Technological Change and the Decomposition of Innovation

Choices and Consequences for Latecomer Firm Upgrading

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TECHNOLOGICAL CHANGE AND THE DECOMPOSITION OF INNOVATION: CHOICES AND CONSEQUENCES FOR LATECOMER FIRM UPGRADING.
THE CASE OF CHINA'S WIND ENERGY SECTOR

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Ph.D. Thesis

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The Case of China's Wind Energy Sector

Lars Oehler

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Für Nicole & Lina

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Three years ago to the day, I had just returned from my first field trip in China. Full of new impressions, I started to write the first lines of what would become this dissertation. It marked the beginning of a truly exciting and enriching journey that would not have been possible without the support of many people. I would like to express my gratitude to those who have contributed to my PhD project, both professionally and privately.

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As I write these lines, we are facing a second lockdown because of the COVID-19 pandemic. As recently urged by the Executive Director of UNEP, Inger Andersen, this crisis highlights that we have been pushing the boundaries of our natural systems for too long. In order to solve the grand challenges, transformative change is imperative. This thesis is intended not only to be a unique and personal learning experience but to contribute to the broader debate on sustainable development.

Lars Oehler
Copenhagen, January 2021

English summary

This dissertation analyzes how changing conditions in the global economy affect the development of latecomer firms. In particular, it analyzes how latecomer firms respond to and effectively manage technological change and the organizational decomposition of innovation. The thesis is positioned at the intersection of innovation and development studies, rooted in evolutionary economics. It specifically addresses the literature on catching up, technological learning, and the upgrading of innovation capabilities. Drawing on the empirical case of latecomer firms in China's wind energy sector, the overarching research question guiding this thesis is: what consequences do technological change and the decomposition of innovation have for the upgrading of innovation capabilities in latecomer firms?

The motivation for this research question is based on the observation that existing studies do not provide an adequate explanation of changing upgrading dynamics (i.e., trajectories, opportunities, and mechanisms) in the face of recent technological change, especially in relation to the green and digital transformation. Specifically, the current literature on latecomer development reveals three significant gaps. First, there is no integrated perspective that evaluates catching up using both market and technology indicators, in particular to assess technological novelty and impact. Second, there is little understanding on why latecomer firms under the same framework conditions develop different levels of innovation capabilities, particularly in the face of new technologies. Third, there are insufficient systematic studies on the coevolution of upgrading mechanisms and R&D networks, in particular when firms reach higher levels of innovation capabilities and increase their global innovation space.

To address these gaps and answer the research question, the dissertation employs a mixed methods approach across multiple case studies. To develop an in-depth understanding of the changing nature of latecomer firm upgrading in emerging economies, this thesis establishes a multi-angle view across three perspectives, each of which is represented in one article. The first article examines catch-up trajectories across countries and sectors and identifies potential catch-up traps. It finds that effective upgrading requires latecomer firms to align their catch-up trajectories with country-specific factor endowments and sector-specific technology cycles. The second article investigates latecomer firm responses to technological change in the wind sector vis-à-vis incumbent firms. It concludes that latecomers under the same framework conditions have different capabilities in responding to technological shifts, highlighting the role of dynamic capabilities at firm level beyond the institutional environment. The third article focuses on the changing properties of R&D networks of lead firms in China's wind energy sector and identifies new forms of upgrading mechanisms that have not been captured by the extant literature. It determines that latecomer firms adopt new upgrading mechanisms to varying degrees, which explains their different levels of innovation capabilities. The findings build on 18 months of field research in China, including 81 interviews, 23 participant observations, and analysis of over 400 archival records and six databases.

Building on the theoretical and empirical findings, the dissertation advances our understanding of latecomer development in an era of technological change. Specifically, it makes the following key contributions: first, it develops an integrated market-technology framework that allows for a differentiated evaluation and holistic understanding of catching up. Second, it conceptualizes technology shifts as significant events for latecomer firm upgrading that, together with firm responses, explain variations in catch-up trajectories under the same framework conditions. Third, it identifies externalized R&D projects as new upgrading mechanisms to acquire high levels of innovation capabilities, ascertaining that latecomer firms do not only exploit but increasingly co-create knowledge through organizational diversification. In addition to these specific contributions, the thesis speaks to the broader debates on economic development, technological progress, and industrial upgrading in emerging market firms and argues that significant synergies exist between the green and digital transformations, and latecomer development.

Key words: Technological change, decomposition of innovation, latecomer firms, catching up, technological learning, upgrading of innovation capabilities, wind energy, China

JEL codes: O33 Technological Change: Choices and Consequences
O31 Innovation and Invention: Processes and Incentives
Q20 Renewable Resources and Conservation
L10 Market Structure, Firm Strategy, and Markets Performance
L60 Industry Studies: Manufacturing

Danish summary

Denne afhandling analyserer, hvordan skiftende omstændigheder i den globale økonomi har en effekt på nytilkomne virksomheder fra udviklings- og vækstøkonomier inden for en etableret industri. Afhandlingen studerer, hvordan nytilkomne virksomheder reagerer på og håndterer den teknologiske udvikling samt den organisatoriske omstrukturering af innovationsprocesser. Afhandlingen er positioneret i skæringspunktet imellem innovation, evolutionær økonomi og udviklingsstudier. Den vedrører specifikt litteraturen omkring vækstmarkeders industrielle 'catch-up', teknologisk læring, og opgradering af innovationsevner. Med nytilkomne virksomheder i Kinas vindindustri som empirisk fundament, drejer det overordnede forskningstema sig omkring spørgsmålet: 'hvilke konsekvenser har teknologisk udvikling og omstrukturering af innovation for opgradering af innovative evner i nytilkomne virksomheder fra vækstmarkeder?'

Motivationen for dette forskningsspørgsmål er, at den eksisterende forskning ikke giver en tilstrækkelig forklaring på de skiftende dynamikker for industriel udvikling og opgradering (dvs. tendenser, muligheder og mekanismer). Især set i lyset af den seneste teknologiske udvikling, som indebærer grøn og digital transformation. Den nuværende litteratur om udvikling af nytilkomne virksomheder fra udviklings- og vækstmarkeder har tre begrænsninger. For det første findes der ikke et integreret perspektiv til at forstå virksomhedernes catch-up processer, som er baseret på både markeds- *og* teknologiindikatorer. For det andet mangler der en forståelse af, hvorfor virksomheder med de samme rammebetingelser udvikler vidt forskellige niveauer af innovationsevner, især når det gælder nye teknologier. For det tredje mangler der systematisk forskning omkring sammenhængen mellem udviklingen af mekanismer for opgradering og udviklingen af netværk inden for forskning og udvikling (F&U). Det gælder især, når virksomheder opnår højere innovationsevner og øger deres globale innovationsrum.

For at adressere disse mangler og for at besvare forskningsspørgsmålet anvender afhandlingen et 'mix' af metoder på tværs af flere casestudier. For at skabe en dybdegående forståelse af skiftende karakteristika i nytilkomne virksomheder fra vækstmarkeders opgradering, udvikler afhandlingen perspektiver, som hver er repræsenteret af en artikel: Den første artikel undersøger modeller for catch-up på tværs af lande og sektorer og identificerer potentielle farer for virksomheder i deres udviklingsproces. Artiklen konkluderer, at effektiv opgradering kræver, at virksomhederne tilpasser deres strategi til landespecifikke produktionssystemer og sektorspecifikke teknologicyklusser. Den anden artikel undersøger nytilkomne virksomheders reaktioner på teknologiske udviklinger i vindenergisektoren set i forhold til de etablerede virksomheder. Artiklen konkluderer, at nytilkomne virksomheder der opererer under samme rammer har forskellige evner til at reagere på den teknologiske udvikling. Dette fremhæver vigtigheden af at kunne forstå dynamiske evner på virksomhedsniveau og relatere disse til effekten af det institutionelle miljø. Den tredje artikel fokuserer på skiftende evner i ledende virksomheder i Kinas vindenergisektors R&D netværk og identificerer nye former for opgraderingsmekanismer. Artiklen konkluderer, at virksomheder i vækstøkonomier bruger nye opgraderingsmekanismer i forskellig grad, hvilket forklarer deres forskellige innovationsevner. Resultaterne bygger på 18 måneders feltarbejde i Kina, 81 interviews, 23 observationer, +400 dokumenter og seks databaser.

På baggrund af de teoretiske og empiriske konklusioner fremmer afhandlingen vores forståelse af, hvordan virksomheder i vækstmarkeder udvikles i en æra præget af teknologisk udvikling. Afhandlingen giver følgende bidrag til den eksisterende litteratur: For det første udvikler den en analytisk ramme, der giver mulighed for en differentieret analyse og holistisk forståelse af, hvad det vil sige at 'catch-up'. For det andet introducerer den begreber til at analysere, hvordan teknologiske udviklingsskridt er vigtige begivenheder for opgraderingen af virksomheder i vækstmarkederne, der set sammen med virksomhedernes reaktioner forklarer variationer i catch-up processen under ensartede vilkår. For det tredje redegør afhandlingen for eksterne F&U-projekter som en ny opgraderingsmekanisme til at øge innovationsevner og konkluderer, at nytilkomne virksomheder ikke kun udnytter, men også i stigende grad er med til at skabe viden gennem, organisatorisk diversificering. Ud over disse specifikke tiltag bidrager afhandlingen til den bredere debat om økonomisk udvikling, teknologisk fremskridt og industriel opgradering af virksomheder i udviklings- og vækstøkonomier og argumenterer for, at der kan være vigtige synergier mellem grøn og digital transformation i udviklingen af nytilkomne virksomheder i disse økonomier.

Nøgleord: Teknologisk udvikling, omstrukturering af innovation, nytilkomne virksomheder, catch up, teknologisk læring, opgradering af innovationsevner, vindenergi, Kina

JEL-koder: O33 Teknologisk udvikling: valg og konsekvenser
O31 Innovation og opfindelse: processer og incitamenter
Q20 Vedvarende ressourcer og bevarelse
L10 Markedsstruktur, virksomhedsstrategi og markedsresultater
L60 Industristudier: Produktion

Chinese summary

本文分析了全球经济环境的变化如何对后发企业的发展产生影响。本文特别分析了后发企业如何应对并有效管理技术变革以及创新活动的全球配置。本文定位于创新研究与发展研究的交叉学科，植根于进化经济学。具体论述了赶超、技术学习和创新能力提升的相关文献。以中国风能行业的后发企业作为实证案例，本文的首要研究问题是"技术变革和创新分解对后发企业创新能力的提升有何影响"。

这一研究问题的动机是基于这样一种观察：即现有的文献无法充分解释在面对最近的技术变革，升级动态平衡（即轨迹、机会和机制）是如何产生变化的，特别是在绿色和数字化转型有关的技术变革中。具体而言，当前关于研究后发企业发展的文献揭示了三个重要的空白领域。首先，没有一个综合的角度，即同时使用市场指标和技术指标，来评估赶超进度，特别是评估技术的新颖性和影响。第二，人们对于为什么在相同的框架条件下，后发企业会展现出不同水平的创新能力，尤其是面对新技术的创新能力，缺乏足够的理解。第三，目前缺乏对升级机制和 R&D 网络协同进化的系统研究，特别是当企业达到更高水平的创新能力和增加全球创新空间时, 这种缺乏的程度更深。

为了弥补这些不足，以及回答上述的研究问题，本文采用了跨多个案例的研究方法。为了深入了解新兴经济体中后发企业升级的性质变化，本文从三个角度建立了一个多元化的视角，每个角度用一篇文章来阐述：第一篇文章考察了不同国家和行业的赶超轨迹，并确定了潜在的赶超陷阱。研究发现，有效的升级需要后发企业将其赶超轨迹与所在国家的要素禀赋和特定行业的技术周期保持一致性。第二篇文章考察了后发企业对风电行业技术变革的应对情况。研究发现，在相同的框架条件下，后发企业对技术转移的反应能力不同，这突出了在制度性环境层面之外的企业层面上的动态能力的影响力。第三篇文章关注中国风能行业领先企业研发网络构建的变化特质，并确定了现有文献中尚未记载的升级机制的新形式。研究发现，后发企业在不同程度上采用了新的升级机制，这解释了其创新能力水平的差异。这些发现建立在为期 18 个月的中国实地考察基础上，包括 81 次访谈、23 次参与者观察、400 多份档案记录和 6 个数据库。

在理论和实证研究的基础上，本文进一步加深了我们对技术变革时代后发企业发展的理解。具体而言，它做出了以下关键贡献：第一，本文搭建了一个综合的'市场-技术'的二维框架，允许对赶超进度进行差异化评估和全面理解。其次，本文概念化的提出技术变革是成为后发企业升级的重要诱因，再加上企业应对变革的不同反应，解释了在相同的框架条件下出现不同赶超轨迹。第三， R&D 外部化将作为获取高水平创新能力的新的升级机制，并观察到后发企业不仅通过组织多元化来开发已有的知识，而且通过组织多元化去创造知识。除了以上具体贡献外，本文还谈到了新兴市场企业在经济发展、技术进步和产业升级方面的广泛争论，并认为绿色和数字化转型与后发企业发展之间可能存在重要的协同效应。

关键词：技术变革、创新分解、后发企业、赶超、技术学习、创新能力提升、风能、中国

JEL 准则： O33 技术变革：选择与后果
O31 创新与发明：过程与激励
Q20 可再生资源与保护
L10 市场结构、企业战略和市场绩效
L60 工业研究：制造业

Table of contents

List of figures

List of tables

List of appendices

List of abbreviations

AI	Artificial Intelligence
BNEF	Bloomberg New Energy Finance
CNREC	China Renewable Energy Centre
CWEA	Chinese Wind Energy Association
DUI	Doing, Using, Interacting
ENV	Envision
EPC	Engineering, Procurement, and Construction
EPO	European Patent Office
ERI	Energy Research Institute
EV	Electric Vehicle
FDI	Foreign Direct Investment
FIT	Feed-in Tariff
GOL	Goldwind
GW	Gigawatt
GWEC	Global Wind Energy Council
GWO	Green Window of Opportunity
HQ	Headquarters
ICT	Information and Communication Technologies
IEA	International Energy Agency
IEEFA	Institute for Energy Economics and Financial Analysis
IoT	Internet of Things
IPC	International Patent Classification
IRENA	International Renewable Energy Agency
IS	Innovation System
JV	Joint Venture
LCOE	Levelized Cost of Energy
M&A	Mergers and Acquisitions
MNE	Multinational Enterprise
MNG	Ming Yang
MW	Megawatt
NDRC	National Development and Reform Commission of the PRC
NEA	National Energy Commission
NIS	National Innovation System
NLP	Natural Language Processing
O&M	Operations and Maintenance
ODM	Own Design Manufacturer
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
PATSTAT	Worldwide Statistical Patent Database
PRC	People's Republic of China
PV	Photovoltaics

R&D	Research and Development
RQ	Research Question
S&T	Science and Technology
SaaS	Software as a Service
SDC	Sino-Danish Center for Education and Research
SGRE	Siemens Gamesa Renewable Energy
SIPO	State Intellectual Property Office of the PRC (*today CNIPA*)
SM-I/II	Schumpeter Mark I/II
SNA	Social Network Analysis
SPIV	Special-Purpose Innovation Vehicle
SSCI	Social Science Citation Index
SSI	Sectoral Innovation System
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
USTPO	United States Patent and Trademark Office
VSM	Vector Space Modelling
WIPO	World Intellectual Property Organization
WOO	Window of Opportunity
WWEA	World Wind Energy Association

List of key concepts

The following provides a brief overview of the key concepts explored more deeply later in the thesis.

Catching up
The process of closing the gap in market share and/or technological capabilities between incumbent and latecomer firms; the process can be linear (path following) or nonlinear (path skipping).

Decomposition of innovation
The organizational process of diversifying, i.e., decentralizing and globally dispersing innovative activities, both at the intra- and inter-firm level, and comprising partners that are both loosely/tightly connected between innovation and production.

