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Published in:
Industrial and Corporate Change

DOI:
10.1093/icc/dtaa008

2020

Document Version:
Peer reviewed version (aka post-print)

THIS IS THE POST-PRINT VERSION OF THE PAPER NOW PUBLISHED AS

Hansen, T. & Hansen, U.E. (2020): How many firms benefit from a window of opportunity? Knowledge spillovers, industry characteristics and catching-up in the Chinese biomass power plant industry. Industrial and Corporate Change, in press

How many firms benefit from a window of opportunity? Knowledge spillovers, industry characteristics and catching-up in the Chinese biomass power plant industry

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Abstract

The literature on the catching-up of latecomer countries has pointed at windows of opportunity as a precondition for catching-up. Previous research has however failed to illuminate the determining factors affecting the number of firms benefitting from windows of opportunity. The current paper addresses this gap by combining insights on the nature of knowledge spillovers with sectoral characteristics. This perspective is applied empirically by analysing the number of firms benefitting from a 'green' window of opportunity in the Chinese biomass power plant industry, specifically related to changes in the institutional framework conditions in the form of a feed-in tariff and specified targets for renewable energy. The paper finds that while a single Chinese firm constituted the initial phase of the catch-up cycle, domestic knowledge spillovers allowed a larger number of Chinese firms to benefit from the window of opportunity in the later stage of the catch-up cycle. The paper points at the importance of combining sectoral characteristics with the degree of domestic knowledge spillovers as key determinants for the number of firms profiting from windows of opportunity.

Keywords

Windows of opportunity, catching-up, knowledge spillovers, China, latecomers

JEL classifications

O31, L60, R58, F23

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1. Introduction

Technological catch-up by emerging and developing economies is an essential empirical characteristic of current capitalism. This calls for theory development in relation to the causes and preconditions for catching-up. Building on previous contributions from the catching-up literature (Bell and Pavitt 1992; Lee and Lim 2001; Fu et al. 2011), Lee and Malerba (2017) propose a framework where catching-up and eventual changes in industrial leadership are conditioned by the opening of windows of opportunity relating to technological advances, changes in demand or modifications of institutional frameworks. Essentially, such discontinuities may change the playing field to the advantage of latecomers *vis-à-vis* incumbents.

As evident from the title of Lee and Malerba (2017), the framework considers the responses of *"firms and countries"* to windows of opportunity. Thus, catching-up and eventual changes in industrial leadership from one country to another happens when global market shares and technological superiority change from firms based in one country to firms based in another. Empirically, it has been shown that such changes are driven by highly varying numbers of firms (Lee and Malerba 2017): to exemplify, catching-up in the wine industry depends on a very large number of producers (Morrison and Rabellotti 2017), while catching-up in the steel industry relates to single firms (Lee and Ki 2017). As argued by Lee and Malerba (2017, p. 339): *"[d]epending on the size and characteristics of a sector, this leadership may imply a large or small number of firms".* Accordingly, catching-up in capital-intensive industries, such as steel, may involve a limited number of firms due to the high entry barriers associated with technology development and production. In contrast, catching-up in the agricultural sector and in the assembled goods industries may involve a substantial number of local producers. However, there is a need to further unpack the relations between country, industry and firm catch-up. Such insights are needed in order to improve the understanding of how the sectoral specificities, in particular capital intensity of core technologies, the modes of learning and innovation, and the characteristics of demand, matter for the number of firms benefitting from a window of opportunity.

In the current paper, we address this issue by complementing the framework on windows of opportunity with insights from the literature on knowledge spillovers. We posit that the number of firms involved in catching-up processes not only depends on the characteristics of the sector in question, but will also be influenced by the domestic conditions for knowledge spillovers. In short, whether the catching-up process of a country depends on a large or a small number of firms will also depend on the degree to which the knowledge necessary for taking advantage of a window of opportunity diffuses domestically. Consequently, the research question guiding the paper is formulated as follows: *how do sectoral characteristics in combination with domestic knowledge spillover influence the number of firms benefitting from* windows of opportunity?

Empirically, we study changes in the industry developing and producing biomass power plants.[i] In particular, we focus on the latest window of opportunity caused by recent developments in the Chinese institutional frameworks in the field of energy, specifically the adoption of feed-in tariffs and specified targets, which have resulted in rapid catching-up of Chinese firms. The paper thus covers what according to Lema et al. (2019) may be considered a 'green' window of opportunity as it pertains to latecomer catch-up caused by changes in framework conditions in the field of renewable energy, as an example of a prominent green technology sector. Given the significant capital intensity, our expectation would be that catching-up in the biomass power plant industry depends on a very limited number of firms. Indeed, our analysis highlights that a single Chinese producer constituted the initial phase of the most recent catch-up cycle.

However, a significant level of knowledge spillovers between this company and other domestic firms in related industries implied that the number of Chinese firms profiting from the window of opportunity increased significantly in the later stage of the catch-up cycle. Thus, the analysis underlines how the degree of domestic knowledge spillovers influences the number of firms profiting from a window of opportunity.

The remainder of the paper is structured as follows: section 2 presents the theoretical framework and section 3 introduces the research methods. Section 4 analyses the window of opportunity that allowed China to catch up in the biomass power plant industry. Sections 5, 6 and 7 examine the catching-up of Delta and Chinese domestic competitors, as well as the role of knowledge spillovers from Delta. Sections 8 and 9 contain discussion and conclusion.

2. Theoretical framework

In this section, we elaborate the conceptual framework adopted in this paper, which draws on a combination of the windows of opportunity perspective and insights from the technology transfer literature on spillover from foreign direct investments.

2.1. Windows of opportunity for catching-up

The literature on the catching-up of firms and industries in developing countries has a long history dating back to studies on the economic development of Japan and the east Asian miracle during the 1980s and 1990s (Abramovitz 1986; Amsden 1989; Hobday 1995; Kim 1997; Mathews and Cho 1999). Building on this literature and the sectoral systems of innovation framework (Malerba 2005), Lee and Malerba (2017) define three types of windows of opportunity that may allow latecomer countries to catch up: (i) technological window; (ii) demand window; and (iii) institutional window. Technological windows include the entry of latecomers into newly created industries emerging as part of a transition from one technological systems to the next, such as from analogue to digital means of communication. Demand windows refer for example to a new type of demand, a major change in the local demand structure or a business cycle. Institutional windows denote changes in public policy and institutions at the national level aimed at supporting domestic firms, such as provision of subsidies, R&D programs, tax reduction, export support, regulations and standards. Latecomers may benefit from such windows of opportunity in order to enter and gain a stronger position within an industry, leading them to catch-up and potentially overtake the position of incumbent industrial leaders. Recently, the concept of 'green' windows of opportunity has been suggested to delineate a new techno-economic paradigm for latecomer catch-up specifically related to the emergence of 'green technologies', such as renewable energy (Lema et al. 2019). In contrast to the sectors covered mostly in studies on latecomer catch-up, such as automobiles, electronics, and steel, green technologies involve a greater degree of directionality as their development paths are steered by polices aimed to addressing environmental problems, such as climate change (Romijn and Caniëls 2011; Grillitsch and Hansen 2019). According to Lema et al. (2019), this implies that green windows of opportunity are often created or at least strongly influenced by governments and are thus likely to be institutional in nature.

Lee and Malerba (2017) suggest that catching-up may imply a large or small number of firms. However, the literature has so far given little attention to the factors that influence the number of firms that catch-up under a window of opportunity, and how this might change over time. We follow Lee and Malerba (2017, p. 339) in suggesting that the *"characteristics of a sector"* will influence the number of firms catching-up. Key sectoral characteristics include the capital intensity of core technologies, the modes of learning and innovation, and the characteristics of the demand. These characteristics are central since they have been found to condition innovation dynamics in different sectors – they significantly influence the ways sectoral innovation systems function (Malerba 2005). Sectors producing capital-intensive goods typically involves a limited number of firms, while assembled goods industries often involves numerous firms (Pavitt 1984; Castellacci 2008). The dominant modes of learning and innovation also differ between sectors, ranging from a focus on production and use of scientific and technical knowledge (Science, Technology and Innovation – STI), to learning through experiences and problem-solving (Doing, Using and Interacting – DUI) (Jensen et al. 2007). Finally, sectors are characterised by demand-side differences, ranging from one-of-a-type products to mass markets (Binz et al. 2017).[ii]

In the current paper, we analyse the biomass power plant industry, which is characterised by high capital-intensity, an emphasis on the DUI mode of innovation and learning, and a demand for one-of-a-type products. Given these characteristics, the industry is likely to consist of a limited number of firms. As DUI learning is tacit and person-embodied, it typically takes time to accumulate experience and knowledge through inter-project learning. In the absence of such accumulated knowledge, the ability of biomass power plant suppliers to benefit from a window of opportunity may depend critically on access to knowledge from experienced personnel. Further, as the market for biomass power plants is characterised by few large-scale, custom-made products delivered on a turnkey basis by suppliers, the barriers to entry are relatively high (see Appendix A). The number of biomass power plant suppliers likely to benefit from a window of opportunity by ensuring a continuous flow of project contracts will thus be limited, compared to the number of firms benefitting from a window of opportunity in industries characterised by mass markets, which offer greater opportunities for growing organically from market niches.

