more demanding stages of technological upgrading that follow the initial phase of production capability accumulation. For instance, in the Chinese solar PV industry, this type of responsiveness within the domestic sectoral system was crucial for the sector's technological development of the sector following contraction of the global market (Binz et al., 2020).

However, firm-level efforts need to be reinforced by institutional efforts to support the shift from facilitating production capability to active support for technology development. These efforts call for public R&D investments and specific programmes and projects to address technological challenges such as process improvements and the application of complementary technologies (Shubbak, 2019). For example, in the Chinese wind sector, the support provided by the innovation system, such as facilitation of university-industry linkages, was fundamental for the shift from onshore to offshore turbine technologies (Dai et al., 2020).

The above discussion suggests that, to exploit GWOs, the sectoral innovation system must be dynamic to allow continuous adaptation to different sector specificities and changing market and technological opportunities. Also, policies need to be tailored to the stage of catch-up and must take account of sectoral specificities. It is important, also, to recognize that it can be difficult empirically to distinguish between a policy which provides a domestic opportunity from a policy response that allows exploration of that window. Ultimately, it is timing that matters, and depending on the type of opportunity, these matters, also for the sequencing of events in the sectoral trajectory. There are some typical patterns, such as use of environmental/energy policy to create a demand window and a subsequent industry/innovation policy to exploit it. For instance, a wind energy strategy could create a demand window which might trigger implementation of a law specifying the share of domestic components in any resulting wind plants (Lema et al., 2013). In the case of the emergence of a technological window, based on a global shift from internal combustion engines to electric vehicles, this is likely to trigger innovation and industry policies to support domestic design and manufacturing to encourage domestic firms to exploit this opportunity. Subsequent transport policies would encourage domestic diffusion of the technology and promote innovation to allow entry to the export market (Konda, 2022). The sequencing of these events and the preconditions in and responses from both the public and private sectors that are key to explaining catch up trajectories.[5]

Green catch up trajectories

Catch-up can be understood as successful attainment of leadership by latecomer firms, which shifts the economic power balance between incumbents and latecomers. The definition proposed by Lee and Malerba (2017), confines catch up to achievement of an increasing share in the global market, whereas the definition proposed by Lema et al. (2020) distinguishes between market and technological catch up (Hobday, 1995).

Market catch-up refers to the acquisition by domestic producers of increasing national and international market shares. In the context of renewable energy sectors, this is quantified and measured as the share of energy generation capacity (in megawatts) that is installed and sold by domestic producers in the domestic and global markets. In other sectors, such as electric vehicles, it is measured based on the number of units sold by domestic producers in domestic and global markets. Domestic market catch-up can be enabled by government policies aimed at stimulating home demand. In this case, market catch-up involves satisfying the domestic market through the provision of local rather than foreign products, which results in a more developed home market (in terms of total installed capacity per capita, number of enterprises and supply chain development) relative to the incumbent home markets in the same sector (Hain et al., 2020). Global market catch-up depends on achievement of internationally competitive quality and prices of green products, such as wind turbines

[5] Lema et al. (2020) discuss the sequencing of the various elements of GWOs.

and solar PV panels, and related services. In certain still immature technologies, such as concentrated solar power (CSP) and green hydrogen, markets are small and not competitive and, although the distribution of market shares indicates involvement in experimental projects, the technological dimension is what matters.

Technological catch-up is defined as the strengthening of technological capabilities relative to competitors. It depends, to a significant degree, on pre-existing knowledge and routines and user-producer interactions, which reinforce and extend capabilities and enable catch-up. It can be measured either quantitatively (e.g., based on number and quality of patents) or qualitatively, based on the distance from the global knowledge frontier in the focal sector, distinguishing between new-to-the-country and new-to-the-world technology. Production catch-up is based, typically, on new-to-the-country technology and manufacturing and service activities based on globally available knowledge. New to the world technology catch up involves innovation that extends the global knowledge frontier (Altenburg et al., 2008).

Both types of catch-up can be mutually supporting. In the latecomer development process, their interaction may allow access to larger and more sophisticated markets that provide critical knowledge enabling technology improvements (Schmitz, 2007). In turn, these stronger technological capabilities may increase the competitiveness of domestic firms in the home and export markets (Lee & Malerba, 2017). However, such outcomes are not automatic. A certain degree of technological capability attainment may enable domestic market development but might not be sufficient to compete in the export market. Also, demand-led domestic development may enable production capability catch-up, but not technological catch up which tends to depend on firm-level advantages provided by access to lead markets (Beise & Rennings, 2005).

The analytical framework proposed by Lema et al. (2020), to investigate GWOs in the context of China's catch-up trajectories in renewable energies, is used to guide the empirical analysis in Section 3. The application of this framework to a larger number of sectors and countries allows the more general discussion of GWOs in Section 4.

3 Green industries in latecomer countries

We use the analytical framework introduced by Lema et al. (2020), described in Section 2, to obtain empirical insights from analysis of a broader range of sectors and developing country experience.

We searched for publications related to each of the industries investigated - bioenergy, solar and wind energy, green hydrogen and electromobility (electric vehicles) – discussing the developments in latecomer countries, allowing exploitation of GWOs. We searched the Scopus database, which includes the largest number of peer-reviewed literature (scientific journals, books, conference proceedings), to identify the relevant literature. The advantage of using Scopus is that it allows the user to navigate world research outputs, based on keyword searches of titles, abstracts and keywords using a Boolean-type query – that is, AND-*OR* operators. The results can be filtered by year, scientific discipline, type of article and other characteristics. To obtain a detailed review of the empirical insights derived from case studies of selected green industries, we also considered grey literature (e.g., reports and research produced by governmental and non-governmental bodies). We confined our searches to publications in English; the methodological details are provided in the Appendix C.[6]

The industries investigated differ along the two dimensions (Lema et al., 2020) of maturity and tradability (see Table 1). We follow the transition studies literature and distinguish between mature and immature technologies, based on the existence and level of development of different socio-technical configurations, including infrastructure, regulation, market and technical standards, maintenance networks and user practices (Geels, 2002). The development of low maturity (or immature) technologies requires significant policy efforts, including large R&D investments, support for market creation and formulation of technical standards (Gosens et al., 2021).

Tradability varies with the energy source. For example, while electricity is difficult to trade over very long distances, liquid fuels (e.g., bioethanol or green hydrogen) are not. Even more important is the underlying energy production technology which also varies in its tradability. At one end of the spectrum is hydropower technology, whose production needs to be located at or very close to the point of energy generation and consumption. At the other end of extreme spectrum are electric vehicles, which are highly tradeable and can be produced far from the point of consumption.

On this basis, we consider the potential of some of the renewable energies included in this study, in terms of developing countries' exploitation of GWOs. This ability differs across green technology types and countries with different economic profiles.

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[6] The government and Non–Governmental Organizations (NGOs) considered include UNCTAD, UNEP, the World Bank, the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). We further refined our search by including green-policy related case studies in on online repositories such the Green Growth Knowledge Program (GGKP) and REN21. The former collects the latest case studies and research produced by various organizations, allowing search on country, region, and industry. The latter is an international network of policy experts from governments, inter-governmental organizations, industry, academia, and NGOs that produce detailed policy reports on renewable energy markets around the world.

Figure 2 provides information on the distribution of global installed capacity: 4.4% for bioenergy, 24.5% for solar and 25.1% for wind energy.[7] Table 2 compares total installed capacity in high-income and the middle-income and low-income countries[8] and shows that, between 2010 and 2020, capacity in the three technologies considered, increased significantly in the middle-income and low-income group.

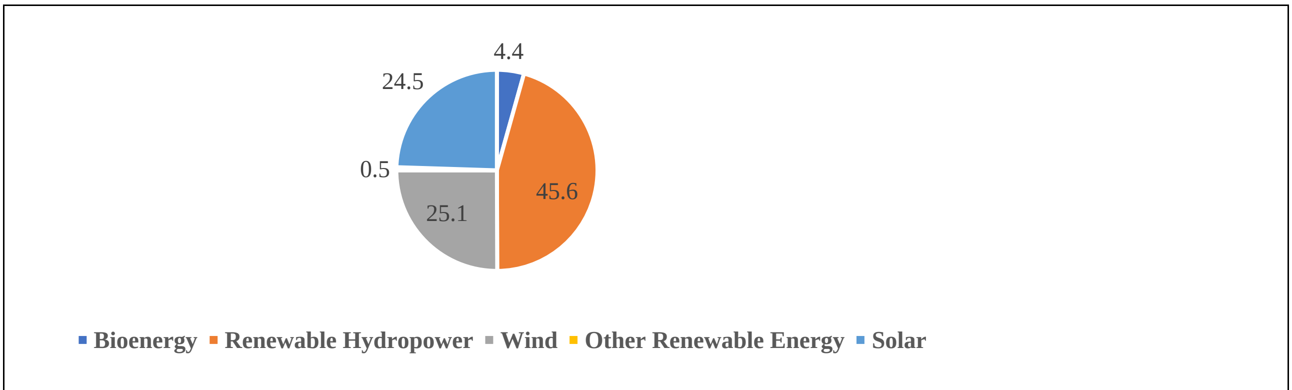
Table 1: Maturity and tradability of different sustainable industries

Tradability \ Technological maturity	High	Medium	Low
High	• Solar PV • Biofuels	• Electric Vehicles	• Green Hydrogen
Medium			• Concentrated Solar Power
Low	• Bioenergy (excl. Biofuels)	• Wind	

Note: See Table 4 for a more detailed description of the different dimensions of tradability

In 2010, solar energy installed capacity was concentrated almost totally on the high-income countries; in 2020, following outstanding growth, the middle- and low-income countries accounted for over 50% of total installed capacity in solar. The middle and low-income countries have also achieved remarkable growth in wind energy, which increased from 26% to 51% of global installed capacity in 2020.

Figure 2: Installed Renewable Energy Capacity: 2020 (% of world total)



Source: IRENASTAT (2021)

[7] Renewable hydropower accounts for an important share of total installed capacity. However, in the present study, we do not consider this sector for the following reasons. There is ongoing discussion about how 'green'the hydropower sector is. The proponents of hydropower argue that it is a renewable, low carbon energy technology crucial for mitigating climate change. Its opponents argue that large hydropower production has large-scale and irreversible environmental impacts, including destruction of the ecosystem, geomorphological changes, hydrological changes, negative effects on aquatic species and habitats and biodiversity losses. In addition, it is an industry characterized by large economies of scale and dominated by China, where about half of the world's large dams are located. For an interesting account of how China has achieved market and technological leadership in the hydropower sector, see Zhou et al. (2020).

[8] Based on the World Bank classification.

Table 2: Installed Renewable Energy Capacity by regions (% of world total)

	Bioenergy			Solar			Wind		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
High-income countries	63,02	56,99	49,88	96,46	74,75	48,50	73,64	56,88	48,62
Middle to low-income countries	36,98	43,01	50,12	3,54	25,25	51,50	26,36	43,12	51,38

Source: IRENASTAT (2021)

These notable expansions have been driven strongly by China, which is the leader in the three technologies considered, in terms of installed capacity. However, the lower-middle-income countries of Vietnam and India and the upper-middle-income countries of Brazil and Thailand are among the world top ten countries for installed capacity in the technologies we analyse (country rankings are provided in Appendix B).

The Appendices provide detailed empirical evidence derived from our literature survey, including the following information. First, we consider the presence of GWOs in the context of institutional, market and technological changes, to understand the nature of the cases analysed. It should be noted that, while certain natural conditions (e.g., solar radiation levels) are often considered opportunities and can favour domestic deployment, which enables dynamic learning, in the proposed analytical framework, they are seen as automatically providing opportunities for latecomer developments which often requires technological upgrading and export diversification. Second, we consider two dimensions of sectoral systems: a) preconditions, that is, the range of proximate industrial activities (Hausmann & Hidalgo, 2011); and b) sectoral system responses (Malerba, 2002). Third, we consider market development and technological upgrading catch-up trajectories.

On this basis, in Section 4 we analyse the capacity of developing countries to take advantage of GWOs. This differs across different types of green technologies and across countries with different economic profiles.

4 Do green industries provide opportunity for developing countries?

To investigate and understand whether and how the capacity to exploit GWOs differs, we consider one of the dimensions of the analytical framework presented in Section 2, that is, the sectoral system, and focus on two related, but distinct components: (a) the preconditions required to exploit the opportunity; and (b) the strategic responses of public and private actors to exploitation of a GWO.

Some countries have appropriate and sufficient public and private sector preconditions, including high levels of industrial capacity and sectoral system capabilities relevant to a given green technology. However, in the absence of a strategic response to a GWO, these countries can remain locked into a fossil-fuel-dependent path or see the new market captured by foreign investors.

Other countries may be focused on green strategies and keen to exploit GWOs, but may be hampered by a weak pre-existing supply base in the relevant sectors. Those countries with sound green strategies, good foresight and a strong political will combined with a well-established production and innovation basis, will be best placed to benefit from the green transformation. Against this background, in this section we discuss inequalities among countries in terms of economic opportunities and the threats posed by the green transformation.

The analysis is guided by the matrix in Table 3. We would point out that this is a simplified matrix, which reduces complexity while providing a summary of the empirical insights gained from widely differing experience (see, also, Appendices D to J. As the ensuing discussion shows, , there are many grey areas between weak and strong conditions.

Table 3: Seizing green windows of opportunity: four scenarios and some examples

Responses / Preconditions	Strong	Weak
Strong	**Scenario 1: Effective GWO exploitation** Solar PV, Biomass, CSP: China Bioethanol: Brazil Hydrogen: Chile (potentially)	**Scenario 2: Missed opportunity** Solar PV: India Biogas: Bangladesh CSP: Morocco Wind: China
Weak	**Scenario 3: Active approach** Biomass: Thailand and Vietnam Hydrogen: Namibia	**Scenario 4: Distant opportunity** Wind: Kenya Bioenergy: Mexico and Pakistan

4.1 Scenario 1: Effective green window of opportunity exploitation

The combination of strong preconditions and a strong response is the most favourable scenario. China has the appropriate preconditions to exploit GWOs in several sectors, arising from techno-economic shifts and enabled by a large internal market, a diversified industrial structure and well developed related capabilities, such as design and engineering capabilities for biomass plant construction (Hansen & Hansen, 2020) and scientific knowledge in solar PV (Zhang et al., 2015). In terms of response to the emergence of a GWO, in China, public sector efforts to co-design environmental and industrial policies apply to several sectors and multiple initiatives have been put in place to diffuse knowledge among firms and organizations. These include government stimulation of knowledge spillovers through loose enforcement of property rights and diffusion through state-owned design institutes (Hansen & Hansen, 2020). In nascent industries, GWOs such as concentrated solar power , R&D, experimentation and significant private entrepreneurship are important (Gosens et al., 2020). Private sector investment in accumulation of technological capabilities to enable acquisition of foreign technology, based on licensing and acquisition of foreign firms, allowed increased domestic production needed to benefit from external demand for solar PV (Binz et al., 2020).

Other emerging economies, such as Brazil, are also managing green catch up (Fankhauser et al., 2019). In Brazil, the preconditions are result of many years of experience with a sugarcane-based ethanol fuel programme that was implemented in the 1970s and knowledge about sugar cane based on Brazil's first experimentation with bioethanol in 1930. Brazil has been active in acquiring and developing bioethanol technology and its success in sugarcane-related technology developments is the outcome of technological learning promoted by innovation policies and efforts made by sugar and ethanol processing plants, technology suppliers and research institutions (Furtado et al., 2011). In addition, collaborative consortia established by private sector firms, have developed the flex-fuelling system for passenger cars to fully exploit the GWO presented by bioethanol. Although these responses were initially driven by the local market, Brazil has made continuous effort to achieve leadership in the global market (Lema et al., 2015).

Keeping abreast with technological developments can require particular gear changes in relation to several components of the sectoral environment. Firm-level efforts on their own are not enough and institutional efforts are needed to support the shift from facilitating production capability to providing active support for technology development. This calls for public R&D investments and specific programmes and projects to address technological challenges, such as the process improvements and application of complementary technologies that happened in the solar PV industry (Shubbak, 2019).