Incumbent firms
Established firms that typically possess power, resources, and large market share; innovation capabilities may be geared towards a specific technological regime, which poses the risk of lock-in routines.

Innovation capability
The degree to which a firm can design and implement new products or processes based on a set of knowledge-related resources; innovation capability builds upon both technological and organizational learning.

Latecomer firms
Firms from developing and emerging countries that entered a given industry historically 'late' and are catching up with incumbent firms; linked to initial competitive advantages (low labor costs) and disadvantages (lack of advanced markets and technology).

R&D network
The configuration whereby a firm can access complementary resources to conduct creative and systematic work in the form of basic research, applied research, and experimental development.

Technological change
The changing conditions associated with the invention, innovation, and diffusion of new or significantly improved technologies; in this thesis the term mainly refers to the green and digital transformation.

Technological learning
The deliberate and costly mechanisms for acquiring and accumulating technological knowledge and skills by individuals and/or by an organization; learning can be both process- or product-focused.

Upgrading
The process of enhancing a latecomer firm's innovation capabilities through effective learning mechanisms.

Windows of opportunity
The conditions under which catching up and potential changes in industrial leadership occur, based on changes in technology, market demand, or institutions, and followed by adequate system and firm responses.

1. INTRODUCTION

Our global economy is undergoing a decisive momentum of transition. Technological change associated with the green and digital transformation is radically transforming previous forms of industrial organization (UNCTAD, 2019; Nambisan et al., 2019). As a result, new industries, firms, and business models are emerging at the expense of incumbent ones (Lee and Malerba, 2017). At the same time, given the accelerating pace of technological change and complexity, firms are increasingly decentralizing and globally dispersing their innovative activities to access new knowledge (Schmitz and Strambach, 2009; Haakonsson et al., 2020). Both phenomena, the emergence of new green and digital industries, and the global dispersion of innovative activities, provide new opportunities for latecomer firms, as clearly exemplified by the wind energy sector.[1]

First, the green transformation: in light of the climate crisis, switching to low-carbon energy systems has become a key priority of governments around the world.[2] The past two decades has witnessed a remarkable transition of renewable energies from a niche to a mainstream and least-cost source of electricity, with wind at the forefront (IRENA, 2019a; Altenburg et al., 2016a). The advance of clean and renewable energies increasingly challenges the once dominant position of conventional energy sectors (Van Mossel et al., 2018; Steen and Weaver, 2017).[3] This trend is very likely to continue. By 2050, wind and solar are expected to supply half of the world's power supply (BNEF, 2019). The green redirection of the global economy is expected to be the next big technological revolution of modern times (Perez, 2016; Mazzucato and Perez, 2014),[4] thereby providing significant market opportunities for new entrants.

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[1] *Note:* The focus of this dissertation is not to study the green and digital transformation, but latecomer firm upgrading in the face of technological change. A latecomer firm is defined along four criteria (Hobday, 1995; Mathews and Cho, 1999; Mathews, 2002; Bell and Figueiredo, 2012a): (1) dislocation from technology sources and advanced markets, (2) initial competitive advantages e.g., low labor costs, (3) late industry entry that is of a historical rather than strategic nature, (4) the strategic intent of catching up.

[2] Decarbonizing the energy sector is of utmost relevance given that it accounts for two-thirds of greenhouse emissions (IEA, 2019). Renewable energy can deliver 75%, and together with energy efficiency measures, 90% of the energy-related CO_2 emissions reductions needed to meet the Paris climate goals (IRENA, 2020).

[3] For the first time in history, crude oil prices dropped temporarily below zero this year and one of the world's largest fossil-fuel multinationals, ExxonMobil, was recently removed from the Dow Jones Industrial Average for the first time since 1928 (Ngai et al., 2020; The Economist, 2020). As a result of the green transition, international energy competition is undergoing a shift from controlling fossil fuels to controlling technology and intellectual property rights of low-carbon technologies (Overland, 2019).

[4] A 'technological revolution' is defined as a 'powerful and highly visible cluster of new and dynamic technologies, products, and industries, capable of bringing about an upheaval in the whole fabric of the economy and of propelling a long-term upsurge of development' (Perez, 2003: 8). Accordingly, technological change occurs in clusters corresponding to successive technological revolutions (Mazzucato and Perez, 2014).

Second, the digital transformation: digitalization and industry hybridization are disrupting industry boundaries at an extraordinary speed and on an unprecedented scale (UNCTAD, 2019; OECD, 2017). With the digitalization of industries and growing technological complexity, it becomes increasingly difficult for one country to master a full range of specialization. As a result, firms are increasingly decentralizing and dispersing their innovative activities globally (Schmitz and Strambach, 2009). Wind energy becomes not only increasingly hybridized, combining multiple renewable and storage technologies, but also digitalized, incorporating different ICTs for energy management and prediction purposes (Haakonsson, 2020; Dai et al., 2021; Sianaki et al., 2018). This technological 'widening' (Malerba and Orsenigo, 2000) in the wake of the digital transformation, from narrow to diffuse technological boundaries, opens up new leapfrogging possibilities for latecomer firms across all sectors (Fu et al., 2020; Dai et al., 2021; Rosiello and Maleki, 2021).

At the same time, the rise of emerging market firms has been 'one of the most significant events of the beginning of the 21st century' (Von Zedtwitz and Gassmann, 2016: 125). Given their rapid industrial transformation from production to significant R&D players, emerging market firms are poised to become driving forces in what Schumpeter described as 'industrial mutation'.[5] In the wind turbine sector, firms from India and China evolved in less than ten years from having no manufacturing expertise to being producers of integrated, state-of-the-art wind systems (Lewis, 2011). This is highly relevant as emerging markets, especially China and India, are among the world's top polluters.[6] Hence, their energy pathways and green investment decisions have a significant impact on the rest of the world (Fu, 2015).

In this respect, China in particular has shown an unprecedented ability to catch up and is now a 'green giant' (Jaffe, 2018). 'Today, Chinese firms produce 72% of the world's solar modules, 69% of its lithium-ion batteries, and 45% of its wind turbines' (The Economist, 2020: 9). Besides production, China has also become a global leader in the deployment of renewable energies.

[5] 'Industrial mutation' describes the process 'that incessantly revolutionized the economic structure from within, incessantly destroying the old one, incessantly creating a new one' (Schumpeter, 1942: 1975; Fagerberg, 2003).

[6] Ranking first and third respectively as the world's largest polluters. Together with the second largest polluter, the United States, they generate half of the world's carbon emissions (Wang et al., 2020). To put the figures into perspective: China and India's CO_2 emissions per capita are lower than Germany's; in terms of cumulative emissions, the United States has to date produced double the amount of China's and eightfold the amount of India's CO_2 emissions (Ritchie and Roser, 2017).

Accounting for more than one-third of the world's wind and solar installed capacity respectively (Murdock et al., 2019), the country has not only created the largest renewable energy market, but also accumulated significant innovation capabilities within an unprecedentedly short time (Hansen and Lema, 2019; Lewis, 2013; Nahm, 2017). In light of recent climate pledges, China is on course to further strengthen its newly envisioned role as the 'green savior of the world' (Kirkegaard, 2017: 8; Xi, 2020).[7]

In sum, we are in the midst of transitioning towards a green and digital global economy, where emerging market firms—led by China—play an increasingly proactive role (Lee and Malerba, 2017; Amendolagine et al., 2020). These transformations do not take place in silos but are closely interlinked. Taking the example of the wind energy sector, the economic and scientific center of gravity is further shifting towards China as a result of its rapidly growing competencies in green and digital technologies (Altenburg et al., 2016a; Guo and Zheng, 2019; Kaplinsky, 2011).[8]

1.1. Motivation

Notwithstanding their vast relevance, our understanding of how these transformations interact is still at a very nascent stage (Perez, 2016).[9] Specifically, we know surprisingly little about the consequences of recently changing conditions in the global economy for the development of emerging market firms. Theories on latecomer firms have long focused on traditional concepts of technology transfers, knowledge spillovers, and learning linkages (Figueiredo and Piana, 2018; Fu et al., 2011; Lema and Lema, 2012; Mathews, 2006, 2017; Hansen and Hansen, 2020). However, they have yet to properly examine two other equally important and interrelated phenomena: (1) upgrading *trajectories*, *opportunities,* and *mechanisms* have changed significantly in the face of

[7] Recently, China made its first long-term climate pledge with the aim of becoming carbon neutral before 2060 (Mallapaty, 2020). As a result, Chinese renewable and green tech firms are likely to continue taking over market share of their incumbent counterparts in Europe and North America (Dai et al., 2020; Quitzow et al., 2017).

[8] By 2050, the world's economic center of gravity is projected to have shifted almost 10,000 km east (starting from the mid-Atlantic in 1980) to lie exactly between India and China (Quah, 2011). In the same vein, the geography of global science is shifting in relative terms from the Unites States and Europe to the Asia-Pacific, mainly driven by China (Gui et al., 2019).

[9] Pfizer and Popp (2008: 2768) state that 'technological change is at once the most important and least understood feature driving the future cost of climate change mitigation.'

recent technological change, especially in relation to the green and digital transformation;[10] and (2) on a broader level, latecomer firms do not only catch up with the Global North, but increasingly co-create 'innovations and socio-technical systems change' (Schot and Steinmueller, 2018: 1565).

Against this background, the objective of this thesis is to provide an updated perspective on latecomer firm development that focuses on the abovementioned phenomena and highlights the potential synergies between the green and digital transformation and latecomer firm development to tackle grand challenges.[11] More concretely, this thesis addresses three significant gaps in the current literature on catching up, technological learning, and the upgrading of innovation capabilities (as explained in detail in Chapter 2 and Chapter 3). First, there is no integrated perspective that evaluates catching up using both market and technology indicators. While the catch-up literature provides a market-oriented perspective (Lee and Malerba, 2017), the innovation capability literature draws on technology-oriented indicators to evaluate latecomer development (Bell and Figueiredo, 2012b).[12] The thesis seeks to address this dichotomy by integrating both perspectives into a single framework.

Second, there is little understanding on why latecomer firms under the same framework conditions develop different levels of innovation capability in the face of new technologies. While many studies have focused on the institutional level to explain China's rapid catch-up,[13] they have not paid sufficient attention to explaining disparities in innovation capabilities at the firm

[10] *Note:* In this thesis, 'upgrading' refers to the upgrading of innovation capabilities through effective learning and technological efforts, not necessarily through global value chains. As stated by Morrison et al. (2008), these aspects are largely hidden in the global value chains literature.

[11] 'Grand challenges' are 'highly significant yet potentially solvable problems [...] [that are] typically complex with unknown solutions and intertwined technical and social elements' (Eisenhard et al., 2016: 1113). Climate change is an example. Solving grand challenges requires highly multidisciplinary sources of knowledge and new forms of collaboration (Coenen et al., 2015).

[12] Lee and Malerba (2017) use the global market or production share of a country's lead firm as a proxy for catching up. This is highly problematic as it neglects two important aspects: On the one hand, it decouples technological and commercial performance, assuming that the first leads automatically to the second and vice versa. For example, firms from countries with large domestic markets and monopolistic structures can easily appear as industrial leaders, even in the absence of any major technological innovations (Hain et al., 2020). On the other hand, firms within the same country show very different catch-up trajectories and respond very differently to technological transformation at the global level (Dai et al., 2021). Hence, the representativeness of a country's lead firm is limited.

[13] Following the argument of the 'development state' to orchestrate successful catch-up (Fagerberg and Godinho, 2004).

level. By isolating country- and sector-specific factors, this thesis seeks to open the black box of firm-level heterogeneity.[14]

Third, there are insufficient systematic studies on the coevolution of upgrading mechanisms and R&D networks, particularly when firms reach higher levels of innovation capabilities and increase their innovation space. By adding recent empirical data, this thesis aims to provide new insights into how latecomer firms reorganize their innovative activities in light of recent technological change. Table 1 summarizes the gaps in the current literature that constitute the point of departure and underlying motivation of this dissertation.

Table 1. Research gaps addressed in this thesis

No.	Research gap
Gap 1	There is no integrated framework that evaluates catch-up trajectories using both market and technology indicators, in particular to assess technological novelty and impact.
Gap 2	There is little understanding on why firms under the same framework conditions develop different levels of innovation capabilities, in particular in the face of new technologies.
Gap 3	There is no systematic understanding on the coevolution of upgrading mechanisms and R&D networks, in particular when firms reach higher levels of innovation capability and increase their innovation space.

1.2. Research objective and questions

The aim of this dissertation is to develop a framework to understand the relationship between changing conditions in the global economy and latecomer firm development. More specifically, it focuses on the consequences of technological change and the decomposition of innovation for the upgrading of innovation capabilities in latecomer firms ('latecomer' is used interchangeably with 'emerging market'). Building on the empirical case of China's wind energy sector, the main question guiding this thesis is: what consequences do technological change and the decomposition of innovation have for the upgrading of innovation capabilities in latecomer firms? This overarching question encompasses various dimensions at different levels. In order to specifically address the research gaps presented in the previous chapter, three sub-questions are formulated, as shown in Table 2.

[14] Evolutionary economics emphasizes the 'persistent heterogeneity in the knowledge and problem-solving capabilities that firms embody' (Dosi, 1997: 1533).

Table 2. Main research questions

Level	Research question (RQ)
Main RQ	What consequences do technological change and the decomposition of innovation have for the upgrading of innovation capabilities in latecomer firms?
Sub-RQ1	How do technological change and the decomposition of innovation influence *upgrading trajectories* of latecomer firms?
Sub-RQ2	How do technological change and the decomposition of innovation affect *upgrading opportunities* of latecomer firms?
Sub-RQ3	How do technological change and the decomposition of innovation change *upgrading mechanisms* of latecomer firms?

The first sub-RQ focuses on the changing upgrading *trajectories* on a sectoral and country level. This perspective is important to gain an initial understanding of the outer boundaries and framework conditions in which latecomer firms operate. Previous studies have found that sectors vary considerably in terms of knowledge regimes (Jung and Lee, 2010; Zhou et al., 2016), forms of learning (Quitzow et al., 2017), and innovation modes (Binz and Truffer, 2017; Capone et al., 2021). Therefore, this question specifically focuses on the interplay between sector-specific dynamics in the wind sector (e.g., changing technology cycles) and latecomer firm responses. This is followed by a closer look at the resulting upgrading *opportunities* for Chinese wind turbine manufacturers vis-à-vis incumbent firms. The literature singles out technological discontinuities as highly relevant events that concurrently destroy previous, and open up new spectrums of business opportunities (Perez, 2003, 2016; Freeman, 2009; Rosiello and Maleki, 2021). Hence, this second sub-RQ investigates how technological shifts in the wind energy sector affect upgrading opportunities for Chinese vis-à-vis incumbent turbine manufacturers. Finally, the third sub-RQ focuses on firm-level upgrading *mechanisms*. It builds on the conceptual framework formulated by Lema and Lema (2012), who identify changes in upgrading mechanisms across development stages, and it compares how Chinese lead firms in the wind energy sector deploy these mechanisms differently over time. Taking these three perspectives together—upgrading trajectories, opportunities, and mechanisms—allows this thesis to establish a multi-angle perspective (Khan, 2014) and an in-depth understanding of changing upgrading dynamics in an era of technological change.

1.3. Contribution of this dissertation

Following the presentation of the research gaps and research questions, this section provides a brief overview of the main contributions of this dissertation (which are further developed in Section 6). This dissertation makes three important contributions to the literature on catching up, technological learning, and the upgrading of innovation capabilities in latecomer firms. First, it addresses the prevailing market- vs. technology-oriented dichotomy by conceptualizing an integrated framework that provides a holistic evaluation of upgrading *trajectories*. It also develops a new evaluation method that uses both market and technology indicators and assesses technological novelty and impact. This conceptual and methodological toolkit can be applied to a wide array of empirical contexts.

