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Catch-up dynamics in early industry lifecycle stages – A typology and comparative case studies in four cleantech industries

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Abstract

The literature on catch-up cycles has not yet systematically conceptualized how catch-up dynamics differ between the various industries that are emerging in the green techno-economic paradigm. We address this gap by connecting catch-up cycle theory with an industry typology from global innovation systems (GIS) literature, which distinguishes four generic industry types with footloose, spatially sticky, market-anchored, and production-anchored innovation system characteristics. Catch-up patterns in early industry lifecycle stages are expected to systematically differ between these four industry types. This assumption is explored based on a comparative case study of the solar photovoltaics, wind power, solar water heaters, and membrane bioreactors industries, each of which exemplifies one of the four generic GIS configurations. We find that the speed and disruptiveness of early leadership changes differ significantly between the four industries, and that the effectiveness of capability upgrading strategies and catching-up policies are contingent on the innovation and valuation characteristics of each industry's underlying GIS type.

Keywords: catch-up cycle; global innovation system; industry typology; clean-tech; China

JEL Codes: O33, Q42, L94

1 Introduction

Industries repeatedly change their spatial configuration, often with dramatic shifts in the relative leadership positions of firms and regions. These changes in leadership have recently been conceptualized as 'catch-up cycles' (Lee and Malerba 2017). Mounting empirical evidence shows that the emergence of windows of opportunity for industry reconfiguration, as well as the generic catch-up patterns and incumbent/latecomer strategies, systematically differ between industry types (Lee and Malerba 2017, Malerba and Nelson 2011, Lee and Lim 2001).

Yet, while mounting evidence shows that catch-up cycles differ between sectors, we lack concise conceptual models for explaining why and how they differ in the clean-tech industries that currently develop in the 'green' techno-economic paradigm (TEP) (Mazzucato and Perez 2015). We argue in line with Lema et al. (this issue) that most of the theorizing in catch-up literature has focused on the dynamics in relatively mature industrial sectors with well-established global value chains and standardized production and market structures (e.g., mobile phones, steel, semiconductors). How catch-up cycles play out in more emergent (clean-tech) industries, which have a public goods character and depend on supportive policy interventions globally, remains under-assessed.

Here, we address this gap by developing a conceptual framework that provides explanations for differing catch-up cycles in the early industry formation phase. We do so by building on an industry typology from the 'Global Innovation Systems' (GIS) framework (Binz and Truffer 2017), whilst incorporating insights from the literature on catching-up in green sectors (Quitzow et al. 2017, Fu and Zhang 2011, Schmidt and Huenteler 2016).

By developing this framework, and by empirically validating it with comparative case studies from four emergent clean-tech industries, we aim to answer the following research questions: How do technology and industry characteristics influence catch-up cycles in emerging green sectors? What type of clean-tech industry is most susceptible for rapid and/or disruptive shifts of early leadership towards latecomer economies, and which are not? How should latecomer countries take such differences into account when designing catch-up policies?

Our empirical results point to systematic differences in the early catch-up cycles of green industries. Windows of opportunity for early catching-up open more frequently in industries that depend on codifiable knowledge and standardisable mass markets. Industries with mass-manufactured products (solar PV, solar water heaters) according to our data experienced more fundamental early leadership shifts, while in industries with project- and DUI-based market structures (wind power, water recycling), we observed more instances of shared leadership between pioneering countries and early followers. Responses from incumbent and latecomer firms/governments in the emerging green TEP thus have to be adapted to each industry's characteristic innovation mode and valuation system.

The remainder of the paper is structured as follows. In section 2, we combine the catch-up cycle concept with recent insights from the literatures on catching-up in green sectors and on global innovation systems to derive a typology of catch-up dynamics in the early industry formation phase. Section 3 introduces the case selection and methods, while section 4 describes global development trajectories and catch-up cycles for the four industries. Section 5 synthesizes findings and outlines policy implications, as well as our contributions to catch-up studies and policy making in developed and emerging economies.

2 Toward a typology of catch-up cycles in emerging cleantech industries

The sectorial systems and catching-up literatures have dealt with global industry dynamics and leadership changes - especially toward emerging economies in South America and Asia - for decades (Lee and Lim 2001, Wade 1988, Evans 1995). Existing explanations of catching-up by latecomer firms and countries emphasized (among others) initial conditions (Fagerberg and Srholec 2008), technological and organizational capabilities (Lee and Lim 2001), strategic policy interventions (Yeung 2009), and/or regional and national support structures (Lundvall et al. 2002). In combination, these perspectives have created a comprehensive picture of the process that allows latecomer countries to gradually upgrade their technological capabilities and compete with globally leading firms.

More recently, scholars have sought to integrate the empirical evidence on global leadership changes into more formal models of 'catch-up cycles' (Lee and Malerba 2017). These catch-up cycles denote the repeated leadership shifts in an industry, which involve pioneers building up and then losing a dominant position, while latecomer firms take over significant market shares. Existing models are based on three conceptual elements: windows of opportunity (technology, demand, and institutions/public policy), countries' stage of development in the catching up process (entry, gradual catching up, forging ahead, falling behind), as well as responses by firms and other actors in the affected sectoral system (Lee and Malerba 2017). Depending on the specific patterns of windows of opportunity and responses by incumbents and newcomers, a sector may be reconfigured in five generic cycle types, including gradual replacement, aborted catching-up, persistence of leadership, coexistence or the return to leadership by pioneering actors (Landini et al. 2017).

2.1 Gaps in existing catch-up cycle models

Work on catch-up cycles – which is rooted in the sectorial systems literature - has led to highly productive scholarly output, but it has also been criticized for ignoring the innovation dynamics in earlier industry lifecycle stages and for or containing an implicit supply-side bias (Coenen and Díaz López 2010). The first gap stems from the fact that most catch-up cycle studies focus on mature sectorial systems with relatively stable market and policy support structures and a well-established global division of labour. The catch-up dynamics in the early industry lifecycle phases (before a dominant design/product architecture has emerged), can however be expected to differ conceptually from later standardized phases (Lee and Lim 2001, Coenen and Díaz López 2010, Lema et al. this issue).

First and foremost, emergent industries often possess a generic 'window of locational opportunity' (Boschma 1997); technologies are not yet fully standardized, markets are still fluid, and regulations and user preferences are yet to be settled. Repeated product innovation as well as complex innovation system building processes (Bergek et al. 2008) and transnational linkages may influence how and where new industries locate and grow (Quitzow 2015, Wieczorek et al. 2015, Gosens et al. 2015). This factor has been shown to be particularly relevant in industries of the green TEP, which emerge in protected niche markets in various parts of the world at once and thus often depend on complex spatial and institutional interdependencies (Quitzow 2015, Andersson et al. 2018).

The second crucial factor that differs from mature industries is thus that the demand side will depend on active market construction and/or strategic policy support (Bergek et al. 2008, Quitzow 2015). This aspect is particularly relevant here, since green industries have strong public good character and in their early lifecycle depend on pro-active shielding from the selection pressure of pre-established sectorial regimes (Lema et al. this issue, Yap and Truffer 2019, Geels 2002). This implies that industry types need to be distinguished not only based on their knowledge base, but also by taking into account the relevant valuation system, which comprises market construction, financial investor's interests, and actors actively working on overcoming hindering institutional structures (Binz and Truffer 2017, Coenen and Díaz López 2010).

Last but not least, discerning industry leadership is more challenging in early lifecycle stages. Catching-up literature traditionally distinguishes between market and technology leadership (Lee and Lim 2001). We here posit that market (or manufacturing) leadership is more indicative in early lifecycle stages, since the dominant technological trajectory has not yet been selected, so it is hard to judge which technological capabilities will turn out to be the most 'advanced' in the long run. Changes in early leadership can accordingly be conceptualized as shifts of dominant market shares or manufacturing capacities from one country to another, similar to conventional catch-up cycle theory. The windows of opportunity (w/o) that will lead to such changes can accordingly be expected to depend on complex mixes of technological, market and institutional factors.

