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Green windows of opportunity: latecomer development in the age of transformation toward sustainability

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Abstract

The world is in the early stages of a paradigm transition toward a global green economy. In this article, we propose the notion of green windows of opportunity, highlighting the importance of institutional changes in the creation of new opportunities for latecomer development. We emphasize how demand and mission-guided technical change influence the directionality of latecomer development and highlight the important role emerging economies may attain in the global green transformation. We provide important insights regarding opportunities for green development in emerging economies, how these opportunities emerge in different renewable energy sectors and their implications for the global green economy.

JEL classification: L10, L50, O10, O20, O30, Q20, Q40

1. Introduction

Although the transformation toward a global green economy is still in its early stages, there is little doubt that a major disruption in the capitalist world economy is under way. As popular pressure increases in line with the mounting global effects of climate change, the transformation agenda and associated investments in the green economy are likely to accelerate (Mazzucato and Perez, 2015; Roberts and Geels, 2019; Schmitz and Scoones, 2019).

Until recently, the idea of green growth was limited to the advanced economies, with developing countries reluctant to take up the challenge of sustainability. Today, the dichotomic relationship between green transformation and latecomer development, inherent in the environmental Kuznets curve (Stern, 2004), has been turned on its head. The "clean up later" model where developing countries wait for the environmental Kuznets curve to set in (Altenburg and Pegels, 2020) is being replaced by a leapfrog strategy, which offers an alternative way to bypass the high pollution models of growth. Countries such as China, India, Brazil, and South Africa, are not only reacting to the paradigm change but also are actively contributing to the green transformation, adopting environmental transformation policies and supporting the emergence of domestic sustainability-oriented industries (Mathews, 2013; Harrison *et al.*, 2017).

Thus, there is increasing recognition that policies aimed at meeting environmental targets may be opening new economic development paths. The green transformation and the related techno-economic paradigm changes across institutional, market and technological domains, are opening windows of opportunity for the emerging economies to achieve leadership in new sustainability-related industries (Mathews, 2018; Lee, 2019; Yap and Truffer, 2019). In this introductory article, we show that Green Windows of Opportunity (GWO) represents a set of circumstances that entail temporary, but favorable circumstances for long-run latecomer catch-up in sectors central to the green economy, and that these GWOs are markedly different from the windows of opportunity that occur in traditional sectors (Niosi and Reid, 2007; Kim, 2011; Lee and Malerba, 2017).

The article provides a conceptual framework for the Special Section on Green Windows of Opportunity: Latecomer Development in the Age of Transformation toward Sustainability. It provides important insights about the significance (and limitations) of the GWO proposition and novel evidence about the heterogeneity of green sector trajectories. On this basis, we distill some common insights and lessons related to green latecomer development.

The collection of articles in this Special Section include case studies of GWOs in several renewable energy industries: biomass (Hansen and Hansen, 2020), hydro energy (Zhou *et al.*, 2020), solar photovoltaics (PVs; Binz *et al.*, 2020), and wind energy (Dai *et al.*, 2020).[1] It also includes several cross sector studies, examining specific aspects of GWOs and their exploitation, namely, the dynamics of catch-up in early industry lifecycle stages (Binz *et al.*, 2020), the risks of market and technology traps (Hain *et al.*, 2020) and policy options related to different demand-led catch-up scenarios in green latecomer development (Landini *et al.*, 2020).

By bringing together theoretical and empirical insights, we show that the green transformation is opening new latecomer development opportunities with synergies between environment-related and economic development strategies. We contribute to the literature by enhancing our understanding of the determinants of changes in green industry leadership and by showing and explaining significant variability in catch-up trajectories at the sector level.

The empirical focus of this introductory article is on green energy sectors with diverse characteristics and on one emerging economy, China, which is moving rapidly toward leadership in several of green technologies. We address the following research questions:

1. What latecomer trajectories are observed in different green industries? Is global leadership changing and being disrupted?
2. What characterizes GWOs? Are these GWOs driven mainly by technology, by demand or by institutional changes, or some combination of these aspects?
3. What are the key determinants of the changes to leadership in different green industries? How are the firm and system level responses influencing latecomer trajectories?

Most green sectors are young in all countries, but 10 years ago China was a latecomer. Since then, it has made huge strides in catching up and it now provides significant quantity and quality of insights into green catch-up processes, more so than any other country (Harrison *et al.*, 2017; Ely *et al.*, 2019). Consumption of renewable energy in China is surpassing consumption of energy from fossil fuels (Wu *et al.*, 2018) and China has been the largest investor in R&D for green technologies in recent years (McCrone *et al.*, 2017). It is the world's largest manufacturer of wind turbines, PV panels, and electric cars and buses (OECD/IEA, 2016; CWEA, 2018).[2]

Our focus on a single country allows inter-sectoral comparison to investigate the specificity of GWOs. Hence, our analysis reveals sector-level differences in the factors that shape catch-up trajectories, such as technological dynamics, markets, and institutional frameworks, while isolating country-level circumstances.

1 The analytical work leading up to this special issue also includes the case of concentrated solar power (Gosens *et al.*, 2020).

2 Data from the Frankfurt School-UNEP Centre (McCrone *et al.* 2016, 2017, 2020) show that China was the world's top renewable energy investor, increasing from USD 41.4 bn in 2010 to USD 83.4 bn in 2019. In the same period, European investment decreased from USD 113.9 to USD 59.9 bn, comparable with US levels (USD 55.5 bn). According to the International Energy Agency (IEA, 2017), by 2016 China accounted for one-third of the world's installed wind power and a quarter of world solar capacity and, in the ten years prior to 2016, China's electricity generation based on fossil fuels reduced by 10%, from 82% to 72%.

However, the single-country focus also has some disadvantages: China has some unique features and the relevance (or not) of our findings for other countries needs to be considered with some degree of caution. However, even though China is the case in point, the scope of our article is wider and brings out implications which are relevant for the green transformation in both advanced and emerging economies.

The article is organized as follows. Section 2 reviews the debate on latecomer development and catch-up and it identifies green sector specificities in this respect. Section 3 describes the analytical framework, which is exploited by the authors of the in the special issue. Section 4 concludes this introduction by highlighting how our findings advance the knowledge about green latecomer development and by highlighting key implications for global policy and future research on global green transformation.

