THE NATURE AND DIRECTION OF INNOVATION IN GLOBAL VALUE CHAINS FOR WIND ENERGY TECHNOLOGIES

Kavita Surana[a*], Claudia Doblinger[b*], Deyu Li[c], Nathan Hultman[a], Laura Diaz Anadon[c]

[a] Center for Global Sustainability, School of Public Policy, University of Maryland, College Park, USA

[b] Technical University of Munich, Campus Straubing for Biotechnology and Sustainability, Germany

[c] Centre for Environment, Energy and Natural Resource Governance, Department of Land Economy, University of Cambridge, UK

*Authors contributed equally

Project funded by the National Science Foundation under grant number 1829252 and the UKRI Economic and Social Research Council under grant number ES/S010688/1

Working paper for the NASEM Workshop on Innovation, Global Value Chains, and Globalization Measurement (5-7 May 2021)

Abstract

This paper maps the global value chain for wind energy technologies and analyzes how the location of suppliers in the global value chain impact the nature and direction of innovation for wind energy. We specifically focus on the activities of hundreds of specialized manufacturing firms, in both industrialized and emerging economies, that supply to OEMs. To do so, we first map the global value chain of wind energy, examining the supplier-OEM relationships between 2006 and 2016. For each supplier and OEM, we identify and analyze the patents filed in this period and the direction of innovation (i.e. the long-term and short-term horizon of patenting activity) using a novel methodology that combines machine learning and text mining of patent descriptions. Specifically, we assess the extent to which the focus of innovation is on delivering short-term returns (0-10 years) or long-term rewards (10-20 years) based on innovation needs identified by global industry-research consortia. Finally, we analyze how the location of manufacturing (i.e. the country of the supplier and the OEM) in the GVC shapes the direction of innovation.

1. INTRODUCTION

Clean energy technologies represent an essential component of addressing a number of sustainable development goals, including a global response to climate change (IEA, 2020). Clean energy technologies are also increasingly seen by many countries as a way to contribute to domestic jobs and economic growth. Accelerating technological innovation in clean energy is necessary to enable broader unsubsidized, cost competitive deployment of knowledge-intensive clean energy technologies. However, accelerating innovation is challenging because it depends on a number of factors, especially the decisions and actions by governments, lead multi-national firms, and suppliers dispersed around the world in global value chains (GVCs). Tensions can arise when clean energy technology is seen as undermining domestic industries embedded in global networks, but synergies can emerge if clean energy manufacturing is partly domestic and supports local industry.

Understanding clean energy innovation in the GVC context is important because much like in other modern industries, manufacturing of clean energy technologies has shifted from Europe, the US, and Japan to emerging economies, most notably China (e.g., Zhang and Gallagher, 2016; Sandor *et al.*, 2020). Research in other modern industries (in automobiles and high-end optoelectronics) has observed that such shifts may not always lead to technological innovation, as manufacturing shifts to Asia "may reduce innovation, domestically and globally, at least in the short to medium term" as research and development (R&D) efforts in firms move away from the most 'advanced' technologies (Fuchs and Kirchain, 2010; Fuchs, 2014). If the *direction* of innovation in global clean energy industries were to also move away from the most advanced technologies that have long-term benefits, it could derail countries' abilities to rapidly meet sustainable development goals. Prior research in clean energy has suggested that manufacturing in China is associated with innovation for scale-up and cost reduction (Lam, Branstetter and Azevedo, 2017; Helveston and Nahm, 2019), which led to large scale deployment globally while potentially undermining advanced alternative designs (Sivaram, Dabiri and Hart, 2018).

Despite the importance of understanding the *nature and direction* of innovation in clean energy GVCs—i.e., the technological focus of innovative activities and the extent to which they focus on longer-term sectoral innovation needs that are 10 to 20 years into the future—little is known about the factors that affect these longer-term innovation outputs. Given the difficulty of measuring the (longer-term) nature and direction of innovation, prior research on clean energy technologies, such as wind energy, has mostly focused on the ‘amount’ of innovation by evaluating patents, citations or publications in large firms or in countries, not distinguishing the time horizon of expected results of innovation. In particular, extant literature has focused on understanding the impact of a combination of demand-pull or technology-push energy policies on innovation amounts in countries or on technology strategies in large firms (Nemet, 2009; Lewis, 2011). For example, research on wind energy has studied extensively the factors that enabled innovation in local industries initially in Denmark, Germany, and US, and eventually in China, and India (Garud and Karnoe, 2003; Lewis, 2011; Lema and Lema, 2012; Awate, Marcus M Larsen and Mudambi, 2015). These important studies, however typically focus only on the 10-15 original equipment manufacturers (OEMs), i.e., lead firms that assemble wind turbines. The focus on OEMs largely overlooks the fact that energy technology innovation comprises globally distributed manufacturing and hundreds of small supplier firms, where supplier firms manufacture and deliver the many and often critical technologies for cost and performance improvement in integrated systems such as wind turbines (Navigant Research, 2014; Surana *et al.*, 2020).

Recognizing the limitations of country- or OEM firm-centered analyses, recent research has started to focus on suppliers in the GVC (see for example, our paper analyzing how technology complexity of wind energy components shapes international shifts in the GVC (Surana *et al.*, 2020) and other recent contributions, e.g. (Zhang and Gallagher, 2016; Meckling and Hughes, 2017, 2018)). Extant research has qualitatively analyzed global knowledge flows and international dimensions of energy innovation and component suppliers under different policy contexts (Binz and Truffer, 2017; Lema, Rabellotti and Gehl Sampath, 2018) or the linkages between location of manufacturing and innovation from the research and development (R&D) strategy perspective of OEM firms (Awate, Marcus M Larsen and Mudambi, 2015). Recent case-base studies aim to further understand the linkages between manufacturing location in the GVC and innovation (Haakonsson and Slepniov, 2018; Haakonsson, Kirkegaard and Lema, 2020). However, most studies do not capture factors related to the nature and direction of innovation. Most assessments also leave out measuring suppliers’ innovation activities, which are often small and medium firms (SMEs), consequently paying insufficient attention to the competitiveness of the manufacturing industry in most countries, and their contributions to longer-term innovations in the wind industry.