While the sectoral specificities matter, we argue that to arrive at a more comprehensive understanding of the factors influencing the number of firms catching-up under a window of opportunity, and in particular how this might change over time, we suggest that there is a need to complement the focus on sectoral characteristics with attention to the contextual conditions, in particular the nature and degree of knowledge spillovers. Hence, whether the industrial catching-up of a country depends on a large or a small number of firms will also be contingent on the degree to which the knowledge necessary for taking advantage of a window of opportunity diffuses domestically. In the following section, we describe how domestic knowledge spillovers may influence the number of firms catching-up under a window of opportunity.

2.2. Knowledge spillovers

As a complement to the windows of opportunity perspective, we draw on literatures on branch plant economies and spillover effects of inward FDI. These literatures specify the key mechanisms through which spillovers from a focal firm may contribute to broader domestic industry development.[iii] At the one extreme, the focal firm may become firmly integrated into the economy and significantly contribute to the development of local or national clusters. At the other extreme, such focal firms may become enclaves operating in near isolation from the surrounding economy

(Arias et al. 2014; Phelps et al. 2015). Thus, as argued by Farole and Winkler (2014, p. 12) *"spillover effects often do not materialize automatically"* and there are no guarantees that the broader domestic industry will benefit from knowledge spillovers. However, in particular, four mechanisms are emphasized in these literatures – labor mobility, supplier relationships, demonstration effects and university-industry collaborations – which may impact whether few or many firms benefit from a window of opportunity.

Labor mobility

Thompson (2002) argues that labor mobility is a central mechanism through which a focal firm contributes to domestic industrial development. The expectation is that employees in the focal firm can develop competencies and subsequently use these skills in other domestic firms (Blomström and Sjöholm 1999; Smeets 2008). Learning by interacting with experienced colleagues may enable the exchange of tacit knowledge, which is particularly pertinent in sectors dominated by the DUI mode of learning and innovation. In such sectors, apprenticeship training can form a key part of acquiring the required craft. Supporting this argument, it has been pointed out that some focal firms invest relatively large amounts of resources in training and competence development compared to other domestic firms (Phelps et al. 2003), which is a key factor for domestic industrial development (Marin and Bell 2006). In industries characterised by project-specific products, such as the biomass power plant industry, employment may often be temporary in relation to specific projects, which means that the labor turnover ratio may be relatively high (Bredin and Söderlund 2011). However, positive effects on domestic industrial development cannot be taken for granted. First, the need for skilled labor in the focal firm cannot be taken for granted (Sonn and Lee 2012). Secondly, employees in high-skilled jobs do not necessarily stay in the country after their employment ends. Due to this, Phelps (2008) suggests that positive effects on labor mobility might be less significant today compared to a few decades ago.

Based on these insights, we suggest that more firms will benefit from a window of opportunity if, first, pioneering firms locate activities requiring high-skilled labor in domestic business departments rather than abroad, and second, that people, who are likely to stay in the country after their employment ends, fill these high-skilled jobs. We can further expect that labour mobility to be an efficient form of spillover of the tacit, person-embodied knowledge, which is essential in the biomass power plant industry.

Supplier relationships

A second important mechanism that may contribute to domestic industrial development is that the focal firm may have sophisticated demand, which pushes local suppliers to develop their competencies further (Crespo and Fontoura 2007; Hamida and Gugler 2008). In some cases, focal firms actively seek to stimulate this development by engaging directly with suppliers in an upskilling process (Saggi 2002; Javorcik 2004). Especially in industries, which produce tailored, capital intensive products such as the biomass power plants, the main technology suppliers often engage closely with their sub-component suppliers in projects, which run over long periods of time. Such producer-supplier interaction may facilitate the exchange of tacit knowledge and information, which may contribute to the upgrading of the local suppliers. However, again such impact cannot be taken for granted. Sonn and Lee (2012), for example, find mixed evidence of the importance of local backward linkages. Positive effects are found particularly when focal firms are relatively small and when the home government actively seeks to create local linkages and encourage a local supply chain. In other cases, focal firms may only engage with local suppliers for low value-added products and services, while interactive learning takes place with non-domestic firms (Giuliani 2008; Arias et al. 2014). Hence, engagement with local suppliers is not a given (Phelps 2009) and may depend critically on the nature of the sector and industry in question.

Based on these insights, we suggest that more firms will benefit from a window of opportunity if, first, local suppliers have sufficiently high competence levels to engage in fruitful interactions with pioneering firms and, second, these firms choose to source high value added inputs domestically. Specifically in the case of the biomass power plant industry, we can further expect that producer-supplier interaction will form a central part of domestic knowledge spillover.

Demonstration effects

Spillovers in the form of demonstration effects refer to knowledge flows accruing from direct copy and imitation by local competitors from their exposure to the more advanced technologies brought in by the focal firm (Blomström and Sjöholm 1999; De Fuentes and Dutrenit 2011). The literature suggests that such spillovers from a focal firm to the domestic industry may play an important role, but they do not happen automatically (Sonn and Lee 2012). Indeed, McCann and Mudambi (2005) suggest that the magnitude of such spillovers will generally be limited (see also Arias et al. 2014). In industries characterised by highly complex and large-scale products, such as the biomass power plant industry, direct imitation on the basis of visual inspection may be restricted due to enclosed nature of the system. Learning from reverse engineering as a form of knowledge spillover are also less likely in such sectors due to the highly capital intensive nature of the product. It has been suggested that a key factor explaining the extent of knowledge spillovers through demonstration effects is the gap in technological competence levels between the focal firm and the domestic industry (Kokko 1994; Blomström and Kokko 1998). Thus, in some cases domestic firms may have too low absorptive capacity to absorb the knowledge spillovers (Crespo and Fontoura 2007; Hamida and Gugler 2008). Consequently, Phelps et al. (2015) point out that knowledge spillovers will often be of greater significance nationally than locally, since the competence level of actors is a factor of greater importance than geographical proximity to the focal firm.

Based on these insights, we suggest that more firms will benefit from a window of opportunity if domestic competitors are sufficiently skilled to be able to absorb the knowledge spillovers from pioneering firms. Further, we may expect that demonstration affects may be less effective as a form of knowledge spillover in the biomass power plant industry.

University-industry collaboration

Finally, collaboration with domestic research organizations has been emphasized as an additional way in which a focal firm contributes to developing technological competencies in the domestic industry (Iammarino et al. 2008). The argument here is that a focal firm may stimulate the development of high-quality research environments, which can eventually support the development of absorptive capacity in domestic industry. Still, Phelps et al. (2003) question the extent to which university-industry collaboration plays an important role given that collaborations with domestic partners, including universities, in research, development and design activities are relatively insignificant compared to intra-corporate sources. However, as with the potential impact of relations with suppliers, it can be expected that the effect of university-industry collaboration on the contribution of a focal firm to the development of the domestic industry is highly contingent upon the quality of the domestic universities. In other words, a university that carries out excellent research is an interesting collaboration partner that may also be able to benefit from collaborating with the focal firm. Such university-industry knowledge spillover may however mainly be relevant in sectors characterised by the STI-mode of learning and innovation.

Based on these insights, we suggest that more firms will benefit from a window of opportunity if high-quality research of relevance to pioneering firms is carried out at domestic universities. Further, in industries dominated by the DUI-based mode of learning, such as the biomass power plant industry, the role played by university-industry spillover is likely to be limited.

3. Research methods

This paper analyses the case of the Chinese biomass power plant industry, focusing on a pioneering firm, Delta[iv], for its rapid development. As accounted for in sections 5 and 6, both Delta and the Chinese biomass power plant industry as a whole have utilized a recent window of opportunity to catch up to a prominent global position.

The analysis draws on different documentary sources on the development of the Chinese and global biomass power plant industry, including industry reports, papers in peer-reviewed journals, annual reports of biomass power plant producers and thirty interviews with current and previous representatives from Delta, industry experts and a biomass power project developer. Twenty-four semi-structured, face-to-face interviews conducted in 2012, 2013 and 2017 with employees of the Chinese biomass power plant producer firm, Delta, in its offices in Denmark, England and China constitute a central source of empirical material. Key selection criteria for the interviewees were that they should be well-informed on the development process of Delta and the general Chinese biomass power plant industry. Importantly, the interviewee selection was prepared to include the people most likely to be knowledgeable on the four spillover mechanisms, e.g. HR personnel (spillover mechanism: labor mobility) and personnel with responsibilities for component sourcing (spillover mechanism: supplier relationships). Interviewees included former and current employees of Delta and the selection also ensured to cover different levels and positions (ranging from top- to middle-management, as well as engineering and administrative personnel) and divisions in order to triangulate the data collected. Due to the sensitive nature of the topic, interviews with Delta’s competitors were unfortunately not possible. However, additional interviews were carried out with representatives of one of the largest biomass power project developers in China and industry experts with extensive knowledge of the Chinese biomass power plant industry. These interviews enabled information acquired in interviews with representatives of Delta to be verified, thereby avoiding potential bias and enhancing the reliability of the findings.