Another case of potential combination of appropriate preconditions and strong responses is the green hydrogen industry in Chile. This country has a relatively well-developed production system and a tradition of public investment in sustainable industries. Its green hydrogen strategy is part of an ambitious clean energy transition process, which was launched in 2015 and is aimed at decarbonization of the electricity matrix by 2040 and carbon neutrality by 2050. Accomplishment of these national goals depends crucially on the development of a green hydrogen industry, which is being addressed by six pilot projects, selected by the Chilean National Development Agency (CORFO), with strong involvement of international investors. However, the growth of Chile's green hydrogen industry could be affected negatively by the country's location on the southwestern coast of South America which is far aware from the main markets in Asia and Europe. Chilean exporters will have to bear the cost disadvantage presented by shipping, which emphasizes the importance of low-cost production of green hydrogen (Adler, 2022).

4.2 Scenario 2: Missed opportunity

According to our conceptual framework, the combination of relatively strong preconditions and insufficient responses translates into a missed opportunity. Our evidence provides examples of this scenario. Although the solar PV sector is dominated by China, other countries, with large domestic markets, could develop domestic supply given appropriate demand-side incentives to increase domestic installed capacity combined with supply-side support along the value chain. Behuria (2020) shows that, in India, the National Solar Mission prioritized low cost deployment over manufacturing, which strategy has resulted in high dependence on imports. Insufficient attention was paid to training, promotion of linkages to relevant stages of the value chain and R&D to boost competitiveness. When local content requirements were imposed, the lack of early stage domestic business creation meant there were insufficient domestic capabilities able to reduce dependence on imports (Johnson, 2016; Sahoo & Shrimali, 2013). This led to another important aspect. Stimulation of a domestic market, based on feed-in tariffs or national auction systems, that is, the creation of green demand windows, must be carefully designed and implemented to avoid problems such as insufficient protection of domestic investments (Landini et al., 2020; Malerba et al., 2021).

Another example of missed opportunity is the biogas industry in Bangladesh where the existing system of R&D organizations involved in projects related to biomass energy, was not complemented by incentives to encourage biogas plant installations or to increase awareness among farmers about the potential of correct waste management (Chowdhury et al., 2020).

In Morocco, the CSP sector has been promoted by strong political commitment to solar energy and an existing initial production base that has allowed a few domestic companies to accumulate some relevant capabilities (Fritzsche et al., 2011). However, the opportunities for localizing the manufacturing of solar energy inputs and components remain limited due to the small capacity for technology and knowledge transfer to enable acquisition of a strong domestic sectoral system (Vidican, 2015).

It is important, also, to take account of the fact that GWOs emerge over time. The strategies and initiatives related to responding to an initial opportunity, based on building basic production capacity, may not be enough to enable technological capability upgrading and deepening, especially since technologies are constantly evolving. In the Chinese wind sector, the initial preconditions were in place and included heavy industry capabilities needed to manufacture and install wind turbines (Lema et al., 2013). The support provided by the innovation system, such as promotion of university-industry linkages, was fundamental for the shift from onshore to offshore turbine technologies and a major technological shift in the industry. However, these preconditions were not enough to achieve the level of success in other green sectors, such as solar PV, and market leadership. This would have required integration of 'smart systems' for turbine and wind farm management which were beyond the capabilities of China's wind sector (Dai et al., 2020).

4.3 Scenario 3: Active approach

The combination of relatively weak preconditions and strong responses could apply to many low- and middle-income countries. Despite limited initial experience, Thailand's biogas industry has advanced, due to strong responses from both public and private actors. The Thai government augmented this GWO with the launch of an ambitious policy to stimulate investment. Subsidies, tax incentives and mandatory purchase of electricity generated from biogas created favourable conditions for private investors and generated significant response from and learning in the private sector, resulting in a pattern of co-evolution pattern of shifts within and across learning mechanisms involving different sources of knowledge (Reinauer & Hansen, 2021). Vietnam is responding to the opportunity to generate biomass energy from rice husks. A combination of private, including some foreign investors such as Decathlon, and public actors, including domestic R&D institutions has resulted in a dynamic sectoral system (GIZ, 2022).

In the wind industry, despite little experience or activity in proximate industries, Ethiopia managed a strong response. This industry has grown due to the implementation of several major projects despite the unbalanced bargaining power between external consortia and local stakeholders, especially government, but also other firms and organizations involved in these projects. Government has gone beyond production system thinking and has ensured involvement of the knowledge and innovation system, based on incentivizing local learning. It is playing an active role in the design of projects to ensure maximum local learning, by ensuring the involvement of professional users in project execution. According to Gregersen and Gregersen (2021), while both the Kenyan and Ethiopian cases provide evidence of local learning in the field of Operations and Management (O&M) and integrating more renewable energy in the national grid, the Ethiopian case involved more learning about how to design large-scale renewable energy projects.

In Namibia, despite the considerable uncertainty regarding green hydrogen, a sectoral system is being established. The Namibia Green Hydrogen Association was created to provide a platform for private actors and government-business interactions and Namibia has a partnership with Germany that is enabling intense R&D interactions and collaborations, to identify suitable sites for training and production of green hydrogen specialists.

4.4 Scenario 4: Distant opportunity

In the case of poor preconditions and weak responses the potential for GWO exploitation is limited. In wind technology, the case of Kenya provides a stark contrast to Ethiopia, based on (Gregersen, 2020) a relatively weak industrial base related to large scale wind and a poorly developed wider sectoral system. Lack of attention to how to design strategies to ensure local embeddedness and learning from projects has led to failure to seize opportunities for learning and supply chain development (Gregersen & Gregersen, 2021). Gregersen and Gregersen (2020, 2021) argue that major investments in initiatives, such as the Lake Turkana Wind Power Project, should be more deeply integrated with strategies for strengthening the sectoral system of production and the innovation system, providing training for engineers and technicians and supporting research in universities.

The cases of Mexico (Ordoñez-Frías et al., 2020) and Pakistan (Yaqoob et al., 2021) present a similar story in the context of the bioenergy industry. In both countries, there is huge potential for bioenergy activities, but lack of technical competence and poor awareness of industry potential, combined with limited policy attention and weak regulation have resulted in absence of public and private investment, needed to upgrade bioenergy technology knowledge.

4.5 Technology specificities and country-level preconditions/responses

The above analysis considers examined how preconditions and strategic responses affect national capacity to exploit GWOs. However, we need, also, to account for technological characteristics as factors that influence these preconditions and responses. First, we examine preconditions as a 'function' of the role of technology maturity and then consider tradability.

Technological maturity

It is important to recognize that measuring technology maturity is not straightforward. For example, for many years the world automobile sector was based on a single dominant design but is being challenged by immature technologies such as electric and hydrogen powered vehicles, developed to achieve sustainability. Many of the technologies analysed in this paper, have experienced stable first-generation technologies, followed by continuous technological development of new product generations, such as first-generation onshore wind turbines and second-generation offshore turbines. We define low maturity technologies as technologies whose viability is unproven or are currently in the process of becoming dominant. High-maturity technologies are fully developed and depend on a stable dominant design.

In general, low maturity of technologies imply the need for appropriate sectoral system preconditions, in science and R&D. Low maturity technologies (e.g., green hydrogen and CSP) tend to be associated with the OECD countries, which meet threshold precondition levels for investing in new technologies. Engagement with technologies, such as CSP (China) or bioethanol (Brazil) requires a strong domestic system as a precondition for the technology becoming stable.

Technologically mature sectors, such as biomass and solar PV, are less demanding in terms of science and R&D preconditions, because they are able to absorb and exploit the existing market technologies. In these contexts, the preconditions include capability for technology acquisition and creative adaptation to local conditions to allow the benefits of the 'latecomer effect' and exploitation of foreign technologies and machinery. Although the industry capabilities must meet a certain level, they are less demanding in these contexts. However, high levels of tradeability mean high levels of global competition, which can make it difficult for domestic firms to compete with foreign firms in the domestic market. This might require public interventions to increase domestic capacity.

For example, in the case of solar PV, China benefited from the GWO related to importing production machinery and economies of scale. China benefited from entrepreneurial dynamism in the private sector and state support for the supply side. India missed an opportunity due to its inability to manage localisation issues in a context of weak manufacturing capability.

Tradability

Tradability is also difficult to assess, due to at least three of its dimensions: (1) tradability of capital equipment, such as the machinery and inputs needed to produce a particular green technology; (2) tradability of the technology and the processes involved in its use; and (3) tradability of the output, that is, the specific green energy being produced. Table 4 provides an example of tradability measurement, in the various green technologies. It shows that all three dimensions are important to assess the preconditions and responses required to exploit a GWO.

Tradability affects preconditions and responses through its influence on competitive dynamics and modes of technological learning. Sectors with high levels of tradability may need some degree of market protection in the context of a demand window and this may have a major impact on responses. Demand-led industry strategies can be effective but need to be carefully designed and implemented in relation to sectors with high tradability (Landini et a., 2020). In the context of learning, high tradability in capital equipment requires strong capacities in related production domains to allow acquisition and absorption of embodied or disembodied production capability.

Table 4: Dimensions of tradability

Dimensions of tradability	Capital equipment and inputs	Energy generation technology	Green energy outputs
Bioethanol	Medium (Distillery equipment)	Low (Ethanol distillery)	High (Ethanol)
Biogas (a)	Low (Heavy-duty machinery)	Low (Biogas plant, e.g., waste to energy)	High (Gas)
Biogas (b)	High (Anaerobic digestion equipment)	Low (Biogas digester)	High (Gas)
Biomass	Low (Equipment)	Low (Direct-fired biomass plant)	Medium (Electricity)
Solar PV	High (Industrial robots, assembly line designs)	High (Solar PV Panels)	Medium (Electricity)
CSP	Low (Heavy duty machinery)	Low (Solar farm)	Medium (Electricity)
Wind power	Low (Heavy duty machinery, steel)	Medium (Wind turbines)	Medium (Electricity)
Green Hydrogen	Medium (Electrolysis equipment)	Low (Conversion facility)	High (Hydrogen)

In the case of low tradability, learning can be enabled, initially, by foreign direct investment and later through other channels which require capacity for continuous policy adaptation. For example, in the case of wind, turbines can be traded, although transportation costs are high. Kenya was able to use foreign direct investment to import turbine technology. However, the relatively small size of the market and the preconditions in the private sector – especially heavy-industry and electrical engineering experience – resulted in a distant opportunity. In China, the preconditions in place enabled catch up to meet domestic demand.

In contexts of low tradability and low maturity, sectors have to depend on strong pre-existing R&D capabilities and strong capabilities in related industries (suppliers of component technologies). The level of development and low tradability in these sectors, provide opportunities for advancement depending on the level of protection in the home market. For example, in the case of CSP in China, these factors allowed exploitation of a GWO, whereas in Morocco the rather weak supply base and limited R&D capability resulted in a missed opportunity.

5 Concluding remarks and policy implications

5.1 Summary of main findings

We began with the observation that, in developing economies, the green transformation is accompanied by both constraints to and opportunities for economic development. This transformation has accelerated dramatically over the last 10 years and will shape the global economic landscape for the foreseeable future (Perez, 2015). At the root of this shift are changes to the policies and institutions that are shaping the transformations in technologies and markets, but not vice versa (Lema et al., 2020).

Our empirical analysis provides three main findings that extend our knowledge about GWOs. The analytical framework presented in Section 2 is based on the rather successful catch-up experience of China in renewable industries, discussed in Lema et al. (2020).

First, previous work stresses the importance of institutional changes in allowing the emergence of GWOs and identifies the related endogeneity, complementarity and interaction effects , that is, changes to institutions, markets and technologies (Lema et al., 2020). Our analysis of a larger number of countries and sectors, overall confirms the specificities of windows of opportunity in the green economy. The existence of different national strategies and policy frameworks across countries and green industries, supports the finding of the significant economic opportunities arising from domestic institutional changes, driven by efforts to mitigate climate change, transform energy production and consumption, electrify rural communities and increase energy security. In addition, the international dimension and global pressure to speed up the green transformation, are facilitating the diffusion of green investments and establishment of promising new markets in many and diverse countries. However, although the directed nature of the green transformation is increasing expectations about and control over GWOs and is transferring more planning power to public actors, the effects of exogenous technological or demand changes remain substantial. The evidence confirms the complexity involved in policy design and coordination, and how different priorities, instruments and timings of interventions can have a major impact on industrialization outcomes.

Second, we have shown stress that the capacity to exploit opportunities depends on national preconditions and the actions of public and private actors in the relevant production and innovation sectoral systems. At a general level, this is self-evident, but on a case level, it is far from trivial and not straightforward. There is evidence that the introduction of policies aimed at developing domestic markets has not been supported by appropriate incentives and measures aimed at building the sectoral system, which has allowed foreign investors to take advantage of favourable natural conditions (e.g., intense sunlight and low cost energy production) in many countries in the global South. In the context of appropriate responses, the pattern varies according to both sectoral characteristics, such as technology maturity and tradeability of products and services and domestic market size, industrial structure, pre-existing firm capabilities, etc. Our data show significant variety and intensity in both preconditions and response patterns, underlining that one-size-fits-all approach to policies and firm strategies is not viable. In general, the empirical evidence highlights the capability preconditions and agencies that need to be considered by the main players in the sectoral innovation system. The effectiveness of responses increases with the level of development of the sectoral system and underpinning policy and environmental objectives. It indicates, also, that investments in public R&D and accumulation of specialized capabilities, which are the preconditions for even mature technologies, are quite rare. Imported capabilities and technologies require adaptation to the local context. In the case, also, of mature technologies, countries need to identify the stages in the value chain that provide more opportunities for developing innovation and production capabilities and orient their investments to building domestic capacity.

Third, sectoral characteristics determine differences in the depth and speed of latecomer development trajectories. For example, in green energy, mature sectors with significant market creation, such as biomass or solar PV, readily available technologies can provide a relatively fast way to boost economic activity. In these industries, satisfying domestic market demand by employing new-to-the country technologies tends to be the norm. Newer technologies, such as green hydrogen, CSP and electric vehicles are more demanding in terms of technological capabilities and require significant investment in innovation system development.

5.2 Implications for policy

This paper is based on the idea that the global transformation towards sustainability could open important GWOs for latecomer development, across countries and sectors in low- and middle-income countries. However, opportunities differ and require active exploitation. In this section, we make some proposals for policy to allow the emergence of and exploitation of GWOs in developing countries. Such policy interventions require government action, at the national and local levels and involvement of a range of public and private stakeholders. They also require subscription to the idea of the potentially transformative power of green technologies to move developing countries and the world more generally, towards a sustainable and inclusive model of growth.

Strategies to enable a greener economy, based on the emergence and exploitation of GWOs, can be examined through a mission-oriented lens, which involves more than a levelling of the playing field. Policy should be aimed not just at fixing market failure, but at cocreation and shaping of markets

(Mazzucato, 2018). According to Mazzucato (2018), missions related to a greener economy: a) must be well defined with clear intermediate goals and deliverables and embedded monitoring and accountability processes; b) must comprise a portfolio of R&D projects to account for possible failures which should become learning opportunities; c) must involve investment in a range of different sectors and involve different private and public actors; and d) must involve policies that address a wide range of public institutions, with a clear division of labour and well-defined responsibilities for coordinating and monitoring.

In what follows, based on the evidence discussed in this paper and inspired by a mission-oriented framework, we propose some policy recommendations that recognize the need for a more systematic review of existing policy experience in the advanced and developing countries.

The capacity to exploit GWOs involves a sequential and dynamic process, some of whose elements are described below (Lema et. al 2020).

- *Open and augment GWOs*: refers to identification and enhancement and/or creation of GWOs. There are significant differences across types of GWOs and their indigenous or exogenous nature. Different types and elements of GWOs often interact sequentially;
- *Assess, address, and sustain relevant sectoral systems:* this involves the potential capacity for building and enhancing sectoral systems.

While it is possible analytically to separate these steps and their subcomponents, in the real world, they sometimes overlap. For example, assessment of the sectoral system often is (or should be) conducted before or at the same time as the decision to invest in a potential GWO to avoid the missed opportunity scenario described above. Feedback loops allow initial policies to be adjusted.

In many cases, the initial stages in the opening of a GWO are demand side related and the succeeding steps of assessing and addressing sectoral systems are supply-side measures and interventions. This applies to the case of domestic market creation and subsequent localization of related economic activities. In other cases, windows of opportunity are external, and the initial step involved domestic supply-side investment, followed by the shaping of accumulated capabilities to local contexts and market creation. It is crucial that, regardless of the different green window and sectoral system features, capabilities and strategies, the relevant policy processes need to be managed in a coordinated way. This can be difficult even in the context of mission-based and transformative approaches.