This paper maps the global value chain for wind energy and analyzes how the location of suppliers in the global value chain impacts the nature and direction of innovation. We specifically focus on the activities of hundreds of specialized manufacturing firms, in both industrialized and emerging economies (especially China), that supply to OEMs. To do so, we first map the global value chain of wind energy, examining the supplier-OEM relationships between 2006 and 2016. For each supplier and OEM, we identify and analyze the patents filed in this period and develop a methodology that combines machine learning and text mining of patent descriptions to propose a novel measure for the direction of innovation (i.e. the long-term and short-term focus of patents). Specifically, we assess the extent to which the focus of innovation is on short-term returns (0-10 years) or long-term rewards (10-20 years) based on innovation needs identified by global research-industry consortia (IEA Wind, 2001, 2013). Finally, we explore the drivers of innovation, specifically analyzing how the location of manufacturing (i.e. the country of the supplier and the OEM) in the GVC shapes the direction of innovation, especially for suppliers.

2. THE NATURE AND DIRECTION OF INNOVATION IN GLOBAL VALUE CHAINS

Innovation can take different directions, depending on the areas and technologies that are the focus of innovation (e.g. (Stirling, 2010; Mazzucato and Semieniuk, 2018)). Changes in the direction of innovation may imply broad shifts that steer technological development from one sector to another (e.g. from carbon-intensive to low-carbon technologies in the context of mission-oriented innovation policies (Anadon, 2012; Robinson and Mazzucato, 2019)), or the specific technological shifts that change technology development within a sector (e.g., from low-risk innovation for short-term returns to high risk innovation with potential returns in the long-term, and can be based on firms' R&D or strategic choices, cumulative research in that technology, regulations and standards, etc.) (e.g., (Fuchs and Kirchain, 2010; Awate, Larsen and Mudambi, 2012b; Chatterji and Fabrizio, 2014; Awate, Marcus M. Larsen and Mudambi, 2015; Zhou *et al.*, 2016). In this context, innovation scholars have explored several dichotomies that relate to the direction of innovation (high vs. low carbon, radical vs. incremental, exploratory vs. exploitative, product vs. process, technical vs. business/services, short-term vs long-term, etc.)(e.g., (Tushman and Anderson, 1986; Dahlin and Behrens, 2005; Nemet, 2009; Wilson, 2018)).

For energy innovation, recommendations on the direction of innovation have largely referred to accelerating the development of low-carbon technologies (Schmidt *et al.*, 2012; Mazzucato and Semieniuk, 2018) and to promoting radical innovations (or breakthroughs) for meeting net-zero climate goals, rather than only focusing on incremental innovation that delivers slight improvements in the performance of existing products or services (Nemet, 2009; Sivaram, Dabiri and Hart, 2018; Wilson, 2018). Most of these broad approaches do not recognize two key features of the nature and direction of innovation. The first feature is that the nature and direction of innovation is technology-specific as energy technologies are heterogeneous with different technology development trajectories and technology-specific innovation needs (Huenteler, Schmidt, *et al.*, 2016; IEA, 2020; Malhotra and Schmidt, 2020; Wilson *et al.*, 2020). For example, innovation in some technologies may be in process innovation (e.g. in solar photovoltaics) while others may be in components or products (e.g. in wind) (Huenteler, Schmidt, *et al.*, 2016). And even within a specific low carbon technology (e.g. solar) the focus of innovation may be in incumbent (e.g. silicon solar cells) or in new technologies (e.g. perovskite solar cells). Additionally, the second feature is that the nature and direction of innovation has a time-horizon. Assessments for meeting climate and sustainability goals have indicated technology-specific long- and short-term deployment goals and corresponding innovation needs (e.g. (IEA Wind, 2001, 2013; IEA, 2020), however research has not analyzed whether or how these innovation needs will be met especially when the payoffs for firms in the industry are likely to only be in the long term. Consequently, it is important to develop methodologies that speak to the nature and direction of innovation for specific technologies and include the expected time-horizon of innovation returns.

For wind energy, the focus of this paper, technology improvements and cost decreases have been driven by, among other factors, innovation and manufacturing improvements at the component level (GLWN (Global Wind Network), 2014; Wiser *et al.*, 2016, 2018; Elia *et al.*, 2020)—such as in blades, towers, gearboxes, and bearings—highlighting the importance of both the OEMs that assemble wind turbines (and manufacture some parts) and the suppliers that manufacture and supply components to the OEMs. Both innovation and manufacturing have been globally dispersed, and are part of global value chains (Binz and Truffer, 2017; Surana *et al.*, 2020). And with the globalization of clean energy manufacturing and innovation, prior research has suggested differences in the focus of innovation especially emerging from the shifts to China (Nahm and Steinfeld, 2014; Nahm, 2017). Applying a global value chains perspective to energy innovation that includes both suppliers and OEMs present worldwide can provide new insights on the nature and direction of innovation, in particular on what it means over time.

The time-horizon of innovation used in this paper, i.e. the short-term and long-term focus of innovation, diverges from other definitions innovation in that it specifically focuses on the innovation needs specific to the technology, in this case wind. Suppliers could research technologies that are expected to yield results in the short-term (0-10 years) or long-term (10-20 years). The time-horizon of innovation can be related to processes or products, to incremental or radical changes, etc. *Short-term innovation* is closely connected to the OEM's current and anticipated market needs – it may be linked to incremental or exploitative innovation when related to improvements in existing products, or to radical or explorative innovation when working on a component for a specific OEM that can potentially have a transformational impact on markets ((Tushman and Anderson, 1986; Nemet, 2009; Hoppmann *et al.*, 2013). *Long-term innovation* is closer to the anticipated future needs of the OEM. In that it may be radical when related to new parts for an entirely new product, for example in offshore wind (e.g. new design for offshore wind turbine) or incremental when related to supporting technologies for offshore wind (e.g. cables to support offshore wind).

Accelerating innovation therefore involves speeding up both long-term innovation and short-term innovation in a global value chain context. Long-term innovation may be driven by policy signals for long-term industry needs or government R&D that need to be met urgently. Short-term innovation is likely to be driven by markets and current industry needs (and a result of policy induced incentives). Given the global nature of innovation as well as manufacturing, these drivers may also be related to the location of manufacturing in different countries or regions, the relationships between suppliers and OEMs, and the innovative activities of both (e.g., Pietrobelli and Rabellotti, 2011; Binz and Truffer, 2017).

3. METHODS

Our approach comprises three steps: developing a database on wind GVCs (3.1), measuring the nature and direction of innovation (short-term vs long-term) by analyzing the content of patents (3.2), and analyzing where innovation occurs, how it changes over time, and how the location of suppliers in the GVC affect the direction of innovation (3.3).