Interview guidelines were tailored to each interviewee; however, all interviews included questions concerning the development of Delta and the Chinese biomass power plant industry. Furthermore, drawing on literature on branch plant economies and spillover effects of inward FDI from developed country multinationals, questions were asked specifically addressing the spillover mechanisms. Table 1 provides example questions related to the four spillover mechanisms.

Table 1. Example questions addressing the four spillover mechanisms.

Spillover mechanism	*Example questions*
Labor mobility	- From which sources do you recruit new staff? - To what extent do you invest in competence development? - Is it difficult to retain employees? Where do they typically find employment afterwards? - Do you consider the level of staff mobility an advantage or disadvantage?
Supplier relationships	- How do you choose suppliers? - How extensive is your interaction with domestic suppliers on development of components? - Do you generally have a trustful relation with your suppliers? - Do your suppliers also supply competitors?
Demonstration effects	- How do you protect your innovations? - Do IPR violations take place? - Are IPRs enforced effectively?
University-industry collaboration	- How do you choose university collaborators? - How extensive is your interaction with domestic universities concerning research collaboration and other topics? - Do you generally have a trustful relation with your collaborators at universities? - Do your collaborators at universities also collaborate with competitors?

Interviews were recorded, transcribed and subsequently coded using the NVivo qualitative data analysis software. The interview material was coded using predefined categories based on the theoretical framework, but also allowing new themes to emerge during the coding process. To ensure reliability, the material was coded by two coders and the codes analyzed for inter-coder agreement. Generally, the inter-coder agreement was higher than 90%, which corresponds to a nearly perfect agreement (Hruschka et al. 2004). In the last phase of the research process, the importance of each of the spillover mechanisms for the development of the Chinese biomass power plant industry was analyzed. Representative quotes from the interviews, which illustrate the importance of each of the four spillover mechanisms, are compiled in Appendix B, allowing the results to be presented in the form of a coherent narrative.

In addition to the abovementioned interviews, four interviews were carried out with biomass power plant technology experts with extensive knowledge of the development of the global industry. These interviews aimed at identifying key indicators of levels of technological capability among biomass power plant producers. Contrary to other industries, where a single factor can be considered a suitable indicator of technological capability (e.g. turbine size in the wind turbine industry, Gosens and Lu 2013), the interviews revealed that this is not the case in the biomass power plant industry[v]. Rather, it was argued that combining the following six indicators provide a comprehensive description of technological capability levels at the firm level (see Appendix A for details): boiler steam temperature, boiler steam pressure, ability to internationalize, ability to undertake turnkey projects on EPC basis, ability to diversify, and ability to offer products with state of the art components.

Thus, in addition to market share, which is traditionally used in windows of opportunity studies, these six indicators are used to assess the potential catching-up of Delta and the Chinese biomass power plant industry as a whole in the subsequent analysis. We examine the specifications of 236 plants constructed by Delta and other Chinese biomass power plant producers provided in Gosens (2015) in relation to plants recently completed by European producers, which were identified by the interviewed experts as the leading incumbents[vi].

Table 2 provides an overview of how our two central theoretical constructs, catching-up and spillover mechanisms, have been operationalized, the basis for their operationalization, the core data and the data analysis strategy.

Finally, we make use of Lee and Malerba (2017) suggestion to use the share of China in the global market for biomass power plants in order to assess the extent to which China as a latecomer country has caught up with leading incumbent countries. Accordingly, we assess the respective share of China in the total installed capacity of grid-connected biomass power plants constructed globally over time. This assessment draws on available country-level data taken from various reports and international agencies monitoring renewable energy market development.

Table 2. Central theoretical constructs.

Theoretical constructs	Operationalization	Basis for operationalization	Core data	Analysis of data
Catching-up	Boiler steam temperature	Four interviews with biomass power plant technology experts	Quantitative data collected from various sources including reference lists of firms, the IEA Bioenergy Task 32 database, interviews with industry experts and Gosens (2015)	Preparation of figures showing development in boiler steam temperature and pressure over time; comparison between leading incumbents and, respectively, Delta and Chinese competitors
	Boiler steam pressure			
	Ability to internationalize		Firm webpages, annual reports and reference lists; industry news sources	Comparison of speed in ability to internationalize, undertake turnkey projects on EPC basis and diversify, between leading incumbents and, respectively, Delta and Chinese competitors
	Ability to undertake turnkey projects on EPC basis			
	Ability to diversify			
	Ability to offer products with state of the art components		UNFCCC project design documents, interviews with industry experts	Comparison of plant specifications concerning key components for incumbents and, respectively, Delta and Chinese competitors
	Market share	Lee and Malerba (2017)	Twenty-six interviews with current and former Delta employees and Chinese industry experts	Coding and analysis using the NVivo qualitative data analysis software
Spillover mechanisms	Labor mobility	E.g., Saggi (2002), Smeets (2008) and Thompson (2002),	Twenty-six interviews with current and former Delta employees and Chinese industry experts	Coding and analysis using the NVivo qualitative data analysis software
	Supplier relationships	E.g. Crespo and Fontoura (2007), Javorcik (2004) and Wang and Blomström (1992)		
	Demonstration effects	E.g. Blomström and Sjöholm (1999), Blomström, Kokko and		

	Mucchielli (2003) and De Fuentes and Dutrenit (2011)		
University-industry collaboration	E.g. Iammarino, Padilla-Pérez and von Tunzelmann (2008) and Phelps, Mackinnon, Stone and Braidford (2003)		

4. Rapid catching-up of China – an institutional window of opportunity

Until recently, the leading countries in terms of total installed generating capacity from biomass power were located in Europe, such as Denmark, Germany and Sweden and North America including the United States and Canada. As a corollary, the development and production of biomass power plants has at least since the 1980s been dominated by lead firms from these countries (Hansen et al. 2016). However, during the last 10-15 years there has been a remarkable increase in the number of biomass power plants constructed in emerging economies, such as China, Brazil and India. In China, in particular, the total installed generating capacity of biomass power has increased from zero in 2005 to around 5,300 MW in 2015 (Gosens et al. 2017). In comparison, the total accumulated installed generating capacities of biomass power in 2016 were around 5,600 MW in the UK and 7,600 MW in Germany. Accordingly, China has increasingly been catching-up with the traditionally market-leading (incumbent) countries in a period of only around ten years: the leading countries in terms of electricity generation from biomass were in 2015 the United States (69 TWh), Germany (50 TWh), China (48 TWh), Brazil (40 TWh) and Japan (36 TWh) (REN21, 2017). Importantly, all of the Chinese biomass power plants have been constructed exclusively by Chinese technology suppliers, who have also increasingly moved into export markets in developed and developing countries (see below). Consequently, the global market share of Chinese producers has increased remarkably, and they are, thus, today sharing global leadership with Western producers. The majority of the Chinese biomass power plants are owned and operated by a relatively small group of project developers in China, including the National Bio Energy Company Ltd., Wuhan Kaidi Electric Power Company Ltd. and China's big state-owned power companies (Xingang et al. 2012; Gosens 2015)

The rapid catching-up of China in the biomass power plant industry should be viewed against the background of a general increase in domestic energy demand, which has opened up opportunities for a wide range of energy-related industries in China. However, the take-off of the industry was closely connected to the first renewable energy law in China adopted in 2006 (Lu and

Zhao 2013), which included a favourable electricity feed-in tariff for biomass power plants of RMB 0.25/kWh (US₵3.7/kWh), added to a province-specific coal price. Further, an ambitious target of 24GW was set for biomass energy by 2020, which was, however, significantly reduced in later five-year plans (Gosens et al. 2017). The introduced biomass tariff was approximately double the coal tariff, thus providing strong incentives for investments in biomass power plants. Subsequently, in 2010 the biomass tariff increased to RMB 0.35/kWh (US₵ 5.2/kWh) and again in 2012 to RMB 0.75/kWh (US₵ 11.1/kWh) (Hao and Luo 2012). These changes in the institutional framework conditions in the Chinese energy sector reflect what Lema et al. (2019) define as a green window of opportunity, which involves favourable but time-bound conditions for latecomer catch-up arising from changes in institutions, markets or technologies associated with the green transformation.

As emphasised by Lee and Malerba (2017, p. 345), *"windows can be exogenous or endogenous, depending upon responses by the various actors of a sectoral system"*. In the current case, the window of opportunity was largely created endogenously, as representatives from the industry pioneer firm Delta greatly influenced state officials and decision makers in drafting the initial policies and regulations, which were instrumental to the wider industry development (Binz et al. 2017). As explained by a Delta manager, (Christensen 2015, p. 113, our changes in italics) "*[t]*here were people within our organization who were actually involved in drafting, commenting on the Renewable Energy Law… the creation of the law, which gives… it is for any company who would qualify for it, but we were… at the inception of the creation of an industry [biomass] in China [when] we made *[Delta]*…" Furthermore, Delta was reportedly also directly involved in establishing the feed-in tariff, and in ensuring the subsequent upward adjustments that were vital for the catch-up of the industry (Christensen 2015).