2.2 Typologizing catch-up cycles in emerging clean-tech industries

While the points above are discussed in the literature on catching-up in green sectors (Fu and Zhang 2011, Walz and Marscheider-Weidemann 2011, Lema and Lema 2012, Schmitz and Altenburg 2016), we still lack a characterization of the differences that exist between the catching-up experience in different green sectors. To date, the literature has compiled an impressive host of single-sector case studies, yet only very recently have the observed catch-up patterns been cross-compared in a theoretically more grounded way (cf. Quitzow et al. 2017, Schmidt and Huenteler 2016). Overall, there is mounting evidence *that* catch-up cycles differ between industries in the emerging clean-tech space, but more limited knowledge on *why* they differ, and whether specific types of industries evolve in comparable, generic patterns.

To address this gap, we here propose to build on the industry typology from the global innovation system (GIS) approach. It shares the same theoretical roots as sectorial systems approaches, but has a pronounced focus on early industry lifecycle phases and the formation of innovation system resources in spatially dispersed, multi-scalar actor networks (for a detailed discussion see Binz and Truffer 2017). In addition, it explicitly complements the supply-side bias in the sectorial systems and industry lifecycle literatures with an elaborate conceptualization of the demand-side and institutional conditions for industry formation. So far, it has however not yet been explicitly applied to questions around catch-up patterns and leadership changes in the emerging green TEP.

Its heuristic for distinguishing early innovation patterns builds on two interrelated analytical dimensions. First, emerging industries are characterized by their dominant innovation mode, distinguishing coarsely between industries that depend on a science, technology innovation (STI) model, and industries where innovation depends more strongly on doing, using, interacting (DUI) types of learning; a dichotomy also found in earlier industry taxonomies (Parrilli and Alcalde Heras 2016, Jensen et al. 2007). On a second dimension, the framework distinguishes industries with either standardized or customized valuation systems [1] (cf. Jeannerat and Kebir 2016). This axis contrasts industries where manufacturers create highly standardized products for global mass-markets with industries in which products have to be

[1] For a detailed discussion of the concept of valuation see e.g. (Jeannerat and Kebir 2016). Valuation systems encompass "the relational and institutional dynamics by which different objects and activities are socially valorized (i.e. transformed and commercialized) and evaluated (interpreted, recognized, legitimated and appraised) in the market."

strongly customized to local or individual user preferences and embedding in local institutional structures. When translating these two dimensions to a four-field table, one can distinguish between four generic GIS configurations (Figure 1).

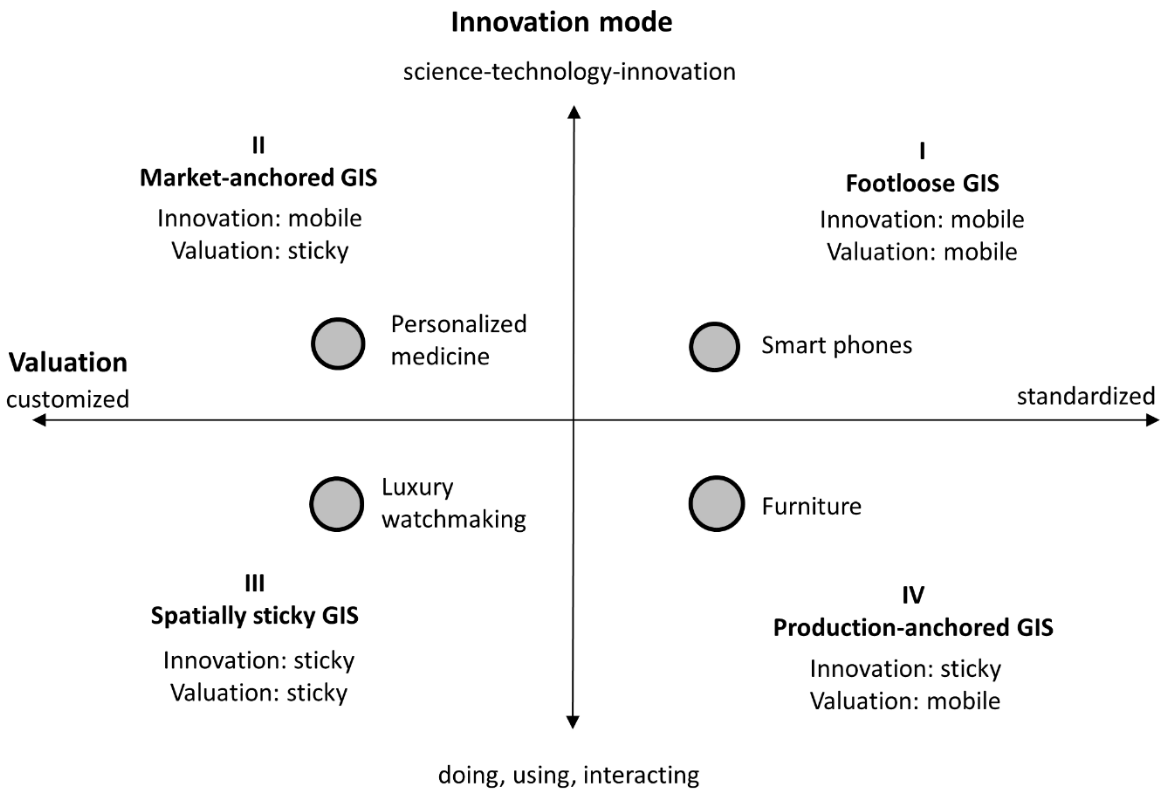

Fig. 1: Typology of global innovation system configurations. Source: Own design, based on Binz and Truffer (2017)

2.3 Expected catch-up dynamics, capability formation and policy models in different GIS types

The characteristics of industries in each of the four quadrants of the GIS typology directly affect the conceivable forms of w/o formation, types and speed of early leadership changes, as well as the early capability upgrading mechanisms and the effectiveness of government's catching-up policies.

The knowledge in industries with an STI innovation mode, like smartphones, is largely rooted in basic sciences and is easily codified into papers and patents, allowing it to be readily exchanged over long distances (Jensen et al. 2007). Windows of opportunity in the form of technological discontinuities, such as e.g., a novel manufacturing process, may therefore spread rapidly, and quickly erode the competitive benefits of early pioneers. In DUI industries like e.g., furniture manufacturing, the learning process is experience-based and embedded in place-based craftsmanship cultures. The innovation-related knowledge is thus predominantly tacit and dependent on repeated user-producer interaction in territorially embedded clusters or industrial districts. The competitive benefits of the substantial experience of pioneering firms can therefore be expected to be more durable, and only slowly eroding as latecomers start their time-consuming processes of capability upgrading.

A similar distinction can be made for an industry's underlying valuation dynamics: In industries with standardized demand structures, such as smartphones, user tastes gravitate around a narrow set of generic product models, and look very similar in various parts of the world (Jeannerat and Kebir 2016). The extent and speed of the expansion of a latecomers' market share is therefore limited predominantly by its capability to scale-up manufacturing capacity, including the access to finance required for such scale-up, access to standard global distribution channels, and knowledge of global market trends. In other industries like personalized cancer medicine, each product is a one-of-a-type design tailored to (often highly specific) user needs (Moors et al. 2017). Of key importance in these industries are close connections to the relevant customers, and a detailed understanding of the relevant local industry standards, regulations and societal norms; all issues that may be expected to require long timeframes to build up, and therefore limit the pace with which latecomers may access the relevant markets when catching-up. At the same time, markets are likely more fragmented in this situation, thus potentially providing latecomers with protected market niches in which they can grow in parallel to incumbent actors (Li et al. 2019).