Below, we discuss policies allowing exploitation of GWOs (see Table 5).

Open and augment GWOs

Predicting and selecting which GWO to develop, for how long and in what way involves choices about the transformation based on incomplete information, long-time horizons and, in the case of emergent developments, in green demand, technology and institutional changes. Policymakers should be informed about and prepared to promote GWOs through public actions. Identification and selection processes need to be combined with assessment of potential, in terms of natural resources (e.g., wind conditions or agricultural waste for bioenergy), demand and dynamic learning. Policymakers must allow for adjustments to the institutional framework conditions as the GWO unfolds.

Select policy instruments and calibrate policy design to different local objectives and features

In sectors characterized by domestic market opportunities, the selection of market creation policy instruments, for example, feed-in tariffs and national auction systems, needs to be adapted to different policy priorities. Matsuo and Schmidt's (2019) comparative study of Mexican and South African national auctions for renewable energy, provides evidence of low-cost deployment being prioritized in the first case and establishment of a domestic renewable energy value chain in the second case, which led to different micro-level policies and different outcomes. To allow emerging countries to take advantage of domestic demand windows requires customized policies that take account of the different objectives and features of the local context.

Table 5: Policies for seizing GWOs

Open and augment GWOs	• Select policy instruments and calibrate the policy design to different local objectives and features Combine relevant policy instruments • Invest in demonstration programs • Support policy interventions with external contributions • Invest in demonstration programs
Assess, address, and sustain sectoral systems	• Evaluate preconditions • Enable and shape responses • Align environmental and energy, STI and industrial policies • Access external knowledge • Invest in domestic R&D • Build domestic capabilities along the value chain • Invest in human capital • Involvement in international collaboration projects • Diffuse knowledge within the domestic sectoral system

Combine relevant policy instruments

The case of China's solar industry suggests that a combination of subsidies, tax incentives, mandatory purchase of electricity from renewable sources and infrastructure projects contributed to the expansion of the domestic market. In the solar sector, domestic demand-pull policies involved subsidies for developers of off-grid and grid-connected projects, to cover up to 70% of the costs of installation as part of the Golden Sun Demonstration Programme, public investment in grid infrastructure and poverty alleviation programmes based on supplying poor households with electricity generated by solar PV panels (Shubbak, 2019).

Support policy interventions with external contributions

The development of the CSP sector in Morocco provides evidence of the important role of external funding to support the development of this technology. CSP was identified as the best technical solution to address domestic market demand and international funding enabled adoption of this new technology. The Moroccan case underlines the importance of concessional financing to fund the capital costs of CSP installations. The Climate Investment Fund, the World Bank, the African Development Bank and some EU funds supported Morocco's initial CSP industry development.

Invest in demonstration programs

In non-mature industries, such as CSP and green hydrogen, demonstration projects are vital for the development of new technologies and designs. In the case of CSP in China, industry development was supported by the promotion of mega government scientific research projects, aimed at building knowledge and experience in domestic firms and developing commercial industrial projects to allow learning by experimenting with different technical designs (Liliestam et al., 2019). In Chile, the National Development Agency (CORFO) is supporting the development of a domestic green hydrogen industry through a range of pilot projects with the involvement of international investors.

Assess, address, and sustain sectoral systems

The opportunity space related to the identification and creation of green windows, allows policymakers to partake in this agency and actively mobilise and combine internal and external sources to address the spaces for learning, innovation and development created by the green window.

Evaluate preconditions

Successful exploitation of GWOs depends on the pre-existing sectoral system conditions, which are dynamic and unfold and develop along an emergent trajectory. Both public and private sector preconditions are important and need to be assessed. Public preconditions include overall state capacity and governance capability in areas, such as regulation, , the extension support system and public good service providers. The involvement of a lead agency to mobilize and coordinate resources and stakeholders is essential and includes stewardship and exchanges of experience and learning among stakeholders. The East Africa case shows the importance of identifying weak elements and potential coordination failures for the exploitation of GWOs. In Kenya's wind industry, the presence of a national agency, embodying domain expertise, and enabling systematic learning and knowledge transfer among different unconnected renewable projects was lacking (Gregersen 2021; Lema 2021).

The preconditions in the private sector underpin the sectoral innovation system. For example, identification of value chain activities in which local firms could engage is critical and allows substitution of imported capabilities. Strategies should be tailed and regularly updated to identify capabilities that are within reach in the upgrading process. In mature industries, such as wind and solar, localization of core component product can be difficult for latecomers, due to competition from incumbents. However, in renewable energy technologies, value chain activities include both the upstream production phases and downstream deployment, such as project development, engineering, procurement, and construction (EPC) (Matsuo & Schmidt, 2019). This is also important because certain policy instruments are dependent on capabilities in the value chain. Baker and Sovacool (2017) highlight that the absence of local private sector preconditions leads to failure in the implementation of local content requirements.

Critical for the evaluation of preconditions is an assessment of the main national innovation system actors, which include national and local government, private companies, universities, research institutes, financial institutions, and civil society organizations. Robust assessment of where and how different production and innovation sectoral systems should be strengthened and changed in the various stages of policy development, is a crucial element of GWO analysis.[9]

There is an urgent need for assessments, to inform local and global action. There have been several calls for interventions in this area, including technical cooperation and assistance for developing countries in the areas of science, technology, and innovation, to increase the capabilities and competitiveness of the value chain (Ministerial Declaration of the Group of 77 and China to UNCTAD XV)

[9] Participatory assessment methods include: (a) policymakers (especially those linked to innovation, in science, technology and innovation, trade, industry and education ministries) have broad decision-making power and ability to design and implement public policies to increase national science, technology and innovation capacities and provide effective support for systems of innovation; (2) private sector actors with an understanding of the challenges involved in building firm-level technology and innovation capacity, local knowledge of the business environment and of the effects of the policies in place and clear ideas about the actions needed for upgrading and innovating; (3) academic and research institutions with expertise in specific technologies and R&D capacity; (4) civil society organizations with knowledge about the concerns and priorities of marginalized groups and the ability to voice these concerns and increase awareness in public institutions.

Enable and shape responses

The process of enabling and shaping responses mostly involves mobilizing actors and resources and enabling learning, capabilities development and upgrading, within a green industrial policy framework. However, the technological, economic, and political uncertainties involved are substantial (Schmitz et al., 2015).

Identifying ways to support the sectoral system requires analysis of the system preconditions to allow governments to reinforce the sectoral innovation system. This should include a wide range of public and private actors and rely on diverse policies and instruments in areas such as policy coordination, R&D investment, domestic capacity building, training and education, external knowledge acquisition and knowledge diffusion, involvement in international collaborations and local community involvement in monitoring and evaluation. In what follows, we discuss sectoral system responses.

Align environmental, energy and science technology and innovation policies

Environmental and energy policies are critical for the emergence of GWOs and their domestic deployment and market creation effects. Industry and science, technology and innovation policies are required to promote firm and system-level capabilities to respond to opportunities. This requires policies related to different domains, to be co-created by the energy, environment, and industry actors. For example, demand-driven initiatives to facilitate energy system greening, such as feed-in tariffs or auctions, need to be developed in alignment with prevailing industry policy and measures to ensure some domestic localization of economic activities and production and innovation capabilities (Landini et al., 2020).

The complementarity among different policies raises coordination and design issues that must be considered. For instance, in the successful case of the biomass industry in Thailand, the Minister of Energy was the agent who promoted environmental legislation that encouraged factories to invest in biogas production, in coordination with policies aimed at strengthening the sectoral innovation system. This led to a network that included the Minister of Science and Technology, involved in R&D on biogas technology and demonstration programmes, the Board of Investment under the Office of the Prime Minister which introduced tax incentives to attract private investors and various public research centres and universities that offered training to build domestic capacities in setting up and maintaining the installed systems (Suwanasri et al., 2015).

Access external knowledge

In the case of an external market opportunity, as in the first phase of development of China's solar industry, policy support should focus on accessing external knowledge and building domestic production capability. In China, solar PV was part of a catalogue of high-tech exports and Chinese firms were encouraged to acquire knowledge and invest in research, in partnership with international research centres (Shubbak, 2019). The creation of domestic production capabilities was supported, also, by the China Development Bank and other state and commercial banks' providing access to credit when the financial crisis was making it very difficult for Western solar manufacturers to obtain credit (Shubbak, 2019). In general, in mature industries, there are many opportunities for international technology transfer and collaboration, as illustrated by some of the cases discussed in this paper.

Invest in domestic R&D

Reinforcement of domestic innovation capacity requires policy efforts to support intensive R&D activity in domestic universities and other institutions, and domestic and foreign firms. In non-mature sectors, system-building policies, based on large investments in R&D and demonstration projects, are needed in the early stages when the domestic market is not sufficient to create a competitive industry (see the examples of the CSP sector in China and the green hydrogen sector in Chile).

Public R&D funding and specific programmes and projects are also needed to address technological issues, such as process improvements and application of complementary technologies in more consolidated sectors such as China's solar PV industry (Shubbak, 2019). In the case of rapidly evolving technologies, such as wind technologies, continuous innovation system investment is fundamental. For instance, in China, the support provided by the innovation system, such as facilitation of university-industry linkages, was essential for the shift from onshore to offshore turbine technologies. However, it was not enough to achieve the success enjoyed by other green sectors, such as solar PV, or market leadership. This required integration of smart systems for turbine and wind farm management which the Chinese wind sectoral system could not deliver (Dai et al., 2020)

Build domestic capabilities along the value chain

The promotion of production capacity building along the renewable energy value chain is an important policy area that involves local content requirements, tax incentives and public procurement. The design of policy matters: for example, a tax incentive can target manufacturing facilities, energy production projects or specific company types, such as joint ventures, with different impacts in terms of domestic capability building (Matsuo and Schmidt, 2019). The case of the South African wind industry discussed in Morris et al. (2021) provides some interesting findings related to the implementation of local content requirements, such as the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) auction system. First, the centralization of localization in industry policy has major effects on domestic production capacity building. However, in South Africa, an increase in the local content thresholds for wind and solar PV investments, was not supported by a renewable energy policy. Second, localization of the industry must involve lead firms and account for the global organization of the industry value chain. In the South African case, the attempt to promote local tower and blade manufacturers was unsuccessful because the global multinationals relied on long-standing relations with global first-tier suppliers. Third, services can offer opportunities for developing domestic high value-added activities and, therefore, industry localization should not focus only on the manufacturing phase and, especially, in sectors, such as wind, where services play a key role in the value chain. The evidence in Morris et al. (2021) shows that lead firms were willing to collaborate with efficient domestic service providers and were keen to encourage their internalization as suppliers in other locations.

Invest in human capital

The accumulation of local specialized scientific, technological, managerial, and organizational capabilities is vital for absorbing, adapting and eventually developing relevant knowledge in renewable energy industries. It is enabled by a dedicated and costly learning process and investments in training, such as the programmes offered by Thai universities and research centres (Suwanasri et al., 2015). In China, central government launched a recruitment programme in 2008 to attract global experts. The Thousands of Talents Plan offered full-time positions with attractive salaries and benefits, in research institutes and universities. The programme attracted Chinese researchers who had graduated from a western university and had expertise in fields such as PV cell technologies (Shubbak, 2019).

Skills are acquired through learning by doing, on-the-job training and interactions within the domestic sectoral system. In China's biomass industry, the state-owned design institutes are important for diffusing technical knowledge within the domestic industry, which has benefited from their interactions with leading biomass firms. These design institutes are licensed to undertake design of construction facilities and their involvement in the construction of biomass power plants is mandatory. These institutes play a leading role in the accumulation of up domestic competencies in biomass technology, and acquisition of knowledge via interactions with pioneers, which then is disseminated to Chinese biomass producers (Hansen and Hansen, 2020).

Involvement in international collaboration projects

Developing countries able to combine acquisition of external technologies with developing domestic technological capabilities can introduce new affordable solutions that contribute to the global green transformation. The insertion of developing countries in the green economy should have internationally beneficial effects, through the provision of more diverse and affordable solutions, and lower prices for energy transition technologies. This requires global level collaboration with international NGOs enabling access to external knowledge for all countries.

International collaborative projects are more frequent in new industries, such as CSP and green hydrogen. We identified several international initiatives involving advanced countries, such as Germany, and African countries starting to invest in green hydrogen. Germany is particularly active in the H2Atlas-Africa project[10] and collaborations with Morocco and Namibia, for example. Germany and Namibia are collaborating on a project involving joint research exchange programmes for researchers and experts, and scholarships for Namibian students.

At the multilateral level, in 2021 UNIDO launched an international green hydrogen industry programme, aimed at enhancing exchange, development and distribution of knowledge on policies, technical guidelines and standards and technical cooperation to promote national green hydrogen roadmaps and pilot projects in developing countries. Both these initiatives are supported by the International Hydrogen Energy Centre in Beijing, established by UNIDO and the Chinese Government.[11]

Another example of multilevel collaboration is the Africa- EU Energy Partnership which provides a forum for political dialogue, knowledge sharing and peer links between EU and African stakeholders, in the field of renewable energies.[12]

An important area of international cooperation is related to formulating and harmonizing international standards for new industries such as green hydrogen. To make green hydrogen competitive will require a significant decrease in production costs and a significant increase in the supply of renewable electricity. This implies that countries with conditions favouring production of abundant low-cost renewable energies could become exporters of green hydrogen. Agreeing on common international standards (e.g., on guarantees of origin, hydrogen purity, equipment specifications, integration with the gas grid) would reduce investor uncertainty and facilitate creation of an international market for hydrogen (Cammeraat et al., 2022). All the stakeholders involved, both public and private and from advanced and developing countries, should be involved in defining a set of international technical norms and regulations.

Reforms to the global intellectual property regime will require global collaboration. The available empirical evidence is limited, but a recent study of a large sample of 59 countries concludes that stronger intellectual property rights protection would increase deployment of renewable energy technologies (Tee et al., 2021). We need to find a balance between the advantages and costs of

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[10] The H2Atlas-Africa project is a joint initiative of the German Federal Ministry of Education and Research and Sub-Saharan Africa region partners, to explore the potential for hydrogen production from renewable energy sources, within sub-regions (H2Atlas, 2022).

[11] More information is available at unido.org.

[12] More information is available at Africa-EU-energy-partnership.

intellectual property rights that would allow developing countries to access frontier technologies. This is an area that requires more robust empirical research into the consequences of implementing instruments such as compulsory licensing, shorter patent protection times and stricter novelty requirements for patents.

Diffuse knowledge within the domestic sectoral system

China's biomass industry highlights the importance of policies and state involvement for stimulating knowledge spillovers that allow many domestic firms to benefit from exploitation of a GWO by a leading pioneer company in the industry. The Chinese government contributed to facilitating the dissemination of knowledge through weak enforcement of intellectual property rights which allowed copying and imitation by domestic competitors. The already mentioned state-owned design institutes acted as knowledge flow mediators (Hansen and Hansen, 2020).

Another example of initiatives to promote knowledge sharing within the domestic ecosystem is the case of the wind industry in Ethiopia where government required national universities to collaborate in wind projects. The Ministry of Water, Irrigation and Electricity liaised with several domestic universities to enable their involvement in early projects and allow them to apply this experience in subsequent projects (Lema et al., 2021).

5.3 Topics for further research

Our findings suggest several directions for future research, related to some of the limitations of this research and to explore new issues.

This research was based on a review of the literature, undertaken to identify cases providing anecdotal evidence on a sufficiently large variety of countries and some selected industries, with the result that the cases investigated are general and not focused only on GWOs. This review identified a diverse range of technological trajectories and GWOs in emerging economies and less developed countries. Further research is needed on selected experiences based on application of the proposed GWO analytical framework, comparable performance data and detailed policy reviews.

Future research should investigate the impact of new technological megatrends – big data, artificial intelligence, energy storage, internet of things - on the global transformation towards sustainability. Understanding which, among the emerging economies, will benefit most from the diffusion of new and emerging green transformation technologies would be beneficial.

Finally, we stressed that relevant preconditions are often critical for exploitation of GWOs. The green transformation is levelling the playing field for some countries and in some sectors, but not for all countries or all sectors. Future research could investigate latecomer effects and developing country-specific advantages and opportunities for leapfrogging in green sectors compared to the advantages enjoyed by rich, incumbent countries.