2. Latecomer development catch-up

2.1. Received wisdom

The notion of catching up has (rightfully) been criticized for being overly linear, viewing latecomer development as a process which necessarily follows the techno-economic trajectories established by innovation in more "advanced" firms and countries. In fact, there are multiple possible latecomer development pathways, which differ substantially from those taken by first-movers in advanced economies (Perez and Soete, 1988). Catch-up involves more than simple imitation of new technologies, it requires creative adaptation and innovation along and beyond the paths followed by the first movers. Latecomer catch-up may skip some stages or follow an entirely unique trajectory. Late entrants build on existing knowledge, but may depart from it to follow their own development path (Altenburg *et al.*, 2008; Lee, 2019).

Perez and Soete (1988) suggested that these departures are prompted by windows of opportunity which emerge when changes to technological regimes reduce the constraints on latecomer development. Although the incumbents may be locked into routines and know-how geared to the existing technological regime, technological changes may lower barriers to entry and reduce learning times. Hence, emerging economies and firms with the relevant capabilities may be nimbler and benefit from leapfrogging possibilities in a phase of paradigm transition (Fu *et al.*, 2011).

These opportunities can emerge as the result of changes to the prevailing techno-economic paradigm, changes in market demand or major modifications to government regulation or policy interventions. Lee and Malerba (2017) describe these opportunities as technological, market and institutional windows and show that, in different sectors, changes in industry leadership depend on the type of opportunity and the strategic responses of incumbents and newcomers. Drawing on case studies of sectors ranging from steel (Lee and Ki, 2017), cameras (Kang and Song, 2017), aircraft (Vértesy, 2017), and wine (Morrison and Rabellotti, 2017), Lee and Malerba show how different types of opportunity windows are decisive for leadership changes and specific catch-up trajectories in various industries.

In summary, changes to technologies, markets, and institutional regimes may open windows of opportunity for emerging economies, enabling catch-up and leapfrogging and significant changes in technological and market leadership among countries (Perez and Soete, 1988; Lee and Malerba, 2017). However, these structural changes are not automatic and depend on the responses of the firms and supporting institutions in both the advanced and latecomer countries (Malerba, 2002; Malerba and Nelson, 2011).

2.2 Paradigm change: the specificities of green sectors and catch-up dynamics

Over 25 years ago, Christopher Freeman brought forth the idea of a green techno-economic paradigm (Freeman, 1992, 1996; see also Kemp and Soete, 1992). A techno-economic paradigm can be defined as "a set of common-sense guidelines for technological and investment decisions as pervasive new technologies mature . . . it is driven not by predetermined natural forces but by economic and social institutions and actors" (Freeman 1992: 198). The change to a green techno-economic paradigm involves a shift in technological and investment decisions toward greener technologies and modes of production.

Rooted in this emerging green paradigm, green sectors have some specificities which make them unique compared with the sectoral systems which are typically studied in the latecomer development literature (Malerba and Nelson, 2011). Our objective is to discuss how these specificities influence the nature of catch-up and therefore, it is useful to highlight the salient features of green sectors.

2.2.1 Emergent pathways and directionality

The emergence of a new green techno-economic paradigm implies that latecomer development moves along a novel trajectory which is distinguished by being more environmentally sustainable than the trajectories followed by the advanced economies. Specifically, green sectors evolve with the massive development and diffusion of climate change mitigation technologies. Because climate change mitigation is an unfolding process, there are limited opportunities for path-following catch-up. Although it is possible to absorb specific foreign technologies and to draw on other countries' experience, the green economy is in "the era of ferment" and latecomer development, necessarily, involves a higher degree of experimentation and different innovation and development orientations.

2.2.2 Public goods, externalities, and social value

The green economy is driven not only by economic utility functions but also by social value. In green sectors, there are exceptional local, national, and international efforts to create and scale up new technologies, based on mounting environmental pressure and negative externalities. The core green economy technologies are public goods, meaning that their direct benefits are non-excludable. This differentiates green sectors from those sectors (such as automobiles, electronics and steel) typically analyzed in the catch-up literature (Hobday, 1995;), and from emerging industries such as 3D printing and artificial intelligence, where market mechanisms play a dominant role (Lee *et al.*, 2020).

2.2.3 Directed development and policy intervention

The social objectives related to the green economy mean that this emerging paradigm, in contrast to previous techno-economic paradigms, is being driven directly by public policy. It is a case of *directed development* supported by widespread acceptance of government interventions—even in liberal market economies. The levels of public policy interventions, regulation, and financing in green sectors, far exceed those typical of other industries. Also, according to Deleidi *et al.* (2020), in the renewable energy sector, direct public investments do not suffer from private investment crowding in/crowding out problems and generate positive externalities and market creation effects. At the same time, domestic policies and institutions are influenced by robust global agendas, rules and mechanisms and, especially, those related to climate change (e.g. the Paris Agreement) which influence national environmental, energy, and economic policies.

These specificities of green technologies have implications for catch-up dynamics. Latecomer development depends largely on the nature, type, and relative degree of policy-induced institutional changes in advanced (incumbent) and emerging (latecomer) economies.[3] Hence, we stress that policy-driven changes in institutional frameworks are essential for understanding green catch-up.

3. Analytical framework and insights from the case studies

3.1 The analytical framework

This section proposes an analytical framework to analyze the nature of GWOs and the dynamics of their exploitation. It can be applied to analyses of different sectors in the effort to understand whether and how the green transformation provides windows of opportunity and reshaping catch-up trajectories.

The framework includes three factors (and their interrelationships), which are summarized in Figure 1 and which constitute the main empirical focus of this Special Issue:

- *GWOs*: the extent and nature of sector-specific opportunities, arising with the green transformation in three areas: institutions, technologies, and markets;

3 In both cases, the level of support depends on the perception of the "economic co-benefits," in other words, whether provision of support makes sense from both an environmental and an economic development perspective (Dubash, 2013). This is highly contentious and requires the institutional black box to be opened in order to understand the political feasibility of green transformation and catch-up. However, here, we focus on the consequences of institutional specificities, rather than sectoral level political economy issues, which would require in depth discussion of the nature and direction of policy interventions.