When combining these perspectives, the catch-up process in STI-based industries that cater for mass markets are arguably the most dynamic and mobile. Both in terms of innovation capabilities and market share capture, spill-overs may happen quickly and over long spatial distances. These industries are therefore expected to experience the most dramatic shifts in early leadership. The relatively mobile innovation patterns also mean that a latecomer that manages to achieve leadership may again quickly lose it to the next challenger. Latecomers would accordingly build up their capabilities in highly internationalized network structures and through absorbing recent advances in the STI space. Conventional RD&D support combined with the creation of favourable conditions for global trade, are expectedly the most promising policy strategy in such an industry type (Binz et al. 2017a).

Industries with both a DUI-based innovation mode and customized valuation system will in turn depend on a much slower and spatially embedded capability formation process, both for innovation/manufacturing and valuation capacities. Producing e.g., high quality mechanical watches will only be possible in a few specialized manufacturing clusters worldwide and depend on historically grown craftsmanship and quality cultures (Jeannerat and Kebir 2016). We therefore expect to see the longest cycle durations and most gradual early catch-up patterns in these industries. The strong localization in innovation processes and the strong market segmentation may lead to shared leadership of several firms or countries, where leadership is attained consecutively in distinct regions. Latecomer firms wanting to catch-up in such an industry would have to invest in long-term, DUI-based capability formation in a localized (niche market) context. Catching-up policies would accordingly have to focus on creating protected spaces for experimentation and interactive learning with a long-term investment horizon (Binz et al. 2017a).

The other two quadrants represent intermediate cases, where either one of the dimensions provides for spatially stickiness while the other allows for significant mobility. We accordingly expect catch-up cycles in these industries to be in between the ‘footloose’ and ‘sticky’ types, with intermediate catch-up cycle length, and a higher likelihood for gradual catch-up or return of old leadership (for a more detailed discussion see e.g. Binz et al. 2017a).

2.4 Conceptual propositions

Based on the above considerations, we formulate three stylized conceptual propositions that will guide the empirical work.

- Proposition 1: The timing and disruptiveness of catch-up cycles differs between industries with varying GIS types. Industries with footloose GIS have the shortest cycle durations, spatially sticky GIS have the longest, while market-anchored/production-anchored GIS lie in between. The spatial reconfiguration of early industry leadership can accordingly be expected to be most dramatic in footloose GIS. If either the innovation mode or valuation system contain sticky elements, gradual catch-up patterns and persistency of leadership are more likely.
- Proposition 2: Mechanisms for capability upgrading differ based on the industry’s GIS characteristics. In footloose GIS, latecomers may profit from international spill-overs, while in sticky GIS, they depend on gradual, territorially embedded capability formation processes. Catching-up mechanisms in market- and production anchored GIS depend on a mix of endogenous capability formation and anchoring of transnational spill-overs.

- Proposition 3: The most effective catching-up policies differ between GIS types. In industries with an STI-based innovation mode and global mass markets, supply-side policies (RD&D support, export zones, tax cuts) will be most effective, while industries depending on DUI-based innovation and product customization profit more from demand-side policies and the establishment of niche markets (renewable portfolio requirements, deployment policies, feed-in tariffs, etc.).

3 Case selection, operationalization and methods

3.1 Case selection

The empirical analysis will reconstruct the early catch-up cycles in the solar PV, wind power, solar water heater and membrane bioreactor industries, each of which is an emblematic case of one of the four GIS configurations (Table 1).

Table 1: Industries covered in the empirical illustrations

	Solar PV	Wind power	Solar water heaters	Membrane bioreactors
Innovation mode	STI	DUI	DUI	STI
Valuation system	Standardized	Customized	Standardized	Customized
GIS type	Footloose	Sticky	Production-anchored	Market-anchored

In Section 4 we will first characterize each industry's early spatial evolution and catch-up cycles from a global perspective. China emerged as the most relevant latecomer in all four cases, so our discussion of capability upgrading mechanisms and policy strategies focuses largely on China. This approach has the advantage of isolating country-level circumstances, which brings out industry-level differences more clearly (see Lema et al. this issue), although care has to be taken when translating conclusions and policy recommendations to other countries (see section 5.3).

3.2 Operationalization, methods and databases

Table 2 provides an overview of how the duration, disruptiveness and capability upgrading/policy strategies were conceptualized and assessed. First, we follow Lee and Malerba (2017) in assessing industry leadership through a combination of quantitative and qualitative indicators. On the one hand, industry leadership is conceptualized as a country's relative share of global manufacturing or market volumes, assessed using publicly available manufacturing/market databases. This quantitative assessment is complemented with a qualitative analysis (derived from interviews and secondary literature) on how the technological capabilities of latecomer firms have developed (see Lee and Lim 2001), and how policy strategies have supported/hindered the catching-up process. The speed of leadership changes is measured with the time that lies between the peak market/manufacturing shares of one country to the next market leader, whilst the disruptiveness depends on the remaining market share of the earlier leader. Capability upgrading strategies and public policy strategies are in turn assessed based on qualitative indicators listed in table 2, based on information from expert interviews.

Each industry's early lifecycle patterns were derived from industry-specific databases. They comprise manufacturing and market data provided by international organizations like IEA, IRENA, and industry associations like the global wind energy/solar councils. This quantitative information is compounded with a qualitative characterization of the capability upgrading and industry formation dynamics in each industry, utilizing secondary sources and interview campaigns. Overall, 143 interviews from prior studies inform the analysis in the empirical part; 26 in the solar PV case (Binz and Diaz Anadon 2018), 37 in the wind case (Gosens and Lu 2013), 36 in the solar water heater case (Yu & Gibbs, 2018), and 44 in the MBR case (Yap and Truffer 2019).

Table 2: Key propositions and indicators

Propositions	**Indicators**
Proposition 1	*(Quantitative assessment)*
Time between early leadership changes	No. of years for market/manufacturing leadership to shift from one country to another
Spatial reconfiguration	Disruptiveness (coexistence of or complete shift of leadership) from one country to another
Proposition 2	*(Qualitative assessment)*
Capabilities upgrading	-Achieved capability stage (assembly, low-tech part development, high-tech part development, product design, product concept creation) -Reported upgrading strategies (build-up of internal R&D vs. cooperation with domestic partners vs. global knowledge flows)
Proposition 3	*(Qualitative assessment)*
Policy approach	- Selected policy support scheme and expert's assessment of the policy support scheme chosen and its effectiveness in supporting catching-up (supply / RD&D vs. export support, vs. demand-side policies)

4 Catch-up cycles in four clean-tech industries

4.1 Solar photovoltaics

Our first case, the solar PV industry, is an emblematic case for a footloose GIS type (Binz et al. 2017b). PV technology converts solar radiation into electric energy based on the photovoltaic effect. At a most aggregate level, the industry depends on STI-based innovation which is driven by advances in materials sciences, semiconductor technology and related fields like electro-chemical engineering (ibid.). The industry's main products, solar panels, in turn, depend on a highly standardized valuation system. Today, PV panels are sold in global mass markets and get traded at spot market prices, similar to basic natural commodities (Huenteler et al. 2016).

4.1.1 Global industry evolution and w/o for catching up

The mobility of the knowledge required for PV panel manufacturing, and the strongly globalized marketplace for PV panels coincide with high spatial dynamics and frequent early leadership changes (Figure 2).