Second, it advances our understanding of firm-level heterogeneity under the same framework conditions by conceptualizing technological shifts as significant upgrading *opportunities* for latecomer firms and providing new empirical insights into latecomer firms' different responses to recent technological shifts. Changing upgrading opportunities in the face of digital/hybrid technologies are highly relevant beyond the wind energy sector.

Third, it sheds a new light on learning strategies of latecomer firms by conceptualizing externalized R&D projects as recently emerging forms of upgrading *mechanisms* and providing new empirical evidence on latecomer's organizational diversification in the face of technological change. Besides providing a considerable level of detail into R&D networks in the wind energy sector, the role of externalized R&D projects is likely to go beyond the empirical setting of this dissertation, thereby only constituting a first entry point into this subject. In addition to these specific contributions, this thesis speaks to the broader debates of economic development, technological progress, and industrial upgrading in emerging market firms and argues that there can be important synergies between the green and digital transformation and latecomer development.

Table 3. Overview of articles

	Article I	**Article II**	**Article III**
Title	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	Catching up through green windows of opportunity in an era of technological transformation: empirical evidence from the Chinese wind energy sector	How do R&D networks change? The upgrading of innovation capabilities in emerging market firms. Insights from China's wind energy sector
Co-authors	Daniel S. Hain, Roman Jurowetzki, Primoz Konda	Yixin Dai, Stine Haakonsson	
Article RQs	What implications does sector-specificity have for market versus technology catch up and leadership? What should latecomer countries consider when entering a new sector? What trajectories and detours can latecomers take to avoid market and technology traps?	How does technological transformation open green windows of opportunity that affect latecomers' possibilities for catching up? What strategies can latecomer firms develop to respond effectively to technological shifts?	In the face of technological change and the decomposition of innovation: What strategies do latecomer firms adopt to upgrade their innovation capabilities? How does their R&D organization change?
Main RQs	Sub-RQ1: upgrading *trajectories*	Sub-RQ2: upgrading *opportunities*	Sub-RQ3: upgrading *mechanisms*
Key findings	The technology cycles of industrial sector vary, which requires latecomer firms to adopt different catch-up strategies in line with their country-specific factor endowments	Latecomer firms from the same country and the same sector show different capabilities in responding to technological shifts, which explains variations in catch-up trajectories under the same framework conditions	Latecomer lead firms from the same country and the same sector adopt unconventional upgrading mechanisms to different degrees, which explains their varying levels of innovation capabilities
Unit of analysis	*Panorama:* comparing countries and sectors	*Zoom in:* comparing latecomer vis-à-vis incumbent firms within the same sector	*Zoom in:* comparing lead firms within the same country and sector
Status*	Published in *Industrial and Corporate Change*, Oxford University Press, doi: 10.1093/icc/dtaa021 (AJG: 3, BFI: 2)	Forthcoming in *Industrial and Corporate Change*, Oxford University Press, doi: 10.1093/icc/dtaa034 (AJG: 3, BFI: 2)	Submitted
		Conference paper accepted for *CICALICS 2019*	Conference paper accepted for *EIBA 2020*

Note: (*) The 'Academic Journal Guide (AJG)' by the Chartered Association of Business Schools and the 'Bibliometric Research Indicator (BFI)' by the Organization of Danish Universities are frequently used indicators to evaluate a journal's impact and quality. 'CICALICS' and 'EIBA' are acronyms for the following two conferences: 'China Innovation Circles and Academy – Learning, Innovation and Competence Systems' and 'European International Business Academy'.

1.4. Overview of research articles

This dissertation comprises this synopsis and three individual articles that form the analytical groundwork of the inquiry. As shown in Table 3, the three research articles are guided by individual research questions covering different angles that together resolve the overarching research puzzle.

The first research article adopts a panoramic (*zoom out*) perspective and provides new empirical insights into the commonalities and differences of the wind energy and electric vehicle (EV) sectors in China, Japan, and South Korea. It finds that while industrial sectors display distinct patterns in technology cycles, countries vary considerably in their key factor endowments, calling for different catch-up trajectories. Building on the insights of the first article, the second article provides an evolutionary overview of the wind energy sector and analyzes how Chinese wind turbine manufacturers responded to technological shifts vis-à-vis incumbent firms. Taking an oligoptic perspective (*zoom in*), it finds that there are significant varieties in firm-level responses to changing conditions in the global economy, which emphasizes the role of dynamic capabilities at the firm level. The third article also adopts an oligoptic perspective (*zoom in*) and provides insights into the changing upgrading mechanisms and R&D networks that lead firms in China's wind energy sector deploy over time. As can be seen, the different levels of analysis are not only highly complementary but play a critical role in overcoming the blindness associated with single-unit perspectives.[15]

1.5. Scope and delimitations

The scope of this thesis is delimited in several ways. First, the *geographical* focus is mainly China, as an extreme case (Flyvbjerg, 2006) for latecomer firm catch-up. However, all articles establish a cross-country perspective in order to benchmark China's market and technology characteristics vis-à-vis South Korea and Japan (Article I), to evaluate the development of China's wind energy sector relative to the technological frontier (Article II), and to analyze China's embeddedness in global R&D networks (Article III).

[15] Latour (2005) describes the complementarity between 'oligoptica' and 'panorama' based on the fact that the first 'see much too little […] but what they see, they see it well' (p. 181) whereas the second 'see everything […] but they also see nothing' (p. 187).

Second, the *technological focus* is on the wind turbine industry, which is arguably at the forefront of the low-carbon transformation (Altenburg et al., 2016b). As wind technologies have significantly changed over time and increasingly incorporate technologies from other industrial sectors, the inquiry is not limited to the narrow definition of 'wind motors' as defined by the World Intellectual Property Organization's (WIPO) International Patent Classification (IPC) class *F03D*.[16] To capture recent technologies in the wind sector, Article II proposes a new patent search code that includes digital, hybrid, and storage-related wind technologies.

Third, in terms of *market segment*, the focus is on original equipment manufacturers (OEMs) in the wind turbine sector (used interchangeably with 'wind turbine manufacturer"). However, to present a holistic industry perspective and capture knowledge flows across the value chain, the articles take an embedded approach, considering both upstream and downstream linkages. This is particularly important in the wind turbine industry as (1) wind turbines comprise up to 8,000 sub-components (IRENA, 2012), which requires close backward linkages between OEMs and sub-component suppliers; (2) wind turbines develop through spatially sticky *doing, using, and interacting* (DUI) innovation modes (Binz and Truffer, 2017), which requires close forward linkages between OEMs, and wind farm developers and operators; and (3) the scope of market segments varies among OEMs and over time.

Fourth, the *temporal scope* varies slightly among the three articles and covers different time periods between 1980 and the first half of 2020 (Article I: 1980–2017; Article II: 1980–2020; and Article III: 1998–2020). As the thesis takes an evolutionary perspective,[17] all three articles cover time intervals of at least 20 years. As China's wind industry started its exponential growth post-2005 with the Renewable Energy Law, earlier periods are considered for comparative purposes.

Finally, as shown in the previous section, the *level of analysis* of this dissertation varies across the three articles. This is important to understand the complex relationship between technological change and latecomer firm development. Article I constitutes a point of departure,

[16] For example, this includes the maritime industry for offshore solutions, the software industry for wind farm management solutions, and other green technologies for hybrid solutions.

[17] An evolutionary perspective derives from the assumption that theory on real-world phenomena must be based on the rigorous study of historical experience (Schumpeter, 1954; Lazonick, 2010).

focusing on the macro-level differences between China, South Korea, and Japan and sector-level differences between wind and EV. Article II zooms into the sector-level perspective by analyzing the variation of technological trajectories of Chinese firms vis-à-vis incumbent firms. Article III conducts a firm-level analysis and compares the evolution of R&D networks of China's lead firms.

1.6. Structure of dissertation

The dissertation is organized around six introductory chapters that build the synopsis, and three research articles that follow the synopsis.

Chapter 1 presents the background, introduces the research objective and questions, and delimits the scope of the inquiry.

Chapter 2 constitutes a short digression in the empirical state-of-the-art of this thesis. It provides a brief overview of the extant literature on China's wind energy sector and points at the empirical gaps addressed by this thesis.

Chapter 3 provides the theoretical and conceptual framework by reviewing the relevant debates on the core concepts, revealing the overarching analytical framework.

Chapter 4 explains the methodological choices that underlie the thesis. It discusses the philosophy of science, the research strategy and design, and the data collection and analysis. The chapter gives an account of the validity and reliability of the research.

Chapter 5 summarizes the three research articles. The chapter outlines how each of the research articles contributes to the overarching research puzzle.

Chapter 6 highlights the key findings in relation to the main research questions and presents the conceptual, methodological, and empirical contributions. The chapter then presents managerial and policy implications and points to avenues for future research.

2. THE EMPIRICAL CONTEXT

2.1. Market scale-up in China's wind energy sector

China entered the wind energy sector later than Europe and the United States (Backwell, 2017).[18] Besides some demonstration projects in the 1980s and experimental development in the 1990s, China's wind market developed only marginally before the mid-2000s (Dai and Xue, 2015; Hansen and Lema, 2019; Gosens and Lu, 2014). Two central policies paved the way for an unprecedented market scale-up: the Wind Concessions Program in 2003 and the Renewable Energy Law in 2006 (Lewis, 2007, 2013; Wang et al., 2012; Nahm, 2017). While the first introduced local content requirements for technology transfer purposes,[19] the second set medium- and long-term targets and prioritized renewable sources in the national grid (IRENA, 2018).

In the aftermath, the number of Chinese wind turbine manufacturers grew exponentially from a few first movers to over 80 by 2008 (IRENA, 2013; Quitzow et al., 2017). Accumulated installed capacity soared from below 0.8 GW in 2004 to almost 45 GW in 2010, thereby overtaking the United States as the world's largest wind energy market (Zhou et al., 2018; GWEC, 2011).[20] China's wind industry witnessed an unprecedented increase in installed capacity, 'from nowhere to world market leadership' (Tan and Mathews, 2015: 417) within only four years. Not surprisingly, this entailed significant quality issues, widespread curtailment, and overproduction problems that required a series of radical regulatory adjustments (Zhu et al., 2019; He, 2016; Backwell, 2017; Kirkegaard, 2017; Korsnes, 2014; Owens, 2019).

Today, China's installed wind capacity has easily surpassed 200 GW, which corresponds to more than one-third of the world's total installed capacity (GWEC, 2020; BNEF, 2020). Chinese firms hold more than half of the top 15 positions in terms of global market share (GWEC, 2020; Dai et al., 2021). Driven by strong industry consolidation, the number of Chinese turbine manufacturers has shrunk below twenty, dominated by three lead firms, Goldwind, Envision, and Ming Yang, which together account for two-thirds of China's market share (CWEA, 2020).

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[18] 'Sector' and 'industry' are used interchangeably.

[19] The *Wind Concession Program* introduced local content requirements of 50% in 2003 and 70% after 2004, which subsequently reduced the domestic market share of foreign firms dramatically from 79% in 2004 to 12% in 2009 (Sun and Yang, 2013).

[20] *Note:* There is a discrepancy between installed capacity (maximum output) and electricity generated, as the output varies depending on the provision of wind and other technical aspects such as equipment failures, maintenance, etc. (FSFM, 2018).

While there is no doubt that China has attained significant market leadership in the global wind energy sector (surpassing the combined installed capacity of the European Union; GWEC, 2020), the extent to which this correlates with technological learning and the upgrading of innovation capabilities has been subject to a number of empirical studies and scholarly debates. The following section summarizes key findings and points at the empirical gaps addressed later in this thesis.

2.2. Technological upgrading in China's wind energy sector

There is a broad consensus that China's early industry formation was the result of conventional technology transfer mechanisms such as technology licensing, FDI, local JVs and joint development with Western, mainly European firms (Lema and Lema, 2012; Lewis, 2013). Studies have particularly highlighted the technology-transmitting role of specialized European component suppliers (Haakonsson and Slepniov, 2018; Haakonsson and Kirkegaard, 2016) and knowledge-intensive business service providers (Lema et al., 2011; Haakonsson et al., 2020), as well as leading foreign wind turbine manufacturers operating in China (Silva and Klagge, 2013; Lewis, 2013). The degree of voluntariness of these technology transfers has been widely discussed (Prud'homme and von Zedtwitz, 2019; Ru et al., 2012). To gain better access to foreign knowledge, Chinese wind turbine manufacturers quickly started to expand into global learning networks (Lewis, 2013; Binz et al., 2017; Slepniov et al., 2015). Technological learning and upgrading transitioned from purely conventional to more unconventional mechanisms such as overseas R&D, M&A of foreign firms and outward FDI (Lema and Lema, 2012). This enabled manufacturers to accumulate a significant set of innovation capabilities within an unprecedentedly short time scale (Hansen and Lema, 2019).

Although there is general agreement that Chinese wind turbine manufacturers have upgraded their innovation capabilities, the extent to which this has occurred is subject to divergence in the empirical literature. Some recent studies are more optimistic (Owens, 2019; Hansen and Lema, 2019; Nahm, 2017) than others (Hu et al., 2018; Zhou et al., 2018).[21] For

[21] There is a large body of literature discussing this; however, only recent studies (since 2017) are included here, as the innovation capabilities of Chinese firms have changed significantly in recent years.

example, Nahm (2017: 68) finds that Chinese wind turbine manufacturers have 'established distinct innovation capabilities' which allows them to contribute significantly to global innovation networks. In contrast, Hu et al. (2018: 241) argue that China's wind sector 'lags the world leaders in [...] technical innovations and outcomes (e.g., export)'. The reason for these diverging views is that, on the one hand, 'the existence of two almost separate markets' (Backwell, 2017: 185) makes direct comparisons difficult, especially as more than 95% of wind turbines produced by Chinese manufacturers are installed domestically (CWEA, 2020). On the other hand, measuring and comparing innovation capabilities in China is notoriously difficult (Altenburg et al., 2008). To assess China's positioning in and contribution to the global wind energy sector in terms of technological progress, existing studies have employed a range of different methods and indicators.[22]

Finally, there is a general tendency to treat China's wind energy sector as a single entity empirically, despite huge firm-level disparities. As stated in the previous chapter, the objective of this thesis is to go beyond the institutional environment and industrial policies to explain China's rapid catch-up (see Binz et al., 2017 for a detailed policy debate) and to open the black box of firm-level heterogeneity in the upgrading of innovation capabilities. This dissertation provides detailed insights into the reasons why firms under the same framework conditions respond differently to technological change and why they develop different levels of innovation capability over time.

[22] They can be broadly divided into qualitative and quantitative approaches. While the former typically draws on case studies to differentiate between different levels of innovation capability contextually (Hansen and Lema, 2019; Nahm, 2017), the latter uses quantifiable metrics, often based on patent data (Zhou et al., 2018; Fu, 2015; Hu et al., 2018; Awate et al., 2012). Both have their advantages and drawbacks. For example, quantitative approaches allow for cross-industry comparisons, which case studies are less suited for (Hansen and Lema, 2019). In turn, traditional science and technology (S&T) input-output metrics such as R&D expenditures or patent counts are limited in their ability to capture (tacit) learning-related practices (Gebauer et al., 2012) and to reflect a firm's actual or 'revealed' (Sutton, 2012) innovation capabilities, especially in a specific (here China's wind industry) context (Lewis, 2013; Figueiredo and Cohen, 2019).

2.3. Empirical gaps

Despite significant progress over the past decade, the current literature on China's technological upgrading in the wind energy sector exhibits three empirical gaps: First, we know little about the overall contribution of Chinese firms to the global wind energy sector, covering both market development and technological novelty and impact. Although the discrepancy between patent counts and technological novelty and impact is not new (Torrisi et al., 2016; Yoon and Park, 2004), there have been limited attempts to go beyond traditional S&T indicators. To address this, Article I develops a new method based on semantic patent quality indicators that allows assessment of technological novelty and impact. Second, there have been limited attempts to analyze the consequences of recent technological shifts in the global wind energy sector for Chinese wind turbine manufacturers, specifically in relation to new digital/hybrid technologies. Article II integrates a wide range of qualitative and quantitative indicators to examine Chinese firms' response times and modes to recent technological change.[23] Third, the current literature provides different empirical insights into the changing sources of learning of China's wind turbine manufacturers over time (Nahm, 2017; Quitzow et al., 2017; Hayashi et al., 2018), specifically in relation to the building of technological capabilities (Lema and Lema, 2012; Hansen and Lema, 2019). However, there are no studies systematically mapping R&D networks of Chinese firms over time. Based on qualitative and quantitative data, Article III creates a longitudinal database on R&D partnerships of China's lead firms that allows analyzing the relationship between upgrading mechanisms and innovation capabilities.