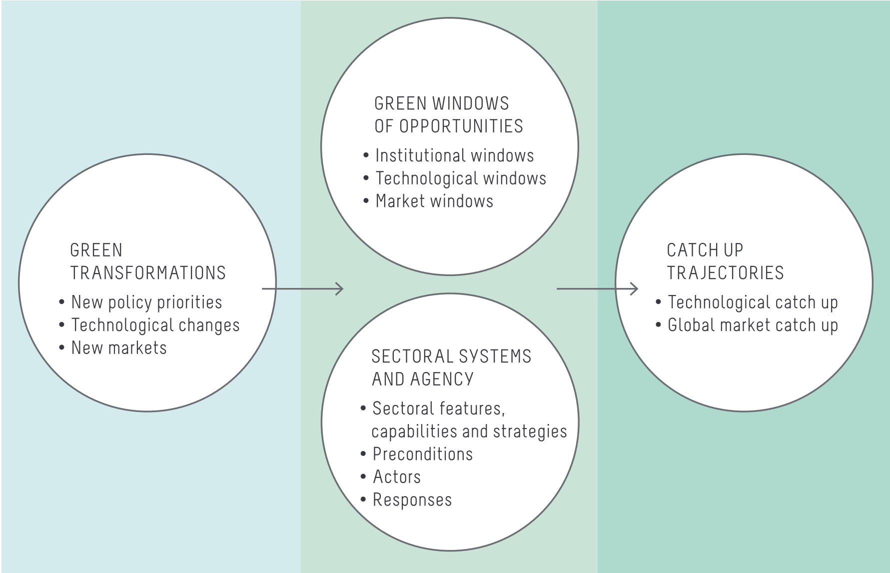

Figure 1. The analytical model: GWO and catch-up trajectories.

- *Sectoral systems and agency*: the specific characteristics of green sectors in latecomer and incumbent countries, including the required capabilities, institutions and strategic actor initiatives needed to turn opportunity into reality;[4]
- *Catch-up trajectories*: which depend on the constellation and interactions of the prior factors.

In what follows, we explore the elements of this framework by bringing together the sector-level empirical findings in the articles in this Special Issue.[5]

Figure 1 suggests that transformation imperatives lead to new policy priorities, induce technological changes and modify market conditions. All these changes may create windows of opportunity which, depending on their nature and on the conditions of their exploitation, may alter sectoral trajectories in significant ways. It is precisely the nature of GWOs and the conditions of their exploitation which our analytical framework addresses.

3.2 Green latecomer catch-up trajectories

We use the general term catching up to refer to successful attainment of leadership by latecomer firms which shifts the balance of economic power between incumbents and latecomers. In particular, we are interested in the changing positions of latecomers within sectors and draw on Hobday (1995) to distinguish analytically between the two dimensions of market and technological catch-up.[6]

Market catch-up refers to the acquisition of increasing national and international market shares. In renewable energy sectors, this can be quantified and measured as the share of energy generation capacity (in megawatts) sold in the domestic and global market. It is possible to achieve *domestic market catch-up*, based on government policies

4 Agency is used to indicate the capacity of actors to act independently and does not imply hypotheses of rational behavior.

5 Where relevant we also refer to additional sector-level case material.

6 Hobday (1995) emphasizes that latecomer firms are typically dislocated from: (i) the main international sources of technology; and (ii) the main overseas markets they seek to supply. Building on Hobday, Schmitz (2007) refers to the "technology gap" and the "market gap" as two key obstacles to latecomer development. Note that, by including both these dimensions, we differ from Lee and Malerba (2017), who define "catching up" with reference to only one dimension, namely, attainment of increasing global market share.

aimed at stimulating home demand. In this case, market catch-up means that the domestic market becomes more developed relative to the incumbent home markets in the same sector, with respect to total installed capacity, number of enterprises and supply chain development (Hain *et al.*, 2020). *Global market catch*up* is dependent on achieving internationally competitive quality and prices (Lee and Malerba, 2017).

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 strengthen capabilities and enable catch-up. It can be measured based on quantitative information (e.g. patent numbers and quality) or qualitative assessments of the "distance" to the global knowledge frontier in a given sector. We distinguish between *new-to-the-country technology* and *world class technology*. The former is typically the route to catching up in production since it enables manufacturing and services activities based on globally available knowledge; the latter refers to catching up in innovation and extending the global knowledge frontier (Altenburg *et al.*, 2008).

Both types of catch-up can be mutually supportive. They may interact during the latecomer development process, since closer connection to larger and more sophisticated markets may provide critical knowledge, useful for technology improvements (Schmitz, 2007), and stronger technological capabilities may increase competitiveness of national firms in the home and export markets (Lee and Malerba, 2017). However, this outcome is not automatic. A certain degree of technological capability attainment may enable domestic market development, but may be insufficient for export competitiveness. Conversely, demand-led domestic development may enable catching up in production capability, but not innovation catch-up which tends to depend on firm-level advantages provided by access to "lead markets" (Beise and Rennings, 2005).

Distinguishing between the market and technology dimensions allows us to chart the range of trajectories in China's green sectors, which are depicted in Figure 2 and described in more detail below.

3.2.1 From domestic imitation to global leadership

With some slight variations, this is the path followed by the hydropower and biomass sectors, which progressed from new-to-the-country technology (bottom-left quadrant) to world-class technology (top-right quadrant). As indicated by the different trajectories and their final positioning, technological upgrading in biomass was achieved faster than global market success, whereas in hydro energy, global market leadership has preceded achievement of the technological frontier (represented graphically by the transition through the top left quadrant).

In both cases, global market leadership is unequivocal. In the hydropower sector, there was an evolution in the last decade, from catch-up to a leading role in global markets, which are now dominated by Chinese champions (Zhou *et al.*, 2020). In the biomass sector, there was a change in global market leadership from western producers to Chinese firms, which latter now operate globally (Hansen and Hansen, 2020).