6 Appendices

A. Sector definitions

Table A-1: Definitions of the industry sectors included in the study

Sector	Definition
Bioenergy*	Bioenergy involves the use of biological materials for energy purposes. A wide range of materials can be used, including residues from agriculture and forestry, solid and liquid organic wastes (e.g., municipal solid waste, sewage, and animal manure), and crops grown especially for energy, such as corn and soy. The energy from these organisms can be burned to create heat, converted into electricity, or processed into biofuels.
Biogas	Biogases are derived through anaerobic digestion and thermal processing of raw materials such as agricultural waste, manure, municipal waste, plant material, sewage, green waste and food waste.
Biomass	Solid biomass as a source of bioenergy covers fuelwood, charcoal, agricultural and forestry wastes, renewable wastes from the paper and pulp industry. Biomass is essentially plant-based material used as fuel to produce heat or electricity. Since biomass can be used as a fuel directly (e.g., burning of wood), the words biomass and biofuel are sometimes used interchangeably.
Waste	This is a sub-category of solid biofuels and biogas or a specific source of these. More generally, waste-to-energy is the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source.
Biofuels	Biofuels are liquid and gaseous fuels produced from biomass and used in the transport sector. They are a convenient renewable substitute for gasoline. Liquid biofuels fall into two main categories: bioethanol and biodiesel. Ethanol is an alcohol fuel derived from sugarcane, wheat, corn, or biomass. It can be blended with conventional petroleum diesel to improve its octane level resulting in reduced greenhouse gas emissions. Biodiesel is made from natural oils such as animal fats or vegetable oils.
Solar Energy*	Solar energy is radiant light and heat from the sun that is harnessed using a range of technologies such as solar power to generate electricity, solar thermal energy including solar water heating, and solar architecture
Solar PV	Photovoltaics (PV), also called solar cells, are electronic devices that convert sunlight directly into electricity. Solar PV installations can be combined to provide electricity on a commercial scale or arranged in smaller configurations for mini-grids or personal use.
Concentrated solar power	Concentrated solar power (CSP) uses mirrors to concentrate solar rays. These rays heat fluid, which creates steam to drive a turbine and generate electricity. CSP is used to generate electricity in large-scale power plants.
Wind Energy*	Wind energy is used to produce electricity using the kinetic energy created by air in motion. This is transformed into electrical energy using wind turbines Many parts of the world have strong wind speeds, but the best locations for generating wind power are sometimes remote and offshore ones
Green Hydrogen*	Green hydrogen is hydrogen generated entirely by renewable energy or from low-carbon power. The most established technology for producing green hydrogen is water electrolysis fuelled by renewable electricity. Compared to electricity, green hydrogen can be stored more easily. The idea is to use excess renewables capacity from solar and wind to power electrolysers which would utilize this energy to create hydrogen, which can be stored as fuel in tanks. This concept is known as ‘Power-to-X’, taking grid electricity (power) and turning it into something else for example in periods where fluctuating renewable energy generation exceeds loads. In this case, the ‘X’ is hydrogen fuel.
Electric Vehicles	Electric vehicles (EVs) use one or more electric motors for propulsion. They can be powered by a collector system, with electricity from extravehicular sources, or autonomously by a battery. As energy-consuming technologies, EVs create new demand for electricity that can be supplied by renewables. In addition to the benefits of this shift, such as reducing CO2 emissions and air pollution, electric mobility also creates significant efficiency gains and could emerge as an important source of storage for variable sources of renewable electricity.

Source: IRENA (2022)

B. Descriptive statistics

Table A-2: Top 10 countries in installed capacity (MW)

Bioenergy						
	2010		2015		2020	
	Country	MW	Country	MW	Country	MW
1	USA	10290	Brazil	13311	China	18687
2	Brazil	7927	USA	12969	Brazil	15650
3	Germany	6222	Germany	8429	USA	11980
4	Sweden	4055	China	7977	India	10532
5	**China**	3446	India	5478	Germany	10367
6	**India**	3145	UK	4808	UK	7243
7	Austria	2176	Sweden	4716	Sweden	5299
8	UK	2160	Italy	3367	Thailand	4389
9	Canada	1927	Thailand	3231	Italy	3554
10	**Indonesia**	1911	Canada	2473	Korea	2726
	Solar					
1	Germany	18006	China	43549	China	254355
2	Spain	4605	Germany	39224	USA	75572
3	Japan	3618	Japan	34150	Japan	68665
4	Italy	3597	USA	23442	Germany	53783
5	USA	3382	Italy	18907	India	39211
6	Czechia	1727	UK	9601	Italy	21600
7	Australia	1091	France	7138	Australia	17344
8	France	1044	Spain	7008	Viet Nam	16504
9	**China**	1022	Australia	5946	Korea	14575
10	Belgium	1007	India	5593	Spain	14089
	Wind					
1	USA	39135	China	131048	China	281993
2	**China**	29633	USA	72573	USA	117744
3	Germany	26903	Germany	44580	Germany	62184
4	Spain	20693	India	25088	India	38559
5	**India**	13184	Spain	22943	Spain	27089
6	France	5912	UK	14306	UK	24485
7	Italy	5794	Canada	11214	France	17382
8	UK	5421	France	10298	Brazil	17198
9	Canada	3967	Italy	9137	Canada	13577
10	Denmark	3802	Brazil	7633	Italy	10839

In bold middle- and low-income countries

Source: IRENASTAT (2021)

Table A-3: Technical potential for producing green hydrogen under USD 1.5/Kg by 2050

SSA	Middle East	North America	South America	Oceania	Asia	Europe
2715	2023	1314	1114	1272	960	88

Source: IRENA (2022)

Table A-4: Top 10 countries: electric vehicles stock 2010-2020*

	2010		2015		2020	
	Country	# Cars	Country	# Cars	Country	# Cars
1	USA	3,774	China	146,349	China	1,504,705
2	Japan	1,783	USA	134,751	USA	595,740
3	Norway	1,341	Japan	45,006	Germany	211,412
4	China	955	Netherlands	29,184	Norway	161,611
5	India	878	UK	24,253	UK	145,098
6	UK	838	Norway	23,059	France	138,862
7	Portugal	719	France	18,167	Japan	99,060
8	Italy	646	Germany	16,101	Netherlands	97,149
9	France	304	Canada	5,897	Canada	69,724
10	Switzerland	160	Sweden	5,305	Sweden	59,587

* BEVs are battery electric vehicles. PHEVs are plug-in hybrid electric vehicles. FCEVs are fuel cell electric vehicles. EVs refers to all electric vehicles (BEVs + PHEVs).

Source: International Energy Agency (IEA) – Global EV Data Explorer (2021)

C. Bibliometric procedures and sources

For each of the industries investigated in the paper, we searched for publications dealing with the issue of how latecomer countries have been developing and seizing green windows of opportunity. We used Scopus, the largest available database of peer-reviewed literature (including scientific journals, books, and conference proceedings). The advantage of using Scopus is that it allows users to navigate through the world's research outputs by searching for keywords within the article title, abstract and keywords section in a Boolean-type of query – i.e., AND-*OR* operators. Next, the results can be filtered by year, scientific discipline, type of article and other characteristics. Moreover, given our objective to discuss empirical insights from case studies available in the literature on selected green industries, the grey literature (e.g., reports and research produced by governmental and non-governmental bodies) has also been considered.[13] The search was limited to publications in English.

The search process summarised in Figure A- resulted in a combination of keywords of the following string: "*renewable*" AND "*innovation*" OR "*production*" AND "*developing country**[14]" OR "*latecomer*" OR "*catch*up*". To focus the survey on publications on green technologies, specific keywords were added to the string, for example, "*solar"* OR "*wind"*. Given the extensive breadth of the available scientific literature, to identify the literature most related to the task at hand, filters for subject discipline were applied, for example, economics, econometrics and finance, social and business sciences, energy policy and environmental science The search returned a total of 38 relevant publications, which were identified, organized, and sorted manually. To this initial group of publications, a snowballing exercise allowed to add other relevant articles. Moreover, additional information deriving from the news or short articles available on the internet was added.[15] Figure A- presents the list of publications included in the study by industry and country.

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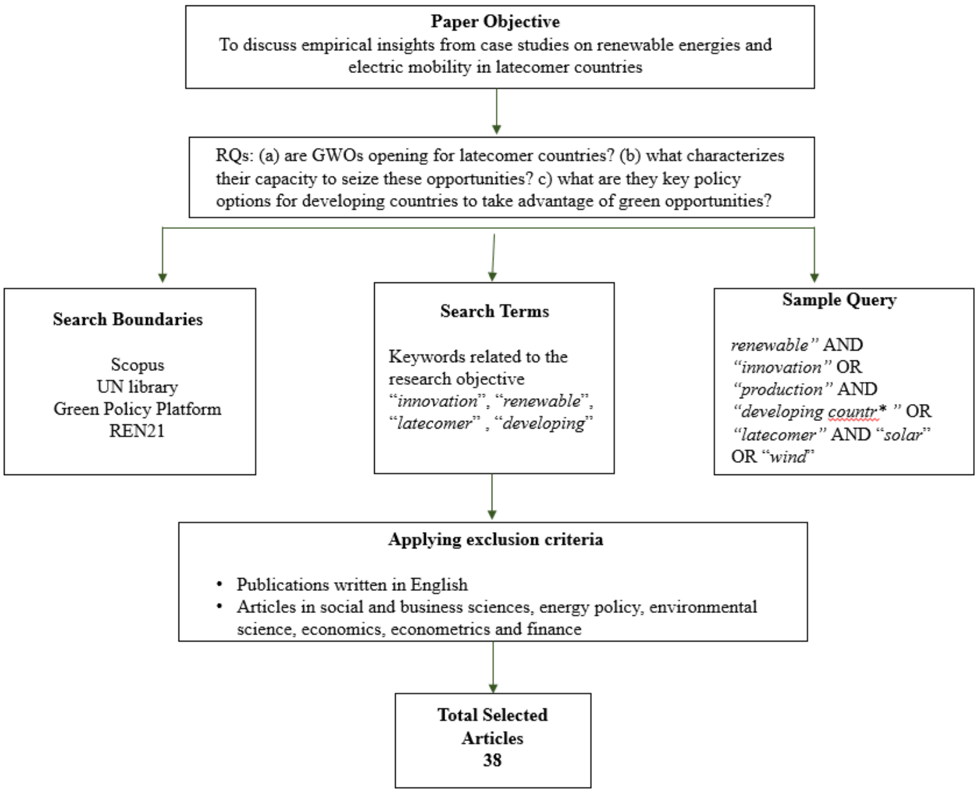
[13] Among the Governmental and Non–Governmental Organizations (NGOs) considered there are UNCTAD, UNEP, the World Bank, International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). The search has been further refined by searching for green-policy related case studies on online repositories such Green Growth Knowledge Program (GGKP) and REN21. The former collects the latest case studies and research produced by various organizations, allowing a search by country, region, and industry. The latter is an international policy network of experts from governments, inter-governmental organizations, industry, academia, and NGOs that produce detailed policy reports on renewable energy markets around the world.

[14] Keywords included an asterisk (*) to allow for stem-words, plurals, and punctuation to be considered. For example: searching for EV* allows to retrieve the articles that have "EVs, E-Vs" in either the title, the abstract and among the keywords.

[15] The appendix presents a schematic summary of the literature search process and an overview of the industries and countries included in the literature survey.

Figure A-1: Summary of the literature search process



The literature identified is examined to extract the following information. First, we consider the presence of Green Windows of Opportunity, depending on the institutional, market, or technological changes, to understand their nature in each case analysed. Second, we focus on the sectoral systems, considering two focal dimensions: a) preconditions, i.e. in the formative sectors the range of proximate industrial activities (Hausmann & Hidalgo, 2011) and b) responses of the sectoral system (Malerba, 2002). Third, we account for catch-up trajectories concerning market development and technological upgrading.

Table A-5: Literature sources by industry and country

Sector	Country	Main sources
Biofuels (liquid)	Brazil	Andersen, 2015; Duque Marquez, 2007; Hira & de Oliveira, 2009; Figueiredo, 2017; Furtado et al., 2011; Pereira & De Paul, 2018; Silva et al., 2019; Stecker, 2013
	Ghana	Antwi-Bediako et al., 2019; Nygaard & Bolwig, 2018
	India	Lahiry, 2018
	Tanzania	Arora et al., 2014
Biogas	Bangladesh	Chowdhury et al., 2020; Lema et al., 2020
	Pakistan	Yaqoob et al., 2021
	Thailand	Reinauer & Hansen, 2021; Suwanasri et al, 2015
	Vietnam	GIZ, 2022; Cuong et al, 2021
Biomass	China	Hansen & Hansen, 2020
	Mexico	Ordoñez-Frías et al, 2020
Electric vehicles	Brazil	Consoni et al., 2019; Costa et al., 2020; Zaparolli, 2019
	China	Altenburg et al., 2022; Hain et al., 2021
	India	Chaliawala, 2020; IESA, 2021; Sasi, 2021; Shalender & Yadav, 2018
	South Africa	Barnes et al., 2017; Justin et al., 2017; Moeletsi, 2021; SEI, 2020; Raw & Radmore; 2020
Green hydrogen	Chile	Adler, 2022
	China	China Hydrogen Alliance, 2018; Dan Murtaugh, 2021; Meidan, 2021; UNIDO, 2022
	Morocco	Torres & Perner, 2021; Friedrich Ebert Stiftung, 2020
	Namibia	Huegemann & Oldenbroek, 2022
	Oman	Paddison, 2021
	South Africa	South Africa Hydrogen Valley Final Report, 2021
	China	Binz et al.,., 2021
Solar photovoltaic	India	Behuria, 2020; Johnson, 2016; Sahoo & Shrimali, 2013
	Iran	Gorjian et al, 2019
	Mexico	Matsuo & Schmidt, 2019
	Kenya	Bhamidipati et al., 2021
	South Africa	Baker & Sovacool, 2017; Matsuo & Schmidt, 2019
	Vietnam	Do et al., 2021
	China	Binz et al., 2021; Gosens et al., 2020; Shubbak, 2019
Concentrated Solar Power	Morocco	Fritzsche et al., 2011; Vidican, 2015; World Bank, 2016
	China	Gosens et al., 2020; Hain et al., (2021)
Wind	China	Lema et al., 2013; Dai et al., 2021; Upstream, 2021; Hain et al., 2021
	Ethiopia	Gregersen & Gregersen, 2021; Lema, Bhamidipati, et al., 2021
	Kenya	Gregersen, 2020; Gregersen & Gregersen, 2021;
	South Africa	Matsuo & Schmidt, 2019; Morris et al., 2021

D. Biogas and biomass

Based on the definition provided in Appendix A, we can identify 3 different sub-technologies of renewable energy deriving from a matter of biological origin: biogas, solid biomass, and biofuels. In what follows, we provide evidence about the first two sub-technologies, then followed by an analysis of the catch-up trajectories in biofuels. Table A.6 presents a summary of evidence about the bioenergy industry.

Green Windows of Opportunity

In 2020 China is the leading country in bioenergy production (see Table A.3). Hansen & Hansen (2020) explain the very rapid catch up of the Chinese biomass industry, which is one sub technology within bioenergy, with an increase of the total installed capacity from almost zero in 2005 to around 5300 MW in 2015, comparing with for instance a capacity of 7600 MW in Germany. The take-off of the biomass industry is explained by the introduction in 2006 of the first renewable energy law in China, which included a favourable feed-in tariff for biomass power which was approximately double of the coal tariff and therefore provided strong incentives for investments in biomass power plants. Hansen & Hansen (2020) stress that these institutional changes in the energy sector clearly define an endogenous GWO. They also add that the representatives of the leading pioneer company in the industry influenced and directly contributed to the drafting of the initial policies and regulations instrumental to the further development of the sector.

In biogas, another sub-technology in the bioenergy category, Thailand is one of the largest producers in the world with the largest domestic market in the South after China and Turkey.[16] Thailand offers another interesting example of a policy window of opportunity. Since the 1980s, anaerobic wastewater treatment has been developed to produce biogas in cassava starch factories but in the beginning, most factories were not interested to invest in biogas production due to high investment costs. However, since early 2000 this changed radically when the Thai government introduced a proactive strategy to attract private investors to the industry. In the following years, several measures were introduced including financial subsidies for the construction and design of biogas production plants, tax incentives for firms involved in waste transformation, the Small Power Purchase Tariff program for increasing the proportion of electricity generation from biogas and the enforcement of an environmental law taxing companies producing pollution (Suwanasri et al., 2015).