3.1 Developing data on an industry-specific GVC

We developed an original global database of component suppliers to major OEM for wind turbines (see details in (Surana *et al.*, 2020)). The database was manually developed by analyzing, in detail, text-based industry reports on the wind GVC and tabulating relevant information at the firm-level (Navigant Research, 2014). We obtained time series data using biennial reports from Navigant Consulting (2006, 2008, 2010, 2012, and 2014), with each relationship reported for a 3-year horizon—for example, the 2014 industry report identified supplier-OEM relationships from 2014 through 2016. In this step, we tabulated information on all major component suppliers (active between 2006 and 2014), the OEMs they supply to (and are expected to supply to until 2016), the relationships of the supplier firms with OEMs (either as in-house development of components for the OEMs or as external or outsourced from OEM to the supplier), and the geographical location of the supplier firms.

Our dataset captures nearly a decade of rapid advancements and international changes in wind energy manufacturing and deployment (e.g. (Lewis, 2011; Awate, Marcus M Larsen and Mudambi, 2015; Surana and Anadon, 2015)) – however, it does not capture the emergence of suppliers before 2006 in the formative stages of the wind energy industry in countries worldwide (e.g., (Garud and Karnoe, 2003)). It also does not capture more recent advancements—such as the merger between two large OEMs, Siemens and Gamesa in 2016—or new technological challenges related to grid integration and storage that suppliers and OEMs now work on (IRENA, 2019). Nonetheless, our dataset also includes part of the period before onshore wind was highly commoditized and is relevant for many other clean energy industries that are still at a formative stage, trying to establish domestic suppliers and to participate in GVCs.

After an initial cleaning of this dataset and excluding missing or incomplete data points, we had information on 389 suppliers and 9 components (i.e., towers, blades, nacelle, gearboxes, generators, control systems, power converters and transformers, bearings, and forgings) including information on which of the 13 OEMs the suppliers worked with for in-house or outsourced manufacturing.

The OEMs were firms with the greatest global market shares between 2006 and 2016 and were based in Germany (Siemens, Nordex, Enercon, REPower/Senvion), Denmark (Vestas), Spain (Gamesa), USA (General Electric), Japan (Mitsubishi), China (Goldwind, Mingyang, Dongfang, United Power), India (Suzlon). Additionally in some cases, suppliers also had multiple subsidiaries with manufacturing locations outside of their home country—for example ABB from Switzerland manufactured in the US and Rothe Erde from Germany manufactured in India, France, China, UK, and others—but a complete dataset on such additional subsidiaries or locations is not publicly available or verifiable and was not used for this assessment. Overall, the suppliers represent a global distribution of firms from major countries home to OEMs as well as others that are trying to develop domestic wind manufacturing capabilities in components and/or OEMs (e.g., France, UK) (see details in (Surana *et al.*, 2020).

We obtained additional data on each supplier firm from additional datasets and company website searches (Bloomberg, Orbis, Amadeus) on firm size, founding year, and specialization—i.e., whether the firm supplies to industries beyond the wind industry, or whether the firm supplies multiple components. Wind companies experienced multiple mergers and acquisitions in the timeframe of our study (e.g., Suzlon, REPower, and Senvion) and following prior research we considered them as individually operating companies if they were not integrated and continued to operate under a different brand.

3.2 Estimating the nature and direction of innovation

We identified the anticipated long- and short-term research priorities using expert reports published by the International Energy Agency's Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (or IEA-Wind), in 2001 and 2013 (IEA Wind, 2001, 2013). IEA-Wind comprises key stakeholders involved in wind energy planning – including national government agencies (such as the U.S. Department of Energy) and industry associations (such as the Chinese Wind Energy Association). IEA-Wind conducts periodic assessments of experts to determine research, development, and demonstration needs for wind energy, which are then published in reports. From these reports, we identified innovation that will deliver in the short-to-mid-term (0–10 years) and long-term (10–20 years) range (details available upon request). After identifying the research and innovation needs, we conducted a natural language processing analysis of the content of patents to identify what firms and inventors aim to achieve from innovation and matched it to the direction of innovation based on the IEA-Wind outlook.

To do so, we obtained patents from the Derwent Innovation Index using a rigorous keyword search for global wind energy patents. Our initial dataset comprised over 70,000 patents in wind turbine components between 1998 and 2018 based on a detailed and previously tested keyword search of the patent text and its Cooperative Patent Classification (CPC) (Huenteler, Ossenbrink, *et al.*, 2016; Huenteler, Schmidt, *et al.*, 2016). We extracted patent information (e.g., title, abstract including translated abstracts, technology classification, priority country where patent was first filed, and date of application) on each of the firms. Our search methodology limits patent results to wind energy technologies and components and excludes innovative activities in other sectors from those suppliers and OEMs that are involved in multiple industries (e.g., large conglomerates like Siemens and GE). Although our approach yields patenting activity unique to wind energy, we expect our approach to be thorough as our analysis emphasizes on the content of the patent in its linkages to wind-specific R&D. 12,975 patents corresponded to a supplier or an OEM in our dataset.

Then, we used the text from the title and description (until the independent claim) of each patent to create a text corpus for natural language processing (NLP). We applied pre-processing techniques to the text corpus comprising the title and description text; (e.g., by removing redundant words in patent language such as "section" or "description" which are likely to be present in most patents, but do not add any significant meaning to the technical content of the invention). We also applied standard data cleaning approaches such as stemming words, removing punctuation and numbers, and removing stop words (commonly occurring words such as 'an', 'the', 'if' etc.).

We used a multi-step approach to identify the focus of innovation and its linkages to long-term innovation. First, we used probabilistic topic modeling with Latent Dirichlet Allocation (LDA) to identify clusters of similar topics related to the technological focus of innovation. The LDA approach assigns a probability for patents to be associated with each topic. Based on IEA long-term research needs, we identified topics clearly associated with long-term research areas with at least 30% probability of being associated with long-term research needs. Second, we used the cooperative patent classification (CPC) system to identify long-term innovation. We mapped the CPC class with general topic areas, where we classified some as long-term research areas, based on IEA long term research needs. Third, we used a simple keyword count of the content of patents, where we counted keywords likely to be associated with long-term innovation needs. We classified patents to be linked to long-term innovation if any one of the approaches mentioned above pointed towards long-term innovation. We also conducted several robustness checks that are available upon request.

3.3 Linking the nature and direction of innovation and the location of suppliers GVCs

We matched and analyzed the patents to individual suppliers (i.e., where the supplier was an assignee on the patent). While patents are by no means a complete reflection of the extent of research and development or innovation activities in a company, they do indicate the focus of innovation within the company. We used this mapping to analyze where innovation occurs, how it changes over time, and how the location of suppliers in the GVC affect the direction of innovation

4. RESULTS

4.1 Mapping the global value chain for wind energy

Note: For details on the analysis in 4.1, please refer to (and cite) Surana et al., 2020. Our dataset builds on industry reports and captures data on 389 suppliers with over 1,600 supplier-OEM market relationships for 13 major OEMs occurring between 2006 and 2016 for 9 key components identified in industry reports (see *Surana et al., 2020).* The OEMs are located in Europe (e.g., Siemens), the United States (General Electric), Japan (Mitsubishi), and later in China (e.g., Goldwind) and India (Suzlon). The number of suppliers and countries associated with each component identified are indicative of the differences associated with the technology complexity—i.e., the knowledge intensity and difficulty of manufacturing each component (see Surana *et al.*, 2020).