In the following two sections, we decompose the catching-up processes of Delta and domestic competitors. This highlights how an increasing number of firms profited from the opening of the window of opportunity.

5. Catching-up of Delta[vii]

Delta was established in Beijing in 2004 as a biomass power plant producer company by a Chinese-Swedish entrepreneur with a background in a large international company. At that time, no biomass power plant existed in China, and coal-fired power plants dominated the energy sector. Consequently, there was generally very limited experience with biomass power plant engineering and related technologies in China.

To take advantage of the window of opportunity, which Delta managers were themselves instrumental in creating, Delta entered into licensing agreements with two world-leading biomass power plant suppliers in Denmark to acquire the necessary technology. The licensed technologies comprised principal drawings of power plants designed to operate on wood chips and straw firing. Using the wood chip-firing design, Delta's first power plant started commercial operation in 2006, becoming the first ever biomass-fired power plant in China. Subsequently, in 2007, Delta made two strategic acquisitions: it acquired a Danish company specializing in the design and manufacture of high-pressure boiler components and a Chinese boiler component production workshop. The Danish investment follow the trend in outward FDI by EMNCs, which is characterized by frequently being motivated by acquiring strategic assets, such as cutting-edge technology, knowledge (including tacit know-how), R&D competencies, brands and management expertise (Rui and Yip 2008; Deng 2012; Ramamurti 2012; Amighini et al. 2015; Anderson et al. 2015). These investments were intended to improve the quality of the boiler components and the performance of the power plants constructed by Delta. Thus, employees from the acquired Danish company trained and supervised Chinese plant managers and shop-floor workers in welding operations, quality and control procedures and general plant management. These knowledge-transfer efforts resulted in significant improvements in plant efficiency and boiler quality, which eventually led to the certification of the Chinese workshop according to European standards.

After construction of the first plant in 2006, Delta expanded rapidly in terms of additional plants constructed and workforce expansion. By 2009, Delta had put twenty biomass power plants into operation, with a further ten plants under construction and thirteen at the planning stage. The technical department of Delta in Beijing had grown to thirteen engineers and was expanding further, including a new R&D unit.

However, plants constructed by Delta proved to underperform, resulting in lower profits than expected. The management concluded that strengthening the engineering capacity and innovative capability of engineers in the Chinese technical department was vital to circumventing this problem. Another strategic asset seeking acquisition in 2009 of one of the Danish licensor companies mentioned previously was intended to play a key role in this respect, as it secured full access to 'state-of-the-art' technology and engineering know-how. The acquisition involved the attainment of relevant IPR and the buyout of around 25 key technology employees, who were transferred to Delta's newly established European engineering office in Denmark. Strengthening the Beijing technical department through the acquisition was achieved through a planned process of knowledge exchange between Danish and Chinese engineers. This process resulted in improvements in the ability of the Chinese engineers to engage in basic engineering tasks and related tools (e.g. modelling combustion processes), which led to plant performance improvements. High-complexity innovation tasks, however, remained the responsibility of Delta's Danish engineering department.

By 2012, Delta had constructed fifty biomass power plants, with a further thirty under development. Concerning the first indicator of technological capability, namely boiler temperature, Delta has been able to construct boilers operating at 540°C since the end of 2006, and subsequently maintained this high temperature level in almost all other plants put into operation. This compares very well with the specifications of plants constructed by European incumbents (see Appendix C), as the majority of plants operate at lower steam temperatures than Delta's plants, and only three plants operate at slightly higher temperatures.

Second, with regard to steam pressure level, the majority of plants constructed by Delta are 30MW plants operating in the range of 9.2-10MPa. One slightly larger plant (35MW) operates at

11.2MPa. These steam pressure levels are fully comparable to those in plants recently constructed by European incumbents in the same size range (see Appendix C).

Third, concerning the level of internationalization of activities, Delta has expanded rapidly across several continents. While Delta's Beijing office now has a hundred employees with around forty technical staff employees working in the engineering department, three additional engineering centers and two manufacturing workshops are found in Poland and the UK respectively. Delta has also established regional offices in other parts of Asia and has started competing for contracts in these regions with incumbent technology suppliers in the industry. Thus, in addition to China and Europe, Delta currently has projects under development in the US, Canada, Australia, Africa and across Asia.

Fourth, in recent years Delta has started winning projects as total plant provider under EPC contracts in foreign markets, including Europe. The ability of Delta to win such EPC contracts in Europe in competition with incumbent technology and industry lead firms is clear evidence of Delta's competitive strength.

Fifth, Delta has diversified into new technologies such as waste-to-energy plants and bioethanol production equipment, and subsequently acquired an Austrian waste management technology provider in 2018.

Sixth, power plants constructed by Delta have included cutting-edge technology components, such as a water-cooled, vibrating grates and specialized biomass fuel-feeding systems, which were designed by Delta and manufactured locally under Delta's supervision. These components were unknown in China before being introduced by Delta on the Chinese market. Furthermore, Delta has over time refined the development and production of these key components.

Finally, available evidence suggests that the market share of Delta in China was around 90% in 2009 after which it gradually decreased to reach 30% in 2018 due to intensifying competition from other Chinese firms. However, increasing presence in global markets, including Western European countries such as Denmark, Norway, Sweden, Spain and the UK, has at least partly compensated for this loss of domestic market share.

In summary, the assessment of Delta's technological capability according to the indicators proposed by industry experts strongly suggests that the company has managed to catch-up with industry incumbents during the recent window of opportunity. According to our interviews, the acquisitions of the Danish firms and their key knowledge assets have been central to allowing Delta to move into a world-leading position in biomass power plant technology and engineering, particularly in straw-fired power plants. However, as evident from the developments in market shares in China, Delta has faced increasingly fierce domestic competition, which we turn to in the following section.

6. Catching-up of domestic competitors in China

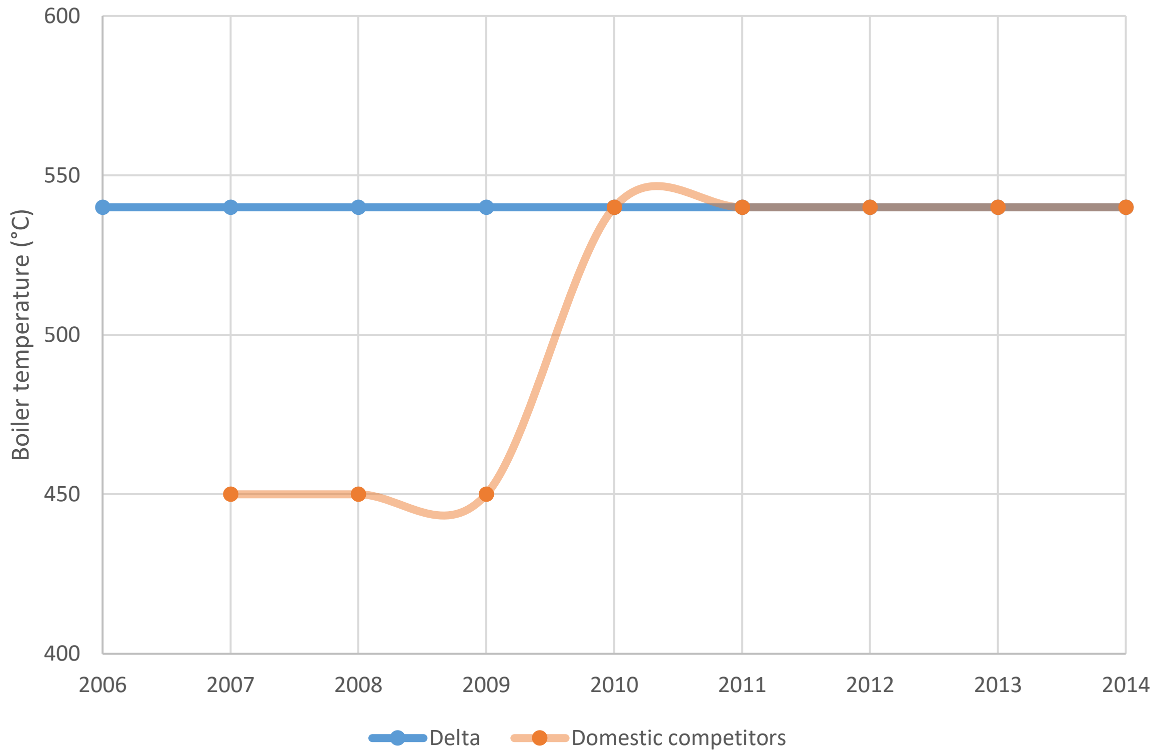
From 2004 to 2015, the Chinese biomass power plant industry grew from consisting of a single firm to a comprising a larger number of producers, as well as a larger number of smaller producers (Gosens 2015). The three most prominent of these in terms of market share are Kaidi Ecological and Environmental Technology, Wuxi Huaguang and China Western Power, while other domestic companies with a considerably smaller market share include Jiangxi Jianglian, Nantong Wanda, Taiyuan Boiler Group and Taishan Group (see Table 3).