3.2.2 Learning from exporting, over domestic strengthening, to global leadership

This was the trajectory followed by solar PV, starting from initial export of new-to-the-country technologies introduced in China by returnee entrepreneurs (top-left quadrant), to a focus on the domestic market and technological upgrading (bottom-left quadrant), to achievement of world-class technology and the reinterring of the global market (top-right quadrant; Shubbak, 2019; Binz *et al.*, 2020).

3.2.3 World-class technology with limited global market progression

This applies to Concentrated Solar Power (CSP), which, after upgrading to world-class technology, experienced little further market development (bottom-right quadrant). 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).

3.2.4 Domestic imitation with limited global progression

This trajectory applies to wind technologies and upgrading of new-to-the-country technology in the domestic market (bottom-left quadrant), but constrained further development (not in the top-left quadrant). Domestic market catch-up in wind power has not been accompanied by the technological catch-up required to achieve clear global market

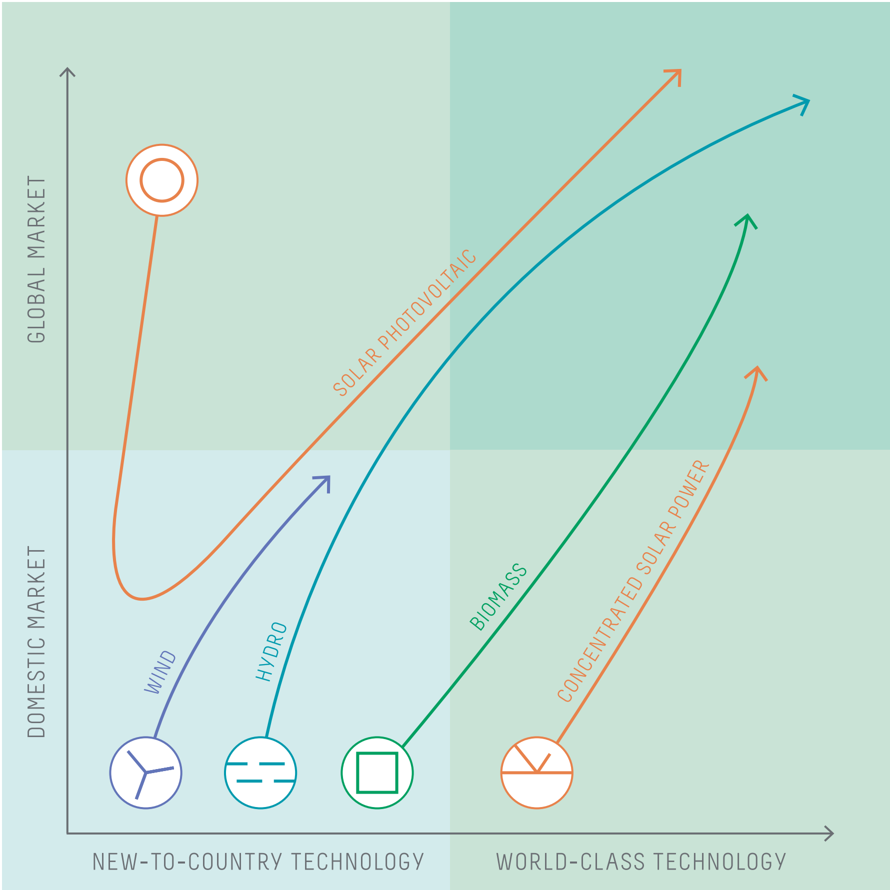

Figure 2. Latecomer catch-up in five green sectors in China. *Source*: Authors' elaboration based on the evidence collected in the Special Issue.

leadership. In the wind turbine sector, Chinese follower firms clearly experienced domestic market catch-up, but lacked the capacity to forge ahead. They have found it difficult to maintain market expansion in the face of other rapidly evolving technological regimes such as the shift to offshore and hybrid-digital technologies (Dai *et al*., 2020). Although there is some export activity, this is mainly confined to small onshore turbines and developing countries.

3.3 Green windows of opportunity

GWOs are defined as favorable, but time-bounded conditions for latecomer development, arising from changes in institutions, markets, or technologies, associated to the green transformation. Due to the sectoral specificities of the green technologies discussed earlier, the role played by public policies, directionality, and externalities, as well as the greater risks and uncertainties associated with the development and commercialization of these technologies, the nature and dynamics of GWOs are different from windows of opportunity in more mature sectors. In what follows, we discuss their idiosyncrasies.

The criticalities related to the *emergence*, *sequencing*, and *interactions* among green windows are based on their origins—institutional, technological, and demand changes (internal *or* external), whose interactions may be more or less conducive to latecomer development. Table 1 shows the GWOs identified in five industries and summarizes the key insights related to their nature and dynamics, observed in the empirical studies indicated.

Table 1. GWO in green energy sectors

	Initial GWO	Most important interacting GWO
Biomass (Hansen and Hansen, 2020)	*Institutional (internal) window;* 2006 energy law opens the domestic market	*Technological window* enables broad-based sectoral development
CSP (Gosens *et al.*, 2020)	*Technological (external) window:* decreasing investments in demonstration projects in incumbent countries create a space in the global industry	*Institutional (internal) window* enables experimentation in this emerging technology
Hydro (Zhou *et al.*, 2020)	*Institutional (internal) window:* large pioneering projects open the domestic market	*Demand window* emerges in the global market as incumbents vacate significant market spaces in the early 2000s
Solar PV (Binz *et al.*, 2020)	*Institutional (external) window:* market opportunities open in the global market, in particular thanks to Germany's *Energy Wende*	*Institutional (internal) window* creates domestic market to address the fall in the global market
Wind (Dai *et al.*, 2020)	*Institutional (internal) window*: 2006 energy law opens the domestic market	*Technological windows* open in the global market shifting the sector to offshore and then to system integration and hybrid technologies

First, in terms of their emergence or *opening*, GWOs are often created by governments and they are institutional in nature.[7] They differ from windows of opportunity in other sectors, which, typically, are promoted by external technological innovation (Lee and Malerba, 2017). Although GWOs are also influenced by demand conditions and technological changes (see below), they are often promoted by public actions and related adjustments to the institutional framework conditions. External pressure arising from 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, are at the root of sector-level opportunities (Dai *et al.*, 2020; Zhou *et al.*, 2020).