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[16] According to IRENA, in 2020 in the biogas sub technology the leading country in terms of installed capacity is Germany with 7500 MW and Thailand ranks 7th with 550 MW.

Differently from the Chinese and Thai cases, in Pakistan, the existence since 2009 of a Biogas Program aimed at promoting an efficient replacement of traditional wood fuel and animal manure for domestic use of cooking and heating in rural areas, has not generated an extensive adoption of biogas technology because of lack of coordinated government initiatives, inconsistent policies, and absence of adequate regulations and construction standards for biogas plants. Yaqoob et al., (2021) underline that the utilization of biogas technology has a huge potential in the country also for creating jobs and generating income but there is still a lack of technical competencies and very little has been done so far to persuade farmers, sugar mills owners and private investors to adopt and invest in biogas technology in the country.

Similarly, the case of the palm oil industry in the Mexican state of Tabasco illustrated by Ordoñez-Frías et al., (2020) confirms that weak regulations and public policies, lack of competent providers and absence of capability building efforts to adapt imported technologies do not allow to take advantage of the market opportunity deriving from the valorisation of the variety of biomass resources from harvest and agro-industrial residues available in the country. In particular, the study illustrates how the increasing production and the lack of proper management of solid by-products generate an increasing impact on the environment with residues left on the ground or open burned, while within a proper management system they could be transformed into energy, establishing a sustainable palm oil industry.

Sectoral system: preconditions and responses

In the Chinese biomass industry, the building up of production and later of innovative capabilities was started by one leading private company established in Beijing in 2004 by a Chinese-Swedish entrepreneur with experience as senior adviser for Volvo taking advantage of the endogenous windows of opportunity, which also contributed to creating. Initially, through licensing of foreign technologies and strategic acquisitions of foreign companies, enabling access to skilled labour, and more recently with a rapid international expansion as well as a diversification strategy into new technologies such as waste-to-energy plants [17]and bioethanol production, the company has managed to catch-up with industry incumbents (Hansen & Hansen, 2020). Moreover, thanks to knowledge spillover, consisting of labour mobility towards local competitors and interactions with local suppliers, an increasing number of domestic firms was able to take advantage of the window of opportunity and a dynamic sectoral system was created. Due to the dominance of the DUI (doing-using-interacting) mode of learning in this industry, labour turnover with high employee mobility

[17] A waste-to-energy plant is a waste management facility that combusts waste to produce electricity.

from the leading company to the competitors played a role as a key channel for knowledge transfer. Moreover, the design institutes, which are State-Owned Enterprises (SOEs) responsible for the design of plants also benefitted from on-site training, careful quality supervision, and continuous interaction with the leading pioneer company, contributing to diffuse knowledge in the domestic sectoral system. Finally, demonstration effects are also important because local firms have been able to copy and imitate, thanks to the weak protection enforced on the patenting activity of the leading firm. Domestic competitors were able to copy components officially protected by patents because weak enforcement of intellectual property laws was tolerated by the Chinese authorities.

The development of a strong sectoral system is also one of the key factors of the success of the biogas industry in Thailand. The existence of a network of private and public actors has helped to disseminate biogas technology and the domestic research sector has developed various technologies which are more efficient and less expensive than imported ones. Some technological solutions developed in Thailand have also been adopted abroad as in the case of the UN project Cows to Kilowatts in Nigeria (UNFCCC, 2021).[18] Thanks to extensive training programs mainly conducted through public institutions such as research centres and universities[19], domestic capability has been built in the setup and maintenance of the production systems, creating in the private sector the confidence that in case of problems a network of public and private consultants could provide adequate technical support (Suwanasri et al., 2015).

Reinauer & Hansen (2021) investigate different learning mechanisms among Thai biogas companies showing that all the investigated firms started from relatively low levels of capabilities and during the period of investigation from 1991 to 2017 they have all transitioned to higher levels. Moreover, they confirm that in this industry experience-based (DUI) learning is important because of the nature of biogas systems which require adaptation to the local contexts. The relevance of external knowledge is also stressed because firms relying only on firm-internal learning mechanisms exhibit low capability levels while firms involved in external domestic and external foreign sources of knowledge have reached a higher level of innovative capacities. A further interesting finding is that for building capabilities, firms need to engage in different learning mechanisms – firm-internal, external-domestic, and external-foreign – involving different types of activities – productivity-driven, innovation-driven, and human-resource-related.

[18] The Biogas Technology Research Centre of King Mongkut's University of Technology Thon- buri (KMUTT) is one of the partners of this UN project in Nigeria.

[19] The two main institutions involved in training and technical advice and consultancy to the domestic companies are BIOTEC, the national center for genetic engineering and biotechnology established by the Minister of Science Technology and Energy, and KMUTT, a national technological university (see Footnote 13)

Similarly, to China and Thailand, with a recent introduction of a feed-in-tariff framework and other measures aimed at facilitating and regulating public-private partnership in renewable energy projects, including biomass energy, Vietnam has started to exploit its great potential to generate biomass energy from rice husks – a by-product of rice processing that otherwise often wasted. One example of public-private collaboration is with Decathlon, of whose many suppliers operate in Vietnam, which has set an ambitious target to use 100% biomass for industrial heat and/or power by 2030. In collaboration with GIZ, Vietnam has started a project for supporting the development of a sustainable market in the biomass industry and for building capability among consultants, project developers and investors on how to draw up feasibility studies. The project also promotes technology partnerships between national and international companies and research and development institutions to develop locally adapted solutions (GIZ, 2022). Nevertheless, Cuong et al., (2021) stress that in the Vietnamese case the lack of a powerful focal point in the government system to coordinate the different incentive policies have impacted their performance, especially in remote and off-grid regions.

The case of biogas production in Bangladesh described by Chowdhury et al., (2020) is also interesting because it shows that notwithstanding the existence of favourable preconditions for the development of the industry, the lack of policies and their weak implementation, as well as the lack of infrastructure hinder a large-scale production and have diminished the capacity of the country to exploit the potential windows opportunity. In Bangladesh, several NGOs have invested in biogas projects decades ago. The country has also established an articulated system of government and non - government organizations involved in R&D projects related to biomass energy. Nevertheless, a proper subsidy policy to encourage biogas plant installation has not been implemented and very little has been done in terms of training programs among farmers to increase awareness and diffuse a correct waste management policy. Besides, the public investments in research with the involvement of national universities have been minimal.

Not very different is the situation of biomass energy in African countries where several national programs are currently introduced, also thanks to international initiatives such as the "Biogas Partnership Programme" and "Biogas for a Better Life"[20] which contribute to the transfer of some basic knowledge, creating an initial base of specialized competences in the countries involved. But national programs are not followed by a coherent set of measures to build an effective sectoral system,

[20] The "Biogas Partnership Program" ended in 2019 and supported national biogas programs in Ethiopia, Kenya, Tanzania, Uganda, and Burkina Faso (ABPP, 2019). The Biogas for a Better Life initiative was launched in 2007 in Nairobi with the aim to install 2 million biogas plants by 2020 (Nes & Nhete, 2007).

developing domestic production and technological capacity, and overall biogas production is still very limited (Scarlat et al., 2018).

Catch up trajectories

Following a trajectory from domestic imitation to global leadership, the Chinese biomass industry has been able to progress from new-to-the-country to world-class technology and technological upgrading was achieved faster than global market success. Whereas the Thai biogas industry has built up a domestic innovative capacity able to satisfy a rather large domestic market. Chinese firms also operate globally and have acquired global market leadership at the expense of western producers.

Table A-6: Biogas and biomass

	Biogas and biomass
Green windows of opportunity • Market windows • Technology windows • Institutional windows	• Renewable energy law (China) • A pro-active approach combining financial and tax incentives, power purchase tariff; Clean Development Mechanism (Thailand) • Biogas Program but not effective implementation (Pakistan) • Potential market (Mexico) • Favourable feed-in-tariff for electricity from biomass (Vietnam)
Sectoral System • Preconditions • Responses	• Government and non-government organizations involved in R&D projects but lack coherent policy framework (Bangladesh) • Multilateral initiatives (e.g., Biogas Partnership Program; Biogas for a Better Life) in African countries but lack of national strategies for building domestic capacity • Great potential to generate biomass energy from rice husks (VietnamWell-developed sectoral system (China, Thailand)of lead firms (China) • Strategic foreign acquisitions (China) • Design and research institutes (China) • Training system (Thailand) • Maintenance system (Thailand) • Involvement of international donors and investors (Vietnam)
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• Domestic market (China, Thailand) • Foreign market (China) • New to the country technology (Thailand) • World-class technology (China)

E. Biofuels

Liquid biofuels, a convenient renewable substitute for gasoline, are mostly used in the transport sector. They offer an alternative fuel for all types of internal combustion engines running on gasoline, diesel, or kerosene, including for use in road, sea and air transport. Biofuels, bioethanol, biodiesel, have an increasing role in climate change strategies, and this has opened opportunities for development in a range of developing countries. This window is particularly significant in countries with the potential for sugarcane production and other crops that do not compete directly with food production.[21]

Green Windows of Opportunity

Brazil is widely known for its policy-driven creation of a demand window in bioethanol with substantial investments in learning in the sectoral system (Andersen, 2015; Figueiredo, 2017; Silva et al., 2019) . The programme to stimulate the adoption of biofuel technology is an important institutional window that was to a large extent a response to an external disruption, namely the oil crisis of the 1970s. When OPEC placed an embargo on petroleum, Brazil began sustaining the development of what has become the most successful biofuel industry in the world (Stecker, 2013). If the USA has been the undisputed leader with a long history of bioethanol production for energy based on corn, Brazil made a substantial investment in developing technology for bioethanol based on sugar cane and is considered the bigger success story (Stecker, 2013). Both countries have engaged in technological development aimed at reducing the cost of biofuel to make it competitive with other fuels. However, the two countries did not reduce costs at the same pace. Between 1980 and today, the USA has reduced the cost of producing one-litre bioethanol by 60%, Brazil has reduced it by 88%, indicating a superior rate of technological learning.

Today, Brazil is the world leader both in terms of technology and usage of ethanol. Moreover, there is significant, yet unrealised, export potential (Hira & de Oliveira, 2009) and Brazil has become the main supplier of biofuels technology also for the developed world (Duque Marquez, 2007). Capability accumulation in this technology has also had many forward linkage effects, for example with the Brazilian new-to-world invention of the flex-fuel engine, enabling alternation between traditional and bioethanol-based fuel in cars (Lema et al., 2015).

While Brazil and other countries such as Australia developed a biofuel industry based on sugar cane, many developing countries experimented with one based on the oils from the seed of the tree, especially during the 2010s. It was highlighted that the oil from jatropha possessed biodiesel and jet fuel production potential. Ghana and Tanzania were the two African countries that attracted the greatest number of private companies prepared to make substantial investments in large-scale jatropha farming. The experiences of the two countries share some similarities. This GWO was largely driven by international organisations and donors: an externally pushed GWO emerged as, after the turn of the millennium, there was a strong global drive for jatropha, with many investors,

[21] The export volume of biodiesel in India was around 50 million litres in 2021 (Statista, 2022). In 2020, ethanol fuel exports from Brazil amounted to 2.68 million cubic meters, out of which 37 % went into the U.S., and 34 % to South Korea.

government and NGOs highlighting it as a promising opportunity for sustainable biofuel production. Jatropha has several positive properties such as high yield, low water and fertilizer requirements, high resistance to pests and ability to grow on marginal land without competing with food crops. A key element of the global GWO was the clean development mechanisms (CDM) which supported sectoral traction in both countries.[22]

This globally emerging GWO was responded to and augmented in the two African countries. In Ghana, for example, it was ingrained in the Strategic National Energy Plan (SNEP) and National Biofuel Strategy in 2006 which refined and specified several earlier policies. On the demand side, this policy enforced mandatory blends of gasoline and biodiesel at 5% by 2010, 10% by 2015 and 20% to increase domestic demand and substitute fossil fuel imports (Nygaard & Bolwig, 2018). The government chose 53 districts throughout Ghana to start pilot jatropha plantations on agricultural lands with low fertility so that it would not compete with the production of food (Ahmed et al., 2017)

However, although several countries enforced such policies, the real window of opportunity was not as significant as expected due to difficulties in ramping up production and low yields.

Sectoral system: preconditions and responses

The reason behind the rapid leadership attainment by Brazil is to be found in a programme to stimulate the adoption of biofuel technology on the demand side, combined with collective learning at the sectoral system level, including the supply side (Furtado et al., 2011). This building up of a well-developed sectoral innovation system has occurred through learning spaces in which interactive learning links have appeared as a consequence of problem-solving activities involved in technology deployment (Andersen, 2015). The development of the biofuel sectoral system is widely regarded as a major achievement in terms of stepping up collective learning (Andersen, 2015; Furtado et al., 2011; Perez-Aleman & Alves, 2016). However, there are also indications that the transition to second-generation biofuels – biofuels that are not based on sugarcane, but agricultural by-products (lignocellulosic feedstocks) – is constrained by path dependencies (not least a major interest in sticking to the current focus on sugarcane production) limiting further investments in technological development which is essentially rooted in a lack of commitment of Brazilian federal institutions to future technologies. Some of this lack of commitment can be traced to the decreased urgency of energy transition after the discovery and development of offshore petroleum reserves. However,

[22] The CDM is a 'project-based' mechanism under the Kyoto Protocol devised to encourage production of emission reductions in developing countries. To stimulate sustainable development, CDM facilitates low-carbon technology transfer from advanced to developing economies in connection with implementation of emission reduction projects (UNFCCC, 2022)

second-generation technology is a crucial ingredient for long-term development in the ethanol industry because of its advantages such as non-rivalry with food production and hence for international competitiveness (Pereira & De Paula, 2018). In other words, further development of the bioethanol sector in Brazil may depend on continued investments and capability stretching in the context of a shifting dominant technology standard, from first to the second generation. It implies that the sector can experience a ‘technological discontinuity trap’ which can happen if a global change in technology is not met with a sufficient response by the sectoral to keep up (Landini et al., 2020).

As mentioned, other sources than sugar canes are also used in liquid biofuels produced in developing countries - such as palm oil diesel and jatropha biodiesel. According to most authors, jatropha strategies have largely been failures, for instance as appears from an analysis of transformations and complexities in six major jatropha investment destinations across the world: Mexico, India, China, Ethiopia, Mozambique, and Ghana (Antwi-Bediako et al., 2019; Nygaard & Bolwig, 2018; Romijn & Caniëls, 2011). Across these countries, proponents of jatropha investments – governments and private investors – adopted a "wait-and-see" stance with positive expectations that technological and land-use problems would dissolve. There were unexpected complexities and most investment projects fell far short of expectations (Antwi-Bediako et al., 2019).

India launched an ambitious programme, but several factors have led to slow progress in the country’s biodiesel development programme. Because the production capacity of jatropha seeds fell short of capacity, the ambitious plans did not materialise. There was also insufficient research by public institutes to achieve a higher yield of feedstock, developing short-duration crops. According to Lahiry (2018), the needed policy changes were not implemented. These include attention to a shift from jatropha to a multi-feed feedstock approach, improved incentive mechanisms, both at the feedstock stage as well as the biodiesel production stage, and lack of research and development for increasing the yield from the feedstock.

In Ghana, a sectoral system was formed comprising a range of actors, supported for instance by the National Jatropha Plantation Initiative (2006) which boosted local demand and with local ‘jatropha champions’ donor-supported projects led by GTZ, UNIDO, and UNDP. In addition, NGOs had a strong influence on the governance and dynamics of the jatropha sectoral system and value chain. Yet, despite the efforts of key firms and individuals to show-case jatropha biodiesel, a low level of learning and knowledge sharing between jatropha actors, alongside weak public R&D support, reduced access to technical and managerial information required to overcome entry barriers in international markets (Nygaard & Bolwig, 2018).

Similarly, an incipient sectoral system of innovation (SSI) had been developing in Tanzania, covering a range of actors but many issues related to the social, environmental and financial sustainability remained unresolved and impeded full system formation (Arora et al., 2014). By 2005 the developing system in Tanzania consisted of a few loosely connected 'experiments' involving around 30 different actors. Organisationally, the system evolved from a grassroots-based organizational model, over a rural-development organizational model to a profit-driven model with contract farming arrangements involving thousands of smallholder out-growers who supplied jatropha seeds to a firm owning a centralized oil-processing facility.[23] The third type of organizational model was structured around large plantations set up by transnational corporations, often to ship unprocessed jatropha seeds to the West for processing in end-market destinations. Like in Ghana, all the initiatives in the innovation system in Tanzania were found to be linked to foreign commercial investors or aid donors (Arora et al., 2014).