Table 3. Central domestic competitors

Company	Established	# of employees	Main activities
Kaidi Ecological and Environmental Technology	1993 (restructured 2015)	4212	Biomass power plants and forestry ownership, as well as wind power and hydropower activities
China Western Power	1983	1928	Various types of boilers and power plants
Wuxi Huaguang	1958	3261	Various types of boilers and power plants
Jiangxi Jianglian	1958	2000	Various types of boilers and power plants
Nantong Wanda	1958	1000	Various types of boilers
Taiyuan Boiler Group	1999	300	Various types of boilers
Taishan Group	1992	4300	Various types of boilers, electrical equipment and refrigerators

In order to assess the level of catching-up of Delta's Chinese competitors, we apply the previously described indicators. First, concerning boiler temperature, the initial plants constructed by Chinese competitors in the period 2007-2009 all operated at relatively low temperatures (450-470°C). The first high-temperature plant operating at 540°C was completed in November 2010, and almost all new plants completed since 2013 have been running at this high temperature. Thus, while initially the steam temperature level in the power plants produced by Chinese competitors did not match those of Delta and the European incumbents, five different Chinese producers have now reached the industry benchmark (see Figure 1 and Appendix C for full data).

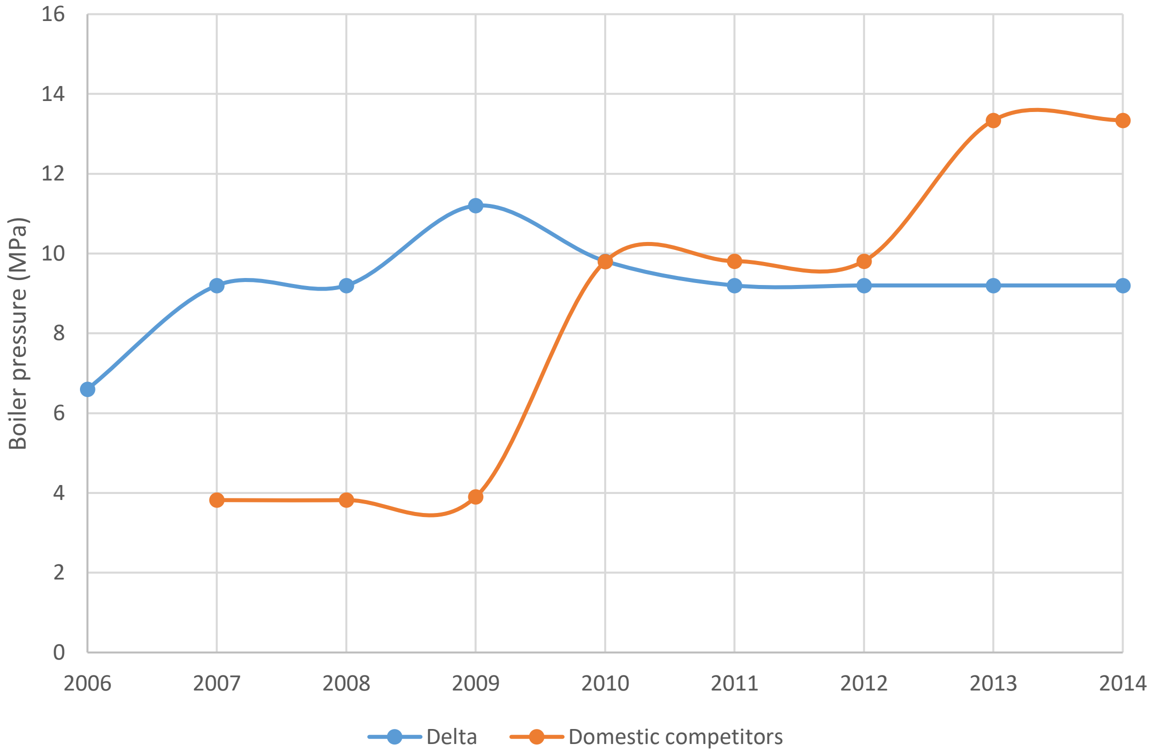
Figure 1. Highest boiler temperature (°C) in constructed biomass power plants.



Source: Data from Gosens (2015).

Second, regarding steam pressure levels (see Appendix C), the majority of plants produced by the Chinese competitors operate in the range of 24-30MW. In the initial years, plants were constructed to run at low steam pressure levels (3.8-5.3MPa). The first high-pressure plant operating at 9.8MPa was introduced towards the end of 2010. As with developments in steam temperature levels, most plants put into operation from 2013 are built to run at high steam pressure levels, the majority up to 13.3-13.7MPa. Considering the size of the plants, this steam pressure level is very high both in comparison with plants constructed by Delta and by European incumbents (see Figure 2 and Appendix C for full data). While only one producer reaches this steam pressure level, an additional four producers have put plants operating at 9.8MPa into operation.

Figure 2. Highest boiler pressure (MPa) in constructed biomass power plants.



Source: Data from Gosens (2015).

Third, concerning the internationalization of activities, in recent years several local Chinese competitors have entered foreign markets with their biomass power plants. In addition to several countries in Southeast Asia and Africa, producers have also started exporting to more developed markets such as Japan, South Korea, Brazil and Eastern Europe.

Fourth, while several producers have considerable experience with EPC contracts from their coal-fired power plant business, such EPC project have also recently been undertaken for biomass power plants in countries such as Japan, South Korea and Russia.

Fifth, as most of the Chinese competitors diversify into biomass power plants from, in particular, coal-fired power plants, they already had a quite broad product portfolio before entering the biomass power plant business. However, it is worth noting that some producers have subsequently further diversified into biofuel production plants, including large-scale biofuel projects in Europe.

Sixth, from interviews and project documents, it is clear that a number of the Chinese competitors have delivered plants with cutting-edge biomass power plant components, such as water-cooled, vibrating grates and fuel-feeding systems specifically catered for combustion of biomass. What is interesting to note here is that, according to our interviews, these components showed a clear resemblance with the design features of similar components supplied by Delta in China.

Finally, in parallel with the development of increasingly higher levels of technological capabilities, the market share in China of the domestic competitors increased from 10% in 2009 to 70% in 2018.

Summarizing, this assessment suggests that Delta's Chinese competitors trailed Delta in terms of technological sophistication in the period 2006-2010. However, local Chinese competitors have managed to catch up in the later parts of the window of opportunity. They gained the ability to handle the design and construction of high-pressure and high-temperature boilers, and the technologically leading positon of Delta in China has therefore diminished rapidly, leading to a substantial decline in Delta's domestic market share from 2010. This was confirmed in interviews where managers from Delta admitted that the technological head start they had gained over their Chinese competitors through the acquisitions made in Denmark was now eroding rapidly. In sum, a comparison of Delta's Chinese competitors with Delta and European incumbents strongly suggests that Delta's domestic competitors have also managed to catch up to an advanced technological stage.

Importantly, this took place despite an absence of capability development programmes for the biomass power plant industry (Lu and Zhao 2013; Binz et al. 2017). Further, channels of biomass power plant technology and related engineering knowledge provided through international linkages between foreign technologies suppliers and local firms in the domestic industry have also been absent. Indeed, we have not been able to identify any sub-supplier relationships between Delta's domestic competitors and foreign (lead firm) technology suppliers. Neither have we identified the existence of license agreements, joint ventures or international M&As with foreign technology suppliers, which could have provided access to biomass power plant technology. Our interviews confirmed that, in fact, the Chinese market for biomass power plants has been exclusively dominated by Delta and other domestic firms, which has meant that no other foreign power plant producers have supplied plants in China. As expressed by an interviewee "*none of the leading biomass power plant suppliers active globally have had a real presence in the Chinese market at any time*".

Thus, to better understand how the biomass power plant industry in China matured in only 5-10 years, compared to 25 years in developed countries (Parker 2015), we analyse the role of knowledge spillovers.

7. Spillover from Delta to local competitors enabling their catching-up

In order to determine the influence of knowledge spillovers in increasing the number of firms benefitting from the recent window of opportunity, we analyze the importance of knowledge flows through the four channels identified previously: labor mobility, supplier relationships, demonstration effects and university-industry collaboration (see also Appendix B for representative interview quotes).

7.1. Labor mobility

It was stressed across our interviews that Delta has faced significant challenges in recruiting skilled labor in China. The main issue was that the skills needed by Delta did simply not exist. Consequently, Delta invested significant resources in upgrading the competencies of the employees in the Chinese part of the firm, with the intention of locating increasingly complex development tasks in the firm's headquarters. However, these investments have not only benefitted Delta, but also its Chinese competitors, as Delta's employees became highly attractive to local industry once they had received training in biomass power plant engineering. Various examples were given of competitors hiring Delta's international staff, and the mobility among Delta's native Chinese engineers was significant and considered an important problem by Delta's management. To reduce this loss of qualified personnel, Delta introduced bonuses to retain employees. Still, turnover rates remained high. One interviewee explained how a competitor hired a number of Delta's employees and thereby gained access to important skills and technical drawings. According to the interviewee, this competitor's plants are further developments of plants initially constructed by Delta. Importantly, the scale of such labor mobility was not negligible and at a certain point involved the loss of 200 employees from Delta's Chinese production plant over a two-year period. Thus, to summarize, our interviews revealed that employee mobility from Delta to other Chinese firms in the biomass power plant industry has made an important contribution to allow a larger number of competitors to catch up in the later phase of the window of opportunity.