All the articles in this Special Section identify institutional windows of opportunities as central underlying drivers of both cross-sectoral changes, such as implementation of the renewable energy law in China in 2006 (Hansen and Hansen, 2020), and sector-focused "missions" such as the Rooftop Subsidy and the Golden Sun Demonstration Programs implemented in the solar sector (Iizuka, 2015). In the context of GWOs, the overall role of government is particularly important (and has greater legitimacy in international policy in relation to sustainable energy compared with other sectors), but the key to GWOs is the synergistic mix of environmental and industrial/innovation policy. This is because many environmental policies have industrial policy effects. For example, feed-in tariffs, aimed at rolling out renewables, provide *de facto* demand-side support to enterprises and public R&D science programs in the environmental field offer supply-side support, similar to what is normally provided by industrial policy.

Also, in the case of solar PV and CSP, where the domestic opportunity followed international participation, it was the institutional disruption caused by the problem of climate change which resulted in the creation of an overseas market and industry-level technical progress which provided the window of opportunity for latecomer development.

Second, the *sequencing and interaction* among institutional, market, and technology changes are the defining features of green windows. The ways that initial GWOs interact with subsequent opportunity windows and other sectoral events and circumstances influencing catch-up, vary hugely. A GWO may originate from an institutional change, which creates new market demand and, subsequently, promotes technological innovation, as in the case of the hydro sector, for instance, or provides a direct incentive for mission-oriented innovations as in the case of biomass (Hansen and Hansen, 2020).

7 We acknowledge that there are some *de facto* GWOs that are not driven by a predominantly green agenda, for example, hydro power in China and in some developing countries, and solar power in Africa and Latin America. In these cases, GWOs emerged as the result of the lack of energy supply and consequent market demand combined with available tchnologies.

The creation of a domestic and external market is a crucial element of institutional windows of opportunity. In this respect, GWOs in renewable energy sectors differ from many "non-green" consumers or capital goods sectors where government-led demand creation is the exception rather than the rule.

All the green energy sectors analyzed in the papers in this Special Issue benefited from demand-pull policies. Feed-in tariffs, aimed at creating competitive parity between green energy and fossil fuels by subsidizing the demand side are common to these policies. Public procurement policies have been implemented in addition to or as an alternative to feed-in tariffs, for instance, in the hydro-power sector where public procurement was key to the initial industry developments in several countries (Landini *et al.*, 2020; Zhou *et al.*, 2020), or in electrical vehicle sector where municipal purchases of electric buses and light vehicles led to market formation in China and India (Hain *et al.*, 2020). Demonstration projects have been used in most sectors, especially in the formative stages of sector development, for example, the Ride the Wind and Golden Sun programs (Shubbak, 2019; Dai *et al.*, 2020). In the case of CSP, which is still in its initial phase, Gosens *et al* (2020) emphasize the importance of demonstration projects for promoting new technologies and designs.

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

Institutional windows also can induce technical change in the form of mission-guided public R&D programs, as in the case of wind offshore demonstration projects in China which has supported the sector although only to a certain extent (Dai *et al.*, 2020) or CSP with government's funding of research organizations for technology development (Gosens *et al.*, 2020). As already mentioned, institutional-cum-demand windows are more frequent than opportunities emerging primarily from technology breakthroughs.

In addition, markets and technology interact. Hain *et al.* (2020) provide a systematic exploration of this relationship and show that optimal development gains require a balance between these two drivers. Market investments in the form of green subsidies in the absence of corresponding investments in technical change, can result in a market trap where latecomers may become the market leaders, but remain in a technology follower position. Conversely, if induced technical change is not matched by (domestic or external) market demand, strong technological capabilities may remain dormant. In similar vein, Landini *et al.* (2020) confirm that creating demand can foster latecomer learning and capabilities building and trigger a catch-up process, but this is not automatic and relies on the presence of certain conditions at the right time. The authors pay particular attention to sequencing and show that an external technological discontinuity following the opening of a demand window could result in the latecomer becoming locked into an outdated technology and rendering its market investment largely obsolete in terms of achieving global leadership.

Third, GWOs and windows of opportunity in other sectors, may emerge *internally or externally*. However, most of the literature on windows of opportunities related to catching up focuses on external technological (e.g. Wu and Zhang, 2010) or market (e.g. Morrison and Rabellotti, 2017) opportunities and tends to ignore internal–external sequencing and interactions.

The GWOs observed in the papers in this Special Issue are mainly endogenous to the country, but intersect and interact with the external environment and with emergent external windows. The primary pathway modeled by Landini *et al.* (2020) depicts domestic demand as a testbed for a virtuous learning and capabilities building and growth cycle, which, if successful, leads to external market competitiveness. However, the original demand for solar PV from China was external to the country and was a response to the rapid increase in demand for solar panels created by public policies, especially in Europe (Fu and Zhang, 2011). The extension of demand to the domestic market, opened a national window of opportunity during a global financial crisis and protectionist measures which drastically reduced global demand (Schmitz and Lema, 2015).

The collection of papers in this Special Section highlights that there are multiple possible sectoral trajectories depending on the initial window and subsequent interactions and sequencing. In some cases, the succeeding, interacting green (and non-green) opportunities were more important than the initial window, which served, merely, to create the pre-conditions for catching up. The key point is that GWOs were foundational for latecomer development, but in order to explain, successful or less successful, specific trajectories it is necessary to consider both the successive changes that occurred and the sectoral engagement with these changes. We discuss this in the next section.

3.4 Firms and other sectoral system actors

Figure 1 suggests that catch-up trajectories depend significantly on how firms and support institutions, such as universities, research centers and standards organizations, respond to GWOs. In general, the ability to exploit windows of opportunity depends on the firms existing capabilities and the sectoral innovation system in which they are embedded and formulate their strategies (Lee and Malerba, 2017). Their responses are influenced, also, by the techno-economic specificities of the particular green sector. It must be recognized that, although all renewable energy sectors are "green," their technological maturity, tradability and organizational models differ greatly.[8] In this section, we discuss the firms and other actors in the sectoral systems explored in this Special Issue, along with their responses and strategies (see summary in Appendix Table A1).