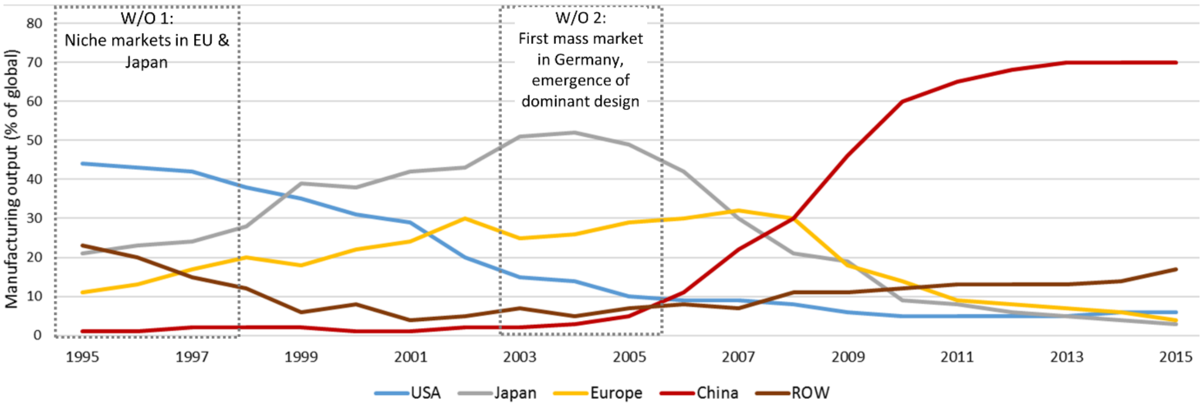

Figure 2: Global evolution of manufacturing shares and w/o for catching up in the PV industry. Data sources: Earth Policy Institute, 2013. Annual Solar Photovoltaic cell production by country, 1995-2013. Available online at http://www.earth-policy.org/data_center/C23. Office of Technology Assessment, 1995.

'Renewing Our Energy Future.' Congress of the United States. Report OTA-ETI-614, Washington, D.C.

Two disruptive leadership changes that followed each other in a relative short time span of less than 10 years can be identified in Figure 2. The first institutional/market-driven leadership change happened in the mid-1990s when European and Japanese governments created protected market niches for PV products, and latecomer companies, mostly from Germany, France, and Italy, entered the field, with detrimental effects on the US pioneers (Varadi 2014). Latecomer firms in Taiwan, Korea and China also tried to enter the industry at this point, but could not yet compete on a quality basis.

A second (institutional/market/technology-driven) w/o led to an even more dramatic leadership change ten years later (around 2001), when the world’s first mass market for renewable energy was created with Germany’s feed-in-tariff system (Hoppmann et al. 2014). Roughly at the same time, a dominant design emerged, and companies from emerging economies swiftly took over a global leadership position (Dewald and Fromhold-Eisebith 2015). Taiwanese and Korean firms entered the industry first, but Chinese firms subsequently ramped up PV cell and module manufacturing capacity so quickly that they could outcompete Western incumbents and East Asian early followers.

From 2001-2007, Chinese companies went from almost 0% market share to supplying more than 60% of global PV panel output (with overall global production volumes exploding at the same time) and shortly after also started dominating global market deployment and (low-quality) patenting activities (Zhang and White 2016). With the steep rise of Chinese competitors, several European, US, and Japanese manufacturers went bankrupt or subsequently specialized in upstream (silicon, turnkey manufacturing lines) or downstream (balance of systems, operation and maintenance) value chain segments (Dewald and Fromhold-Eisebith 2015).

4.1.2 Domestic capability formation mechanisms

The capability formation dynamics that supported the remarkably quick market catching-up of Chinese firms initially relied almost completely on importing manufacturing equipment and other innovation-related inputs from abroad (Binz and Diaz Anadon 2018, Zhang and Gallagher 2016). Many of the pioneering Chinese PV start-ups were ‘born global’ companies, that catered for overseas markets with mass-produced panels, and mobilized manufacturing equipment, financial investment, technological knowledge and quality standards available in the PV industry’s global innovation system structure (Binz and Diaz Anadon 2018). Chinese firm’s internal technological capabilities accordingly remained limited to simple parts manufacturing for an extended period of time and reached the global frontier only very recently.

In a second phase (after 2008), this highly internationalized capability upgrading model was supplanted with more localized capability formation processes in local firms, universities, and industry associations (Lema et al. this issue, Liu et al. this issue). Nowadays, Chinese firms dominate the core of the PV industry’s value chain. Yet, the global industry’s most profitable technological capabilities concentrate in upstream and downstream value chain segments, e.g. related to manufacturing automated PV production lines, managing balance of systems, or financing large utility scale PV plants and aftersales services (Zhang and Gallagher 2016). Since these segments are still dominated by Western firms, current policy documents in China now target these segments with additional R&D subsidies, as well as by supporting overseas acquisitions.

4.1.3 **Supportive policy strategies**

Until 2008, the central government did not support the Chinese PV industry with a strategic industry support program (Zhang and White 2016). Generic policy guidance was available through the renewable energy law and financial support in special export zones, but only in 2008, when the financial crisis created turmoil in the global PV market, did the central government ramp up PV-related dedicated policy support. PV subsequently got included in a list of 'strategic national industries', and was supported with considerable financial investment from large-scale market deployment programs, the economy stimulus package, as well as domestic development banks (ibid.).

Since this inflection point in 2008, catching-up policies targeting the PV sector were continuously improved in an iterative process that could be described as 'compulsive policy making' (Hoppmann et al. 2014). R&D policies targeted the key bottlenecks in the capability structures of Chinese firms, international trade policies were adapted to provide Chinese manufacturers with highly competitive conditions in the global market place, while local deployment subsidies strategically dampened the adverse effects of global financial downturns or the trade disputes emerging after 2012.

4.2 Wind Power

The wind power industry represents a spatially sticky GIS configuration, in which both the innovation mode and valuation system are deeply embedded in specific places (Schmidt and Huenteler 2016). Wind turbines utilize the force of the wind over a set of blades to drive an electric generator. Innovation depends on mastering the interplay of different components in these complex machines. Knowledge creation in the earliest experiments in Denmark accordingly occurred in tightly knit networks of local actors involved in the (DUI-based) design, manufacture, and use of the turbines (Garud and Karnoe 2003). Explicit forms of knowledge long remained less important than in other renewable energy industries (Kirkegaard et al. 2009). Market valuation is relatively customized even in today's large-scale markets, mainly due to the project-based nature of wind farm development (Wüstenhagen 2003). Apart from a few globally leading firms, most manufacturers remain relatively strongly dependent on home market demand (Henze and Thomas 2018).

4.2.1 Global industry evolution and w/o for catching up

Early catch-up cycles in the wind power industry are of the model of 'shared leadership'. The rise of early followers (Germany and Spain, early 1990's), and late followers (India and China, early 2000's), has reduced relative market shares of the early leaders (US and Denmark), but there has been no irreversible loss of leadership by the industry pioneers (Figure 3).

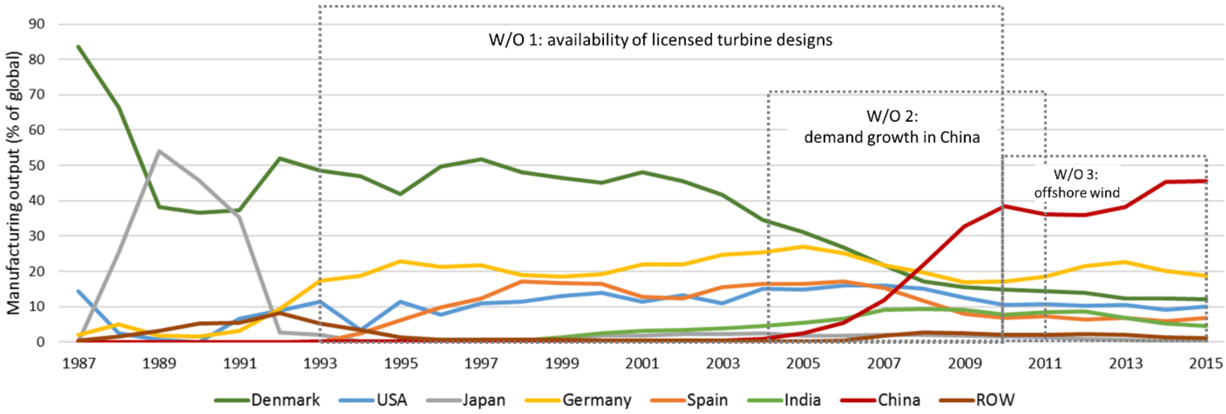

Figure 3: Global evolution of manufacturing shares and w/o for catching up in the wind power industry. Data source: The Wind Power (2016). Wind Energy Market Intelligence; online global database available via: thewindpower.net.