7.2. Supplier relationships

The interviews clearly suggest that Delta's interaction with local suppliers has also played a key role in the catch up of the wider Chinese biomass power plant industry. Delta has engaged with a significant number of suppliers since its establishment, and it was stressed across the interviews that this has led to significant knowledge flows from Delta to local Chinese suppliers. Two types of subcontractors in particular have benefitted from relations with Delta: suppliers of key components such as grates, economisers and furnace walls, and design institutes[viii].

Delta has interacted closely with suppliers of key components to ensure the quality. This involves on-site training of supplier staff and supervision of product quality. As a result, interviewees reported that, despite patent protection, a number of suppliers eventually started producing and selling Delta-developed components to other Chinese biomass power plant producers. Consequently, whenever possible, Delta started to divide components into different pieces that were distributed to various suppliers to avoid knowledge spillover. Thus, Delta used many resources on planning the distribution of supplier responsibilities to make it difficult for suppliers to coordinate their knowledge and put the different parts of the component together. Furthermore, Delta also decided to retain the production of core components in house.

The Chinese design institutes also benefitted significantly from interacting with Delta. These state-owned enterprises (SOEs) are licensed to undertake design of large construction facilities such as power plants and, thus, are mandatory partners for firms like Delta. Consequently, when Delta constructed the first biomass power plants in China, it had to engage in extensive interaction with the design institutes involved to educate them on the functioning and construction of biomass power plants. For this purpose, it is necessary to provide the design institutes with detailed technical drawings, which have subsequently been disseminated further to other Chinese producers. In other words, the Chinese regulation requiring the use of design institutes has also facilitated knowledge flows.

7.3. Demonstration effects

The interviews also highlighted that direct copy and imitation by local competitors was another important type of knowledge flow from Delta that contributed to the catching-up of the Chinese biomass power plant industry during the later phase of the window of opportunity. Several interviewees noted that Chinese competitors have copied products, in some cases identical to the

Delta original. One interviewee even explained that he was aware of two separate cases where Chinese competitors had copied entire plants, each representing a value of €25-40 million, within three years of completion. The interviewees attributed the ability of competitors to carry out such large-scale copying to a number of factors, most importantly that one of Delta's key SOE customers in the Chinese market, had reportedly distributed technical drawings to domestic competitors to increase price pressures on biomass power plants on the Chinese market. Furthermore, a high level of absorptive capacity on the part of Delta's domestic competitors due to their significant expertise in coal-fired power plants, and rent-seeking behavior by Delta employees in the form of engineers selling drawings for personal gains to Chinese competitors also facilitated knowledge spillovers. According to interviewees, such instances were not limited to isolated cases, but happened quite frequently. Finally, patenting by Delta had in fact facilitated the copying of components: since the protection of patents was not enforced, competitors had allegedly benefitted from the drawings and descriptions. Since the interviewees acknowledged that such unintended knowledge flows were difficult to avoid in China, Delta eventually decided to retain knowledge on some key components solely within their Danish office and restrict access to their blueprints for Chinese employees.

7.4. University-industry collaboration

Contrary to the first three channels, we find limited evidence of knowledge flows through university-industry collaboration. This does not reflect lack of interaction with domestic universities; in fact, Delta has long-standing research collaboration with a research group at a local university, one of few in China specializing in biomass power plant engineering. While the interviewees explained that the researchers had probably acquired some knowledge from the collaboration with Delta, it was acknowledged that the collaboration did not live up to expectations due to low capability levels. Essentially, because of the low research quality at the university, it was irrelevant for Delta to engage in research collaboration. This echoes the suggestion (see section 2.2) previously made that university-industry collaboration only contributes to industrial development when relevant research of high quality is carried out at domestic universities. Thus, as the research collaboration eventually became of marginal importance, the content of the relationship turned towards branding and recruitment, which allowed both partners to benefit from the prestige of the other, but had little influence on the opportunities for catching-up by the domestic competitors.

8. Discussion

In the current paper, we have started to unpack the question of how many firms benefit from a window of opportunity. We agree with Lee and Malerba (2017) that sectoral characteristics are central to understand if the catching-up of a country is constituted by a large or a small number of firms. In sectors with relatively few firms, the number of the number of firms that may benefit from a window of opportunity will be equally low. In line with this, catching-up of small countries with limited domestic markets will also in all likelihood involve a smaller number of firms catching-up, than large countries such as China, which provide greater possibilities for domestic market development. However, we provide further nuances to this proposition. The analysis suggests that the number of firms benefitting from a window of opportunity in the biomass power plant industry is closely related to the question of whether and how firms obtain access to specialised know-how. Given the dominance of DUI-based learning, access in particular to accumulated experience and person-embodied (tacit) knowledge appears as an essential element of catching-up in this sector. Indeed, we showed that access to specialised knowledge mainly through foreign acquisitions (enabling access to skilled staff) was essential in the initial catching-up of Delta. Subsequently, as pointed out above, the catching-up of the domestic competitors occurred mainly – although not exclusively – through knowledge spillover from Delta. Hence, the catching-up of the domestic biomass power plant industry in China was directly influenced by the catching up of Delta. Indeed, we find it very unlikely that the catching-up of the domestic competitors would have occurred at the observed rate and level in the absence of Delta. The number of firms benefitting from a window of opportunity thus seems to depend on the existence of a single (or a small number) of what may be referred to as 'frontrunner' firms, such as Delta. As shown in this case, such frontrunners can play a critical role in terms of initiating the catching up process within a given country. Thus, a *sequencing* of the catching-up process may be conceptualized in which Delta dominated the initial phase of the catching-up cycle after which spillover from Delta enabled the subsequent catching up of the domestic competitors at a later stage of the cycle. Due to the project-based nature of the industry, the sequencing of the catching up process occurs in discrete steps as additional firms enter the market via their involvement in specific projects. In contrast, mass-market good industries are likely to be characterized by a more linear sequencing catching up process as firms can enter the market and gradually upscale their products in ever larger batches.

Further, our analyses highlight the importance of labour turnover as a particularly effective source of knowledge spillover, which is most likely due to the dominance of the DUI mode of learning in this sector. Given the characteristics of demand in the industry – large-scale, custom-made products – which foster the formation of long-term and close relations with component suppliers, it was also expected that supplier relations were important for knowledge spillovers. The analysis also highlighted the crucial role played by demonstration effects, which were in particular facilitated through the actions of an SOE (see also below). Finally, university-industry spillovers were of marginal significance, however, in industries dominated by the STI modes of learning, university-industry spillover might be of substantial importance for knowledge spillover. Thus, the relative importance of different knowledge spillover mechanisms for understanding the number of firms benefitting from a window of opportunity may vary according to industry characteristics.

Finally, in term of implications for the understanding of specificities of green windows of opportunity, our analysis firstly underlines the importance of institutionally created windows. Given the double-externality problem of green technologies, i.e. that they not only produce positive externalities through knowledge spillovers from technology development, but also produce benefits for non-payers through their application (Rennings 2000), public policies can be expected to be particularly important for catch-up in green industries (see also Zhou et al. 2018). This is especially the case in the energy sector, which in most countries is characterised by strong state involvement due to the strategic importance of ensuring energy security. Conceptually, we point at the closely intertwined nature of institutional and demand-related windows of opportunity in the energy sector: changes in institutional framework conditions, for example in the form of feed-in tariffs, translates directly into market demand through economic incentives. Furthermore, the analysis highlights how policies and state-involvement were not only central for allowing the initial catch-up of Delta, but also for increasing the number of firms benefitting from the window of opportunity. Essentially, the Chinese government stimulated knowledge spillovers and acted as a mediator of knowledge flows, for instance through weak enforcement of intellectual property rights in the biomass power plant industry, which promoted unregulated copying and imitation by domestic competitors. More importantly, the state-owned design institutes, as well as the state-owned utility company played central roles in distributing technical drawings to domestic competitors. This meant that core plant design drawings were ultimately disseminated throughout the domestic industry. This indicates that the possibilities of the government to facilitate knowledge spillovers and thereby allow for a larger number of firms to benefit from a window of opportunity will be particularly important in green industries due to the government's central role in creating and stimulating markets.