Our analysis provides detailed insights on the wind manufacturing industry over time (2006 to 2016) by quantifying the supply relationships between suppliers and their large OEM partners in the GVC (see *Surana et al., 2020).*

OEMs and suppliers were dispersed globally, but their relationships remained largely domestic, albeit with some exceptions discussed below. In our study period, 78% of suppliers (305 out of 389) were in countries that had a large OEM and 58% of relationships between OEMs and suppliers (1,239 out of 2,121) were domestic, i.e., involving suppliers and OEMs from the same country (see the full analysis in *Surana et al., 2020)*).

Our analysis, detailed in Surana *et al.*, 2020, suggests that starting in 2006, a domestic manufacturing supply chain initially developed in countries with large OEMs, which were the countries that also had the largest wind deployment markets in the study period (i.e. Germany, Denmark, Spain, United States, China, India, and Japan). The emergence of suppliers in new locations, especially in countries without an OEM, relates to the technology complexity of the components. For low complexity components (i.e., towers and generators), suppliers from new locations in emerging economies emerged (including countries in Africa, Latin America, and Asia-Pacific regions). For high complexity components (i.e., blades and gearboxes), the emergence of new supplier countries was significantly lower, potentially because more complex products required suppliers with skilled manufacturing, higher absorptive capacity, and tacit knowledge that may be more difficult for suppliers originating in developing and emerging economies (Asheim and Coenen, 2005; Surana *et al.*, 2020).

4.2 Assessing the direction of innovation in the GVC

In total, nearly 40% of the patents in the study period were from suppliers. Figures 1 and 2 show the short- and long-term wind patents filed by suppliers and OEMs in emerging economies (primarily China) and in industrialized countries (primarily EU, Japan, and the United States). These trends show three key features.

Figure 1: Direction of innovation in suppliers and OEMs in emerging economies (primarily China) and industrialized countries (primarily in the EU, the US, and Japan)

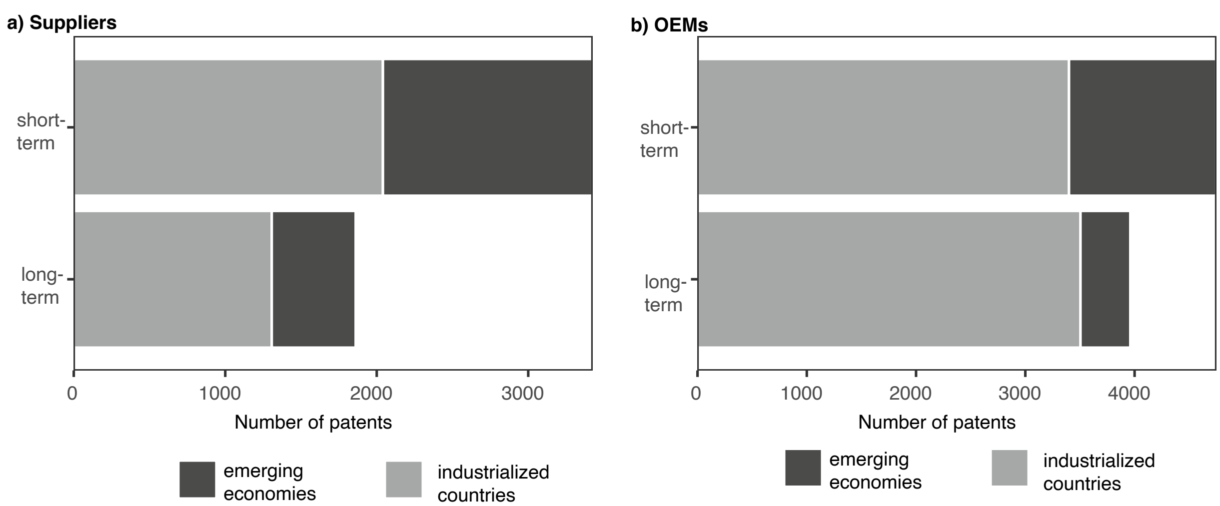
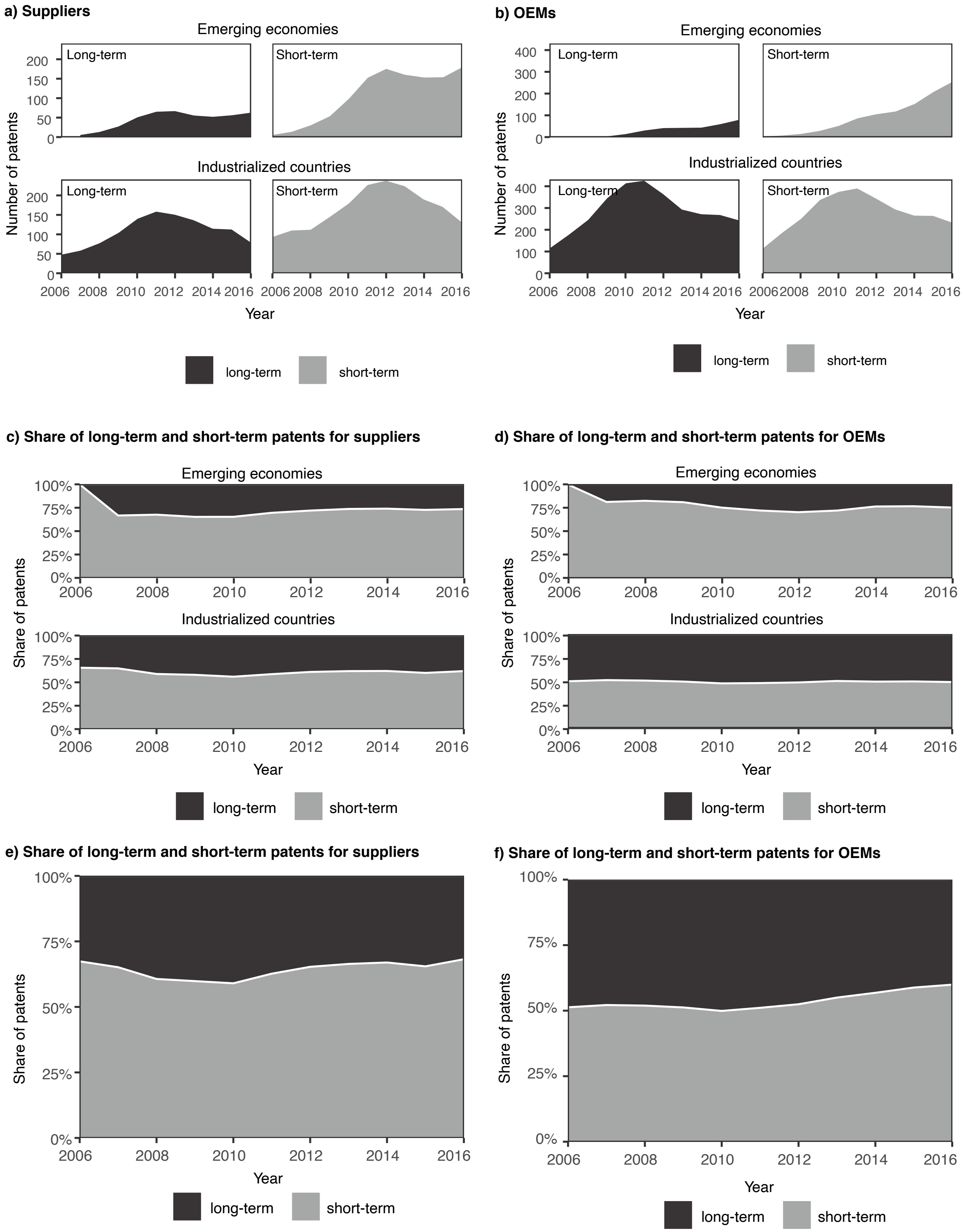