Figure 3 reveals that a first w/o for catching-up opened up in the early 1990's, when manufacturing technology became accessible on the global marketplace at relatively affordable rates (Kirch Kirkegaard 2015), due to two simultaneous developments. First, some of the market leaders considered licensed production as a sensible boost to profits, and/or as a strategy to enter into new foreign growth markets (Wüstenhagen 2003, Lewis 2007). Second, market shares had quickly consolidated, with just five companies becoming responsible for 88% of global installations by 1995 (The Wind Power 2016). This put strong pressure on smaller manufacturers and design houses to find customers for their designs, or get acquired, as an alternative to bankruptcy or industry exit. This w/o, although largely technological, was compounded by growing policy-induced demand in Germany, Spain, India and China, etc.

A second w/o for catching-up emerged when Chinese policy, from circa 2005 onwards, created rapidly growing domestic market demand. In most major wind power markets, there is a preference for domestic equipment, amongst others due to the high cost of transport of some components, or the requirement for local maintenance and servicing industries familiar with specific turbine models. These characteristics have driven equipment manufacturers to establish local subsidiaries or seek local partners in foreign markets (Wüstenhagen 2003). China, however, is unique in the very high share (more than 95%) of domestic suppliers in the home market, and very limited exports (Gosens and Lu 2014). This separation was due to differences in valuation with respect to turbine characteristics (see section 4.2.2.), and has led to rapid dominance of Chinese latecomer firms in the (very large) home market, whilst early leaders largely retained their market shares elsewhere.

A third w/o opened more recently with the development of off-shore wind turbine markets, including in China (cf. Dai et al. this issue). Chinese manufacturers have had trouble capturing much of these markets, however, largely due to a remaining competency gap for product development with foreign lead firms (He et al. 2016).

4.2.2 **Domestic capability formation mechanisms**

From its inception through to recently, Chinese capability formation has largely been reliant on the slow and gradual absorption of foreign technology inputs. This started in the early

1990s with a learning process in training programmes and Joint Ventures with foreign manufacturers (Lewis 2007). From circa 2000 onwards, Chinese firms started to seek quicker routes to build in-house competencies through licensing of foreign turbine designs, though they long kept trailing the global technology frontier (Wang et al. 2012). From the late 2000's onwards, when leading Chinese firms had further developed their manufacturing competencies and financial strength, a number of firms acquired foreign design houses, or sought cooperation for product development in JV with foreign manufacturers (Gosens and Lu 2013, Wang et al. 2012).

These methods of industry entry were used until roughly 2010, after which successful entries dropped off steeply. It provided opportunity only for gradual catching-up because there was no major technological discontinuity, but mostly incremental improvements (for increased turbine sizes, grid integration, improved blades, gearboxes, control systems etc., and adaptations for specific environments like low wind, high altitude, etc.). The dependency on supplemental knowledge from foreign sources has been slowly reduced, with an ever larger share of R&D activity by Chinese market leaders performed in domestic labs, but with remaining competency gaps with foreign leaders (Pan et al. 2019).

In terms of catching-up in market shares, Chinese turbine manufacturers long prioritized domestic markets, as its rapid growth offered plenty opportunity, whilst being more accessible than foreign markets (Gosens and Lu 2014). Driven by policies that long prioritized installation targets over power generation targets, Chinese customers have focused to a greater extent on pure installation costs, essentially valuing turbines as commodities, much more than is the case in the global market (ibid.). The response of domestic manufacturers to the demand for sharp cost reductions per MW made them very competitive in China, but simultaneously reduced their competitiveness in foreign markets (Gosens and Lu 2014).

4.2.3 Supportive policy strategies

The wind turbine manufacturing sector in China was the target of a government orchestrated, long-term catching-up programme. Politically steered domestic capability formation was initiated in the early 1990s, when government programs teamed up domestic firms with leading foreign manufacturers, to develop manufacturing capabilities in less complex components or full turbines sets that were somewhat behind the global frontier (Lewis 2007). Test beds for domestic equipment were created in Western provinces to induce DUI-based learning-by-doing. Sectoral policies kept close track of domestic capability formation, and targeted domestic production of incrementally larger turbines, from 200 to 600 to 1500 kW over the course of a decade (Gosens and Lu 2013). In 2012, policy even targeted 10 MW offshore turbines, beyond the capabilities of even the more experienced of global leaders at the time, and Chinese manufacturers are currently still developing such machines (GWEC 2019).

Chinese policies also provided sufficient and growing demand in the home market, including local content requirements, and expecting state-owned developers to prioritize domestic manufacture (Wang et al. 2012). In concession programmes and large-scale tenders, the overriding selection criteria was cost per MW (Wang et al. 2012), which played in very well with Chinese manufacturers competencies in mass-manufacturing and cost-reduction (Nahm & Steinfeld, 2014).

4.3 Solar water heaters

The solar water heating (SWH) industry represents a production-anchored GIS, with a localized innovation mode and standardized valuation system. The key component in a SWH system are solar collectors that absorb solar radiation and convert it to heat. Although the initial development of solar collectors relied on lab-based scientific advances, innovation has been mainly embedded in the production process, with incremental technology improvements based on user-producer interactions, ever since a dominant design emerged in the 1990s. SWH design is based on rather low-tech components that get integrated to standardized products in a DUI-based learning process. The valuation system is in turn strongly standardized, with a few basic technology configurations catering for most user needs, and fierce price competition among several producers of systems with strongly comparable performance characteristics.

4.3.1 Global industry evolution and w/o for catching-up

Similar to the PV and wind power industries, two key w/o could be identified that led to major shifts in early leadership (figure 4).

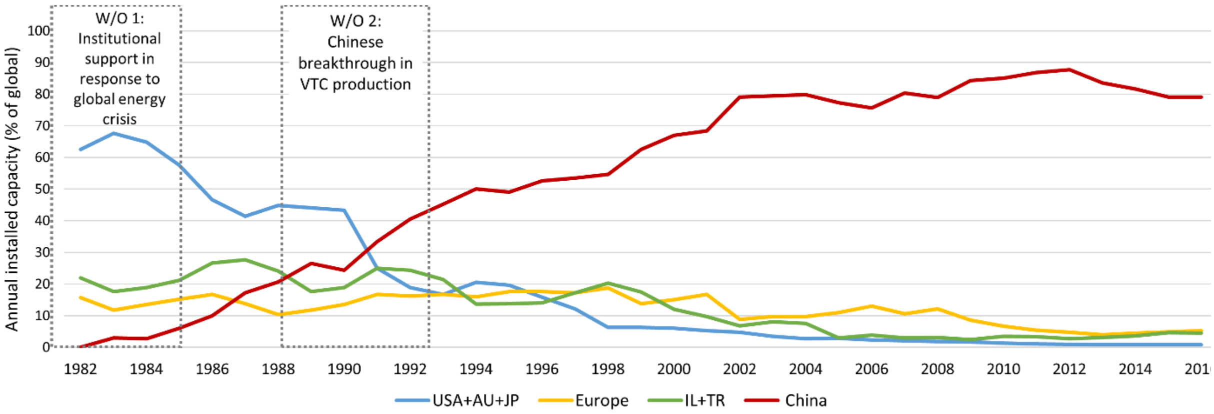

Figure 4: Global installation shares and w/o for catching up in the solar water heater industry. Data sources: Compiled from IEA Solar Heating & Cooling Programme (2018): Solar Heat Worldwide, several annual editions used. Note: Europe = EU+CH+Norway, EU members are different in different years.