9. Conclusion

In this paper, we set out to explore the question of how sectoral characteristics in combination with domestic knowledge spillover influence the number of firms benefitting from windows of opportunity. This question was analysed in relation to the catching-up of China in the global biomass power plant industry. We found that China has rapidly –developed an industrial leadership position in terms of installed generating capacity and has caught up with incumbent countries in technological capability levels. The window of opportunity enabling the catching-up of China was related to parallel changes in the demand structure and institutional reform pertaining to adoption of renewable energy policies aimed at promoting biomass power. These observations stress the important role of the state and the intertwined nature of institutional and demand-related windows of opportunity in the context of 'green' windows of opportunity in the energy sector. Further, we pointed at the significance of a single Chinese producer (Delta) who constituted the initial phase of the catch-up cycle. Importantly, however, spillovers from Delta allowed a larger number of domestic Chinese firms to benefit from the window of opportunity in the later stage of the catch-up cycle. This highlights that the degree of domestic knowledge spillovers is a key influential factor enabling a larger number of firms to profit from windows of opportunity. The paper also emphasised that knowledge spillovers may happen through labour mobility, supplier relations, demonstration effects and university-industry collaborations, and that industry characteristics influence the relative importance of these knowledge spillover mechanisms. The theoretical novelty of the paper thus lies in considering knowledge spillover in combination with sectoral characteristics as central aspects of whether and how latecomer firms responds to and catch up from windows of opportunity.

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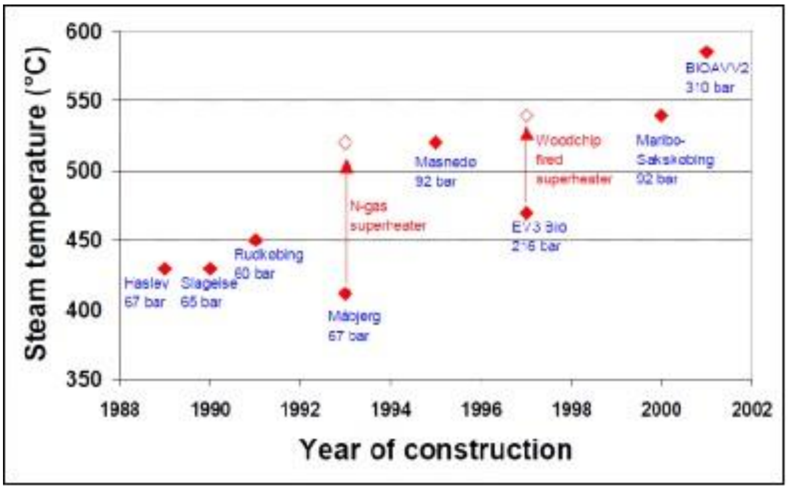
Appendix A. Indicators of technological capability levels in the biomass power plant industry

The global biomass power plant industry is characterized by high capital- and technology-intensive products and high barriers to entry in terms of investments, economies of scale and advanced technology (Hansen et al., 2016). The industry is dominated by large, multinational lead firms mainly from Europe and the US with core competencies in R&D and engineering know-how, which are specialized in development and construction of large-scale, high-temperature and high-pressure biomass power plants. Competition between lead firms is based mainly on technological advances through continuous R&D and previous record of accomplishment. The plants supplied by lead firms are often delivered as operational turnkey plants under engineering, procurement and construction (EPC) project contracts. Due to the complexity of EPC projects, only lead firms have the technological and organizational competencies to undertake these. The prospects for moving into a lead firm position in the global biomass power plant industry are therefore not particularly favorable.

Four interviews with biomass power plant technology experts, led to the identification of six indicators, which jointly provide a comprehensive description of technological capability levels in the biomass power plant industry. The level of steam pressure and temperature are the two main technical parameters that influence the thermal efficiency, and hence, the economic performance, of biomass power plants: boilers that operate at higher steam pressure and temperature levels results in an increase in plant performance, but are also more difficult to engineer and tend to be more costly (Gosens, 2015; Yin et al., 2008). This has meant that a key focus of the R&D activities carried out over the past around 25 years has focused on developing technology that enables plants to operate at high steam pressure and temperature levels, much of which have been based on experimental R&D and trial and error (Yin et al., 2008). In the beginning of the 1990's, the average steam pressure and temperature levels in the existing plants in operation at that time were around 70 bar and 490°C respectively, which in 2010 reached a maximum level of around 130 bar and levelled at 540°C (due to insufficient progress in basic research aimed at developing high temperature resistant metals) (see figure A1). The gradual increase in the steam pressure and temperature levels have been the result of the development of a number of key components, such as water-cooled vibrating grates and specially-designed fuel feeding systems, which have contributed to overcome some of the main problems related to the slagging of ash and corrosion of materials in the boiler furnace (Danish Energy Agency, 2012; van den Broek et al., 1996).

Figure A1. Steam and pressure levels of straw-fired power plants in Denmark (1988-2002).



Source: Skytte et al. (2004).

Thus, a first indicator involves assessing whether biomass power plant producers manufacture boilers operating at this temperature level. We use the steam pressure in the boiler as second indicator of technological sophistication. However, according to the interviewed experts, interpreting steam pressure levels as direct representations of technological capability has been problematic during the last ten years. This is still the case today, since the size of the plant and the expected sale price of the electricity will influence the choice of steam pressure level. Thus, while direct comparisons between individual plants are difficult, a second indicator suggested by the experts who were interviewed was the ability to construct plants operating at a high steam level, taking into account the size of the plant.

Third, the experts emphasized the level of internationalization of activities, in particular the ability to win contracts in demanding markets. While high quality of the offered products is not a sufficient condition to ensure access to markets in developed countries by EMNCs (for instance, project financing is more expensive when the developed products do not have a track record in developed countries), it is of course a necessity.

Fourth, the ability to manage large and complex EPC contracts was highlighted as an important indicator. Since such turnkey projects are characterized by higher technological and organizational complexity, many producers do not have sufficient competencies to undertake them.

Fifth, experts highlighted as a final indicator the ability to diversify into related products. A diverse product portfolio (in contrast to the specialized niche market operator) – including, for example, waste-to-energy plants or co-firing plants – indicates an ability to undertake production and development in multiple areas, which not all firms have.

Sixth, as suggested by the industry experts, we consider the ability of Delta and the local Chinese competitors to supply plants with cutting-edge biomass power plant components used by world-leading incumbents. Such components mainly include (i) water-cooled, vibrating grates and (ii) specialized fuel-feeding systems, which are the result of prolonged R&D to improve the combustion process and plant performance. We interpret the ability to independently design, manufacture and supply plants with such components as an indication of catching-up to lead firm standards.

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Appendix B. Representative interview quotes

Table B1. Representative interview quotes for the analysis (section 7).

Section	*Direct interviewee quotes*
7.1. Labor mobility	• *"most recruited engineers had a background in the coal-fired power plant industry and thus had very limited knowledge about biomass power plant engineering"* • *"[t]he turnover ratio, the people, the loyalty to the company is relatively low compared with our European colleagues. That's basically the culture"* • *"we lost some people to* [firm name] *down in Shanghai and they very quickly became a real competitor because they got our IPR this way and started to sell copies of our central components"* • [competitor hired a number of Delta employees and thereby gained access to important skills and] *"all our drawings"* • *"we really lost a lot of engineers from* [location of boiler production facility] – *around 200 over a two-year period* […] *and they are definitely skilled enough to use the drawing they take with them in their next job"*
7.2. Supplier relationships	• *"they were reselling it under another brand* […] *having worked on our designs for so many years* [they] *build up some amount of knowledge and expertise on it"* • [Delta started to divide components into different pieces that were distributed to various suppliers in order to] "*avoid any of them acquiring all the know-how*" • [Delta also decided to retain the production of core components in house in order to make sure that] "*at least some drawings are not out in "the system"* • "*now there are more than twenty firms who have had our drawings* […] *things also get out this way, and it is almost institutionalized* […] *so you really get the feeling that it is encouraged by the system*" • *"the design institutes have been super important for the diffusion of knowledge from Delta"*
7.3. Demonstration effects	• [Customers were] *"clearly of the opinion that when you bought a plant, you had also bought a blueprint to build the next one"* • *"The clearest example of the pivotal role of Delta in providing the domestic competitors with access to key components is the water-cooled, vibrating grates and the fuel feeding systems, which they simply did not have before Delta entered the market"* • *"The main problem is that they are simply very good at copying… so it's basically about starting the copy machine…* [which means that] *..several boilers have been built that are exact copies of our boilers"* • *"There is a lot of 1:1 copying"* • *"Some of the copies have improved over time, but a lot of the plants are not running well"*
7.4. University–industry collaboration	• [collaboration had] *"not developed as originally envisioned"* • *"they are 10-15 years behind leading western universities, even though they have the most advanced instrument collection that you can imagine. But the competencies are just not there yet"* • *"The university relationship mainly became an opportunity to recruit engineering talents rather than a channel for research cooperation"*