[23] The current empirical literature has been criticized for offering a fragmented, often 'piecemeal' selection (Hu et al., 2018) of either qualitative or quantitative (input, output, or outcome) indicators, thereby limiting the validity of individual studies. Common indicators are directly technology-related data (e.g., patents, turbine size, turbine reliability, design adaptions, subcomponent technology groups, novelty of technologies, state-of-the-art testing facilities, and certifications by internationally recognized bodies) or indirectly inferred from other market-related (global market/production share, onshore/offshore statistics, and exports) or financial data (R&D expenditure, R&D projects, M&A activities, revenue, and turbine cost/LCOE reductions) (Lewis, 2013; Tan and Mathews, 2015; He, 2016; Backwell, 2017; Quitzow et al., 2017; Hu et al., 2018; Hansen and Lema, 2019). A drawback of many patent analyses is that they are based on WIPO's IPC class F03D ('wind motors'), which does not cover new digital/hybrid wind technologies. In addition, patents involve a significant time lag between filing and grant, which precludes the evaluation of recent capability levels (Hain et al., 2020).

3. THEORETICAL AND CONCEPTUAL FRAMEWEORK

The thesis is positioned at the intersection of innovation and development studies, rooted in evolutionary economics. To analyze the consequences of changing conditions in the global economy for latecomer firm development, this chapter reviews the relevant literature on two conceptual building blocks: *technological change* and *the organizational decomposition of innovation*; and it also examines the core concepts from the latecomer development literature: *catching up*, *technological learning,* and *the upgrading of innovation capabilities.* It finally presents the overarching conceptual framework that guides the empirical analysis consisting of the three research articles.

3.1. Literature review

3.1.1. Technological change

How does technological change affect latecomer firm development? To understand the relationship, we have to look at key contributions to theories around technological change. Dating back to 1956, Robert Solow was one of the first scholars who proposed that the role of technological change deserved more attention as a source of economic growth, beyond capital and labor in the production function (Solow, 1956; Perez, 2016). His work had a significant impact on subsequent economic analyses (Nobel Media, 1987).[24] In the aftermath, economists undertook major efforts to pin down the 'residual' that positively affected output per worker, now framed as 'technological change' (Nelson and Winter, 1982).

Some twenty years later, in the 1980s, evolutionary economists established an alternative route to mainstream economic theories in studying the role of technological change for growth differences across geographies (Nelson and Winter, 1982; Freeman, 1982, 1987, 1989; Dosi, 1982, 1984). Their main argument was that, contrary to neoclassical equilibrium assumptions, new technology was not a public good that could be easily distributed across countries and firms, but required costly, risky, and dedicated learning processes (Rock and Toman, 2015; Pack and Nelson,

[24] In 1987, he was awarded the Nobel Prize for his contribution. He argued that besides capital and labor, technological development would be the motor for economic growth in the long-term (Nobel Media, 1987).

1999).[25] Following this line of reasoning, cross-country differences in economic growth were not only the result of institutional constraints that hindered the free flow of technologies, but were linked to market—specifically information and coordination—failures (Rodrik, 2004). Hence, evolutionary economics highlighted that the ability of established firms to adjust to changing conditions was often limited in a number of ways, for instance, by lock-in routines and path-dependent effects (Jimenez, 2019; Nelson and Winter, 2002; Nelson, 2008; Arthur, 1989; Nelson, 2020).

Changing technology could, at the same time, open considerable opportunities for new industry entrants. Freeman (1989: 85) argued against Posner's (1961) 'Technology Gap Theory' that 'whilst accepting that technical change can indeed sometimes exacerbate problems of uneven development, some latecomers may actually have advantages over the established industrial powers' (Section 3 in this chapter provides a detailed account on the catch-up debate). To understand the nature of these opportunities, one of the leading evolutionary economists, Dosi (1982), developed an important conceptual framework on the determinants and directions of technological change that was further developed by Perez (1983, 1985, 2003). Rather than treating the market as the main agent, the role of technological change was highlighted as the result of an 'interplay between scientific advances, economic factors, institutional variables, and unsolved difficulties on established technological paths' (Dosi, 1982: 147). These factors could lead to incremental or radical technological change, along 'technological trajectories' or 'technological paradigms', with the 'technological frontier' defining the state-of-the-art.[26]

Technological (Dosi, 1982) or 'techno-economic' (Perez, 1985) paradigms constitute the overarching 'best practice' model, pattern, and territory of innovative practice at a given point in time, geared towards a prevailing technological problem.[27] They can be understood as

[25] Katz (1987: 2) commented on this in a very pertinent way: 'The assumption that a stock of technologies—a 'book of blueprints' or a 'technology shelf'—exist somewhere in libraries and archives of universities and manufacturing firms of the developed world and is waiting to be used by any odd LCD [least-developed country], has been a standard assumption among economists during the industrialization process of developing nations. Such notions were frequently complemented by the presumption of an almost complete passiveness from the part of the recipient society, as if no domestic knowledge generation efforts worth taking into account could be expected to emerge in less developed societies'.

[26] Perez (2016) highlights that technological change is constant but not continuous.

[27] Other authors used 'generalized natural trajectories' (Nelson and Winter, 1977) or 'avenues of innovation' (Sahal, 1985) to connote similar ideas.

successive clusters that cause 'radical discontinuities in overall technological evolution' (Perez and Soete, 1988: 460). Hence, each new cluster is associated with a period of turbulence and re-structuring of the entire industrial organization by introducing an interrelated set of new products, technologies, and infrastructures (Freeman and Perez, 1988; Perez, 2003). A shift in clusters concurrently destroys a previous and opens up a new spectrum of investment and business opportunities (Freeman, 2009).[28] This opens the possibility of 'quantum leaps' in productivity (Freeman, 1989). However, these shifts do not occur rapidly or automatically. It can take decades until new techno-economic paradigms crystalize and diffuse into the system as they undergo a process of selection from a range of technologically feasible combinations of innovations (Freeman, 1989).

Each techno-economic paradigm shift redefines the outer boundaries of possible technological directions of advance or 'technological trajectories' (Dosi, 1982). These technological trajectories within a techno-economic paradigm vary in multiple dimensions with some being more circumscribed and powerful than others.[29] In line with Nelson and Winter (1977), Dosi (1982) ascribes a cumulative characteristic to progress upon a given technological trajectory, based on incremental innovations. Consequently, a firm needs to accumulate a certain 'threshold level' (Perez and Soete, 1988) of knowledge and technological capabilities to advance on a technological trajectory. The 'technological frontier' represents the highest level reached on a specific technological trajectory (Perez, 2010). A latecomer firm needs to reach the technological frontier to close the gap with incumbent firms and produce new-to-the-world technology (Dutz et al., 2011; Dutrénit, 2000; Figueiredo, 2003; Bell and Figueiredo, 2012b).[30] While it may be difficult to enter or switch trajectories within a given cluster, a techno-economic paradigm shift can provide significant opportunities for industrial latecomers to enter an industrial sector.[31]

[28] This line of thinking in long technological waves or cycles characterized by strongly diverging clusters of innovation dates back to Kondratieff (1925) ('long economic cycles') and Schumpeter (1939) ('business cycles') and, more recently, was further advanced by Freeman and Louçã (2002) and Perez (2003).

[29] For example, Dosi (1982) mentions nuclear and oil power-generation equipment as a powerful technological trajectory at that time as it excluded many other sources of energy.

[30] This sentence illustrates the difference between 'catching up' and 'upgrading'. While the former emphasizes the process of closing the gap between incumbent and latecomer firms in terms of market share and technological capabilities, the latter generally refers to the process of enhancing a firm's innovation capabilities through effective learning mechanisms.

[31] Techno-economic paradigm shifts are associated with technological revolutions (Perez, 2003). The *First Technological Revolution* was Great Britain's age of wrought iron, steam power, and railways, whereas the most recent, the *Fifth Technological Revolution*, is

Based on the frameworks presented above, the dissertation focuses specifically on two aspects of how technological change affects latecomer firm development: First, it conceptualizes the green transformation as a set of significant regime changes in the techno-economic paradigm that opens 'Green Windows of Opportunity' (GWO) for latecomer firms, i.e., avenues to gain leadership in new green industries such as wind and EV (see Special Issue for a cross-sector comparison, Lema et al., 2021). Second, it looks at how technological discontinuities or 'shifts' related to digitalization and industry hybridization affect the pace of catching up and the direction of innovation capabilities.

3.1.2. The decomposition of innovation

What is the decomposition of innovation and how does it affect latecomer firm development? The organizational decomposition of innovation (ODIP) refers to an ongoing transformation in the way firms organize for innovation: while innovative activities used to be concentrated at or near the headquarters, they are increasingly decentralized and globally dispersed within the company or outsourced to external partners (Schmitz and Strambach, 2009; Lema et al., 2015; Haakonsson et al., 2020).

The observation that innovative activities are undergoing a profound decentralization is not new. It unfolded with the 'globalization of innovation' debate after the turn of the millennium (Gerybadze and Stephan, 2003; Narula and Zanfei, 2004; Greenspan, 2004; Pavitt, 2005; Amin and Cohendent, 2004). In 2003, Chesbrough (2003) coined the 'open innovation' notion, which attracted significant scholarly attention and accrued a large body of literature (Du et al., 2014; Lichtenthaler, 2011; Mina et al., 2014; Enkel et al., 2009; Dahlander and Gann, 2010; Vanhaverbeke, 2017). Subsequently, studies pointed to a number of factors to explain the shift in innovation processes, arguing for both push and pull factors: on the one hand, the growing pace and complexity inherent to technological change requires firms to adopt more flexible and

referred to as the *Age of ICT* or *Digital Revolution* (Perez, 2003, 2010; Van Ark, 2001). Perez (2016) argues that since 2008, we have shifted from the installation to the deployment period of the fifth technological revolution, called 'Green Global Golden Age'. This green age is expected to disrupt our global economy and society to a similar extent as previous technological revolutions and provide 'the new direction for our age' (Perez, 2016: 4; Mazzucato and Perez, 2014; see Appendix A1 for an overview of the five successive technological revolutions).

open forms of organizing for innovation (Mazzoleni and Nelson, 2007; Fu et al., 2020). This is closely linked to the 'red queen hypothesis', i.e., in order to remain in a competitive position, firms have to accelerate their innovation cycles and produce a continued set of new technologies in response to their increasingly competitive environment (Derfus et al., 2008). On the other hand, external sources of knowledge open up new learning opportunities and significantly augment a firm's innovation capabilities as opposed to developing new products and services in-house (Chesbrough, 2003, 2006, 2017; West and Bogers, 2014; Enkel et al., 2009; Laursen and Salter, 2006).[32] A recent study by Fu et al. (2020) supports the argument that high disciplinary diversity of global R&D partners is positively associated with the novelty of innovation outputs.

While the open innovation literature has mainly focused on large high-tech MNEs within advanced economies or their host country subsidiaries (Popa et al., 2017; Vanhaverbeke, 2017; Chesbrough and Bogers, 2014; Gassman and Enkel, 2006; Curley and Salmelin, 2018; Cantwell and Mudambi, 2005), the ODIP literature has been concerned with the spatial effects across continents, i.e., the ramifications of the decomposition of innovation for the balance between OECD and developing countries.[33] In its initial formulation, Schmitz and Strambach (2009) provided a useful typology to understand different ODIP activities. It is an integrative concept, building on insights from the international business, global value chains, and global innovation networks literature (Lema et al., 2015). The ODIP framework differentiates along two dimensions: (1) ODIP activities that are performed internally/externally to the firm, and (2) ODIP activities that exhibit loose/tight links to the production of goods and services. It rests on the observation that, on the intra-firm level, firms increasingly set up knowledge communities (Paavola et al., 2004; Linkdkvist, 2005) or delegate the development of new products to globally dispersed subsidiaries (Quadros and Consoni, 2009; Zander, 2002). On the inter-firm level, commissioning research from universities (Perkmann and Walsh, 2007) or engaging external organizations in developing new products play an increasingly significant role (Haakonsson et al., 2020; Simmie and Strambach, 2006).

[32] For example, the acceleration of innovation cycles and technological progress, shared commercial returns, reduced times to market, organizational agility, and R&D savings.

[33] According to Schmitz and Strambach (2009), we know little about whether ODIP contributes to a global dispersal vs. continuing concentration of innovative activities.

Despite highlighting that 'the global distribution of innovation activities is moving away from the OECD countries and towards the developing world' (Schmitz and Strambach, 2009: 243), the ODIP literature suggests that the decomposition of innovation originates from advanced country 'flagship' or 'lead' firms and spreads towards other regions in the world.[34] For instance, Lema et al. (2015) recently studied the build-up of innovation capabilities in the software and automobile industry. They found that subsidiaries and independent suppliers in India and Brazil ('new powers') accumulated significant innovation capabilities through linkages with 'old powers' in Western Europe and the United States. Similarly, Haakonsson et al. (2020) found that European providers of knowledge-intensive business services played a significant role in unlocking the rapid catch-up of Chinese wind turbine manufacturers.

While recognizing its major contribution to the understanding of latecomer firms' upgrading through the decomposition of innovation, the current ODIP debate reveals an important conceptual shortcoming: it neglects the growing trend that emerging market firms no longer only react to dispersed knowledge by advanced country firms, but increasingly co-opt ODIP strategies themselves to expand their innovation space and co-create knowledge in global innovation networks. This is particularly important for emerging market firms that upgrade to higher levels of innovation capability, beyond the initial catch-up stage (Peng et al., 2020; Dutrénit, 2000).

3.1.3. Latecomer development: key concepts and debates

Both the literature on catching up and the literature on technological learning and upgrading of innovation capabilities seek to identify the reasons behind differences in economic development and global competitiveness over time. However, while the former is mainly concerned with the relationship between exogenous change (i.e., windows of opportunity) and latecomer firm and system responses, the latter focuses on the firm-level mechanisms that lead to a gradual accumulation of technological knowledge and formation of innovation capabilities.

[34] This assumption stems from the global value chains, and modularity and systems integration literature that suggests that global dispersal is often limited to non-strategic (Schmitz, 2007; Parrilli et al., 2012) or problem-solving rather than problem-framing (Brusoni, 2005) activities.

Despite their high degree of complementarity, both literatures have tended to exist in tandem. This thesis draws on a combination of both strands, which helps bridge their respective gaps.

3.1.3.1. Catching up

Catching up is herein understood as closing the gap in market share and/or technological capabilities between incumbent and latecomer firms. The roots of the catch-up debate date back to the 1800s and were originally linked to broader, macro-level ideas of economic catch-up. Stunned by the UK's technological and economic leadership during the first industrial revolution, Friedrich List (1841) advised a national catch-up plan for Germany, based on long-term industrial and education policy.[35] This triggered a first, yet initially inter-European catch-up debate.[36]

Albeit using a different terminology, Veblen (1915) initiated a discussion on how technological change altered the conditions for catching up. He argued that the shift from tacit knowledge embodied in workers to codified technology in machines should facilitate industrialization of latecomer economies (Fagerberg and Godinho, 2004). In contrast, Gerschenkron (1962) stressed the growing difficulty of the catch-up process, arguing that the mounting technological complexity required new institutional instruments to overcome the 'economic backwardness' of some European countries. He criticized the Marxian hypothesis of industrial development for being too linear, and suggested that country-level catch-up was not only marked by significant differences in terms of speed but also character.[37]

In the 1980s, perspectives on catching up were extended in important ways. Based on a new compilation of historical data, Abramovitz (1986) explained catch-up differences among countries based on the concepts of 'technological congruence', i.e., (dis)similarity in market size and factor supply, and 'social capability', i.e., different capabilities to absorb and exploit foreign technologies for improving productivity levels.[38] At that time, Eurocentric views were gradually

[35] See Freeman (1989) for a detailed discussion.