Before the 1970s, the US was the world’s manufacturing centre of SWH, particularly in unglazed collectors for use in e.g. swimming pools. A first (institutional, as well as market and technology-driven) w/o opened following the global oil crisis in the 1970s. SWH systems were widely encouraged by Western governments and supported through subsidies (e.g.

Germany, Austria, Greece) or mandatory deployment regulations (e.g. Israel). Companies sprung up to fill the demand for SWH equipment, and many countries boosted investment in solar thermal research. Two different designs for solar collectors existed in this era of ferment, flat plate collectors (FPC) and vacuum tube collectors (VTC). In the 1980s, European companies took over global leadership from the US, largely focusing on FPC systems that subsequently became the dominant design (Epp 2008). However, due to the high cost of FPC systems, it remained heavily reliant on government subsidies, and did not result in strong global market growth.

A second w/o, driven by a technological breakthrough with concurrent market elements, opened in the early 1990s, when a Chinese innovation in VTC production technology significantly reduced the cost of SWH systems and enabled their mass manufacturing. Rapidly growing incomes and urbanization led to strongly increased demand for affordable residential hot water supply (Hu et al. 2012). Chinese manufacturers managed to largely capture this domestic market with their novel VTC products and thus China gradually became the dominating country in SWH production and installation.

In recent years, while the global market for single-family SWH systems is declining, new markets have opened for large-scale SWH installations in residential complexes, and for industrial processes and district heating. These markets are largely driven by solar and renewable building obligations in many countries.

4.3.2 Domestic capability formation mechanisms

The mechanisms that enabled Chinese catching-up were based on local capability and market formation, supplemented with foreign knowledge imports. Chinese research on solar thermal technologies started already in the late 1970s, with the establishment of solar energy research institutes, and support for solar research in top universities. In 1986, the Beijing Solar Research Institute imported a Canadian FPC manufacturing line. Private entrepreneurs recognized the potential market demand for low-cost hot water supply, and began to enter the SWH sector, by benefitting from FPC technology spill-overs from public research institutes. Yet, due to high cost of FPC systems and their ineffectiveness in cold winters, as well as the limited spending power of Chinese consumers at the time, the industry grew only slowly (Hu et al. 2012).

In the early 1990s, Tsinghua University made a substantial breakthrough in VTC technology and developed large-scale manufacturing equipment, which enabled the mass production of VTC SWH and significantly reduced its cost. Tsinghua University further hosted technology workshops to encourage its commercial application, leading to a flood of private entrepreneurs entering the industry (Yu and Gibbs 2018). In the following decades, the Chinese SWH market saw annual growth rates of around 30% (Wang and Zhai 2010).

At its peak, the domestic industry consisted of more than 3000 manufactures, mainly concentrated in Beijing, Shandong, Jiangsu, Zhejiang, and Yunnan (Hu et al. 2012). While most small manufacturers imitated and assembled simple SWH products, many large SWH firms continued to further improve the technology by establishing international R&D teams and cooperating with China’s top research universities. Himin soon became the world’s largest SWH manufacturer and attracted investment from international investors.

Chinese firms subsequently retained their leadership position in VTC innovation and manufacturing and now successfully export their products to international markets, such as South Korea and India, which heavily rely on China’s VTC technology.

4.3.3 **Supportive policy strategies**

Responding to the global energy crisis, China's early policy strategies in the SWH field focused on supporting some solar thermal research in public research institutes and universities through national S&T projects (e.g. Project 863). As the VTC technology matured in the early 1990s, this research support basically ended. For a while, the SWH industry was viewed as an ordinary low-tech household appliance, rather than a strategic green industry, so market-pull was the main driving force. Only at the local level (i.e. in Shandong province) were some SWH enterprises listed in the high-tech enterprise catalogue by local governments and thus enjoying some preferential policies (Hu et al., 2012).

When China's Renewable Energy Law took effect in 2006, the environmental value of SWH was rediscovered and national and local policies were initiated to support the SWH industry again, this time mainly focusing on expanding the domestic market. In 2007, China's Medium and Long-Term Plan for Renewable Energy (2007-2020) set specific targets for SWH: a total heat collecting area of 300 million m^2 to be installed by 2020. Institutional and market w/o further opened when China subsidized SWH purchase in the rural market between 2009 and 2012, and many cities mandated the integration of SWH into urban new residential buildings. Though with many implementation barriers, these deployment policies enabled the industry to significantly scale up in the urban market.

4.4 Membrane bioreactors

Membrane-Bioreactor (MBR) technology represents a market anchored GIS, with an STI-based innovation mode and customized valuation system. It is an advanced filtration process for wastewater treatment and reuse. Innovation for its key components, hollow-fibre or flat-sheet membranes, depends on lab-based experimentation and advances in highly formalized basic material sciences (Binz et al. 2014). The markets for MBR-based treatment systems in turn strongly depend on local discharge standards or environmental policies. Each MBR plant is essentially a 'one-off' design that gets tailored to customers' specific needs and local physical conditions.

4.4.1 Global industry evolution and w/o for catching up

Figure 5 shows that the early industry evolved in two consecutive w/o, leading to co-existence of leadership, similar to the wind power case. The global MBR market was strongly dominated by the US, Japanese, and European firms until the early 2010s, when Chinese firms leapfrogged in terms of market shares. Although Chinese MBR firms are mainly serving the country's domestic market, while US and Japanese firms retain significant shares in their home regions, Chinese firms have also been gradually increasing their exports to international markets in recent years.

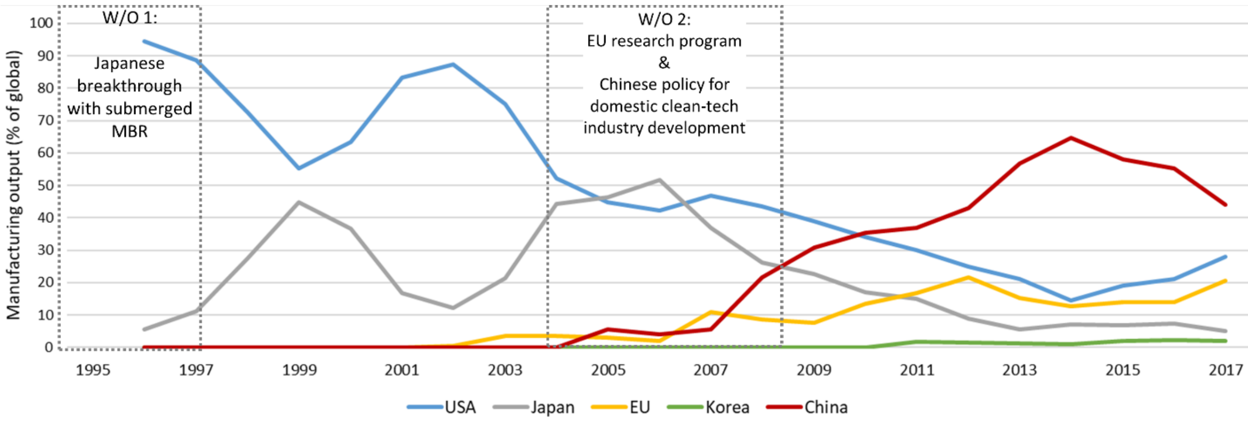

Figure 5: Global evolution of manufacturing shares and w/o for catching up in the membrane bioreactor industry. Data sources: The MBR Site (2018). Online overview of municipal wastewater treatment plants, retrieved from https://www.thembrsite.com/largest-membrane-bioreactor-plants-worldwide/ & https://www.thembrsite.com/interactive-map-history-of-municipal-mbr-installations. With revisions for membrane suppliers for Chinese projects based on interviews. Note: 3-year running averages of market shares to reduce erratic shifts.