3.4.1 Firm responses

Firms can use various strategic initiatives in an attempt to exploit GWOs. An important insight from the cross-sector analysis is that different capabilities (and actors) are needed for different types of green industries and the associated catching up trajectories.

However, there are some responses that are common to most of the sectors investigated with the exception of CSP, which is a new and relatively less well established technology. Given that, at the sector level, most GWOs result from environmental policies aimed at increasing sustainable energy, the initial enterprise-level response is to acquire the basic production capabilities available globally, to allow the firm to exploit the opportunity. In mature sectors, it is relatively easy for firms to acquire world-class technologies and market success depends more on capital investment and the development of organizational capabilities. For example, when the renewable energy law was introduced in China in 2006, entrepreneurial activity in the biomass and wind sectors was enabled by the licensing of core technologies and production plant designs from, mainly, European firms (Hansen and Lema, 2019; Dai *et al.*, 2020; Hansen and Hansen, 2020). Similarly, the hydropower sector was initially dependent on foreign technology and know-how (Landini *et al.*, 2020; Zhou *et al.*, 2020) and solar PV production capability, although initially responding to external demand, depended on acquisition of machinery in the international market, to allow manufacture of solar panels according to a globally dominant design (Binz *et al.*, 2020).

It is evident, also, that certain firms were better able to exploit opportunity windows, and often these firms have become national champions. This applies to Dragon Power in the production of biomass, Suntec for solar PV, Goldwind for wind technologies and China Hydro in the hydropower sector. These lead firms play a crucial role in building knowledge linkages within the global economy. They moved from initial licensing and more conventional technology transfer to mechanisms such as outward foreign direct investment in technology lead markets and linkages to foreign universities (Fu and Zhang, 2011; Lema and Lema, 2012). For example, Dragon Power's acquisition of a Danish company was crucial for its leadership in the international biomass sector (Hansen and Hansen, 2020), while Goldwind's and Envisions' R&D subsidiaries in Europe have established links with foreign universities and benefited from recruitment of very experienced engineers (Dai *et al.*, 2020; Haakonsson *et al.*, 2020).

3.4.2 The sectoral innovation system

The different cases show that the strategies and initiatives related to responding to initial opportunities, based on building basic production capacity, are insufficient for technological capabilities upgrading and deepening. This requires a gear change in relation to several components in the sectoral environment. Firm-level efforts are not enough; institutional efforts are needed to support a shift from facilitating production capability to active technology development support. This requires public R&D investments and specific programs and projects to address technological challenges such as process improvements and application of complementary technologies (Shubbak, 2019). For example, in the 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).

8 Note that sectoral systems are also subject to a degree of fluidity. Firms, such as engineering, procurement, and construction companies and knowledge-intensive business services, may interact with different green sectors, in new ways (Castaldi *et al.* 2013). However, most firms are technology specific, which reinforces sectoral trajectories and extends countries' spatial connectedness, thereby facilitating latecomer countries' access to knowledge (Strambach and Lindner, 2017; Haakonsson *et al.*, 2020, 63).

In hydro energy, the increasing role of public R&D is evident in the repositioning of Chinese universities that has occurred in the last ten years, from the periphery to the core in patent citation networks related to hydro technologies, which, in turn, has led to the "greening" of the sector and increased reliability and efficiency of generators (Zhou *et al.*, 2020).

Sectoral innovation systems have been reinforced by more intense interactions among lead firms, suppliers, technology providers and financial institutions (Fu, 2015). Several of the papers in this Special Issue show that stronger linkages within the sectoral innovation system have contributed significantly to technological deepening during the more demanding stages of technological upgrading that followed the initial phase of accumulation of production capability (Dai *et al.*, 2020; Hain *et al.*, 2020). For instance, in solar PV, this type of responsiveness within the domestic sectoral system was key to the technological development of the sector after the global market contracted (Binz *et al.*, 2020).

Conversely, in still evolving technologies, such as wind, inability of the system to progress from technology absorption and domestic deployment to technological leadership in the global market will result in domestic firms failing to achieve market leadership. Hain *et al.* (2020) propose the idea of a market trap where latecomers remain in a follower position and catch-up is aborted. 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).

In contrast, the CSP sector, which is in its formative stage and still lacks a dominant design, there is an urgent need to establish a well-functioning innovation system with technical standards and certification organizations, R&D funding institutions and consortia to coordinate firms and institutions. Catch-up type learning to satisfy market demand needs to be complemented by high levels of active search and technological experimentation support, for example, in the form of demonstration projects with different designs. Based on its well-developed innovation system, China has been able to engage in search and learning alongside competing countries (e.g. Spain and USA), so entry barriers are low until a dominant design emerges, and technology leadership is achievable.

The above discussion indicates that to allow exploitation of GWOs, the sectoral innovation system must be dynamic and adapt continuously to different sector specificities and changing market and technological opportunities. Also, policies need to be tailored to the particular stage of catch-up and take account of sectoral specificities. In the market development phase, in addition to supporting for the creation of basic production capability through the acquisition of foreign technology, protection against foreign capture of domestic demand, by imports and multinational companies operating in the local economy, will be important in several sectors (Landini *et al.*, 2020). For example, in the wind sector, the Chinese government introduced a requirement for 70% local content in total project value, effective between 2005 and 2009 when the sector was nascent. Discontinuing such policies once there was a critical mass of firms and capabilities, was an important aspect of policy responsiveness (Dai *et al.*, 2020).

As already mentioned, in the technology upgrading stage, formation and strengthening of the sectoral innovation system is especially important and includes diffusion of innovation from first mover lead firms to followers in the domestic industry. 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 linkages, 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 particular window of opportunity and cased a change in global market leadership from Western producers to Chinese firms.