Catch up trajectories

Brazil has been the leader in market development, with around 30% global market share of ethanol production over the last 10 years. It fully supplies its local market and unblended fuel ethanol competes directly with gasoline at the station. While most production is consumed domestically there are also exports, with the US, South Korea, the Netherland as the most important buyers. Technologically it is the leader in first-generation liquid biofuels, and it was the pioneer in new-to-the-world technology. It has the largest fleet of flexible-fuel vehicles. Brazil could draw on first-generation capabilities to compete in the second-generation arena. With respect to competition, only a small number of countries have wide-ranging biofuel policy frameworks, and these are mostly in the domain of agriculture rather than industry. But observers point out challenges concerning its leadership in the future. This is because the country may be unable to upgrade into new generation bioethanol based on a variety of crop residues and food waste. Developing leadership in this technology of the future will require a shift in the innovation system (Pereira & De Paula, 2018).

In Africa, the failure to capitalize on the initial high expectations regarding jatropha biofuel production is to be found in the absence of domestic demand for biodiesel related to weak policy support despite the efforts of local firms and innovation system actors to promote the biofuels agenda, e.g., in Ghana. The high entry barriers in the global markets combined with the increasing scepticism and dwindling support mean that the jatropha is a 'failed investment space' (Antwi-Bediako et al.,

[23] In contract farming, an out-grower is a farmer who commits to supplying a buyer and to meet certain requirements. In return, the buyer agrees to make the purchase, sometimes at a pre-agreed price, and the buyer may provide other support.

2019). Unmet expectations led to recent land-use changes from jatropha to the cultivation of other crops or total land abandonment.

Table A-7: Bioenergy

	Biofuels
Green windows of opportunity • Market windows • Technology windows • Institutional windows	• Market disruption with the oil crisis in 1973 (Brazil) • Opportunities for greening of transportation and benefitting from the increase in global demand for biofuels (Global) • The institutional window is particularly significant in countries with potential for sugarcane production, but also other crops (Brazil) • Sugarcane-based ethanol fuel program (Brazil) • RenovaBio - Green Certificates (Brazil) • Strategic National Energy Plan (SNEP) /National Biofuel Strategy (Ghana)
Sectoral System • Preconditions • Responses	
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• World-class technology (Brazil) • Exports to the USA, South Korea and the Netherlands (Brazil) • Nascent domestic market deployment (India, Ghana, Tanzania)

F. Solar PV

Green Windows of Opportunity

In solar PV installed capacity, the dominant country is China with 254 GW of installed capacity in 2020.[24] This world-leading position has been built thanks to evolving institutional support aimed at taking advantage of the market opportunities and at progressively building a domestic production and innovation system, composed of public and private business actors in the different stages of the solar PV value chain as well as of supporting and regulating research institutions. In 2006 the Renewable Energy Law and the inclusion of the solar PV industry in the catalogue of high-tech products for exports motivated Chinese firms and research institutes to acquire knowledge and technologies setting up collaboration partnerships with leading foreign partners. Thanks to the technology transfer, the Chinese solar PV industry was able to enter the international market dominated by the European countries, until when after the 2008 financial crisis Germany and several other countries reduced their PV subsidy programs causing a dramatic decline in demand and due to a huge overcapacity, a drop

[24] Data are from IRENA. 1 GW is equal to 1000 MW.

in prices across the value chain. So, in reaction to the crisis in the international market, the Chinese government introduced policies aimed at domestic demand-pull such as the Concession Program for Large Scale Solar PV Power Plants, the Solar Rooftop Subsidy Program, and the Golden Sun Demonstration Program, offering subsidies up to 70% of total investment (Shubbak, 2019).

The Chinese PV case highlights the important role played by GWO open by public policy supporting the industry development but focusing on renewable energy policy in Mexico and South Africa, Matsuo & Schmidt (2019) stress the importance of unpacking the policy design calibrations, driven by different prioritizations which can deeply influence the industrialization outcomes. With a focus on solar, and wind industry, they indicate that both countries adopted the same policy instrument, a national auction[25], through which successful bidders are awarded contracts, or power purchasing agreements, that guarantee the price per unit of electricity generated but how the auctions have been implemented are different and so are the outcomes in terms of industry development.

In the Mexican approach, the clean energy auctions are technology-neutral with all clean technologies competing on the offered price and driven by free-market cost competition with no explicit target of developing a domestic renewable energy value chain. Instead, South Africa has developed a framework known as Renewable Energy Independent Power Producer Procurement Program (REIPPPP), which although it also has a market-based logic, introduces several additional regulatory requirements aimed at fostering specific socio-economic development outcomes. So, South-African auctions are technology-specific, and competition is not only on price but also on socio-economic objectives such as black economic empowerment, job creation, local content, and community ownership, with a respective weight of 70% and 30% (Matsuo & Schmidt, 2019).

The Indian case described in Behuria (2020) confirms that the strategy of prioritizing installed capacity of solar energy competing only on price is incompatible to build up a domestic manufacturing capacity. The National Solar Mission launched in 2010 has been successful in terms of increasing installed capacity but domestic manufacturing has received very limited support. The national program has prioritized deployment, attracting large projects offering low tariffs and has, therefore, incentivised national and international energy developers to rely on cheaper imports of solar cells and panels. In general, very limited emphasis has been devoted to R&D and to building up domestic and production capabilities.

Vietnam has seen rapid progress in solar energy installed capacity and it is considered a successful case with respect to other ASEAN countries, such as Malaysia and Indonesia which have seen smaller

[25] For a detailed description about how a national auction works see Box 1 in Section 5.

increases (Do et al., 2021). As we have seen in the previous section on bioenergy, starting with the Government National Strategy on Renewable Energy Development in 2015 then followed by a Party's Resolution on the Orientation for National Energy Development in 2020, Vietnam has implemented a combination of measures, including a feed-in-tariff, a temporary tax exemption for solar developers, a tariff exemption for imported equipment. Besides, Vietnam has a very favourable environment for attracting foreign direct investments which also apply to renewable energies, with no local content requirements, unlike for instance Indonesia and Malaysia. This combination of measures has rapidly created a large domestic market, and Vietnam in 2020 is the 8th largest market in terms of installed capacity in the world, increasingly attracting foreign developers but with limited impact on its domestic production and technological capacity.

A rapidly growing market for solar PV is also Sub-Saharan Africa (SSA) where initially the development has been driven by donor-backed projects but more recently has been characterized by a raising presence of private companies, facilitated by international financiers. Kenya is among the frontrunners in SSA regarding the diffusion of PV technologies and it has become a global hub for clean energy companies, particularly in small-scale decentralised energy generation and consumption (Bhamidipati et al., 2021).

Sectoral system: preconditions and responses

In the initial phase, the Chinese solar PV industry built up domestic production capacity thanks to foreign technology and external knowledge transfer. A key program was the Thousand Talents Plan aimed at recruiting global experts and Chinese returnees through the attraction of some prominent Chinese researchers in the field of PV cell technologies (Shubbak, 2019). Then in the following phase-oriented to the domestic market, the sectoral system transitioned to more localized capability formation processes in local firms, universities, and industry associations (Binz et al., 2020). From the technological point of view, the catch-up process progressively took place across the whole PV industry, starting from portable lightning devices to solar PV panels and then developing a domestic cell and wafer industry, also accumulating technological capabilities to become able to produce polysilicon, previously imported from the USA and to enter the production of power electronics devices such as inverters (Shubbak, 2019). The intense interactions undergoing among lead firms have also been key to the technological development of the sector after the global market contracted (Binz et al., 2020).

From the comparison of the Mexican and South African cases, it comes out that in Mexico, the auction design led to the attraction of large foreign developers and specialized vertically integrated foreign RE companies, opening very limited opportunities for the development of domestic capabilities across the value chain. While in South Africa the different auctioning scheme attracted a more diverse set of international and local project developers and the local content requirements, based on an increasing percentage of total project value, led to some involvement of local engineering, procurement, and construction (EPC) companies, contributing to domestic capability building. Although due to the starting limited availability of semi and skilled labour force, a study by Baker and Sovacool (2017) reveals that the high share of local content requirements resulted in the narrow technological upgrade. On top of this, the inadequate enforcement of the regulations and loopholes in the definition of local content requirements has led to solar PV foreign developers refraining from setting up production plants and instead of locating in South Africa warehouses to eliminate some of the transaction costs involved in shipping and transportation of PV modules.

The limited domestic capacity has also hampered the upgrading of the Indian solar PV industry. In fact, after increasing pressure from domestic manufacturers, in 2018 the Indian government introduced a safeguard duty against Chinese and Malaysian manufactured solar cells and panels but the increase in protection has forced developers to buy panels at higher costs slowing down the bidding process and with few positive benefits on the domestic manufacturing industry. Moreover, the government has not adopted a coherent strategy identifying which specific products or production stages to support within the solar PV value chain. Even if at this stage of the industry development, the manufacturing of cells and panels which is dominated by China, Taiwan and Malaysia could be out of reach for a late developer such as India, there are possibilities for building up capabilities more downstream in the service stages of the value chain and the manufacturing of balance-of-systems (BOS) components.[26]

Similarly, in Iran, solar PV generation has grown thanks to the commitment of the government to increase the share of renewable energy sources in the national electricity generation, but local industrial capacity remains very limited. A few domestic factories are assembling the modules but although there are plans for entering the upstream PV value chain exploiting the silica resources available in the country, Iran is an importer of the raw materials for producing the modules. According to Gorjian et al., (2019) in Iran, there are barriers to the development of solar PV both in terms of clear and implemented regulations and incentives for attracting investments in the industry and in R&D efforts oriented to take advantage of the existing domestic theoretical knowledge for developing a domestic capacity in the effective local deployment of the PV technology.

[26] BOS components refer to all components of a PV system other than the modules. These includes wirings, inverters, switches, and battery chargers and other elements involved in the 'deployment chain' (as opposed to the core technology manufacturing chain) of solar energy (Lema, Hanlin, Hansen, & Nzila, 2018).

In the Kenyan case, Bhamidipati et al., (2021) show that, notwithstanding the dominant role of international companies, domestic solar PV firms have been able to face and navigate international competition and are present in different market segments, having moved from standalone installations to relatively larger-scale plants, from distribution to installation and from government tenders and donors projects to commercial contracts, which is an indication of their scaling up and competence upgrading. In some cases, the upgrading has been the result of strategic networking with international actors and of investments in building internal capacities and skills. Nevertheless, Bhamidipati et al., (Bhamidipati et al., 2021) also conclude that domestic companies continue to face significant challenges in the areas of finance, skills and policy, which constrain their opportunity of gaining larger shares of the growing domestic market.

Catch up trajectories

In solar PV China followed a trajectory characterized by learning from exporting, over domestic strengthening, to global leadership, starting from initial export of new-to-the-country technologies introduced in China by returnee entrepreneurs, to a focus on the domestic market and technological upgrading, to achievement of world-class technology and reinterring the global market (Binz et al., 2021; Shubbak, 2019).

The Kenyan case also shows some opportunities for the domestic companies to catch up in the domestic market but there is a need for closer collaboration between the industry players and the supporting institutions, such as the commercial banks, the training and academic institutions, the ministries and the various public bodies to develop a well-functioning and coordinate sectoral system to strengthen the domestic solar PV industry (Bhamidipati et al., 2021).

Table A-8: Solar Power

	Solar PV
Green windows of opportunity • Market windows • Technology windows • Institutional windows	• 2006 the Renewable Energy Law and the inclusion of the solar PV industry in the catalogue of high-tech products for exports (China) • Concession Program for Large Scale Solar PV Power Plants, the Solar Rooftop Subsidy Program, and the Golden Sun Demonstration Program to develop the domestic market (China) • National auction mechanism: Mexico (no technology-specific, price competition) vs South Africa (technology-specific, socio-economic objectives as local content requirements) • India National Solar Mission based on price competition • Vietnam Power Development Plan • Domestic market (Kenya)
Sectoral System • Preconditions • Strategies	• China • Domestic firms and research institutes acquiring foreign technologies through collaborations • A Thousand Talents Plan aimed at recruiting global experts and Chinese returnees • Localized capability formation processes in local firms, universities, and industry associations • Building capabilities in the whole value chain

	• Strong linkages within the sectoral system • R&D investments • South Africa: some domestic capacity but insufficient so foreign developers mainly assemble locally • India: no building of domestic capacity until when a safeguard duty against Malaysian and Chinese exports • Some potential space for building capacity in BOS components • Only foreign investors (Mexico) • Iran: • Some local theoretical knowledge and raw materials availability • Some domestic capacity but lack of R&D, dependence on imports and lack of sustainable roadmap • Lively production system with many domestic companies operating in different market segments and value chain stages (Kenya)
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• China dominates the global market and is the world technology leader • Some domestic market catch-up (Kenya)

G. Concentrated Solar Power

Green Windows of Opportunity

In CSP, in 2020 the two leading countries in terms of installed capacity are Spain and the United States, followed by Morocco, China, and South Africa, which have been responsible for the bulk of capacity additions in the past five years.[27]

The Morocco decision to invest in CSP was driven by the need to satisfy a demand for electricity picking in the early evening. While solar PV has lower costs, it can only generate electricity when the sun is shining and instead CSP allows thermal storage. The investment was made possible by the availability of concessional financing from the World Bank, the African Development Bank and other European financing institutions. The involvement of international financial institutions was driven by the opportunity to support the development of a new technology that could play a critical role in the global shifting away from fossil fuels. The Clean Technology Fund has also invested in the Moroccan CSP project, contributing to building some initial domestic capacity. After successive projects and a dropping in the CSP price, the industry has also started attracting private investors. Moreover, CSP plants are often developed in remote areas, bringing development and jobs to poorer communities (World Bank, 2016).

[27] Data are from IRENA.

The development of the Chinese CSP industry is still a recent and ongoing phenomenon but it has followed a rather different path compared to other renewable industries in China, which initially have been largely dependent on foreign imported technologies and, as in the case of solar PV, also driven by foreign demand. In the case of CSP, China has exploited a technological window deriving from decreasing investments in demonstration projects in incumbent countries creating a space in the global industry. In the late 2000s and early 2010s, the CSP global market was almost entirely dominated by Spain thanks to generous support policies which were abandoned in 2012 while in the US the support measures were characterized by a stop-and-go nature which caused some bankruptcies in the industry. In both countries, the interest, and investments in the CSP industry were largely resized. In 2015, in China, the National Energy Administration asked for bids to develop CSP demonstration programs and in 2016, 20 projects were selected and funded by the government, by domestic utilities and project developers and by domestic banks. At the same time, there was a strong investment in R&D activity in Chinese universities in collaboration with domestic firms, with the only limited acquisition of foreign technology licenses (Gosens et al., 2020).

Sectoral system: preconditions and responses

In Morocco, the sectoral system is still very immature although some incentives have been provided for higher value-added domestic manufacturing of parts and components, trying to increase sourcing of local components (World Bank, 2016). In general, notwithstanding the political commitment towards renewable energies is quite strong in Morocco, it has been observed a lack of a coordinated approach between the multitudes of potential donors and a limited capacity in promoting technology and knowledge transfer to build up a solid domestic capability in the industry (Choukri, Naddami, & Hayani, 2017).

In the Chinese CSP industry, the knowledge is mainly domestic, rooted in domestic research institutes and corporate R&D. The whole industry innovation system is largely dominated by domestic actors including component providers, system developers, researchers, and financiers, mainly. The market is also mainly domestic, consisting of a public-funded small pilot and larger demonstration projects, although, the recently formed Chinese CSP industry has also started to contribute to the technology diffusion outside China. Domestic research institutes and firms have attracted research contracts from foreign entities, including for testing and developing next-generation receiver technologies in demonstration-scale projects. Chinese banks, under the flag of the Silk Road fund, have provided substantial amounts of investment to the development of foreign projects. More recently, Chinese firms and research institutes are also contributing to defining global project design and equipment standards, helping set quality benchmarks for firms from other countries (Gosens et al., 2020).

Catch up trajectories

Concentrated Solar Power in China after upgrading to world-class technology, experienced little further market development. China rapidly caught up in terms of capabilities development and has reached the global knowledge frontier. However, its leadership applies, mainly, to domestic demonstration projects with export activity confined to a limited number of engineering, procurement and construction projects in Europe and the Middle East (Gosens et al., 2020).