Figure 2: Evolution in the direction of innovation in suppliers and OEMs in emerging economies and industrialized countries. Note: data shows 3-year moving averages of patents based on application year and assignee


a) Suppliers
Emerging economies
Long-term
Short-term
Industrialized countries
Number of patents
Year
long-term
short-term
b) OEMs
c) Share of long-term and short-term patents for suppliers
d) Share of long-term and short-term patents for OEMs
e) Share of long-term and short-term patents for suppliers
f) Share of long-term and short-term patents for OEMs
Share of patents
0%
25%
50%
75%
100%
2006
2008
2010
2012
2014
2016

First, over the study period, the share of patenting focusing on long-term innovation was meaningful, but lower than that for short-term innovation for both suppliers and OEMs (about a third of supplier patents and less than half of OEM patents focused on long-term innovation) (see Figure 1). This is consistent with the idea that firms would prioritize short-term innovation to support current industry needs. Suppliers are more likely to focus on the needs set by the OEMs, which are in turn likely to engage more with long-term industry directions discussed in fora such as the IEA-Wind.

Second, over the study period, emerging economies (primarily China) were somewhat behind industrialized countries in the focus on long-term innovation (see Figures 1a-b). In emerging economies, about a third of suppliers' patenting activities and a quarter of OEM's patenting activities focused on long-term innovation. In industrialized countries, about two-fifths of suppliers' patenting activities and half of OEMs patenting activities focused on long-term innovation. While this cumulative trend partially agrees with prior research that suggests manufacturing shifts to China may have changed the direction of innovation (Awate, Larsen and Mudambi, 2012b; Awate, Marcus M. Larsen and Mudambi, 2015; Lam, Branstetter and Azevedo, 2017; Dai, Haakonsson and Oehler, 2020; Hain *et al.*, 2020), the temporal trends indicated in the next paragraph offer additional insights (also see Figures 1c-e).

Third, in emerging economies' suppliers and OEMs, patenting increased (or stabilized) over time, for both long-term and short-term innovation. In contrast, in industrialized country suppliers and OEMs, patenting activity first increased and then decreased for both long-term and short-term innovation. In 2016, the share of long-term patents in emerging economies was nearly half for suppliers and a quarter for OEMs. The differences observed in emerging economies and industrialized countries add new insights to previous research that suggests a change in direction moving away long-term innovation with manufacturing shifting 'east'. Past research may have looked at different time periods, specific countries, or only the OEMs and not the full GVC. It is also possible that once emerging economies (especially China) 'caught up', their long vs. short-term emphasis may resemble that of other industrialized countries.

5. DISCUSSION

This paper explores how the increasing globalization of the supply chain impacts the direction of innovation. We developed and analyzed an extensive dataset on component suppliers and applied machine learning and text mining to estimate the direction of innovation using the technological content of patents of each supplier. Our findings make the following contributions to the literature highlighting the measurement of innovation as well as that of global value chains in a specific technology.

Our firm-level analysis is a first of a kind study that maps the GVC for a specific clean energy technology over an extended period of time (see Surana et al., 2020 for details). We contribute to GVC literature that tends to focus on broad industries such as automobiles, electronics, etc. or on trade patterns in countries across industries. Our data-driven analysis and "micro-level" focus on both supplier firms and OEMs in wind energy can help understand changes in the GVC at the industrial level, where GVCs remain 'heavily debated but hardly measured' (OECD, 2018).

Clean energy overall has only recently been studied in the context of GVCs (Cattaneo *et al.*, 2013; Haakonsson and Kirkegaard, 2016; Zhang and Gallagher, 2016; Haakonsson and Slepniov, 2018). Within clean energy, we specifically contribute to the literature on wind energy that has so far focused on public policies or innovation in the context of OEMs and only recently recognized (through case-based studies) the key role played by component suppliers (Kamp, Smits and Andriesse, 2004; Lewis, 2011; Awate, Larsen and Mudambi, 2012a; Qiu and Anadon, 2012; Gosens and Lu, 2014; Haakonsson and Kirkegaard, 2016). Our focus on innovation in the GVC (i.e., including both) component suppliers and OEMs responds to the recent emerging literature integrating innovation systems research (with its focus on country and institutional context) with GVC research that recognizes the global features of manufacturing and innovation (Pietrobelli and Rabellotti, 2011; Haakonsson and Kirkegaard, 2016; Zhang and Gallagher, 2016; Jurowetzki, Lema and Lundvall, 2018; Surana *et al.*, 2020).

Our analysis on the nature and direction of innovation emphasizes on the time-horizon of innovation in a specific technology rather than focusing on the direction of one technology over another (e.g. clean over fossil fuel-based energy). This is particularly important in the context of multiple clean energy technologies that are all essential for meeting long-term decarbonization targets. Each technology (such as wind, solar, etc.) has different innovation needs that need to be met to keep up with long-term deployment goals and each has its own nature and direction of innovation. In addition, our methodological approach using machine learning and patent data contributes to literature analyzing and quantifying technological innovation in clean energy (Johnstone, Haščič and Popp, 2010; Popp, Hascic and Medhi, 2011; Bettencourt, Trancik and Kaur, 2013; Choi and Anadon, 2014; Huenteler, Schmidt, *et al.*, 2016), adding a novel measure for the time-horizon of innovation within a technology.