As already mentioned, sectoral characteristics have important implications for the type of policy support that is relevant. Binz *et al.* (2020) find that industries characterized by high tradability (not only solar PV but also solar water heaters) profited extensively from policies aimed at supporting international technology transfer through licensing, joint ventures, highly skilled migrants, and overseas R&D centres. In low-tradability sectors, such as membrane bioreactors and offshore wind, what matters is support for capabilities accumulation based on doing, using and interacting.[9]

In high-tradability sectors, such as solar PV, globalization tends to take the form of direct sales, whereas in low-tradability sectors it generates foreign direct investments. This has implications for promotion strategies. In the case

9 Jensen *et al.* (2007) distinguished between DUI (doing, using, and interacting)- and STI (science, technology, and innovation)-based modes of learning and innovation.

of the hydro sector, foreign investments were facilitated by the China Export–Import Bank as part of a new "Going Out Strategy," aimed at enhancing the overseas activities of Chinese enterprise in response to global demand, which emerged in the early 2000s due to the withdrawal of development banks from the hydro energy sector worldwide (Landini *et al.*, 2020; Zhou *et al.*, 2020). In the wind energy sector, also characterized by low tradability, sufficient support for overseas expansion was not put in place (Dai *et al.*, 2020).

4. Green transformation and latecomer catch-up: main findings and global policy implications

Global transformation toward sustainability could open important opportunities for latecomer development in emerging economies. This is because the worldwide transformation toward sustainability is a major and increasingly disruptive force in the global economy, akin to a "successive industrial revolution" in long wave innovation cycles theory (Schumpeter, 1942).

This article and the other articles in this Special Section contribute to the catch-up literature in several important ways because the green transformation changes latecomer development dynamics. In this concluding section, we bring together the main insights from our work to show how the notion of GWOs contributes to the existing literature and we discuss the policy implications of our findings and suggest key topics for further research.

4.1 Main findings

The empirical material and analysis in this article and the articles in this Special Section provide three main findings with implications for theory.

First, in relation to *the nature of GWOs*, we underlined the importance of institutional changes for creating new opportunities for latecomer development in the green economy. In sectors as diverse as mobile phones, cameras, steel, and wine, Lee and Malerba (2017) found that institutional/public policy windows are less important and their effects are limited to facilitating adoption of new technological innovations. However, our empirical evidence for five green sectors shows that GWOs, opened by institutional changes, in particular, new policies and new legislation, related to domestically or global sustainability transformation agendas, are central to latecomer catch-up in all sectoral "take off" cases. Subsequent demand and technological windows are also essential, but tend, ultimately, to be driven by institutional changes. In addition, extending previous prior conceptual frameworks, we consider GWOs to be characterized by endogeneity, complementarity and interaction effects among different types of opportunity windows.

These findings add to discussion on latecomer development; they suggest that catch-up dynamics in green sectors are markedly different from those identified in the prior literature. In a diverse range of sectors associated to mass production and information technology (Bellak and Cantwell, 2005; Hobday, 2009; Lee *et al.*, 2014), new windows of opportunity tend to open up unexpectedly, because they depend mainly on exogenous technological or demand changes. However, although we acknowledge that policy interventions are complex, we believe that the directed nature of the green techno-economic paradigm increases the predictability of GWOs and transfers more planning power to public actors.

Second, in terms of *leveraging GWOs*, we stress that the eventual effects of policy-induced opportunities depend on the actions of firms and other sectoral system public and private actors. We show, also, how the conditions for successful exploitation of these opportunities differ among green sectors and that the pattern of appropriate responses varies according to key sectoral characteristics, such as technology maturity and tradability of products and services.

The empirical case studies of the five sectors depicted in Figure 2 show that despite their seeming similarity (all are green energy technologies), they diverge significantly in their dynamics and response patterns. This is not a trivial finding. It means that policies and firm strategies for green latecomer development need to be sector specific and that a one-size-fits all approach to green energy sectors is not viable. The papers in this Special Issue, show significant variety and complexity in response patterns, ranging from a single company taking the lead in exploiting an initial window, to action from multiple firms simultaneously and, sometimes, involving different sectors. In some cases, the public policy response is concentrated on mission-oriented technological change based on demonstration projects, whereas in other industries industrial policy measures such as local content requirements are put in place. Government policy typically allowed for significant innovation system openness during the formative phase of sectors, but restrictions were imposed during the scaling up phases. This hints at another condition for successful latecomer development in the context of endogenous creation of windows of opportunity, namely the need to protect domestic investments. This is emphasized by Landini *et al.* (2020) whose simulation analysis confirms that a demand-led catch-up strategy needs to be accompanied by a tailored and responsive protection policy in order to develop and maintain market share.

In general, the findings from the studies in this Special Section confirm the importance of firms' and public policy responses to GWOs and highlight the capability pre-conditions and agencies that need to be considered by the main players in the sectoral innovation system. We discuss this further below.

Third, *latecomer development trajectories and global changes in leadership* differ greatly among green energy sectors. In contrast to most of the literature (e.g. Morrison and Rabellotti, 2017; Vértesy, 2017), this article and the companion papers in this Special Issue, distinguish between market and technology leadership to analyze catch-up. This allows to identification of a range of diverse latecomer trajectories, whose start points, direction and relative speeds differ and are difficult to detect using a unidimensional approach.

In certain industries, such as hydro, biomass, and solar PV, China has attained clear global market and technology leadership, whereas in others, such as wind, catch-up is confined, mainly, to the domestic market and there is a lack of the technological capabilities required for leadership.

We show that sectoral characteristics are the key to explaining these differences in trajectories. Technologically mature sectors, such as hydropower, biomass, and solar PV, have been the most successful in latecomer development and leadership attainment. This contrasts to traditional cases of catch-up, for example, in consumer goods sectors where "short technology cycles" are an advantage (Lee, 2019). In green energy sectors, when the dynamics shifts toward market creation, more mature technologies with established standards, provide additional opportunities for capabilities acquisition and the definition of successful business models for global and local markets. Where the technological frontier is changing more rapidly (e.g. in wind technology, but also water membrane reactors, see Binz *et al.*, 2020), catch-up does not result in significant export competitiveness; this requires a qualitative shift in innovation system support which is more difficult to achieve.

4.2 Implications for global policy

The findings from our research have important implications for global green transformation policy.