Table A-9: Solar Power

	Concentrated Solar Power
Green windows of opportunity • Market windows • Technology windows • Institutional windows	• Domestic market (Morocco) • Technological window (China) • Public funded pilot projects (China) • Foreign pilot projects funded by public banks (China)
Sectoral System • Preconditions • Strategies	• Morocco: • Local communities • Some local manufacturing capacities • Lack of coordination in the sectoral system • International funding (World Bank; ADB; EU; CTF) and private foreign investors (Morocco) • China: • R&D in research institutions and private companies • Incipient sectoral system • Chinese firms and research institutes are contributing to defining global project design and equipment standards, helping set quality benchmarks for firms from other countries
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• Domestic market: China and Morocco • Technology: China

H. Wind power

Wind energy has been increasingly deployed in developing countries. As an energy source, it is highly dependent on natural conditions, with being most conducive at a distance from the equator or in mountainous areas. It can be deployed onshore or offshore, with the latter being more demanding and costly and only recently taken up in countries such as Brazil, India, and China. The majority of lead firms are based in Europe or the US, but a few emerging market multinationals have emerged on the global scene after the turn of the century (Lema et al., 2013; Lewis, 2007). The majority of deployed wind turbine technology is grid-connected 'large' wind (large turbines in large farms) but there is also a concurrent niche focused on 'small' wind (Wandera et al., 2021) which is often particularly relevant as a complement to solar PV in rural mini-grids (Johannsen et al., 2020). A summary of the evidence about the wind industry is provided in Table A.8.

Green Windows of Opportunity

The overall window of opportunity stems from the increasing policy drive to promote renewables, the changing preference from public and institutional investors and technological developments which sees onshore wind below parity with electricity produced from fossil fuel sources (IRENA, 2021). This window has emerged in upper-middle-income as well as in lower-middle-income countries and to some extent also in low-income countries. In China and India, external pressure arising from a commitment to the Kyoto Protocol and, particularly, the Paris Agreement, and domestic pressure to reduce air pollution in megacities such as Beijing and New Delhi, is at the root of sector-level opportunities. This has translated into the sector and sometimes regional specific opportunities, often promoted with mission-driven programs such as the Ride the wind program in China which was initiated for embryonic sector formation (Dai et al., 2020). This programme by China's State Planning Commission, launched in January 1997, specified the first wind target at 1GW to be developed by 2001. The Planning Commission selected a German company, Nordex as the first foreign partner to develop these projects. The first 400 MW was financed through Chinese and foreign government loans (IRENA, 2013). While the financial underpinnings were typically global and supported by international organizations, in the beginning, the GWO has been internalized, supported by public finance although private sources of investment have been increasingly crowded in with loan guarantees to international investors provided by China Development Bank (Upstream, 2021).

In South Africa, wind deployment targets and a feed-in tariff were introduced to meet wind energy deployment goals with the Integrated Resource Plan (IRP) in 2010. In addition, as mentioned in the section on solar PV, support for a competitive renewable energy auction was introduced in 2011, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). Key in this framework is the integration of multiple criteria for procurement such as support of local firms, including small firms and firms owned by disadvantaged groups. So while seeking to stimulate at the same time domestic and foreign investments, REIPPPP requires EPCs to have 40% local ownership (Matsuo & Schmidt, 2019).

In other countries in sub-Saharan Africa, GWOs are more heavily influenced by international actors. This is shown by Gregersen & Gregersen (2021) who compare large scale projects in Kenya and Ethiopia. Systematic frameworks for the evaluation of project proposals are often absent. This means that there are no mechanisms to ensure that projects are not developed on an ad-hoc basis, promoted by specific consortia of finance and technology supply. Ad-hoc project approval, while constituting an opportunity for deployment, weakens the bargaining power of governments and typically comes along with informal 'foreign content requirements' tied to external sources of finance. Foreign lead firms and investment consortia, including Chinese groups, tend to take on coordinating roles in the absence of action schemes like the one implemented in South Africa (Lema et al., 2021).

Demand windows dominate. There is a significant difference in the degree to which windows of opportunity are domestically created (as in China) or are externally provided, e.g., in Kenya. South Africa is experimenting with domestic window creation, but as discussed further below, the country is struggling with defining effective supply-side responses (Morris et al., 2021)

Sectoral system: preconditions and responses

In China, Dai et al., (2020) show how recent transformations in the global wind energy industry have considerable implications for Chinese firms seeking to catch up. The technological frontier has advanced first from onshore to offshore wind turbines and later towards digital systems both at the level of individual turbines and in terms of management of wind farms.[28] These technological shifts open new green windows of opportunity for firms in the industry. The authors find that Chinese turbine firms show differentiated capabilities in responding to technological transformation at the global level, which explains variations in catch-up trajectories. Overall, however, they are not at par with global leaders in the domain of digital and hybrid systems. Hain et al., (2020) propose the idea of a 'market trap' where latecomers remain in a follower position and catch up is aborted which seems to correspond with the Chinese wind industry. It remains to be seen whether Chinese firms can leverage complementary capabilities in adjacent sectors to integrate advanced software capabilities and make inroads in the 'post-turbine technology regime' (Dai et al., 2020).

For the case of South Africa, Morris et al., (2021) investigates the wind sectoral system under REIPPPP and examine the effects on the wind energy value chain with respect to the localisation of goods and services. They highlight the interplay between energy and industrial policy and argue that policy failure driven by coal-based vested interests, disrupted system integration and undermined the

[28] Digital and hybrid technologies are integrated in smart energy systems. Technology comprises digital solutions (SaaS, IoT, and AI) for wind turbines and various up and downstream technologies as well as energy storage (Dai et al., 2020)

renewable energy programme which was the cornerstone of the wind GWO. The policy drive was not sufficiently strong and took on a stop-and-go nature. Problems with continuity and predictability of the auction bidding process within energy policy have knock-on effects down the wind energy chain, impacting industrial policy attempts to localise domestic and foreign enterprises adversely. The uncertainty of the policy (stop and go) meant that foreign enterprises could not implement local content requirements as local investment became risky. Local suppliers could not take advantage of new opportunities provided by the policy because banks would not fund investment projects. Overall, according to the authors, the South African government failed to prioritise, develop, and embed renewable energy as a green economy strategy within its industrial policy framework.

Given the large multinational involvement in the wind sector in East Africa, Gregersen & Gregersen (2021) explore 'learning spaces' in foreign-dominated projects in large scale wind, one European and one Chinese, project. Focusing on how interactions between different stakeholders in wind power megaprojects can lead to the accumulation of technological and managerial capabilities, they show that both formalised and tacit knowledge interaction can occur, even in the megaproject setting, but it has limits. In Kenya, the multiplicity of actors involved in the complex infrastructure, Lake Turkana Wind Power (LTWP), project, involves multiple loops of interactions that could foster local-learning opportunities, but such learning largely failed to materialise because of weak pre-existing capabilities among local actors and because no industrial policy was tied to the expansion of wind (Gregersen, 2020).

By contrast, in the Ethiopian case, the government and the Ministry of Water, Irrigation, and Electricity (MoWIE) tied wind projects to industrial development aims by introducing local university consultants to the projects and creating a local pool of experts. This, according to Gregersen & Gregersen (2021), explain that while there was some local learning in both the Kenyan and the Ethiopian cases in the field of operations and maintenance (O&M) as well as some learning about and how to add more renewable energy to the national grid, the Ethiopian Adama case involved different types of learning that did not happen in Kenyan LTWP. Specifically, this was learning about how to design projects. The Government of Ethiopia requested that national universities submit proposals and act as owners' consultants on the project. MoWIE liaised with several universities that could help to meet wider objectives, and, in the process, they gained valuable experience in both government agencies and universities. This is an example of how the government has gone beyond the production system thinking and has involved the knowledge and innovation system, building elements to ensure more local learning in and around the domestic projects. While still with several shortcomings, the Ethiopian government has taken an active role in the design of the wind projects to guarantee maximum local learning, by ensuring that professional users are more involved in the project execution (Lema et al., 2021).

Table A-10: Wind Energy

Green windows of opportunity • Market windows • Technology windows • Institutional windows	• Institutional (internal) window: 2006 Energy Law opens the domestic market (China) • Technological windows open in the global market shifting the sector to offshore and then to system integration and hybrid technologies
Sectoral System • Preconditions • Responses	• Foreign technology acquisition for production capability development to exploit the initial institutional window to meet domestic demand (China). • Local adaptation, acquisition of design and co-design capabilities of simple products for the local market (China). • Building of basic production capabilities and then attempts to develop a domestic R&D system (e.g. experimentation with offshore technology) (China) • The local content requirement in the initial stage of development (China). • Reliance on international networks and insufficient capacity to react to new global technology windows (China). • REIPPP (South Africa) • Creation of university-industry linkages (Ethiopia)
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• Global technology, including integration of IT-enabled functions (China) • Nascent exports to the global market (China) • Domestic market deployment (China / South Africa/Ethiopia)

Catch up trajectories

No countries, apart from China, have managed to exploit foreign markets. And there are differences in the degree to which economic activities of domestic wind deployment are localised and the importance of foreign firms mentioned above. There is some, but limited, technological upgrading in upper-middle-income countries, but in general the upgrading process is confined to services in the deployment chain, as opposed to production activities in the manufacturing chain. Overall, there are three broad types of sectoral system responses, active, passive, and in-between. China represents the most active system response. South Africa is an in-between case, while Kenya is passive, and Ethiopia is a case of active response despite relatively weak preconditions. These cases present weak preconditions such as the inadequate shape of the sectoral system and the industrial base capacity. Low capacity in the wind sector means that European and Chinese lead firms dominate the GWO, especially in Kenya but also in South Africa. In Ethiopia, while still in the very nascent stages of developing a sectoral system around wind power, certain basic preconditions have been developed which will be important in subsequent deployment processes.

I. Green hydrogen

Green, also called clean hydrogen, produced by using renewable energy sources such as solar and wind power and currently mainly taking place in demonstration projects, is only 4% of the total hydrogen production, which is still mostly based on natural gas and coal (IRENA & UNIDO, 2020). Nevertheless, very recently green hydrogen production is gaining momentum worldwide thanks to a) decreasing renewable energy (solar and wind) electricity costs; b) technological improvement with several technologies in the hydrogen value chain already been deployed on a small scale and ready to scale up; c) need for increasing flexibility of power systems based on renewable energies taking advantage of the possibility to store green hydrogen for long periods, therefore complementing other energies; d) broad use across the entire economy; e) opportunity for countries with large renewable resources to become net exporters. According to IRENA (2022), the ability of different regions to produce large volumes of low-cost green hydrogen varies a lot and Africa and the Middle East have the highest technical potential Table A.4.

Green hydrogen also faces barriers that need to be addressed for its future development: a) its production costs are still two to three times higher than grey hydrogen, although carbon pricing increases the costs of alternative fossil fuels; b) there are limited dedicated infrastructures for its transportation and so far, its production has taken place close to its use; c) there is not yet a green hydrogen market and its production are not even counted in official energy statistics of total final energy consumption because there is not a differentiation of green from grey hydrogen; d) its sustainability is not easy to be assessed because grid-connected electrolysers, which are the most efficient, can be alimented with electricity produced from different sources, included fossil fuels (UNIDO, 2022). A summary of the evidence on green hydrogen is presented in Table A.9.

Green Windows of Opportunity

Since 2019, an increasing number of countries have announced, drafted, or published national hydrogen strategies, in developed countries including the European Union, Austria, Denmark, France, Germany, Italy, the Netherlands, Norway, Portugal, the UK and Spain as well as in Australia and Canada but also emerging countries such as Brazil, Chile, Uruguay, Vietnam, Turkey, Morocco, Namibia and South Africa (Cammeraat et al., 2022).

Considering the case of Chile, the country has a Green Hydrogen Strategy published in November 2020, which identifies its advantages for green hydrogen production in an increasing capacity to efficiently generate renewable solar (in the North) and wind (in the South) energies, with the expectation by 2030 that 70% of the power grid will be from renewable sources (Ministry of Energy, 2022). The strategy envisages three steps: a first phase starting from 2025 in which green hydrogen will mainly target the domestic market replacing grey hydrogen with uses in heavy and long-distance transportation; a second stage from 2030 in which the start of export activities is envisaged as well as the extension of local uses and a final third, long term stage after 2035 in which there is the expectation of the opening of new markets both domestically as well as internationally (McKinsey, 2020).

In September 2021, South Africa approved the Hydrogen Society Roadmap, which indicates how hydrogen could be a game-changer for the country's economy to become competitive with domestic production by 2030. Three green hydrogen hubs have been identified in what has been named South Africa's Hydrogen Valley[29]: a) the Johannesburg hub where the demand is primarily driven by the industrial sector; b) the Durban hub driven by the mobility sector, port activities and oil refining; and c) the Limpopo hub driven by the mining sector. In the feasibility report launched in October 2021 by the South Africa's Department of Science and Innovation, it is stated that the country has already put in place many policies to promote renewable electricity but there are some constraints to address because a) green electricity is still limited on the grid; b) there is a need to scale up electrolysers; c) there are no clear targets and strategies to identify sectoral demand of green hydrogen and d) infrastructure is missing for transportation and storage of green hydrogen (Department of Science and Innovation, 2021).

Green hydrogen is also indicated in Namibia's Harambee Prosperity Plan as a transformative strategic industry for the country's economic development in the next years (HPPII, 2021). Namibia has the potential to achieve large-scale low-cost renewable energy production and, given the limited national demand, exports will be key to the green hydrogen strategy (Huegemann & Oldenbroek, 2022). So far, the Government has launched the Southern Corridor Development Initiative and established a Green Hydrogen Council supported by a Technical Committee to collect and coordinate projects and infrastructures related to the development of the industry, including a green hydrogen and ammonia plant with wind, solar electrolysis and desalination assets, a wind blade manufacturing plant and adequate port facilities.

Sectoral system: preconditions and responses

In general, given the very low maturity of the industry, sectoral systems are still very incipient and in a formative stage. In the Chilean case, the State is identified as a facilitator, coordinator, and promoter of a mission-oriented strategy. Its role is the identification and the lowering of existing barriers as

[29] Hydrogen valleys are characterized by a) large scale projects, beyond mere demonstration activities; b) a clearly defined geographic scope; c) the presence of multiple phases in the hydrogen value chain production; d) the supply to various end sectors (Weichenhain et al., 2021).

well as the reduction of regulatory, financial, and technical risks to achieve long term objectives. This should allow private actors, academia, and business associations in collaboration with the government to invest in the development of capabilities, technologies, businesses, and projects required to scale up projects in the domestic and export markets. An articulated action plan has also been developed based on several instruments: a) the provision of funds for supporting companies, and national and international consortiums to invest in scalable and replicable green projects; b) a roadmap towards adequate pricing mechanisms of fossil fuel emissions to level the field for competition between conventional energy and renewable sources; c) the establishment of clear stable regulations and standards throughout the hydrogen value chain to ensure safety and give certainty to investors; d) the creation of early and transparent participatory mechanisms of local communities in green hydrogen-related projects; e) the building up of an innovation and R&D system involving the industry, the academia and the technological centres to guarantee the needed skills and the capacity to solve local implementation challenges.

Since 2017, Chile is also operating a micro-grid powered by green hydrogen, providing 24 hours of clean energy from the sun without any diesel-based power backup system The main advantage of this system developed by the Italian company, Enel, is that it can work with both on-grid and off-grid systems, and it can also be moved geographically to provide power at any location such as small community camps. The project demonstrates that hydrogen can help provide a power backup option in micro-grids, which are traditionally supported by diesel generators (IRENA, 2019).

In the case of Namibia, private actors are emerging, and the Namibia Green Hydrogen Association has been created to provide a platform for public-private interactions. In January 2022 the President has announced that the first bid to produce 300,000 tons of green hydrogen and ammonia per year was won by Hyphen Hydrogen Energy (HHE, 2022).

Within the framework of the H2Atlas-Africa project[30], Namibia has also established a partnership with Germany aimed at the identification of suitable sites for green hydrogen production. An important part of this collaboration is research that will be undertaken about green hydrogen production in arid areas with the use of water desalination. Exchange programs for researchers and experts as well as scholarships for Namibian students are part of the collaboration aimed at building domestic knowledge in the industry.