The global development of the MBR industry can be traced back to an invention in the US in the mid-1960s, when flat-sheet ultrafiltration plates were first utilized in a sewage filtration plant (Radjenović et al. 2008). Initially, the technology was only viable in industrial niche markets. A first technological and institutional w/o emerged in the late 1980s, when the

Japanese government funded an initiative to develop better solutions for wastewater treatment. Yamamoto et al. (1989) created a major breakthrough by introducing membranes directly into conventional wastewater treatment processes. This 'submerged MBR' system subsequently diffused into European, Japanese, and the US markets for industrial and municipal wastewater treatment (Sutherland 2010).

In the early 2000s, an institutional w/o emerged in the EU that drove technological and market development of MBR. The European Commission funded a substantial RD&D program for MBR technology, which involved universities and firms from 12 different countries and subsidized various experimental pilot plants. From the mid-2000s on, a hype for MBR technology applications swept through the US, European, and Japanese markets, and Korean and Chinese firms first entered the industry. In the early 2010s, a dominant product architecture emerged around submerged, hollow fibre membranes and Chinese MBR companies quickly obtained the largest manufacturing shares in the world for such systems (see Figure 5). As of 2017, Chinese firms contributed to 60% of the treatment capacity in the world's top 50 largest MBR plants[2] by catering mainly for the domestic market.

4.4.2 Domestic capability formation mechanisms

Capability formation in the Chinese MBR industry relied crucially on the strategies of key firms to endogeneize a global w/o that emerged around the increasing demand for clean water. Instead of just responding to exogenous drivers, private entrepreneurs proactively shaped the domestic selection environment to create new criteria and expectations that lead to a rise in demand for MBRs inside China (Yap and Truffer 2019).

In the early 2000s, following some basic science grants under the National 863 project,

[2] m^3 per day; own calculations

Tsinghua University was collaborating closely with a Japanese MBR company. A Chinese company - Beijing Origin Water - , which was part of the research team, seized the opportunity to reverse-engineer the then most advanced foreign technology. Meanwhile, new actors entered the industry, including Tianjin University, a Shanghainese company (SINAP), and Tongji University.

However, the growth of the Chinese MBR industry did not really take off until a network of key actors (i.e. Origin Water, Tsinghua University, Beijing Design Institute, the MBR alliance, and more informal actor coalitions) began to shape MBR as the preferred choice in the Chinese urban water management sector (Yap and Truffer 2019). When the central government decided to showcase high-tech water reuse solutions during the Beijing Olympics in 2008, Origin Water articulated that their product offered the most promising technology and so the first Chinese large-scale MBR plant was built.

In subsequent years, the key industry actors continued to lobby the central government to increase national wastewater discharge standards to a level that could be achieved almost exclusively by MBR systems. Since the early 2010s, Origin Water, together with Tsinghua University and Beijing Design Institute, instigated the process of formulating domestic MBR product standards, ensuring that these standards matched their own capabilities whilst eliminating smaller competitors (Yap and Truffer 2019). These industrial and technical standards fuelled innovative activities towards new design for MBR systems with much lower costs. In consequence, the Chinese MBR industry achieved a dominant design and exponential growth and reached its peak around the mid-2010s.

The relevant capability formation mechanisms depended on the absorption of external inputs in the science system, combined with extensive experience-based experimentation in the booming Chinese market. Lobbying national policy makers created large test-beds for Origin Water to build up their technological capabilities while learning about the institutional complexities of the water recycling field. While Origin Water grew to be the monopolist in the Chinese MBR market, the selection environment institutionalized by firms and the government have allowed also smaller companies to be increasingly competitive in the global market, including Tianjin Motimo and SINAP. Today, Chinese MBR companies have achieved advanced capability levels and are able to treat China's particularly heavily polluted wastewater streams, allowing them to offer one of the most advanced MBR systems available in the market today.

4.4.3 Supportive policy strategies

The innovation policies in place for MBR date back to the National 863 project in the early 2000s. However, initial support was rather superficial by encompassing a broad range of innovation areas. More targeted policies for supporting the MBR industry in China came in the mid-2000s, when the Chinese government began mandating strong visions to achieve technological catch-up and environmental sustainability simultaneously. Conforming to that, policy makers and local governments increasingly favoured high-tech solutions like MBR over conventional solutions for addressing water challenges.

Environmental policies and regulations played a decisive role in facilitating Origin Water's strategies to create domestic demand for MBR. In particular, by mobilizing public concerns and promising new future visions, Origin Water and the other key actors were able to persuade national policy makers to impose highly demanding wastewater discharge standards (Yap and Truffer, 2019). The enforcement of these standards led to both a surge in domestic demand for MBR and a quick upgrading of local capabilities.

5 Conclusion & discussion

5.1 Catch-up dynamics in the four GIS industry types

This paper aimed at creating a taxonomy of catch-up cycles in the early industry formation phase of various 'green' industries. Our conceptual framework and the above results now allow us to systematize and explain the observed differences in a theoretically grounded way. Here we discuss these differences along the propositions outlined in section 2.4.

Table 3: Overview of empirical results

Results	Solar PV	Wind	Solar water heaters	Membrane bioreactors
RQ 1				
Time between leadership changes	<10 years	>25 years	15-20 years	15-20 years
Spatial reconfiguration	Radical shifts in leadership (From US/JP to EU, then CN)	Co-existence of leadership (between firms in EU, US, CN)	Radical shift in leadership (EU/US to CN)	Co-existence/ persistence of leadership (US, JP, EU, CN)
RQ 2				
Capability upgrading strategy	Import & embedding of external technology, born global firms	Licensing, M&As, local learning by doing, using & interacting	Collaboration with local universities, 'bricolage' in domestic market	Global research collaboration, proactive domestic market formation
RQ 3				
Policy approach	Generic policy support in high-tech export zones, followed by deployment and investment support	Dedicated & concerted catching-up strategy drawing on local content requirements and technology test beds	Unintended outcome of strong market dynamics and R&D policies, especially in Eastern provinces	Dedicated lead market strategy, drawing on highly demanding water quality standards & winner selection

The results summarized in table 3 and figure 6 indicate that the first and second proposition are largely confirmed by our results. The industry with the most footloose GIS type (solar PV) experienced the shortest-paced early leadership changes (<10 years), which were furthermore most disruptive to the early pioneers. The industry with the spatially most sticky GIS type (wind power), in contrast, developed in the most stable trajectory, in which several w/o accumulated over more than 25 years, yet without leading to disruptive leadership changes, even several decades after industry entry by latecomer countries. The two other cases lie somewhat in between these two extremes. The SWH industry experienced one radical shift in industry leadership, followed by persistent leadership of Chinese firms, while in the MBR case, latecomers from China achieved a co-existence of leadership position after considerable market formation and w/o endogeneization inside China. Overall, the emerging green TEP thus seems to have created the most disruptive catch-up patterns in clean-tech industries with a footloose GIS configuration. Industries with sticky elements in either the innovation mode, valuation system, or both, appear more prone to persistency or coexistence of early leadership.