First, we provide an example of very rapid latecomer catch-up in renewable energies, involving significant disruption and transfers of leadership and different trajectories, driven mainly by institutional change. Some cases, such as solar PV and hydropower, involve external technological or market change pull, although, fundamentally, their rapid growth has been driven by global institutional change. All of our findings show the possibilities provided by GWOs for latecomer economies. China was able to catch-up in production and technology and, in some sectors, has become the world leader and extended the knowledge frontier and influenced the technology through significant contributions to standards development (Gosens *et al.*, 2020). These facts suggest that the efforts of international organizations, governments and non-governmental organizations across the world have been effective in promoting institutional change-led, mission-oriented GWOs for all countries. The global community should continue its efforts in order to produce new global green innovation leaders based on active exploitation of these opportunities.

Second, these GWOs can be exploited by both developed and developing economies. Countries that take active measures to enhance their technological capabilities and build open national and sectoral innovation systems through trade and investment policies and internationalization of R&D, may achieve faster catch-up and, even, leadership. Developing countries that are able to combine acquired or gradually developed technological leadership with low-cost production resources, will be able to offer affordable solutions to the global green transformation. The emergence of latecomer countries in the green economy will have an internationally beneficial effect by reducing the price of energy transition technologies. This may facilitate mobilization of finance and technology for more affordable greening of energy systems in poor countries in the global South (Lema *et al.* 2018). Moreover, green latecomer development could increase the diversity of environmental technologies and solutions, which suggests the need for collaboration and engagement rather than containment and decoupling. Space and support should be provided for responsible new green innovators to lead the fight against climate change and contribute to a green transformation.

Third, environmental and energy policies are critical for the emergence of GWOs, based on their domestic deployment and market creation effects. At the same time, industrial and innovation policies are also important to promote the firm and system level capabilities to respond to opportunities. The complementarity among different policies raises several coordination and design issues, which need to be considered. As already mentioned, in mature sectors, emerging economies can build domestic production capability by acquiring external knowledge and capabilities, which requires an open innovation system. In the Chinese case, public policies have provided support for several channels, including inward and outward foreign direct investment and schemes for skilled human capital mobility. To strengthen innovation capacity, policy efforts have focused on building a well-functioning sectoral innovation system, characterized by technical standards and certifications, robust R&D activity in domestic universities and consortia of firms and institutions. In new emerging sectors, system-building policies are needed in the early stages when the domestic market is not sufficient to create a competitive industry; this requires mission-oriented policies and large investments in R&D and demonstration projects (Hain *et al.*, 2020).

Finally, the lessons provided by the papers in this Special Issue may have some valuable policy implications for other sectors, such as public health and digital infrastructure, which are critical for building an inclusive society. In a closely inter-connected and globalized world, there is a collective interest in enhancing international technological and productive capability in R&D and production of vaccines and medicines and a digital infrastructure. The findings from the studies in this Special Issue suggest that policy coordination and the efforts of the global community in ensuring equal access and responsible provision of global public goods, could create "global challenge-led windows of opportunity." The global community should facilitate and support disruption to these sectors and changes of leadership through engagement, collaboration and regulation-based supervision to ensure equal access to high quality, responsible, economically affordable, and technologically appropriate services, products and facilities.

4.3 Further research

Our findings suggest several directions for further research, in terms of both overcoming some of the limitations of our research and exploring new issues.

First, this and the other papers in this Special Section have a limited focus on renewable energy sectors. It would be useful to extend the sectoral perspective to include other green industries and other sectors providing public goods, such as health or digital infrastructure, and investigate how and to what extent the findings from this research, especially those regarding the role and sequence of the changes in institutions, technologies, and markets, lead to similar windows of opportunity.

Second, our work is limited to one geographical location but offers several stylized facts that could be investigated empirically in the cases of countries at different levels of development and with preconditions different from those found in China. China's scale and political power makes it unique in terms of its ability to push toward a new model of green development, but we need to investigate the prospects for creating GWOs related to the energy transition in other emerging economies and in less developed countries.

Finally, it would be interesting to investigate the impact of new technological megatrends—big data, artificial intelligence, energy storage, and internet of things—on the global transformation toward sustainability. Understanding who, between the advanced and the emerging economies, will benefit more from the diffusion of new and emerging technologies in green transformations would be very relevant.

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Appendix

Table A1. Firms and other actors in green energy sectors

Sector	Tech maturity	Tradability	Enterprise responses	Domestic sectoral system responses
Biomass	High	Low	• One leading company acquiring foreign technology for production capability development to exploit the initial institutional window, meeting domestic demand and subsequently addressing the global market. • A second wave of local companies imitating technologies and designs, actively learning from the pioneering company and its linkages.	• Building of basic production capabilities and then strengthening of the domestic sectoral system. • Government stimulation of knowledge spillovers with loose enforcement of property rights and diffusion through state owned design institutes. • Insufficient investments in front-end capabilities required for success in advanced lead markets.
CSP	Low	Medium	• Significant entrepreneurship and R&D experimentation to address the green technology window. • Consortia building by sectoral pioneers and other firms from related sectors.	• Establishment of a well-functioning innovation system with agencies for technical standards and certification, strong R&D activity in domestic universities and consortia coordinating firms and institutions. • Setting up of significant demonstration projects to explore CSP technology. • Experimentation with alternative designs.
Hydro	High	Low	• Foreign technology acquisition and collaboration for production capability development to meet initial domestic demand. • Consortia for addressing the global market led by engineering, procurement and construction firms.	• Building of basic production capabilities and then strengthening of the domestic sectoral system. • Facilitation of foreign direct investments (e.g. China Export–Import Bank and "Going Out Strategy)." • Research investments in domestic universities and development of a support system aimed at the "greening" of hydropower.
Solar PV	High	High	• Foreign technology acquisition for production capability development to exploit the external demand window. • Subsequent knowledge acquisition through foreign R&D centers and skills mobility.	• Building up of a domestic R&D system, also with external knowledge inputs (e.g. licensing, joint ventures, highly skilled migrants, overseas R&D centers) in conjunction with the domestic demand window. • Experimentation and demonstration projects.
Wind	Medium	Low	• Foreign technology acquisition for production capability development to exploit the initial institutional window to meet domestic demand. • Local adaptation, acquisition of design and co-design capabilities of simple products for the local market.	• Building of basic production capabilities and then attempts to develop a domestic R&D system (e.g. experimentation with offshore technology). • Local content requirement in the initial stage of development. • Reliance on international networks and insufficient capacity to react to new global technology windows.