[36] Early catch-up literature mainly conducted macro-historical and macro-economic analyses underlying a convergence theory, which were later increasingly complemented by comparative studies on a sectoral and firm level.

[37] In *Das Kapital*, Karl Marx (1867: Preface IX) wrote '[t]he industrially more developed country presents to the less developed country a picture of the latter's future' [orig. 'Das industriell entwickeltere Land zeigt dem minder entwickelten nur das Bild der eigenen Zukunft!'].

[38] Social capability describes catch-up efforts such as improving education, infrastructure, and other innovation-related capabilities (e.g., reflected in R&D expenditure or patents) (Fagerberg and Godinho, 2004). Previous 'simple catch-up hypotheses' did not

replaced by a growing focus on the rapid industrialization of Asian countries, spearheaded by Japan and a little later followed by Singapore, Hong Kong, South Korea, and Taiwan. In this context, based on the Japanese model of catching up, Freeman (1989) highlighted the beneficial role of new technologies for latecomers over established industrial powers.

Following this line of reasoning, Perez and Soete (1988) introduced the concept of 'windows of opportunity' (WOO) to describe favorable catch-up conditions for late industrializers. While latecomer firms typically face significant entry barriers,[39] WOO constitute radical transitions in technology or techno-economic paradigms that temporarily minimize entry thresholds for late industrializers equipped with sufficient pre-existing capabilities and factor conditions to compete in the new technologies. Perez and Soete (1988) further emphasized that effective catch-up was not a unidirectional race along fixed tracks and therefore a question of relative speed, as assumed in product life cycle theory, but also concerned running in new technological directions, a concept that was further developed by Lee (2019).[40]

On this basis, Lee and Lim (2001) studied differences in technological catch-up patterns across South Korean industries and identified three catch-up strategies: *path following* (following incumbents' technological paths), *path skipping* (skipping to the technological frontier) and *path creating* (creating new technological directions).[41] This was an important landmark in understanding the relationship between sector-specific features and catch-up trajectories. Malerba and Nelson (2011) placed more explicit attention on the sectoral learning processes underlying catching up. Based on the evidence of six industries, they found that the key factors of sectoral systems vary considerably, calling for different conditions and policies to support catching up effectively.

More recently, the catch-up debate was significantly advanced by a Special Issue in *Research Policy*, in which Lee and Malerba (2017) developed the 'catch-up cycle' framework to

incorporate the social capability dimension, assuming that the larger the technological and, therefore, the productivity gap between leader and follower, the stronger the follower's potential for catching up in productivity (Abramovitz, 1986).

[39] For example, (lack of) accumulated scientific and technological knowledge, as well as locational and infrastructural (dis)advantages.

[40] See Nahm (2017) for a detailed discussion on diverging technological directions and complementary core competencies in the global wind energy sector.

[41] While the latter is more likely to happen in Schumpeter Mark I industries with frequent changes in the innovative environment (Malerba and Orsenigo, 1995; Breschi et al., 2000), the first and second are more likely to occur in Schumpeter II industries with opposite features.

analyze catching up and successive changes in industrial leadership. Their catch-up cycle framework expands Perez and Soete's (1988) WOO concept by linking it to changes in institutions, market demand, and technology as well as to strategic firm and system responses.[42] The Special Issue applied the catch-up cycle framework to a number of empirical studies, including the global camera industry (Kang and Song, 2017),[43] the memory industry (Shin, 2017), and the wine industry (Morrison and Rabelotti, 2017), and resulted in two key findings: (1) there is a general shift of industrial leadership towards Asian countries and (2) the relationship between the emergence of WOO and patterns of catching up is based on diverse combinations that are highly sector specific.[44]

While the recent catch-up literature provides relevant insights into the sources and processes involved in catching up, its operationalization is founded on a country's lead firm's market or production shares (see Special Issue, Lee and Malerba, 2017). This carries three significant drawbacks: first, it decouples technological and commercial performance, assuming that the first leads automatically to the second and vice versa. However, this distorts the picture in favor of firms from countries with large domestic markets and monopolistic structures, and says little about the level of innovation capabilities. Second, firms within the same country show very different catch-up trajectories and develop different technological competencies over time. Perez and Soete (1988) explicitly highlighted the possibility of multiple development pathways. Hence, the representativeness of a country's lead firm is highly limited. Third, there has been a strong focus on competition among same-sector industries, based on Malerba's (2002, 2005) sectoral systems framework. However, this neglects two important aspects. On the one hand, firms in relatively new industries, such as wind, do not primarily compete against one another or other green technologies, but against conventional energy sectors based on fossil fuels. On the

[42] However, the opening per se does not guarantee a successful leadership change among firms. For this to happen, several conditions must occur at the same time: First, latecomers have to identify the opportunity and respond effectively to it (including both firms and the institutional environment); second, incumbents have to respond ineffectively, e.g., due to lock-in routines or competence-destroying changes; third, latecomers need to accumulate sufficient technological capabilities to be able to advance on the technological frontier and move into technological trajectories that *detour* from previous paths (Bell and Figueiredo, 2012b; Lall, 1992; Dutrénit, 2000; Perez and Soete, 1988; Lee and Malerba, 2017; Lee, 2019; Chandy and Tellis, 2000).

[43] For example, in the global camera industry, industrial leadership shifted in the mid-60s from Germany's rangefinder to Japan's single-lens reflex and then to South Korean's mirrorless cameras in the late-2000s (Kang and Song, 2017).

[44] The resulting policy recommendation is that 'latecomer countries should be prepared to build sector-specific capabilities that support actors, networks, and institutions' (Lee and Malerba, 2017: 350)

other hand, in times of globalized R&D networks and the decomposition of innovation, firms do not only compete but increasingly collaborate across countries and sectors. This raises the question of whose innovation capabilities are ultimately reflected within territorial boundaries (Altenburg et al., 2008; Schmitz and Altenburg, 2016).

3.1.3.2. Technological learning and the upgrading of innovation capabilities

The literature on technological learning and upgrading of innovation capabilities is concerned with the processes whereby latecomer firms enhance their global competitiveness. It focuses in particular on the rate and extent with which latecomer firms accumulate sufficient technological knowledge and skills (through effective learning) to be able to carry out increasingly advanced innovative activities after entering a given industry (Bell and Figueiredo, 2012a).

Technological learning is herein defined as the deliberate and costly mechanism for acquiring and accumulating technological knowledge and skills (Bell, 1984). Sources of learning comprise knowledge from both inside and outside the firm (Cohen and Levinthal, 1990; Kim, 1997), with the latter gaining in importance due to rapid technological change and the decomposition of innovation (see introductory chapter). *Innovation capability* is understood as the degree to which a firm can design and implement new products and processes (Dutz et al., 2011), while *upgrading* refers to the process of enhancing a latecomer firm's innovation capabilities through effective learning—linked to both the technological (Lall, 1992) and organizational (Dutrénit, 2000) dimension, as explained later in this section.

The literature on technological learning and innovation capabilities in latecomer firms evolved in the 1980s from works by Carl Dahlman, Sanjaya Lall, Jorge M. Katz, and colleagues. Based on his experience at the World Bank, Dahlman (1987) highlighted the sequence in which various capabilities should be developed for successful industrialization.[45] Rather than trying to be self-sufficient and seek to invent new products and processes from scratch, latecomer firms should learn by combining already existing foreign and local technological elements. Similarly, Lall (1987) and colleagues found that the largest productivity gains were often not based on

[45] More specifically, this work was part of a research program funded by the World Bank on 'The Acquisition of Technological Capability'. It covered firm-level studies from India, South Korea, Brazil, and Mexico (Dutrénit, 2004).

major technological inventions (or movements *of* the frontier), but minor changes to existing technologies (or movement *along* the frontier), related to equipment, materials, processes, and designs. Katz (1987) supported this view and found that manufacturing firms in Latin America were not only passive recipients of imported technology, but were building up technological capabilities through effective learning efforts.[46] The basic idea that the upgrading of innovation capabilities was not so much about making leaps through inventions but based on learning processes (e.g., by using existing technologies) was expressed by several other scholars at that time (see e.g., Westphal et al., 1985; Scott-Kemmis and Bell, 1985; Amsden, 1989). Bell (1984) made an important distinction here between learning-by-doing and other learning mechanisms.[47]

As latecomers' innovation capabilities improved, subsequent studies developed theoretical constructs to better understand the link between learning and growing capability accumulation. Hobday (1995) studied how East Asian firms narrowed the technological gap in electronics and found that they had shifted from simple manufacturing to genuine innovation by learning though subcontracting and OEM/ODM mechanisms.[48] Similarly, Mathews and Cho (1999) introduced the concept of 'single-' and 'double-loop organizational learning' to better understand the rapid expansion of innovation capabilities of South Korean semiconductor manufacturers.

During the 1990s and early 2000s, a number of taxonomies were introduced based on extensive case study evidence (mainly using data from interviews and questionnaire-based surveys). One of the most influential was developed by Lall (1992) and Bell and Pavitt (1993, 1995). This framework differentiates between four technological capability 'levels' or 'stages': *routine production*, and three levels of ascending innovation capabilities (*basic*, *intermediate,* and *advanced*; see Bell and Figueiredo, 2012a for a more recent overview with *world leading* as an additional fifth capability level). Important indicators are 'innovation events', i.e. product- or process-related milestones or activities that reveal the maximum level of a firm's innovation capability (Sutton, 2012; Lema et al., 2015). This analytical framework established an important

[46] These insights were drawn from the 'Research Program in Science and Technology of IDB/ECLA' that included 30 individual studies of firms in manufacturing industries across Latin America. Contributors include Richard R. Nelson and Joseph E. Stiglitz.
[47] Doing-based learning includes learning by operating and changing; other mechanisms are system performance feedback as well as learning by training, hiring, and searching (Bell, 1984).
[48] 'Original equipment manufacturing (OEM)' and 'Own design manufacturing (ODM)' (Hobday, 1995).

point of departure for a number of subsequent empirical studies, and yielded various extensions and modifications (see e.g., Lim, 2004; Ariffin, 2000; Figueiredo, 2001, 2003; Dutrénit and Vera-Cruz, 2003; Hobday et al., 2004; Tsekouras, 2006).[49] Dutrénit (2000, 2004, 2007) made two important contributions to the framework: first, by linking the purely technological notion of learning to an organizational one.[50] Second, by paying more attention to transition processes, i.e. the strategic capabilities needed to approach the technological frontier.

Over the last two decades, the literature on latecomer firm development has generated a huge body of work with a particular focus on external sources of learning (Appendix A2 provides an overview of commonly used concepts). While earlier concepts understood technological learning as largely one-directional, from OECD to developing and emerging country firms (through technology transfers), recent literature understands learning processes as increasingly multi-directional, reciprocal, and collaborative (see e.g., Figueiredo and Piana, 2018; Nahm, 2017; Mathews, 2017). An important contribution to understanding the changing upgrading mechanisms in latecomer firms has been made by Lema and Lema (2012). Based on empirical evidence from China and India's green technology sectors, they introduced a significant distinction between *conventional* (e.g., technology licensing, inward FDI) and *unconventional* (e.g., joint R&D, M&A, outward FDI) upgrading mechanisms. This was more recently complemented by a number of studies on the relative importance of learning mechanisms when latecomer firms enhance their innovation capabilities (Figueiredo and Cohen, 2019; Hansen and Lema, 2019; Hansen et al., 2020).

In sum, the literature over the past 40 years on technological learning and upgrading of innovation capabilities has emerged as an important cornerstone in our understanding of latecomer firm development. However, like the literature on catching up, it faces a number of limitations: first, it has correctly argued that conventional R&D and patent-based indicators do not reflect the full spectrum of innovation capabilities. Yet purely qualitative case studies are

[49] Most of the analytical extensions were developed as PhD theses under Martin Bell's supervision (Dutrénit, 2007).

[50] Dutrénit (2000) described the firm's organizational orchestration capability as exponentially important along the technological capability levels. She drew inspiration from Kim's (1997) framework based on the empirical study of Hyundai and Samsung that had sequenced their learning through organizational factors, i.e., the continuous cycle of external knowledge acquisition and internal assimilation and improvement.

limited in their ability to offer comparisons across larger samples, especially across sectors (Hansen and Lema, 2019). Therefore, it could benefit from complementing qualitative and quantitative methodological approaches in the future (Bell and Figueiredo, 2012b). Second, the literature mainly adopts a technology-oriented perspective on latecomer firm upgrading. However, latecomers can become leaders in technology but still fall into development traps if commercialization remains low. Hence, it is important to develop an integrated market-technology framework that simultaneously benefits from the combined perspectives of both literatures and bridges the gaps inherent in the current dichotomy.

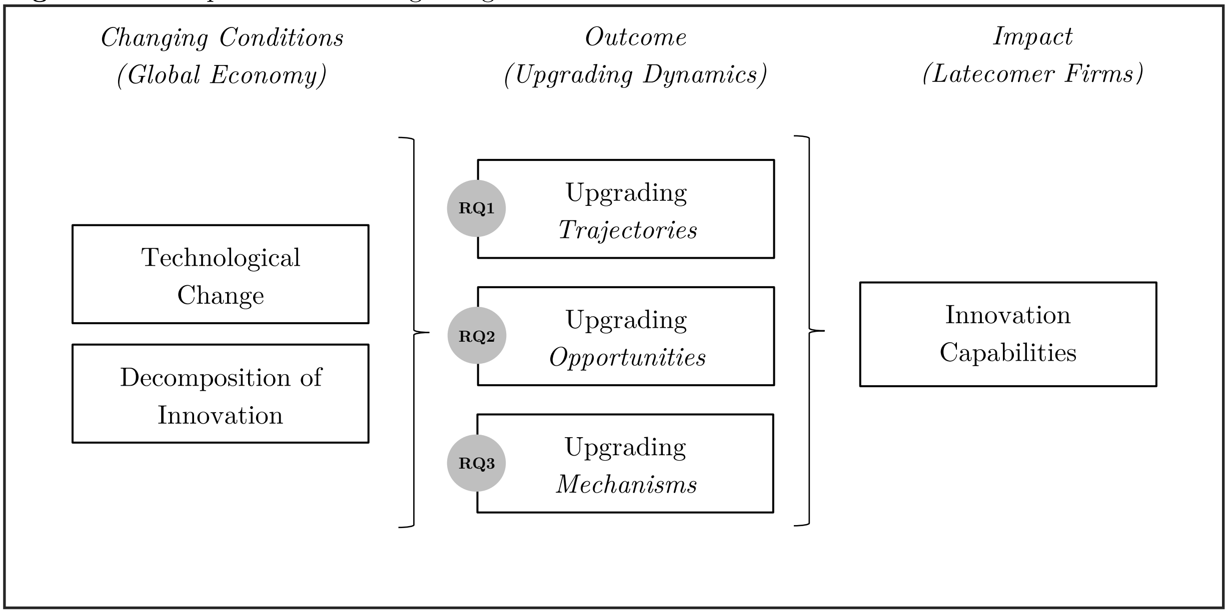
3.2. Conceptual framework

Based on the framing perspectives presented in this chapter, the following conceptual framework guides the thesis to respond to the overarching research question: what consequences do technological change and the decomposition of innovation have for the upgrading of innovation capabilities in latecomer firms?