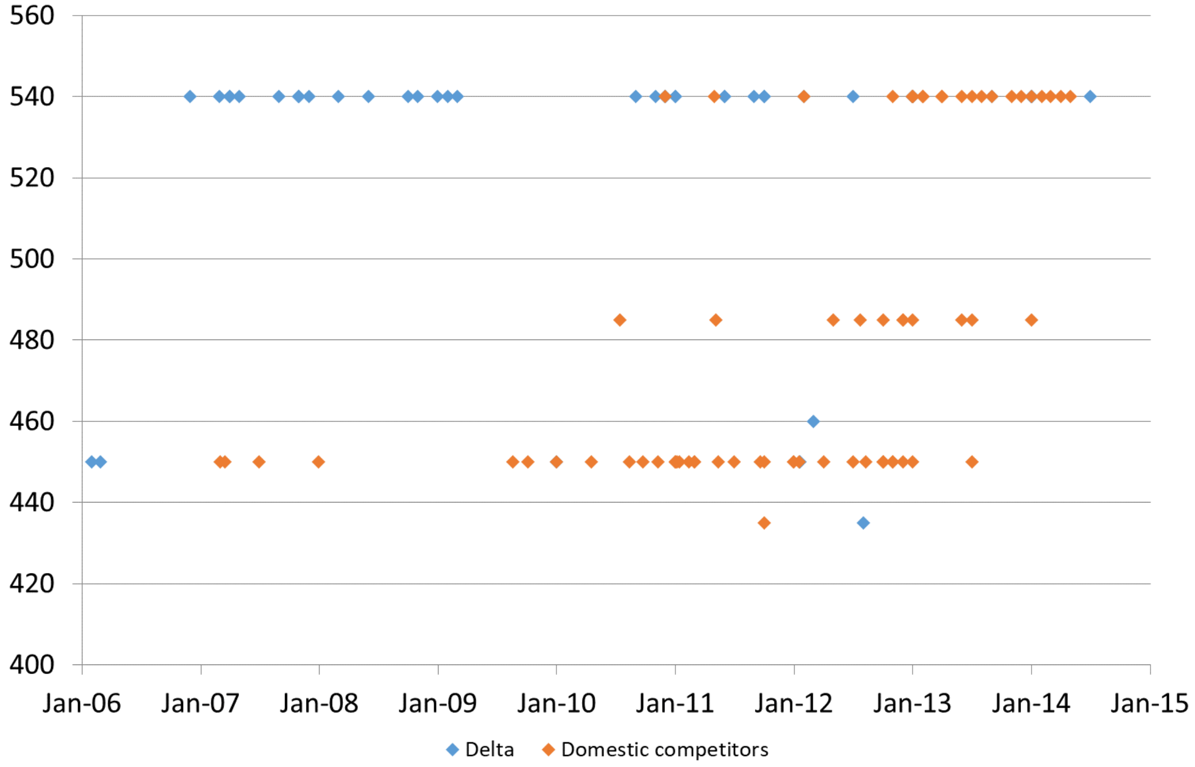
Appendix C. Biomass power plant steam temperature and pressure data

Table C1. Biomass power plants produced by leading European incumbents since 2006.

Producer	*Plant name*	*Operating year*	*Boiler pressure (MPa)*	*Boiler temperature (°C)*	*Output (MW)*
Alstom	Evermore	2015	8.3	482	18
Alstom	Plainfield	2013	10.2	510	20
Alstom	South Boston	2013	12.5	540	23
Andritz	Amakhulu	2008	8.6	490	25
Andritz	Portucel Soporcel Group	2009	9.3	472	26
Andritz	Workington	2013	10.2	540	38,5
Babcock & Wilcox Vølund	Wanze	2009	9.3	520	44
BWE	Sleaford	2014	11.2	542	46
BWE	BEKW Emlichheim	2013	11.0	522	49,8
BWE	Amager 1	2009	18.5	540	49,9
Foster Wheeler	BMHKW Emlichheim	2006	8.9	500	50
Foster Wheeler	Simmering	2006	12.0	520	50
Foster Wheeler	A&S Oostrozebeke	2010	8.5	500	50
Foster Wheeler	Konin	2012	9.7	540	55
Foster Wheeler	Igelsta	2009	9.0	540	65
Foster Wheeler	Kaukas	2010	11.5	550	80
Foster Wheeler	Polaniec	2012	12.6	535	85
Foster Wheeler	Jyväskylän	2010	16.4	560	100
Metso	Dalkia Facture	2010	11.9	520	125
Metso	Pori, Finland	2008	8.4	522	190
Metso	Gainesville	2013	11.2	540	200

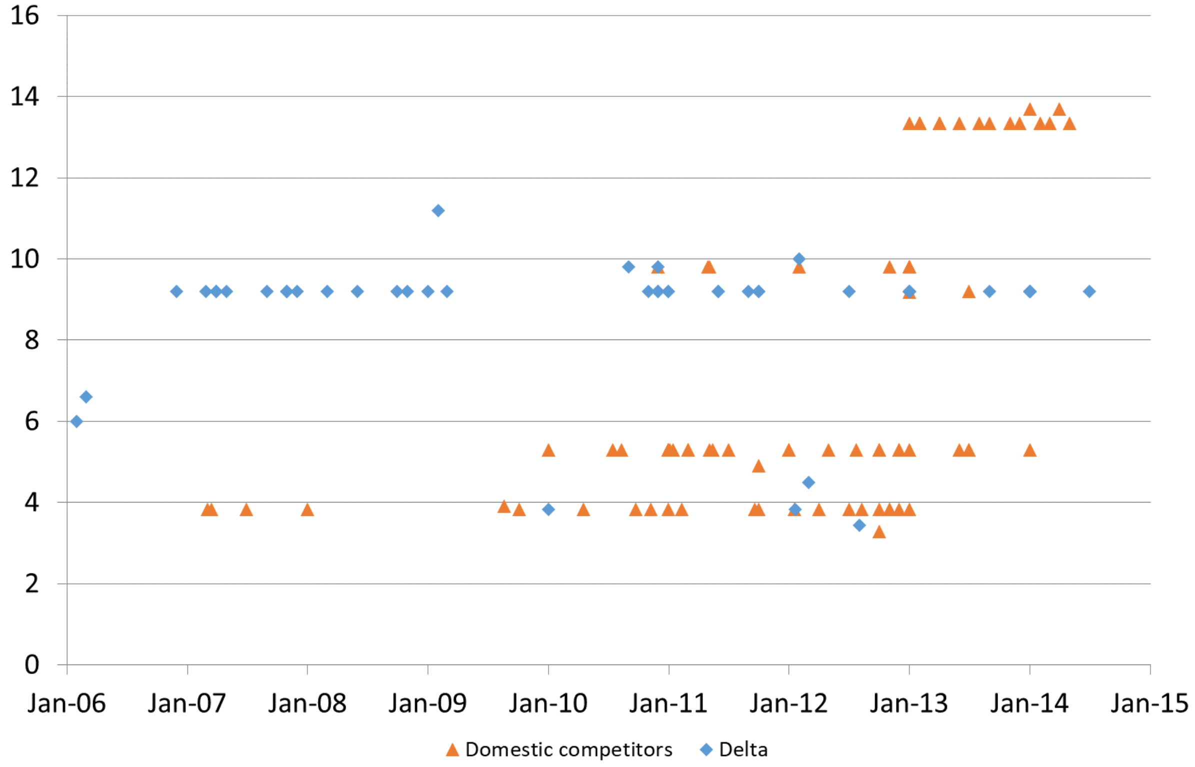
Source: Webpages and reference lists of the producers.

Figure C1. Boiler temperature (°C) in biomass power plants constructed by Delta and domestic competitors.



Source: Data from Gosens (2015) and own data collection from company reference lists.

Figure C2. Boiler pressure (MPa) in biomass power plants constructed by Delta and domestic competitors.



Source: Data from Gosens (2015) and own data collection from company reference lists.

[i] We do not consider the operation of biomass power plants as part of this industry.

[ii] It should be noted that these characteristics relate to each other in different ways in different national contexts. To exemplify, the effects of capital intensity on the functioning of the sectoral innovation system depends on the relevant market size. Thus, capital requirements constitute a greater barrier to entry in a small economy than in a large economy such as China, where the market is sufficiently large to provide room for a greater number of firms operating at efficient scale. We are thankful to one of our reviewers for highlighting this point.

[iii] The literatures on branch plant economies and spillover effects of inward FDI focus on the effects of inward FDI and diffusion of knowledge from foreign affiliates to host country firms. While this is a different empirical phenomenon from the one studied in this paper (diffusion of knowledge obtained through outward FDI in the form of strategic asset seeking investments), there are no reasons to expect that the spillover channels differ. Further, a substantial literature exists on spillovers from inward FDI, while little has been written on domestic spillovers from outward FDI.

[iv] Due to confidentially concerns, the Chinese firm has been anonymised in this paper under the name of Delta.

[v] The interviews also highlighted that patenting is not a suitable indicator, since it was actually known to lead to the diffusion – rather than protection – of knowledge in the Chinese biomass power plant industry.

[vi] The six identified firms were Alstom, Andritz, Babcock & Wilcox Vølund, Burmeister & Wain Energy, Foster Wheeler, and Valmet (previously Metso Power). A portfolio of the biomass power plants they have completed since 2006 was compiled. This resulted in a collection of 21 biomass power plants (see Appendix C).

[vii] Please see Hansen et al. (2016) for a more detailed account of the development of Delta.

[viii] Design institutes are state-owned enterprises responsible for the overall design of the plants, aside from the key technological component, the so-called boiler island.