Finally, our findings linking the direction of innovation with the location of manufacturing in the GVC suggest that manufacturing shifts to China did not directly translate to shifting away from long-term innovation, at least in the wind energy industry. These findings add to emerging theories on the linkages between location of manufacturing and innovation, that have so far been studied in industries such as optoelectronics (e.g., Fuchs and Kirchain, 2010; Fuchs, 2014; Yang, Nugent and Fuchs, 2016).

Our findings highlight opportunities for the development of manufacturing in new areas and for generating employment and export opportunities in a growing industry. We specifically offer insights for public policy resulting from its emphasis on component suppliers who are important for technological innovation as well as economic development. These manufacturing suppliers are often small and medium businesses, which constitute the backbone of most economies (Department of Business, Energy, and Industrial Strategy, UK, 2016; US Small Business Administration, 2016). Suppliers in developed country markets face competitive pressures from products manufactured, often at lower costs, in emerging economies. Because these suppliers can often not compete on price (e.g., due to high labor costs), it is particularly important for them to continuously innovate and deploy new technologies to stay competitive in their home markets and to export. Policymakers need to ensure that adequate incentives are in place for both short-term and long-term innovation not only for OEMs but also for suppliers to stay competitive.

6. CONCLUSIONS

Our study takes the perspective of suppliers and develops a novel method that enables the assessment of the direction of innovation. Our approach contributes to emerging literature linking global value chains and innovation systems perspectives, with a first of a kind study that presents a detailed data-driven analysis of technological innovation in knowledge intensive and rapidly changing GVCs. Our research brings a strong focus on the relationship between manufacturing and innovation outcomes across the component value chain. Our novel, micro-level dataset and empirical findings can provide evidence for policy design for enabling sustainable transitions, through domestic, competitive industries that provide local energy and economic benefits while simultaneously advancing technological innovation to achieve long-term climate goals. Our approach also opens up new pathways to developing new and automatized datasets on GVCs and the direction of innovation through advanced machine learning tools.

However, as with all empirical studies, ours is not without limitations. We based our analysis on the location of innovation based on the headquarters of the suppliers or the OEMs, and we use the location of component supplier rather than the location of manufacturing (e.g., supplier subsidiaries in other countries) because of incomplete publicly available data on manufacturing especially for smaller firms. Comprehensive data on location of manufacturing relative to the GVCs may become available in the future through new data collection efforts (e.g., the Trade in Value Added indicators and the World Input-Output tables) and are being modeled in emerging research on global value chains (Ahmad et al., 2017). This approach may not be fully accurate for larger or diversified suppliers.

Our novel measure for long- vs. short-term innovation using machine learning techniques and patent text data combined with wind energy reports needs additional verification in other contexts and time frames. Ideally, an evaluation after certain years would help in determining the actual contributions to long-term innovation, which can only be fully determined in retrospective. Moreover, our machine learning approach combined with patent data and wind specific reports needs further validation in other sectors than wind energy. We see exciting opportunities for future research to further develop our approach to establish a measure for the direction of innovation.

Future work indicated by this research includes the need to remedy the marked absence of industry- or technology-level datasets for clean energy, for example beyond the largest OEMs for wind. The need to analyze these GVCs is evident in growing efforts, for example by the Organisation for Economic Cooperation and Development (OECD) (OECD, 2018), the World Bank (World Bank, 2019), and many national level agencies. However, these broad efforts are useful for industry but insufficient to advance energy specific goals—our work is the first detailed analysis at a major clean energy industry's GVC and provides evidence-based policy insights for coupling energy and economic development goals.

REFERENCES

Ahmad, N. *et al.* (2017) 'Indicators on global value chains'. Available at: https://www.oecd-ilibrary.org/content/paper/8502992f-en.

Anadon, L. D. (2012) 'Missions-oriented RD&D institutions in energy between 2000 and 2010: A comparative analysis of China, the United Kingdom, and the United States', *Research Policy*, 41(10), pp. 1742–1756. doi: 10.1016/j.respol.2012.02.015.

Asheim, B. T. and Coenen, L. (2005) 'Knowledge bases and regional innovation systems: Comparing Nordic clusters', *Research Policy*, 34(8), pp. 1173–1190. doi: 10.1016/j.respol.2005.03.013.

Awate, S., Larsen, M. M. and Mudambi, R. (2012a) 'EMNC R&D internationalization: Going global for catch up'..

Awate, S., Larsen, M. M. and Mudambi, R. (2012b) 'EMNE catch-up strategies in the wind turbine industry: Is there a trade-off between output and innovation capabilities?', *Global Strategy Journal*, 2(3), pp. 205–223. doi: 10.1111/j.2042-5805.2012.01034.x.

Awate, S., Larsen, Marcus M and Mudambi, R. (2015) 'Accessing vs sourcing knowledge: A comparative study of R&D internationalization between emerging and advanced economy firms', *Journal of International Business Studies*, 46(1), pp. 63–86. doi: 10.1057/jibs.2014.46.

Awate, S., Larsen, Marcus M. and Mudambi, R. (2015) 'Accessing vs sourcing knowledge: A comparative study of R&D internationalization between emerging and advanced economy firms', *Journal of International Business Studies*, 46(1), pp. 63–86. doi: 10.1057/jibs.2014.46.

Bettencourt, L. M. A., Trancik, J. E. and Kaur, J. (2013) 'Determinants of the Pace of Global Innovation in Energy Technologies', *PLOS ONE*, 8(10), p. e67864. doi: 10.1371/journal.pone.0067864.

Binz, C. and Truffer, B. (2017) 'Global Innovation Systems—A conceptual framework for innovation dynamics in transnational contexts', *Research Policy*, 46(7), pp. 1284–1298. doi: 10.1016/j.respol.2017.05.012.

Cattaneo, O. *et al.* (2013) *Joining, upgrading and being competitive in global value chains: a strategic framework*. Policy Research working paper WPS 6406. Washington DC: World Bank.

Chatterji, A. K. and Fabrizio, K. R. (2014) 'Using users: When does external knowledge enhance corporate product innovation?', *Strategic Management Journal*, 35(10), pp. 1427–1445. doi: https://doi.org/10.1002/smj.2168.