In Figure 1, the term ‘upgrading’ encompasses ‘catching up’ and ‘technological learning’ with the former referring to the earlier stage of closing the gap between incumbent and latecomer firm and the latter defining the general process of acquiring and accumulating technological knowledge. *Upgrading* is used here as the preferred terminology as it departs from the notion of linear development pathways with incumbents setting the pace and direction of techno-economic progress (Schot and Steinmueller, 2018; Perez, 2016). Instead, upgrading is understood in more neutral terms with the explicit possibility of running in new directions.[51] To gain an in-depth understanding of how changing conditions in the global economy—technological change and the decomposition of innovation—affect the upgrading of innovation capabilities in latecomer firms, this thesis adopts a multi-angle perspective across three levels of upgrading dynamics: (1) upgrading *trajectories*, (2) upgrading *opportunities*, and (3) upgrading *mechanisms*. Each of the three levels constitute one sub-research question and correspond to one research article.

[51] Despite using different terms, ‘running in new directions’ is referred to as ‘detours’ (Lee, 2019) or ‘path-creating’ (Lee and Lim, 2001) in the literature.

Figure 1. Conceptual framework guiding the thesis



Source: Author's compilation. *Note:* 'Outcome' is defined as likely or achieved short-term and medium-term effects; 'impacts' as positive and negative, primary and secondary, long-term effects produced (OECD, 2020).

4. METHODOLOGY

This fourth chapter explains the methodological choices made in this dissertation. The chapter begins with a description of the underlying philosophy of science, followed by a presentation of the research strategy and design, data collection, and data analysis.

4.1. Philosophy of science

The way a researcher sees the social world or 'reality' (*ontology*) relates to a research paradigm that defines the nature of knowledge (*epistemology*) and the creation of knowledge about social phenomena (*methodology*) (Saunders and Lewis, 2012).[52] This thesis takes a *critical realist* stance (Olsen, 2007; Sayer, 2000; Mingers, 2006). According to this set of beliefs, we live in a world of real objects, structures, and causal mechanisms that are independent from our experiences and minds (Jackson, 2016). However, as we cannot directly see and measure causality, we have to observe, theorize, and produce knowledge claims about it, while acknowledging that we cannot assert any final truth (Beach and Pedersen, 2016, 2019). As each of us are socialized differently, and equipped with a unique set of experiences, norms, and values, all scientific knowledge is to a certain extent socially produced and not entirely representative of the real-world complexity (Patomäki and Wright, 2000; Saunders et al., 2016). Hence, studying social phenomena requires constant reflexivity and transparency in our research strategy and design, which is the objective of the present chapter.

This thesis emphasizes the complementarity of mixed-methods inquiry for a more extensive and profound understanding of social phenomena (Newman and Benz, 1998; Creswell, 2003; Yousefi Nooraie et al., 2020; Olsen, 2007). *Mixed methods* are herein defined as collecting and analyzing data, integrating findings, and drawing inferences using both qualitative and quantitative approaches in a single study or set of inquiry (Tashakkori and Creswell, 2007). This thesis follows a *convergent* mixed-methods design, where results from both qualitative and quantitative standpoints are merged and compared (Creswell and Plano Clark, 2018). For

[52] As highlighted by Saunders and Lewis(2012), research questions are rarely answered within a single philosophical domain as philosophies are placed on continua.

example, measuring and comparing innovation capability illustrates that it is important to value and cherish multiple ways of making sense of the social world (Greene, 2007). A purely quantitative approach based on S&T metrics (see for example Hu et al., 2018; Fu et al., 2011; Awate et al., 2012) can be limited (e.g., to investigate the diffusion of tacit knowledge) or even misleading, particularly in the Chinese context where patenting is closely linked to institutional patent subsidy programs (Dang and Motohashi, 2015).[53]

At the same time, a purely qualitative approach to 'measuring innovation' can also be limited in various ways, e.g., in its ability to include a large number of indicators and generalize the findings to broad populations across industrial sectors (Hansen and Lema, 2019; Lee and Baskerville, 2003). In turn, combining both qualitative and quantitative evidence allows for new perspectives while improving validity and reliability by offsetting the weaknesses that arise when the approaches are employed separately. The underpinning assumption is that studying social phenomena is an inherently complex process (Davis and Eisenhardt, 2011). Therefore, insisting on theoretical and methodological parsimony at the ontological level would result in explanatory sacrifice (Weaver and Gioia, 1994). Rather than building internally parsimonious theoretical explanations, the primary objective of this thesis is to capture and analyze social action in its complexity (Sil and Katzenstein, 2010), thereby following the Weberian notion of '*Verstehen*'.[54]

4.2. Research strategy and design

To get an in-depth understanding of the complex and variegated processes underlying the upgrading of innovation capabilities in latecomer firms, this thesis combines within-case and cross-case comparisons (Bennett and Checkel, 2015; George and Bennett, 2005; Beach, 2017). To ensure a high level of validity and reliability, the thesis is based on a variety of qualitative and quantitative evidence that was collected over a three-year period and includes 18 months of field research in China, as outlined later in this chapter. It adopts 'appreciative theorizing' (Nelson

[53] Multiple studies have shown that patent numbers do not correlate with patent quality in terms of technological novelty and impact (Hain et al., 2020; Torrisi et al., 2016). Hence, it is important to treat patents not as equal units of observation but to adopt a differentiated and qualitative view on them.

[54] Each occurrence of a particular social phenomenon is the result of an infinite number of cause–effect relationships that together produce the social phenomenon (Gross, 2018).

and Winter, 1982: 46; Lee and Malerba, 2017), meaning a 'causal explanation of observed patterns'. Contrary to formal theories, appreciative theorizing develops causal arguments that are based on real phenomena (here the upgrading in China's wind energy sector) and is thus closer to the empirical substance (Nelson and Winter, 1982; Nelson, 1994).

4.2.1. Case study: selection and design

To address the research problem, this thesis adopts a 'multiple case-study' design (Yin, 2009) based on purposive sampling of information-rich cases (Miles and Hubermann, 1994; Patton, 2015). Case studies are 'cumulatively contingent generalizations that apply to well-defined types or sub-types of cases with a high degree of explanatory richness' (George and Bennett, 2005: 31). Since case studies investigate social phenomena within their real-life context (Yin, 2009), they allow for an 'extremely rich, detailed, and in-depth [understanding]' (Berg, 2007: 283) of processes, conditions, and mechanisms under which certain outcomes and impacts occur (Woodside and Wilson, 2003; Patton, 2015). George and Bennett (2005) identify four key advantages over purely statistical methods that make case studies a useful tool in testing hypotheses and developing theory: (1) their high level of conceptual validity (i.e., selecting the best indicators for an intended concept); (2) their strong heuristic identification of new variables and hypotheses (e.g., through diverse or deviant cases); (3) their value in examining causal mechanisms in the context of individual cases; and (4) their capacity to model and assess complex causality (e.g., equifinality and path dependency).[55]

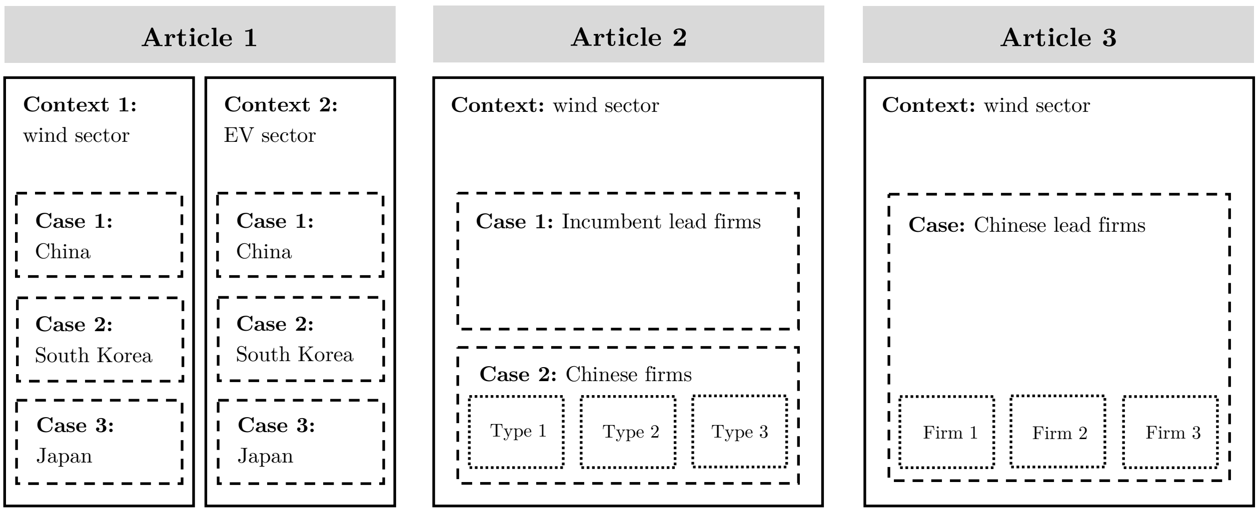
China's wind energy sector was selected for two principal reasons: first, it constitutes an *extreme case* (Flyvbjerg, 2006; Seawright and Gerring, 2008) of 'compressed development' (Whittaker et al., 2010) in the catch-up and upgrading of the innovation capabilities process (Lewis, 2013; Tan and Mathews, 2015; Schmitz and Altenburg, 2015).[56] As emphasized by Hansen

[55] Case studies are also limited in some dimensions (George and Bennett, 2005): (1) they are prone to selection bias (by deliberately choosing cases that share a particular outcome); (2) they are much stronger in assessing *under what conditions* and *how* a variable mattered in the outcome rather than assessing *how much* it mattered (causal weight); (3) their lack of representativeness of a larger population (trade-off between internal and external validity); (4) their relative inability to render judgements on the frequency of particular cases.

[56] Extreme cases do not intend to generalize across large populations, but provide valuable contributions to the understanding of a range of possible outcomes (Flyvbjerg, 2006). As the extreme case China serves as an entrée into a larger sample of firm-level cases within China that provide a full range of variation, the analysis is not subject to sample bias problems (Seawright and Gerring, 2008).

and Lema (2019: 250), China's wind turbine industry is 'one of the most striking examples of rapid technological catch-up in emerging economies'. Second, upgrading in the wind energy sector requires particularly effective learning mechanisms due to its high level of complexity and concurrently low level of standardization, particularly in offshore wind (Hain et al., 2020; Binz and Truffer, 2017; Huenteler et al., 2016). As such, it provides highly relevant insights into 'localized learning' of spatially sticky industries (Binz et al., 2017; Schmidt and Huenteler, 2016).[57] Figure 2 provides an overview of the individual case study designs adopted in the three articles. As can be seen from the diagram, the individual case study designs of the articles transition from a multiple-case (Article I) to a single-case, embedded design (Article III; Yin, 2009). In combination with the case studies, the articles draw upon two further methods that are typically not used in the context of the study and therefore allow for a new perspective on the upgrading of innovation capabilities. These methods are presented in the following two sections.

Figure 2. Case study design of three research articles



Source: Author's compilation, based on by Yin (2009).

[57] 'Spatially sticky' refers to the combination of a high level of customization in the valuation system and a doing, using, interacting innovation mode (Binz and Truffer 2017).

4.2.2. Natural language processing and vector space modelling

Natural language processing (NLP) is an interdisciplinary method at the intersection of artificial intelligence, computational linguistics, and cognitive science that 'aims to model the cognitive mechanisms underlying the understanding and production of human languages' (Deng et al., 2018: 1). It is generally concerned with analyzing large amounts of meanings ('semantics') from texts and speeches.[58] While there are many different areas of application, this thesis used NLP for *machine reading*, a probabilistic approach to extracting facts and hypotheses from vast quantities of text (Hirschberg and Manning, 2015). More specifically, NLP was used in Article I to harness the textual data of 12 million patent titles and abstracts with the purpose of detecting their technological novelty and impact (Arts et al., 2021; Motohashi and Zhu, 2020; de Rassenfosse et al., 2019; deGrazia et al., 2020).[59] NLP was combined with vector space modelling (VSM), which facilitated the creation of high-dimensional technological signature vectors to measure the technological similarity between patents ('patent-to-patent similarity mapping'). The advantage of this method over patent citation analysis (see e.g., Huenteler et al., 2016) is that it is able to capture overall similarities between patents without the presence of explicit links ('backward/forward citations'). This allows not only for a substantially deeper analysis of patent interrelatedness and technological significance but also overcomes potential drawbacks associated with strategic patenting strategies (Yoon and Park, 2004; Torrisi et al., 2016). Supplementary Appendix A of Article I provides a detailed account of the methodological approach.

4.2.3. Social network analysis

Social network analysis (SNA) is a pivotal and well-established analytical tool in social sciences, particularly in innovation research (Powell and Grodal, 2004; Stephan et al., 2017; Freeman, 2004; Fu et al., 2017). It is an interdisciplinary method developed for the purpose of investigating social structures and relationships among interacting units through the use of network visualizations (Canter and Graf, 2006). Rooted in network theory, the generic hypothesis

[58] NLP is used in a number of everyday applications e.g., spam filters, voice recognition, and smart assistants such as Apple's Siri or Amazon's Alexa.

[59] The similarity mapping is originally based on 48 million patent abstracts, which is reduced by applying time (1980–2017), technology (IPC class wind/EV), and quality filters (e.g., granted patents and earliest priority filings per extended patent family).

is that actors face a set of opportunities and constraints depending on their position in a given network (Borgatti et al., 2013). The fundamental idea that individuals are embedded in 'thick webs of social relations and interactions' (Borgatti et al., 2009: 892) was already a central tenet of sociologist Norbert Elias (1938: 35–36), who stated in his influential book *Society of Individuals*:

> 'But as a model for thinking about human interweaving, it is sufficient to give a somewhat clearer idea of the manner in which a net of many units gives rise to an order that cannot be studied in the individual unit. […] In the same way, ideas, convictions, affects, needs and character traits are produced in the individual through intercourse with others, things which make up his most personal 'self' and in which is expressed, from this very reason, the network of relations from which he has emerged and into which he passes.'

Social network analysts are particularly interested in constructing diagrams of social structures that reveal patterns generally not apparent or recognizable to human observers (Scott, 2011). For example, previous studies have focused on identifying guanxi networks inside Chinese organizations (Lin, 2001), elite networks in Denmark (Ellersgaard et al., 2013), or media coverage of the US presidential elections (Sudhahar, 2015). A network structure consists of multiple actors or 'nodes' and the relationships between them, also referred to as 'ties', 'edges', or 'links', which can be stronger or weaker (Granovetter, 1973; Hansen, 1999). In this thesis, SNA is used in Article III to map the R&D networks of Chinese lead firms in the wind energy sector over time. This method was deemed the most appropriate to investigate R&D collaborations (and their underlying upgrading mechanisms) and innovation capabilities over time. After identifying approximately 400 R&D partnerships between 1998 and the first half of 2020, the collected data was converted into two spreadsheets: (1) a node list including all attributes, e.g., location and sector, and (2) an edge list or adjacency matrix, which contained all central information about the relationship between two nodes, e.g., collaboration type and period. The methodological choices and consecutive steps of collecting and analyzing network data are described in detail in Supplementary Article A of Article III.

4.3. Data collection and analysis

The dissertation draws on multiple data collection techniques and data sources. Primary data comprises 81 semi-structured interviews and 23 participant observations; secondary data was collected from six databases and over 400 archival records and documents. Table 4 and Table 5 provide a detailed overview of the data sources as used in the three articles.

4.3.1. Semi-structured interviews

Overall, 81 semi-structured interviews were collected over five rounds from December 2017 to August 2020, including three short visits to China, one to Germany and 1.5 years of consecutive fieldwork in China (see Appendix A4 for a chronological list of interviews). Interview partners were selected according to their *target group* (nine broader target groups were identified as relevant; see Table A3 for an overview), *position* (targeting decision-makers; Dexter, 2006), and *experience* (in-depth industry/firm knowledge). Potential interview partners were contacted through various channels: e-mail, social media (mainly LinkedIn), or at conferences and industry fairs. The ease of recruiting interview partners increased over time due to *snowball sampling techniques* (Noy, 2008; Suri, 2011) and the considerable advantage of *in situ research* (Stake, 1995; Miles and Hubermann, 1994), i.e., spending a total of 18 months in China and having the opportunity to build up a local network.