[30] The H2Atlas-Africa project is a joint initiative of the German Federal Ministry of Education and Research and African partners in the Sub-Saharan region to explore the potentials of hydrogen production from the renewable energy sources within the sub-regions (H2Atlas, 2022).

Germany would also be an important partner in the future development of a green hydrogen industry in Morocco. GIZ has recently provided to the Moroccan Government, within the framework of the German Moroccan Energy Partnership (PAREMA), the technical support for the elaboration of a roadmap for the industry. With a potential that exceeds its needs, Morocco would be able to export green energy to other regions in the world, such as Europe, to help meet decarbonization targets internationally (Torres & Perner, 2021).

The MENA region is considered ideal for its potential to develop a supply of green hydrogen to satisfy the fast-growing demand in the EU (Table A.4). Its geographical location as a neighbour of the EU and its abundance of renewable energy potential both in terms of solar and wind power are combined with already existing gas pipelines connecting North Africa to the EU which can be used for transporting green hydrogen (Friedrich-Ebert-Stiftung, 2020). In the region, another country starting to invest in green hydrogen, which has a huge potentiality for producing thanks to a combination of daytime sunlight and strong winds at night, is Oman. These favourable natural conditions are at the base of the project to build one of the largest green hydrogen plants in the world set by a consortium of companies including the state-owned oil and gas company OQ, the Honk Kong-based renewable hydrogen developer InterContinental Energy and the Kuwait base energy investor Enertech to export most of the product as hydrogen or ammonia, which is easier to store and ship, to Europe (Paddison, 2021).

Support for the initial establishment of a sectoral system and regional knowledge exchange in Africa is offered by the Africa Hydrogen Partnership Trade Association (AHP), a non-profit company incorporated in Mauritius, aimed at enabling member companies to exchange knowledge on economic, technical, and other relevant social topics, including the treatment of political, legal and tax issues as well as to lobby with governments and administrative bodies with one voice (AHP, 2022). One of the AHP projects is the emission of Green African Hydrogen Bonds for collecting low cost, long term financial capital, creating mutually beneficial opportunities for African governments and financial institutions (Huegemann & Oldenbroek, 2022).

To conclude with China, policies aimed at developing hydrogen date back to the 10th Five Year Plan (2001-2005) and indeed China is the world's largest producer of hydrogen, but coal remains the most common source for its production. Currently, China lacks the key technologies for renewable-based hydrogen production, and it lags advanced countries in hydrogen storage and transport technologies. Nevertheless, the production of renewable energies is expected to increase in the future, and we can expect a gradual shift from grey to green hydrogen also in China (Meidan, 2021). Very recently, China has launched a green hydrogen mega project aiming at building a cluster of plants in Inner

Mongolia that will use solar and wind energy to produce 66,900 tons of green hydrogen a year (Dan Murtaugh, 2021). A further initiative is the Renewable Hydrogen 100 Initiative, launched by China Hydrogen Alliance which includes China Energy Corporation and several large Chinese companies from the energy, transportation and metallurgical industries as well as universities and research centres and it is set to install 100 gigawatts of electrolysers to produce hydrogen by 2030 (China Hydrogen Alliance, 2018).

China is also at the centre of the UNIDO Global Program for Green Energy in Industry. The program is aimed at accelerating a global strategic dialogue to enhance knowledge exchange on policies and technical standards and at promoting technical collaboration for the industrial application of green hydrogen. One of the key actors in the program is the International Hydrogen Energy Centre established in Beijing. The Centre will operate as a knowledge partner by supporting technology research, development, and application as well as by building-up green hydrogen economies (UNIDO, 2022).

Catch up trajectories

The green energy industry is a very immature industry in which both advanced and emerging countries are starting to experiment. Green hydrogen is an opportunity for developing countries because it could enhance national energy security by reducing the dependence on oil price volatility and supply disruptions, offering in the long-term lowering energy costs (De Sisternes Jimenez & Jackson, 2020). This is a technological solution that can facilitate the coupling of different renewable sources by converting solar, wind and other sources into energy which can be used to decarbonize industry, mobility, and electric power.

Moreover, as indicated by Altenburg et al., (2022) countries located in Africa, Southern Asia and the Western regions of South America endowed with abundant solar and wind resources are likely to become very attractive sites for producing green hydrogen (see also A.4). The same authors also emphasise that beyond the factor endowments developing countries will also need to improve their techno-institutional capacity and invest in electrolysers and infrastructures for storage and transportation to take advantage of the expected demand boom. Most of the developing countries with high potential to produce green hydrogen have relatively small domestic markets so they can become exporters to the advanced countries, exploiting the fact that, unlike electricity, green hydrogen will be transportable over long distances by boat.

Table A-11: Green Hydrogen

Green windows of opportunity • Market windows • Technology windows • Institutional windows	• Opportunities vested in existing or forthcoming national strategies (e.g., Brazil, Chile, Uruguay, Vietnam, Turkey, Morocco, Namibia, and South Africa) • Export opportunities for development through forward linkages from other renewable sources • Export opportunities for exporting over long distances
Sectoral System • Preconditions • Responses	• Abundant renewable energy sources (Chile; Oman; Morocco; Namibia) • Low energy production costs (Namibia) • Multilateral initiatives (e.g., Africa Hydrogen Partnership Trade Association; UNIDO Global Program for Green Energy in Industry) • Incipient sectoral system • R&D system (Chile) • The platform for public-private interactions (Namibia) • China Hydrogen Alliance (including companies, universities, and research centres) • International investors (Chile, Namibia) • Foreign partnership for research and training (Namibia) • International Hydrogen Energy Centre (China)
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• Not applicable • Very immature, the nascent industry

J. Electric Vehicles

Electric vehicles (EVs) have started to diffuse in large volumes across the world, but only to a limited extent in developing countries when it comes to passenger cars. Countries like India, Indonesia and Brazil possess the infrastructure to support two-wheeler electric vehicles but do not have policies for a full-scale transition to electric-run transportation comparable to those, for instance, in Europe (TRT World, 2022). Electric mobility offers ideal opportunities to create synergies with other technologies discussed in this paper and for the wider phasing-in of renewables to the transport sector. Electric vehicles create new demand for electricity that can be supplied by wind, solar, biomass and other renewable sources. In addition to benefits such as reducing carbon emissions and air pollution, electric mobility could also play an important role in providing decentralised storage for variable sources of renewable electricity. The list of the top ten world EV producers is presented in Table A.5 and Table A.10 is a summary of the evidence on EV.

Green Windows of Opportunity

The energy demand-side of the green transformation is still in the stage of the open-ended search for effective green solutions in many areas. In the transportation sector, there are relatively clearer paths forward: with the increasing technological maturity and price reduction of battery-electric vehicles, electromobility is now a key viable option – along with some alternative but still less certain solutions such as biofuels and hydrogen.

It is not yet clear how this transition from combustion engines to electric vehicles will affect the position of emerging markets in the global automotive sector. It could increase entry barriers and make the competition more demanding, or it could decrease them and provide new competitive advantages. Much will depend on the speed of the transition from conventional cars to EVs, on its global geography and the knock-on effects in global value chains. In principle, the opportunity is significant because EVs are simpler, with fewer parts, compared to traditional cars. Traditionally, the automotive sector has been dominated by relatively small numbers of global lead firms that have developed region-specific car models and supply chains, with differentiated industrial structures as a result (Sturgeon et al., 2008). Consequently, the automotive industries in Brazil, China India and South Africa differ widely and each has widely different prerequisites for gaining or losing from the green transformation of the automotive sector. Apart from imports of complete electrical vehicles, there is still relatively little globalisation of production, also spurred by protectionist measures such as import duties.

Technological windows dominate following the techno-economic paradigm shift from combustion engines to electric vehicles in the automotive industry. But Chinese intervention in the EV sector can be seen as creating a GWO for domestic take-off by stimulating the demand side and speeding up deployment. Konda (Konda, 2022) shows the role of two distinct policy phases during sector formation. The goals for deployment set in the first period had not been achieved by 2012 and so the government introduced a new plan for the next eight years which was more comprehensive and paid more attention to developing capabilities, not just to deployment. In India, the government started the path towards electro-mobility with the 'National Electric Mobility Mission Plan 2020' (NEMMP2020) in 2013. The plan provided a roadmap to achieve sales of 6-7 million xEVs in 2020, among which 400,000 units of e-passenger cars. In 2015, the government supported the plan with the "Faster Adoption and Manufacturing of Electric Vehicles" (FAME) scheme, which transitioned in its second phase (FAME-II) two years later. FAME-II ends in 2022 and includes stimulation for the purchase and the deployment of charging infrastructure. Some variety in GWO depends on natural resources for battery production, e.g. in South Africa where increasing global use of EVs provides the country with special opportunities to explore a competitive advantage in the lithium-ion batteries value chain (TIPS, 2022).

Sectoral system: preconditions and responses

To address the rising pollution in the urban and intense-production areas, Brazil introduced the first policy for cleaner transportation in 1986 (PROCONVE). In early 2000, the government introduced several incentives for R&D, and a decade later for building the charging infrastructure. Looking at the policies supporting domestic production, the government introduced four incentives in the last decade. Starting in 2011 with BNDES Fundo project and two years later with "Inovar Auto" covering the period from 2013 to 2017, which was later replaced with the current "Rota 2030 program". Brazil is rich in natural resources needed for EV batteries production, having the third biggest reserves of graphite and nickel, and the seventh of lithium (Statista, 2021). Despite having 8% of global lithium reserves, Brazil only accounts for 0.7% of world production, thus lithium has to be imported (Zaparolli, 2019). The country also has existing low-voltage battery production of industrial and stationary batteries, based on local knowledge. However, there is a lack of connection between scientific research and production (Consoni et al., 2019). Moreover, Brazil has some existing lead-acid batteries manufacturers (e.g., Moura Group) and it is involved in the R&D and development of lithium batteries. Finally, the Brazilian company Pxis (a collaboration between CODEMGE and Oxis Energy) is planning to establish the first mass-production plan of lithium-sulfur batteries, which in the laboratory stage have overperformed the current lithium batteries (Zaparolli, 2019).

In India, the FAME policy encourages manufacturers to use batteries with advanced chemistry—lithium—, instead of environmentally less-friendly lead-acid variants. The EV policy in India is spread among three levels of authority—national, state, city—and most laws and regulations are placed at the state or city level. Aside from the FAME scheme, India supports the automobile industry with the "Make in India" program, which stimulates FDI, provides tax incentives for R&D, and with the "Phased Manufacturing program" (PMP). The PMP has reduced a "basic custom duty" (BCD) in 2017 (between 0 - 25%) for electric vehicles, assemblies, and EV parts to support electro-mobility development. In 2020, BCD started gradually increasing (10 – 50%) to stimulate domestic manufacturing (DPIIT, 2020). India's auto component sector is growing faster than the sector of complete vehicles and exports a quarter of the production. In the last three years, it attracted high investments from domestic and foreign entities, e.g., Japan Bank for International Cooperation (US$ 1 billion), Toyota Kirloskar Motors (US$ 272.81 million) for EV components. The electrification of the automobile sector allows establishing a new battery sector and interconnects with the existing IT sector. According to the Indian Energy Storage Alliance, the battery market potential was $580 million in 2019 and it is forecasted to grow to $14.9 billion by 2027 (IESA, 2021). Currently, India is dependent on the import of lithium, but the newly discovered lithium resources in 2020 could enable faster development of the sector (Sasi, 2021). In electric two and three-wheelers, the battery cost presents up to half of the vehicle's price. Thus, the government allowed manufacturers to sell vehicles without batteries, and in parallel, encourage the development of different battery swapping services (Chaliawala, 2020).

In 2013, the government in South Africa introduced the 'Automotive Production and Development Programme' (APDP, 2013-2020), which did not specifically address the EV sector but the whole automobile industry. The policy's four pillars—import duty, production incentives, assembly allowance, investment scheme—managed to keep the industry stable but had not improved its global position. In the middle of the previous decade, a policy targeting increasing pollution by road transportation (GTS 2018 – 50) was implemented. It stimulates domestic production, R&D, and consumption of alternatives to vehicles on internal combustion. At the end of the APDP period, the government updated it with the South African Automotive Masterplan (SAAM 2021-2035), with the primary goal to address the decreasing local content in the automobile industry (from 46.6% in 2012 to 38.7% in 2016). Despite policy emphasis on the importance of EVs in the future, it does not make special provisions (Barnes et al., 2017). Overall, the EV development has explicit support in the policies related to cleaner transportation, mainly with penalizing dirtier solutions—Environmental CO2 levy— but not in the manufacturing (SEI, 2020). South Africa has established battery production and recycling, mainly lead-acid type[31]. The country is also rich in some required raw materials—Manganese (78% of the world's resources), Nickel, Calcium fluoride, Titanium, Aluminium, Copper, and Iron. The government plans that an existing industry will also cover electric vehicles' batteries and supports it under the 'The Technology and Human Resources for Industry Programme', which involves the University of the Western Cape, the uYilo e-mobility program, the Council for Scientific and Industrial Research, and Zellow Technology (Raw & Radmore, 2020). The first lithium-ion mega-factory—The MegaMillion Energy Company—plans to start a manufacturing plant in 2022 (TMEC, 2020). South Africa is an important automotive hub, especially for spare parts. The stable position in GVC could be upgraded by the development of the electric vehicle sector, however, slower adoption of new technologies poses a threat to losing the GVC position.

In 2009, China began mass production in the EV sector without any novel technical knowledge (Hain et al., 2020). Despite the subsidies that were made available, customers did not demand EVs in the following years, mostly owing to their shortcomings compared with internal combustion engine vehicles. In 2010, the battery technology was not satisfactory as the manufacturing cost per kWh was between 3,400 and 5,000 yuan, and this presented a large proportion of the total EV costs. Battery life was between three and five years or circa 160,000 kilometres, making EVs much less of an economic proposition than conventional vehicles (World Bank, 2011). By February 2014, battery production cost had decreased to around 3,150 yuan per kWh, which was still much higher than the 2,000 planned for 2015. The core technology was thus immature until recently. Hence the government had to address all aspects of the ecosystem. The policies evolved from traditional green industrial towards broader policies that enable catching up by combining climate and economic goals. The first creates a demand for a technological solution that is still economically less efficient than dirtier solutions. The second enables knowledge transfer and creation, and the third boosts production to fulfil the demand. The case shows that strategies and initiatives related to responding to initial green window opportunities based on building basic production capacity were insufficient for technological capabilities upgrading and deepening (Konda, 2022).

Catch up trajectories

In general, advanced OECD economies dominate the EV sector. Emerging economies are mainly making inroads in non-passenger cars, such as two-wheelers, three-wheelers, and buses. China had surpassed the United States (USA) in EV stock, with 32% of the global share and 44% of worldwide annual sales in 2016 (IEA, 2019). The country is seeing some exports, but still at a low level. Some

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[31] Automotive or car battery is a rechargeable battery used to start a motor vehicle and not batteries for EVs

technological upgrading has occurred, but there is still uncertainty regarding global competitiveness and markets for low-cost EVs. Ambitious strategies, for domestic deployment especially in China, have spurred a high degree of domestic market sales. In India, responses are mainly confined to national flagship automotive firms with a weak innovation system formation. For South Africa, the insertion into automotive GVCs means that the techno-economic paradigm shift could make significant parts of the domestic supply chain obsolete because many locally produced components are no longer needed. In Brazil, the success of the locally produced flex-fuel engine and bioethanol industry makes the innovation system path-dependent and there are vested interests in keeping the focus on bioethanol. Insufficient response means that other regional hubs in proximity to lead markets may be better positioned to seize GWO in this industry.

Table A-12: Electric vehicles

Green windows of opportunity • Market windows • Technology windows • Institutional windows	• Purchase subsidies (China, India) • Mandatory public purchasing (China) • Pilot cities and privileges to owners (parking and charging) • Green Transport Strategy (GTS) for South Africa
Sectoral System • Preconditions • Responses	• Financial support to incentivize for e-buses, e-2 wheelers, e-3 wheelers and e-4 wheelers advanced batteries and registered vehicles (India) • Made in India Strategy (India) • South African Automotive Masterplan – SAAM (South Africa) • R&D by e.g. Tata Motors and Mahindra (India) • Insufficient policy support (Brazil) • Difficulty to transform suppliers in automotive GVCs to electric vehicles (South Africa)
Catch up • Domestic market • Foreign market • New to the country technology • World-class technology	• Global technology, including integration of IT-enabled functions • Nascent exports to the global market (China) • Some domestic deployment

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