The second proposition on mechanisms for capability upgrading could also be supported, though with some qualifications (Figure 6). Again, the PV and wind cases support the proposition most clearly: many successful PV start-ups in China and other latecomer countries used a dedicated 'born global' strategy to profit from innovation system resources available in the industry's highly internationalized innovation system structure. In the wind power industry, a significantly slower and more incremental 'localized learning' strategy was required in order to effectively catch up, with gaps remaining between Chinese capabilities and the global technological frontier. Latecomers in the MBR industry proactively created (and profited from) a dedicated 'lead market', in which technological capabilities and market expertise could co-evolve. The SWH case, finally, diverges from the theoretical propositions to some degree, since international exchanges in the science system, combined with DUI-based learning in a largely unregulated market - and not as expected collective learning in manufacturing clusters - seemed most decisive for explaining China's fast catching-up.

The third proposition relates to the policy approach chosen and its effectiveness in supporting catching-up. Here, our results first and foremost reveal remarkable variation and flexibility in the observed policy mixes. Rather than applying a one-size-fits-all policy approach, Chinese latecomer firms profited from support policies that were adapted to each industry type in an evolutionary and iterative policy learning process. Our proposition is supported in the sense that the wind power and MBR industry (both with strong needs for product customization) profited strongly from demand-side policies like local content requirements, public procurement, or the creation of local niche markets. The SWH and PV industries in turn, profited more from supply-side policy support like embedding Chinese firms in international R&D networks, liberal trade and export support policies, as well as industry-university linkages in nationally funded research projects.

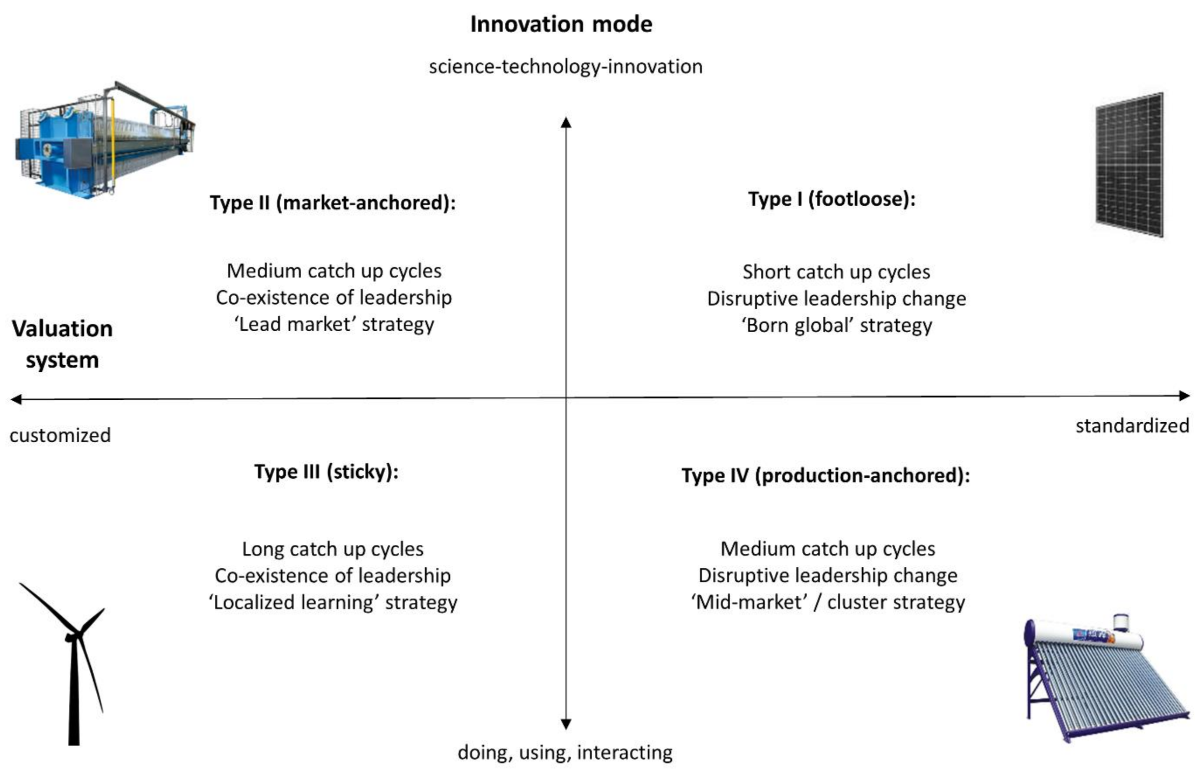

Figure 6: Main results on the effects of different GIS configurations on early catch-up dynamics and effective policy interventions

5.2 Similarities in the w/o and catch-up dynamics among the four cases

Apart from these generic differences, our findings also point to some striking similarities across the cases. First, generic policy guidance was of decisive importance in all four cases, and in particular for industries with a DUI-based innovation mode. We thus confirm the literature on catching-up in green sectors, that this element is of key importance in the early industry formation and localization phase (Schmidt and Huenteler 2016, cf. Lema et al. this issue). Providing stable policy guidance (i.e. through 5-year plans) is one of the hallmarks of the Chinese governance system. While liberal democracies may struggle more with this issue, there might be other means to provide such meta-guidance, i.e. through the establishment of R&D and deployment policies that are implemented in a long-term policy framework (like the FIT system) that is somewhat resistant to short-term fluctuations in the political landscape (Hoppmann et al. 2014).

A second generic insight emerging from this comparison is that early catch-up dynamics are more disruptive in industries with standardizable products and market structures. Our results show that Chinese industry entry had the more dramatic effects on incumbents, the more standardized a technology's *valuation* system could get. In the PV and SWH cases, products could get highly standardized and exported to foreign mass markets, which is less the case in the wind power and MBR industries. China arguably has a comparative advantage in industries with mass-producible characteristics (Nahm & Steinfeld, 2014), while its innovation policies seem less effective in industries with customized valuation systems and more systemic innovation problems. Other latecomer countries could profit from this, as the key challenge for early catching-up in industry types with customized valuation systems (wind power, water recycling, etc.) is establishing a high-quality domestic, and not necessarily a high-volume export market.

Third, we could show that bottom-up and transnational entrepreneurship plays a key role in all four cases. Chinese firms appear to be particularly skilful in mobilizing innovation-related resources not only inside the country, but also in wider international networks. China is particularly well positioned to conceive of the global opportunity set thanks to its large diaspora and high enrolment numbers of Chinese students at overseas universities. Other latecomer countries could emulate this approach by supporting the global mobility of students and industry experts in strategically selected emerging (green) industries.

5.3 Needs for further research

A first caveat of our analysis is the strong focus on catching-up processes in China. While China emerged as a key focal area from our global analysis, it may well be that some of the observed mechanisms are particular to China's socio-political context and its particularly huge market. I.e. all four industries experienced a boost around the years 2004-2006, which coincides with the formulation of the renewable energy law and related policy changes in China. This shift of policy priorities at the top may have stronger guiding effects in the Chinese political system, than in other, more liberal and democratic varieties of capitalism. Other latecomers looking to emulate some of China's catching-up strategies should thus not directly copy the concrete (policy) instruments, but use our framework to develop industry-specific support policies that are tailored to the industry's GIS type and specific local context conditions.

Second, we have provided a rather rough characterization of industries' GIS types, in particular for industries with complex value chains. Since innovation processes in many industries differ between different parts of the value chain, more fine-grained analysis would be needed that analyses the innovation mode and valuation systems separately for the upstream, core and downstream parts of the relevant global value chains (see e.g. Malhotra et al. 2019). Also a more fine-grained analysis of the specific timing of the opening of w/o and early leadership changes would be warranted in future research (Bell 2006).

Third, an in-depth analysis of the potential for latecomer countries (beyond China) to 'endogeneize' green w/o remain largely absent from the catch-up cycle literature. The evidence provided suggest that a deeper examination of these dynamics may be a fruitful avenue for future research (see Yap and Truffer 2019). Lastly, we encourage research that would apply our heuristic to other emerging industries, in particular beyond clean-tech, to further validate and refine the key conceptual ideas.

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