Table 4. Primary and secondary data sources of research articles

Article	**Primary data**	#	Label	**Secondary data**	#	Label
I	Interviews	67	R1-3	Databases	3	D1, D3, D6
				Documents	50	A1-7
				Interviews	111	Rx
II	Patent database	1	Similarity edgelists of 12 million patent abstracts	Databases	2	D1, D4
				Documents	35	A1-2, A4, A7
III	Interviews	81	R1-5	Databases	5	D2, D4-6
	Participant observations	23	O1-5	Documents	350	A1-7

Before each interview, a list of interview questions was drawn up on the basis of extensive background research on a specific interviewee. This guided the interview and minimized power imbalances between the interviewer and interviewee (Berry, 2002; Lønsmann, 2016). Where possible, the interview took place face-to-face, either at the interviewee's office or in a public space (restaurants or cafés).[60] Depending on the level of confidentiality and appropriateness (e.g., interviewee not comfortable with being recorded), interviews were either recorded or documented through detailed minutes. Questions were open-ended and covered both general macro- and meso-level topics (e.g., public policies and key industry trends) as well as specific micro-level questions on firms' R&D strategies, partnerships, and innovative activities (see Table A5 for examples of interview questions). The OECD's (2015, 2018) *Frascati* and *Oslo Manual* provided useful guidance on formulating the interview questions and interview questions were guided by themes (Brymann, 2012) arising from the conceptual frameworks. The duration of interviews varied between 25 and 175 minutes and were mostly conducted in English, with a small number in German and one in Mandarin.

All recorded interviews were transcribed and, alongside interview minutes, coded using NVivo software, following the analytical procedures as described by Schreier et al., (2019). In total, interview transcriptions amounted to 410,000 words or over 1,000 pages. To ensure a high level of internal validity, three triangulation methods were used (Meijer et al., 2002): first, to ensure a balanced view, interviews were conducted with both current and former employees across different locations and functional divisions (including HQs, subsidiaries, and R&D hubs). The relatively high level of company rotation of people working in the wind energy sector, in particular between Western and Chinese lead firms, helped establish valuable comparative perspectives. Second, some key interview partners were interviewed twice over a span of almost three years, which allowed for cross-examining of their statements. Third, interview transcriptions were supplemented with observation material (notes and pictures) and complemented with information from secondary data to scrutinize interview statements.

[60] A number of interviews during the first two collection phases were conducted jointly with the primary supervisor, which allowed for rapid learning of interview techniques and ensured a high degree of internal validity.

Table 5. Specification of data collection

	Label	Data source	Specification		Examples
			Country	Period	
Interviews	**R1**	Round one	DK, CN	Dec17-Jan18	FTI Consulting, GIZ, CASTED, AHK
	R2	Round two	DE, DK	Mar18	SGRE, AMSC, Norwin, Vestas, ENV, Vensys, Senvion, Aerodyn
	R3	Round three	CN	Apr18	ERI, CNREC, World Economic Forum, Titan, Envision, GWEC, GOL
	R4	Round four	CN	Mar-May19	ENV, GOL, MNG, Sinoma, CSIC Haizhuang, ABB, WWEA, Longyuan, Nordex, McKinsey
	R5	Round five	DE, DK	Apr20	CWEA, UNEP, IEA, World Bank, OECD
	Rx	Previous interviews	CN, DK	2014-2019	Secondary interview data previously conducted by the co-authors
Databases	**D1**	Bloomberg Terminal	Financial and market data		Onshore/offshore statistics e.g., market share, revenues, exports, cost structure, renewable energy targets
	D2	Platts	World Electric Power Database		Plant-level installed capacity
	D3	Espacenet	Patent data		Combined search codes for T3 (Article II)
	D4	PATSTAT	Patent data		Comparing wind and EV IPC classes (Article I), Co-patenting activity of Chinese wind turbine manufacturers (Article III)
	D5	EBSCOhost, Scopus, WoS	Scientific publications		Scientific co-publications between case-study firms and other organizations (Article III)
	D6	Crunchbase Pro	Financial data		M&A and other corporate investments of the case-study firms
Archival records & documents	**A1**	Industry Reports			Wind Market Update (FTI), Global Wind Reports (GWEC), Annual Reports (CWEA), Future of Wind (IRENA), World Energy Outlook (IEA), Global Trends in Renewable Energy Investment (FS-UNEP), China Annual Reports (IEEFA), Renewables Global Status Report (REN21)
	A2	Company Reports			Corporate Annual Reports (e.g., Vestas, SGRE, GOL, MNG), Investment Memorandums (e.g., ENV)
	A3	Company Websites			Vestas, GOL, ENV, MNG
	A4	Technical & Consultancy Papers			Wind Turbine Models (DTU), Offshore Wind Note (IRENA), Incentives for Renewable Energy (KPMG), Wind Turbine Order Analysis (Wood Mackenzie), Trade in Value Added China (OECD), Catalogue of Encouraged FDI (NDRC)
	A5	Social Media			LinkedIn, WeChat, Twitter, Facebook
	A6	Newspapers and Magazines			Wind Power Monthly, Recharge News, Energy Iceberg, China Energy Portal, The Economist, The Guardian
	A7	Research Articles			Mainly from the following journals: Research Policy, Energy Policy, Climate Policy, Industrial and Corporate Change, Technological Forecasting and Social Change, World Development, Asia Pacific Journal of Management, Journal of Cleaner Production
Participant observations	**O1**	Conferences			Wind Power 2019
	O2	Summits			Renewable Energy Investment Summit
	O3	Workshops			Corporate Innovation Day; IEA Wind Digitalization
	O4	Seminars			GWEC Response Hub
	O5	Company visits			Goldwind, Envision, Sinoma, Longyuan (exemplary)

4.3.2. Participant observations

Participant observation is herein defined as 'the systematic description of events, behaviors, and artifacts in the social setting chosen for study' (Marshall and Rossmann, 2016: 78). Relevant events in the context of this thesis were mainly wind energy conferences, summits, and workshops, as well as company visits. Participation in events such as the Wind Power Conference and the Renewable Energy Investment Summit 2019 were not only highly relevant to expand the local network and recruit interview partners, but also to gain an in-depth understanding of practice (Bogner et al., 2009), i.e., how industry practitioners exchange knowledge and learn about new industry trends.

Besides attending industry-relevant events, interviews were often combined with company visits, providing relevant insights into company structures, daily routines, and working methods as 'social facts' (Atkinson and Coffey, 2003). For example, one interviewee granted access to the firm's technology center, where data on the management of various wind farms in China was collected and analyzed. Another interview partner displayed posters on an office wall showing the pipeline of ongoing or planned innovation projects and global collaborations. A third interview partner invited me to visit a local wind farm. This exposure into the practice itself (Bueger, 2014) and seeing the world through the eyes of an interview partner provided an important building block in the creation of knowledge about daily practice in China's wind energy firms. Due to the various interaction points between interviewer and interviewee, the focus was more on 'participation' rather than 'observation'; the latter suggests a more passive researcher role (Czarniawska, 2007).

Futhermore, participant observations were crucial to ensure a high level of construct validity (Bryman, 2016), i.e., the consistency between conceptual constructs and the way these were operationalized, informed by real-life observations (Adcock and Collier, 2001). For instance, the plan to draw upon Lee and Malerba's (2017) catch-up cycle framework emerged early during the PhD. However, it soon became apparent that this framework did not capture all intended elements, i.e. the upgrading of innovation capabilities in Chinese wind turbine manufacturers from both a market and technology perspective. Hence, it was important to complement the analytical framework with additional conceptual approaches (as shown in Chapter 3). This resulted in a new, integrated market-technology framework (see Article I).

In sum, it is important to emphasize that participant observations, despite their low level of direct visibility in the data collection and analysis process, were of significant importance in developing a high degree of contextual sensitivity. An 18-month period in China, including numerous informal dialogues and meetings, was crucial to overcome the liability of foreignness, build trusted networks (Hine, 2008), and access information 'behind the scenes'. In a number of cases, informal conversations following the interviews provided information that was as valuable as the interviews per se.

4.3.3. Databases, archival records, and documents

Databases were used for different purposes. To obtain market-related production and deployment data on a country, firm, and plant level (e.g., onshore and offshore statistics, market share, exports, renewable energy targets), the Bloomberg Terminal at the CBS Library Data Lab was used together with the S&P Global Platts World Electric Power Database. Patent data was used from the European Patent Register's (EPO) PATSTAT (autumn 2018 edition) and Espacenet (version 1.10.0).[61] Financial data (e.g., M&As and other corporate investment activities) was mainly collected from Crunchbase Pro. To identify scientific co-publications between the case-study firms and other organizations, EBSCOhost, Scopus, and the Web of Science were accessed.[62]

Besides databases, secondary data was collected from multiple sources: annual industry and company reports, company websites, technical and consultancy papers, social media, newspapers and magazines, and research articles. Table 6 provides a detailed overview of example documents that were used through the data collection process. The purpose of collecting secondary data varied across the articles. Besides triangulating interview data, it served the following purposes. Article I focused on analyzing market and technology development based on wind and EV

[61] PATSTAT is used to retrieve raw data, while Espacenet offers a simple interface to conduct patent searches online. EPO's patent database covers patent documents from more than 100 patent offices worldwide (EPO, 2020).

[62] The databases belong to different publishing houses that use different citation methods, i.e., EBSCOhost (EBSCO Information Services), Scopus (Elsevier), Web of Science (Clarivate).

deployment and patent data. Article II aimed to identify technological shifts in the evolution of the wind energy sector, which required a systematic examination of onshore, offshore, and digital/hybrid wind data. The objective of Article III was to identify and map a wide range of R&D collaborations over a 20-year period by scrutinizing multiple annual reports, newspaper articles, and other social media activities, in addition to interviews.

4.3.4. Remarks on validity and reliability

To ensure findings had a high level of validity and reliability, a number of techniques were adopted (Yin, 2009; Bryman, 2016; Neuman, 2016). First, *internal validity,* or the integrity of identifying causal relationships, was ensured by congruence testing to identify alternative explanations (George and Bennett, 2005). In this regard, it was very important to triangulate from a wide range of different sources, to spend a substantial amount of time in China carrying out fieldwork, and to draw on continuous, external feedback on the progress of the research, e.g., during the work-in-progress seminars, department presentations, international conferences, interviews, and through the rigorous peer-review system that underlies the publication process of scientific journals. Critical feedback on preliminary results from different scientific directions and industry practitioners triggered important reflections that improved validity and opened new research avenues. Second, *construct validity,* or the credibility of measuring what a conceptual construct intends to measure, was established by adopting methodological pluralisms based on multiple sources of evidence and abductive reasoning (Reichertz, 2004), i.e., the non-linearity between finding rich conceptual frameworks that can explain specific patterns found in the empirical material collected. Third, to enhance the *external validity* or the transferability of the findings, this thesis deploys a multi-angle view including multiple comparative case studies (Khan, 2014). The thesis acknowledges that the context-bound empirical character—China as an extreme case and the wind energy sector displaying high degrees of sector-specificity—makes the research outcomes contingent in several ways (Yin, 2013). However, the goal of this thesis is not to make claims about the frequency or extent to which the studied outcomes occur across large populations. Rather, the objective is to develop a deep understanding of the complex causal mechanisms for the purpose of testing hypotheses and developing theory (George and Bennett, 2005). More specifically, by isolating country- and sector-specific factors, this thesis focuses on finding explanations for firm-level heterogeneity under the same framework conditions. Building on these new insights and recent empirical evidence, it aims to push the boundaries of existing concepts that are relevant to the broader context of latecomer firms. Fourth, the *reliability* or replicability defines the degree to which the study can be repeated at a later point in time and arrive at the same conclusions. This thesis seeks to provide a high level of reliability by providing supplementary methodological appendices of two articles and interview guides. In addition, NVivo codes of interview transcripts were shared with and reviewed by co-authors. The findings are based on internal databases and other triangulated material that allows different researchers to replicate the research process.

5. SUMMARY OF ARTICLES

5.1. Article I—Upgrading trajectories

The first article, 'From catching up to industrial leadership: towards an integrated market-technology perspective,' provides a panoramic perspective by comparing the upgrading *trajectories* of China, Japan, and South Korea in the wind and EV sector. The country cases were selected alongside the following criteria: industry relevance, geographical proximity, different stages of industrial development, and different market regimes (or 'technological congruence' in Abramovitz (1986) terms), thereby providing a *diverse case* (Seawright and Gerring, 2008) or maximum variation (heterogeneity) sample (Patton, 2002).[63] The EV sector was chosen due to its frontrunner status in the low-carbon transformation alongside wind (Altenburg et al., 2016a), and to explore potential network effects between green supply- (wind) and demand-side (EV) technologies.

The article departs from the observation that studies on latecomer development, in particular the literature on catching up, technological learning, and the upgrading of innovation capabilities, use different approaches to evaluate latecomer firms' levels of development and competitiveness. While some use market and production shares (Lee and Malerba, 2017), others refer to technological capabilities regardless of market outputs (Figueiredo and Cohen, 2019). This dichotomy leads to three central problems (see Section 3.1.3. for a detailed discussion). First, a lack of a holistic understanding of latecomer upgrading that integrates both market- and technology-related capabilities, despite both being highly relevant to avoid development traps. Second, comparative perspectives on upgrading trajectories across industrial boundaries are hindered. Third, a lack of insights into a country's overall contribution to the technological advancement of sectors, something that is particularly important for green technologies that compete with conventional industries.

Based on this observation, the article proposes an integrated market-technology framework to analyze latecomer development that can be applied to a wide array of empirical contexts. After

[63] A 'diverse case' aims to achieve the maximum variance along relevant dimensions (Seawright and Gerring, 2008). Here, these are industrial development stages and market regimes.

presenting the framework, the article tests its robustness by adopting a multiple and embedded case study design (George and Bennet, 2005) that compares the two industries across the three country cases. In addition to establishing a new framework, the article also develops a new method that measures technological novelty and impact based on semantic patent-to-patent similarity scores. The empirical analysis of the article is guided by the following research questions: (1) What implications does sector-specificity have for market vs. technology catch up and leadership? (2) What should latecomer countries consider when entering a new sector? (3) What trajectories and detours can latecomers take to avoid market and technology traps?

The analysis determines that, first, sectors vary significantly in their knowledge base complexity and technology regime dimension (technology cycles), which denotes different entry and upgrading strategies. For instance, longer intervals and low fluctuations in technology cycles provide path-skipping opportunities, whereas shorter intervals and high fluctuations allow high-risk-high-impact trajectories to create new technology paths. Second, countries differ significantly in their factor endowments, which calls for different catch-up trajectories. Since latecomer firms typically face competitive disadvantages in terms of market sophistication and technological advancement, a market-technology trajectory can provide an important detour. This means 'they manage to capture substantial market share, but also gradually improve their capabilities and knowledge base on the technological side' (Hain et al., 2020: 5). The article highlights the risk of development traps i.e., an imbalance between commercialization and technological capabilities. This means, latecomers remain in a follower position and may have to abort their catch-up process. Third, deploying multiple green technologies such as wind energy and electric vehicles can precipitate positive network effects. For example, EVs create both market demand for clean electricity from wind turbines and concurrently provide technological support in the form of energy storage.[64] Hence, successful upgrading does not only depend on capabilities in single technologies but also on crosscutting capabilities i.e., to build up advanced capabilities in complementary industries.

[64] To balance wind production and load during the night. One of the fundamental challenges to date is that renewables such as wind power cannot be stored in a financially feasibly way. This means supply and demand must be matched.