Choi, H. and Anadon, L. D. (2014) 'The role of the complementary sector and its relationship with network formation and government policies in emerging sectors: The case of solar photovoltaics between 2001 and 2009', *Technological Forecasting and Social Change*. doi: 10.1016/j.techfore.2013.06.002.

Dahlin, K. B. and Behrens, D. M. (2005) 'When is an invention really radical?: Defining and measuring technological radicalness', *Research Policy*, 34(5), pp. 717–737. doi: 10.1016/j.respol.2005.03.009.

Dai, Y., Haakonsson, S. and Oehler, L. (2020) 'Catching up through green windows of opportunity in an era of technological transformation: Empirical evidence from the Chinese wind energy sector', *Industrial and Corporate Change*, 29(5), pp. 1277–1295. doi: 10.1093/icc/dtaa034.

Department of Business, Energy, and Industrial Strategy, UK (2016) 'Business Population Estimates for the UK and Regions 2016 - Statistical Release'. Available at: https://www.gov.uk/government/collections/business-population-estimates.

Elia, A. *et al.* (2020) 'Wind turbine cost reduction: A detailed bottom-up analysis of innovation drivers', *Energy Policy*, 147, p. 111912. doi: 10.1016/j.enpol.2020.111912.

Fuchs, E. R. H. (2014) 'Global manufacturing and the future of technology', *Science*, 345(6196), pp. 519–520. doi: 10.1126/science.1250193.

Fuchs, E. R. H. and Kirchain, R. (2010) 'Design for Location? The Impact of Manufacturing Offshore on Technology Competitiveness in the Optoelectronics Industry', *Management Science*, 56(12), pp. 2323–2349. doi: 10.1287/mnsc.1100.1227.

Garud, R. and Karnoe, P. (2003) 'Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship', *Research Policy*, 32(2), pp. 277–300. doi: 10.1016/S0048-7333(02)00100-2.

GLWN (Global Wind Network) (2014) *U.S. Wind Energy Manufacturing and Supply Chain: A Competitiveness Analysis*. U.S. Department of Energy. Available at: https://energy.gov/sites/prod/files/2014/09/f18/U.S.%20Wind%20Energy%20Manufacturing%20and%20Supply%20Chain%20Competitiveness%20Analysis_0.pdf.

Gosens, J. and Lu, Y. (2014) 'Prospects for global market expansion of China's wind turbine manufacturing industry', *Energy Policy*, 67, pp. 301–318. doi: 10.1016/j.enpol.2013.12.055.

Haakonsson, S. J. and Kirkegaard, J. K. (2016) 'Configuration of technology networks in the wind turbine industry. A comparative study of technology management models in European and Chinese lead firms', *International Journal of Technology Management*, 70(4), pp. 281–299. doi: 10.1504/IJTM.2016.075892.

Haakonsson, S. J. and Slepniov, D. (2018) 'Technology Transmission Across National Innovation Systems: The Role of Danish Suppliers in Upgrading the Wind Energy Industry in China', *The European Journal of Development Research*, 30(3), pp. 462–480. doi: 10.1057/s41287-018-0128-5.

Haakonsson, S., Kirkegaard, J. K. and Lema, R. (2020) 'The decomposition of innovation in Europe and China's catch-up in wind power technology: the role of KIBS', *European Planning Studies*, 0(0), pp. 1–19. doi: 10.1080/09654313.2020.1712329.

Hain, D. S. *et al.* (2020) 'From catching up to industrial leadership: towards an integrated market-technology perspective. An application of semantic patent-to-patent similarity in the wind and EV sector', *Industrial and Corporate Change*, 29(5), pp. 1233–1255. doi: 10.1093/icc/dtaa021.

Helveston, J. and Nahm, J. (2019) 'China's key role in scaling low-carbon energy technologies', *Science*, 366(6467), pp. 794–796.

Hoppmann, J. *et al.* (2013) 'The two faces of market support—How deployment policies affect technological exploration and exploitation in the solar photovoltaic industry', *Research Policy*, 42(4), pp. 989–1003. doi: 10.1016/j.respol.2013.01.002.

Huenteler, J., Ossenbrink, J., *et al.* (2016) 'How a product's design hierarchy shapes the evolution of technological knowledge—Evidence from patent-citation networks in wind power', *Research Policy*, 45(6), pp. 1195–1217. doi: 10.1016/j.respol.2016.03.014.

Huenteler, J., Schmidt, T. S., *et al.* (2016) 'Technology life-cycles in the energy sector — Technological characteristics and the role of deployment for innovation', *Technological Forecasting and Social Change*, 104, pp. 102–121. doi: 10.1016/j.techfore.2015.09.022.

IEA (2020) *Clean Energy Innovation*. Paris: IEA. Available at: https://www.iea.org/reports/clean-energy-innovation.

IEA Wind (2001) *Long-term Research and Development Needs for Wind Energy for the Time Frame 2000 to 2020*. Available at: https://www.ieawind.org/long-term%20reports/IEA%20R_D.pdf.

IEA Wind (2013) *Long-term Research and Development Needs for Wind Energy for the Time Frame 2012 to 2030*. Available at: https://www.ieawind.org/long-term%20reports/IEA%20Long%20Term%20R_D_Approved%20July%2023%202013.pdf.

IRENA (2019) *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf (Accessed: 19 May 2020).

Johnstone, N., Haščič, I. and Popp, D. (2010) 'Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts', *Environmental and Resource Economics*, 45(1), pp. 133–155. doi: 10.1007/s10640-009-9309-1.

Jurowetzki, R., Lema, R. and Lundvall, B.-Å. (2018) 'Combining Innovation Systems and Global Value Chains for Development: Towards a Research Agenda', *The European Journal of Development Research*, 30(3), pp. 364–388. doi: 10.1057/s41287-018-0137-4.

Kamp, L. M., Smits, R. E. H. M. and Andriesse, C. D. (2004) 'Notions on learning applied to wind turbine development in the Netherlands and Denmark', *Energy Policy*, 32(14), pp. 1625–1637. doi: 10.1016/S0301-4215(03)00134-4.

Lam, L. T., Branstetter, L. and Azevedo, I. M. L. (2017) 'China's wind industry: Leading in deployment, lagging in innovation', *Energy Policy*, 106, pp. 588–599. doi: 10.1016/j.enpol.2017.03.023.

Lema, R. and Lema, A. (2012) ‘Technology transfer? The rise of China and India in green technology sectors’, *Innovation and Development*, 2(1), pp. 23–44. doi: 10.1080/2157930X.2012.667206.

Lema, R., Rabellotti, R. and Gehl Sampath, P. (2018) ‘Innovation Trajectories in Developing Countries: Co-evolution of Global Value Chains and Innovation Systems’, *The European Journal of Development Research*, 30(3), pp. 345–363. doi: 10.1057/s41287-018-0149-0.

Lewis, J. I. (2011) ‘Building a national wind turbine industry: experiences from China, India and South Korea’, *International Journal of Technology and Globalisation*, 5(3), pp. 281–305.

Malhotra, A. and Schmidt, T. S. (2020) ‘Accelerating Low-Carbon Innovation’, *Joule*. doi: 10.1016/j.joule.2020.09.004.

Mazzucato, M. and Semieniuk, G. (2018) ‘Financing renewable energy: Who is financing what and why it matters’, *Technological Forecasting and Social Change*, 127, pp. 8–22. doi: 10.1016/j.techfore.2017.05.021.

Meckling, J. and Hughes, L. (2017) ‘Globalizing Solar: Global Supply Chains and Trade Preferences’, *International Studies Quarterly*, 61(2), pp. 225–235. doi: 10.1093/isq/sqw055.

Meckling, J. and Hughes, L. (2018) ‘Global interdependence in clean energy transitions’, *Business and Politics*, 20(4), pp. 467–491. doi: 10.1017/bap.2018.25.

Nahm, J. (2017) ‘Renewable futures and industrial legacies: Wind and solar sectors in China, Germany, and the United States†’, *Business and Politics*, 19(1), pp. 68–106. doi: 10.1017/bap.2016.5.

Nahm, J. and Steinfeld, E. S. (2014) ‘Scale-up Nation: China’s Specialization in Innovative Manufacturing’, *World Development*, 54, pp. 288–300. doi: 10.1016/j.worlddev.2013.09.003.

Navigant Research (2014) *Supply Chain Assessment 2014 – Wind Energy 2014-2018*.

Nemet, G. F. (2009) ‘Demand-pull, technology-push, and government-led incentives for non-incremental technical change’, *Research Policy*, 38(5), pp. 700–709. doi: 10.1016/j.respol.2009.01.004.

OECD (2018) *Multinational enterprises in the global economy - Heavily debated but hardly measured*. Available at: https://www.oecd.org/industry/ind/MNEs-in-the-global-economy-policy-note.pdf.

Pietrobelli, C. and Rabellotti, R. (2011) ‘Global Value Chains Meet Innovation Systems: Are There Learning Opportunities for Developing Countries?’, *World Development*, 39(7), pp. 1261–1269. doi: 10.1016/j.worlddev.2010.05.013.

Popp, D., Hascic, I. and Medhi, N. (2011) ‘Technology and the diffusion of renewable energy’, *Energy Economics*, 33(4), pp. 648–662. doi: 10.1016/j.eneco.2010.08.007.

Qiu, Y. and Anadon, L. D. (2012) ‘The price of wind power in China during its expansion: Technology adoption, learning-by-doing, economies of scale, and manufacturing localization’, *Energy Economics*, 34(3), pp. 772–785. doi: 10.1016/j.eneco.2011.06.008.

Robinson, D. K. R. and Mazzucato, M. (2019) 'The evolution of mission-oriented policies: Exploring changing market creating policies in the US and European space sector', *Research Policy*, 48(4), pp. 936–948. doi: 10.1016/j.respol.2018.10.005.

Sandor, D. *et al.* (2020) 'Clean Energy Manufacturing: Renewable Energy Technology Benchmarks', in Uyar, T. S. (ed.) *Accelerating the Transition to a 100% Renewable Energy Era*. Cham: Springer International Publishing (Lecture Notes in Energy), pp. 195–206. doi: 10.1007/978-3-030-40738-4_9.

Schmidt, T. S. *et al.* (2012) 'The effects of climate policy on the rate and direction of innovation: A survey of the EU ETS and the electricity sector', *Environmental Innovation and Societal Transitions*, 2, pp. 23–48. doi: 10.1016/j.eist.2011.12.002.

Sivaram, V., Dabiri, J. O. and Hart, D. M. (2018) 'The Need for Continued Innovation in Solar, Wind, and Energy Storage', *Joule*, 2(9), pp. 1639–1642. doi: 10.1016/j.joule.2018.07.025.

Stirling, A. (2010) 'Keep it complex', *Nature*, 468(7327), pp. 1029–1031. doi: 10.1038/4681029a.

Surana, K. *et al.* (2020) 'Effects of technology complexity on the emergence and evolution of wind industry manufacturing locations along global value chains', *Nature Energy*, 5(10), pp. 811–821. doi: 10.1038/s41560-020-00685-6.

Surana, K. and Anadon, L. D. (2015) 'Public policy and financial resource mobilization for wind energy in developing countries: A comparison of approaches and outcomes in China and India', *Global Environmental Change*, 35, pp. 340–359. doi: 10.1016/j.gloenvcha.2015.10.001.

Tushman, M. L. and Anderson, P. (1986) 'Technological Discontinuities and Organizational Environments', *Administrative Science Quarterly*, 31(3), pp. 439–465. doi: 10.2307/2392832.

US Small Business Administration (2016) 'Small Business Profile'. Available at: https://www.sba.gov/sites/default/files/advocacy/United_States.pdf.

Wilson, C. (2018) 'Disruptive low-carbon innovations', *Energy Research & Social Science*, 37, pp. 216–223. doi: 10.1016/j.erss.2017.10.053.

Wilson, C. *et al.* (2020) 'Granular technologies to accelerate decarbonization', *Science*, 368(6486), pp. 36–39. doi: 10.1126/science.aaz8060.

Wiser, R. *et al.* (2016) 'Expert elicitation survey on future wind energy costs', *Nature Energy*, 1(10), p. 16135. doi: 10.1038/nenergy.2016.135.

Wiser, R. *et al.* (2018) *2018 Wind Technologies Market Report*, p. 103.

World Bank (2019) *World Development Report 2020*. The World Bank (World Bank Publications, 32437). Available at: https://ideas.repec.org/b/wbk/wbpubs/32437.html.

Yang, C.-H., Nugent, R. and Fuchs, E. R. H. (2016) 'Gains from others' losses: Technology trajectories and the global division of firms', *Research Policy*, 45(3), pp. 724–745. doi: 10.1016/j.respol.2015.12.005.

Zhang, F. and Gallagher, K. S. (2016) 'Innovation and technology transfer through global value chains: Evidence from China's PV industry', *Energy Policy*, 94, pp. 191–203. doi: 10.1016/j.enpol.2016.04.014.

Zhou, Y. *et al.* (2016) 'Comparing the knowledge bases of wind turbine firms in Asia and Europe: Patent trajectories, networks, and globalisation', *Science and Public Policy*, 43(4), pp. 476–491. doi: 10.1093/scipol/scv055.