The relevance of this article in the context of the overall research puzzle is to show that market leadership does not automatically correlate with technological capabilities and vice versa. Successful upgrading requires both commercialization and technological learning. Yet possible upgrading trajectories are predefined by outer boundaries and framework conditions such as market size, institutional regulations, and pre-existing knowledge base.[65]

5.2. **Article II**—Upgrading opportunities

The second article, ‘Catching up through green windows of opportunity in an era of technological transformation’, zooms into the global wind energy sector and compares how Chinese wind turbine manufacturers respond to new upgrading *opportunities* vis-à-vis incumbent firms. Firm cases were selected along the following criteria: (1) Incumbent firms: according to their positioning at the global technological frontier (i.e., being first-movers in turbine size or other new digital/hybrid technologies), (2) Chinese firms: *deviant cases* (Seawright and Gerring, 2008) that ‘exemplify contexts where [the upgrading of] innovation [capability] was perceived notably as a success or a failure’ (Suri, 2011: 67).[66]

The article is based on the observation that changing conditions in the global economy—the transformation towards low-carbon and digital/hybrid technologies—provide significant upgrading opportunities for latecomer firms: first, the wind energy sector is shifting from a niche to a mainstream source of electricity, thereby providing significant market opportunities for new entrants (GWEC, 2020). Second, the industry is transitioning to new digital/hybrid technologies, thereby challenging previous business models and opening new leapfrogging opportunities for latecomer firms (IRENA, 2019a; UNCTAD, 2019). However, in light of rapid technological change and growing complexity, established concepts on latecomer development have not yet sufficiently incorporated the consequences of more recent technological shifts for latecomer firm upgrading.

[65] A metaphorical comparison of ‘outer boundaries’ is a bowling lane, which provides a rough direction but leaves room for a plethora of different strategies within the lane. To prevent aborted catch-up (or the bowling ball falling into the gutter), commercialization and technological learning must be sufficiently balanced. The role of policies is to provide a protective space for new green technologies during the initial stage (by pulling up the bumper rails) e.g., this happened with China’s Renewable Energy Law in 2006. The protective space was gradually removed to encourage competition e.g., by reducing feed-in-tariffs and introducing reverse auction schemes.

[66] Categories for case selection are based on Lee and Lim’s (2001) differentiation between *path-following* and *path-skipping* and Lee and Malerba’s (2017) concept of *aborted catch-up*.

Therefore, this article seeks to answer the following two research questions: (1) How does technological transformation open green windows of opportunity that affect latecomers' possibilities for catching up? (2) What strategies can latecomer firms develop to respond effectively to technological shifts?

To answer the research questions, the article adopts a comparative case-study design with incumbent and latecomer firms in the wind energy sector as the unit of analysis. It finds that, first, technological shifts in the evolution of an industry can have two-fold implications: they contribute to either technological *deepening* or *widening* by changing the technological regime conditions, with the former entailing path-skipping and the latter path-creating upgrading opportunities. Second, latecomer firms from the same country and same sector show different capabilities in responding effectively to these technological shifts, which highlights that successful catch-up can only be partially attributed to the institutional environment.

Conceptually, the article introduces *technological shifts* as highly relevant events, particularly in the context of green industries. Empirically, the article provides new insights into the variations of catch-up responses by latecomer firms based on insights from the Chinese wind energy sector.

The contribution of this article to the larger research puzzle is to develop a more nuanced perspective on upgrading opportunities (as further elaborated on in Chapter 6). It enhances our understanding of the role of technological discontinuities in the upgrading of innovation capabilities of latecomer firms and highlights the variety in endogenous responses, i.e., both on a system and firm level. This article contributes to a larger research project that aims to provide a systematic, inter-sectoral comparison across green industries in China (see Special Issue, Lema et al., 2021).

5.3. **Article III**—Upgrading mechanisms

The third article, 'How do R&D networks change? The upgrading of innovation capabilities in emerging market firms. Insights from China's wind energy sector', zooms further into the Chinese wind energy sector and compares upgrading *mechanisms* of the three lead firms, which were selected according to a *most-similar case* study design (Seawright and Gerring, 2008). This means they display a very high similarity in their background conditions (country, sector, and market position), yet low similarity in one key dimension (upgrading strategies) and in the outcome (here 'revealed' innovation capabilities; Sutton, 2012). As the three lead firms account for two-thirds of domestic and one-third of global market share, they exhibit a high level of analytical generalization for latecomer firms in transition processes (Dutrénit, 2007) that are entering into a beyond catch-up stage (Peng et al., 2020).

The article investigates how two major trends affect the upgrading mechanisms of industrial latecomer firms. First, rapid technological change and growing technological complexity require firms to adopt more flexible forms of organizing for innovation (Mazzoleni and Nelson, 2007; Fu et al., 2020). Second, external knowledge is increasingly dispersed globally and openly accessible, which provides significant benefits through collaboration as opposed to developing new products and services in-house (Chesbrough, 2003, 2006; West and Bogers, 2014; Enkel et al., 2009; Laursen and Salter, 2006). Therefore, firms are increasingly decentralizing and diversifying their organizational structure to better adapt to changing market needs and to access complementary, exogenous knowledge (Du et al., 2014; Greco et al., 2016).

However, little is known about the coevolution of upgrading mechanisms and R&D networks, in particular when latecomer firms reach higher levels of innovation capabilities and increase their global innovation space (Hansen and Lema, 2019; Bell and Figueiredo, 2012b; Dutrénit, 2000). Given this research gap, this article raises the following two research questions: In the face of technological change and the decomposition of innovation: (1) What strategies do latecomer firms adopt to upgrade their innovation capabilities? (2) How does their R&D organization change? Methodologically, the article draws upon various data collection techniques to create a firm-level dataset that allows a systematical comparison of R&D networks of China's lead firms in the wind energy sector since the 2000s.

The article finds that properties of R&D networks change over time (as further elaborated on in Chapter 6). However, some firms are faster in responding to technological change and reorganizing their innovative activities than others, which highlights the need to build up both technological and organizational capabilities. The article identifies recently emerging forms of upgrading through externalized R&D projects and finds that there are significant differences between the lead firms in how they are deployed that are closely linked to their underlying upgrading strategies (e.g., path-following vs. path-creating). On a broader level, the article enhances our understanding of the consequences of the decomposition of innovation for latecomer firm upgrading and highlights that latecomer firms do not only exploit existing knowledge from advanced country firms but increasingly co-create new knowledge in global innovation networks.

6. CONCLUSION

This thesis investigates how changing conditions in the global economy affect the development of latecomer firms. In particular, it advances our understanding of how latecomer firms respond to and effectively manage technological change and the decomposition of innovation. This final chapter summarizes the key findings in relation to the main research question, presents the scientific and practical implications, and points at avenues for future research.

6.1. Key findings

The first sub-RQ, 'how do technological change and the decomposition of innovation influence upgrading *trajectories* of latecomer firms,' was addressed in the first article. The comparison of the wind energy and EV sector in China, Japan, and South Korea reveled three key findings: First, upgrading trajectories are predefined by technological advancements, market size, and system responses. While China was able to create the largest wind and EV market through endogenously created support schemes ('green windows of opportunity'), Japan's market scale-up was—despite stronger technological capabilities in both sectors—thwarted by less effective system responses e.g., in the form of unfavorable policies. Second, depending on a country's factor endowments, latecomer firms can either pursue a market-technology or technology-market trajectory. Third, depending on the pace and direction of technological change, sector-specific technology cycles require different entry and upgrading trajectories for latecomer firms.

The second sub-RQ, 'how do technological change and the decomposition of innovation affect upgrading *opportunities* of latecomer firms', was addressed in the second article. Based on the empirical insights of the wind energy sector, technological change was identified as crucial in the provision of new upgrading opportunities. First, the green transformation constitutes a techno-economic paradigm shift that opens new upgrading opportunities for latecomer firms. By capturing green windows of opportunity, Chinese firms have achieved an unprecedented market catch-up and secured leadership in multiple green technologies, including wind. Second, technological shifts on a given technological trajectory (the wind energy sector) within a given techno-economic paradigm (the green transformation) have been conceptualized as highly important events. Both the sectoral *deepening* from onshore to offshore, and the more recent sectoral *widening* with the emergence of digital/hybrid technologies, provided significant leapfrogging opportunities. However, to benefit from technological change and enhance their innovation capabilities, latecomer firms need to identify windows of opportunity and respond effectively to them—both on an institutional and firm level.

The third sub-RQ, 'how do technological change and the decomposition of innovation change upgrading *mechanisms* of latecomer firms', was addressed in the third article. As the analysis of China's lead firms in the wind energy sector showed, the type and relevance of upgrading mechanisms shifted over time. While conventional upgrading mechanisms were primarily used for path-skipping during the early catch-up stages, rapid technological change and ODIP strategies provided new unconventional upgrading options with externalized R&D projects constituting a recently emerging phenomenon. These new upgrading mechanisms allow latecomer firms to shift from exploiting existing to co-creating new knowledge at the technological frontier, alongside market- and science-based partners in global R&D networks. To benefit from this upgrading mechanism, latecomer firms have to, first, fundamentally decentralize their R&D architecture and globally disperse their innovative activities. Second, besides expanding and diversifying their innovation space, latecomer firms have to build up their organizational capabilities to 'orchestrate', i.e., effectively absorb and coordinate external knowledge inside the organization.

This leads us to the main research question guiding this thesis, 'what consequences do technological change and the decomposition of innovation have for the upgrading of innovation capabilities in latecomer firms'. Technological change and the decomposition of innovation have proven to precipitate profound consequences for the upgrading of innovation capabilities in latecomer firms. On the one hand, the three article found that latecomer firms can significantly benefit from the green and digital transformation as they face lower knowledge-related entry and switching costs than incumbent firms, and have to risk new paths or *detour* (Lee, 2019) to challenge global industry leaders.[67] In addition, the decomposition of innovation does not only provide a rapidly growing opportunity to exploit existing knowledge from advanced country firms but also to co-create new knowledge in global innovation networks. On the other hand, an important key finding is that latecomer firms do not equally benefit from technological change and the decomposition of innovation, despite the same framework conditions. While effective institutional responses, in view of new techno-economic paradigm shifts, play an important catalyst function in the short term, latecomer firms only become competitive in global markets in the long term if they develop effective learning strategies that allow for an accumulation of technological and organizational capabilities (with the latter growing exponentially, see Dutrénit, 2000, 2007). Latecomer firms have to reach a certain capability threshold level to benefit from changes in the global economy. Otherwise, they may face the 'red queen effect' and stay in the same place or fall behind in an increasingly competitive environment.

6.2. Scientific implications

This dissertation makes specific scientific contributions to the literature on catching up, technological learning, and the upgrading of innovation capabilities in latecomer firms. These can be divided into theoretical/conceptual, methodological, and empirical across the three articles, as shown in Table 6. While the contributions were already introduced in Section 1.3, this section seeks to discuss the novelty of the core contributions that are organized around three overarching themes: (1) the market-technology perspective on upgrading trajectories, (2) the technological shifts perspective on upgrading opportunities, and (3) the co-evolutionary perspective on upgrading mechanisms and innovation capabilities.

First, the *market-technology perspective on upgrading trajectories* conceptually builds upon the rich frameworks in the current latecomer development literature and further advances them. However, rather than sticking with the prevailing dichotomy, this perspective develops an integrated market-technology framework that facilitates the evaluation of upgrading trajectories in a more nuanced way. Alongside the conceptual framework, it develops a new method that

[67] Incumbents face particularly high lock-in routines in the face of competence-destroying changes in technology (Tushman and Anderson, 1986).

extends existing perspectives in two important ways: market development is understood in relative output terms (e.g., wind capacity relative to the overall energy mix, EVs as a percentage of the overall automotive/transport sector) and technology development is understood in novelty and impact. Both approaches allow for a better evaluation of a country's positioning in and contribution to overall sectoral development. Future scientific studies can benefit from this toolkit to analyze upgrading trajectories across different empirical settings. The market-technology framework is particularly suitable for assessing upgrading trajectories in low-carbon sectors where both market scale-up, and technological novelty and impact are imperative to reach efficiency levels that exceed the ones of conventional sectors with negative environmental externalities (e.g., to reach grid parity in the electricity sector).

Second, the *technological shifts perspective on upgrading opportunities* departs from the observation in the current literature that technological discontinuities can open important windows of opportunity for latecomer firms. However, rather than focusing on windows of opportunity emerging from major discontinuities related to shifts in techno-economic paradigms, the technological shifts perspective adds another layer of upgrading opportunities through less pronounced discontinuities in the evolution of a given sector ('technological shifts'). Building on insights from evolutionary economic theory and innovation studies, it develops a new typology on the relationship between changing technological regime conditions and upgrading opportunities. This framework can be used to analyze the consequences of technological shifts for latecomer firms across different sectors. At the same time, the technological shifts perspective highlights the need to take a dynamic perspective on the definition of sectoral boundaries. To this end, it proposes a new patent search code for the wind energy sector that incorporates more recent digital/hybrid wind technologies.

Third, the *co-evolutionary perspective on upgrading mechanisms and innovation capabilities* pushes the boundaries of the extant literature on technology transfers and learning mechanisms in three important ways. (A) First, it provides a new level of detail on the changing properties of firm-level R&D networks using the empirical case of China's wind energy sector. (B) On this basis, it identifies important changes in upgrading mechanisms that have previously not been captured by the literature: latecomer firms increasingly co-create knowledge in externalized R&D

projects through ODIP strategies. (C) It then leverages these new insights to develop an updated typology on the coevolution between upgrading mechanisms and innovation capabilities. This perspective is of significant relevance for subsequent scientific studies on latecomer firms in transition processes once they have entered into a beyond catch-up stage. Both the conceptual framework and the mixed-methods approach can be applied to a wide range of empirical settings in the future.

Finally, the overall scientific implication is that the role of technological change and the decomposition of innovation deserve a more central role in the latecomer development literature.

Table 6. Scientific contributions

Type	Contribution	Article
Theoretical/ conceptual	i. Developing an integrated *market-technology framework* to evaluate catching up holistically, using both market and technology indicators	1
	ii. Developing a *typology* on changing technological regime conditions in the wind sector as a result of technological shifts	2
	iii. Developing a *typology* on upgrading mechanisms across different innovation capability levels and conceptualization of externalized R&D projects	3
Methodological	i. Developing a *new method* to measure technological novelty and impact based on semantic patent-to-patent similarity	1
	ii. Defining a new *patent search code* for digital/hybrid wind technologies	2
	iii. Adopting a *mixed-methods* SNA to identify changing upgrading mechanisms	3
Empirical	i. Providing new empirical insights into the implications of sector- and country-specificity for *upgrading trajectories*	1
	ii. Providing new empirical evidence on the consequences of technological change for *upgrading opportunities* of latecomer firms	2
	iii. Providing new empirical evidence on the coevolution of *upgrading mechanisms* and R&D networks	3

6.3. Policy and managerial implications

This dissertation speaks to the broader debates of economic development, technological progress, and industrial upgrading in emerging market firms, and includes a number of managerial and policy implications. On a general level, it argues that there can be important synergies between the green and digital transformation and latecomer development. However, there is no one-size-fits-all solution, which is why practical implications must always be considered in a specific empirical context.

The key findings of this PhD reveal dual implications for policy. First, supportive policy schemes play an important catalyst role for the market entry and catch-up process of latecomer firms. With the 'right' policy mix (local content requirement and medium-/long-term renewable targets), China's wind energy sector experienced an unprecedented market scale-up and took over market leadership only four years after the advent of passing the Renewable Energy Law in 2006. In green sectors in general, the role of domestic strategic initiatives and domestically created windows of opportunity has been found to be particularly crucial. There is a significant risk of market traps if the support schemes (e.g., feed-in-tariffs) are faded out before latecomer firms can accumulate a minimum threshold level of innovation capabilities. Hence, policies should aim at providing sufficient protective space for emerging technologies that have the potential to substitute conventional technologies based on fossil fuels, while transitioning to more competitive (e.g., reverse auction) schemes and design capability-building measures (e.g., through mission-guided R&D programs). This prevents the creation of domestic 'zombie markets', including a large number of globally uncompetitive firms. In addition, the deployment of multiple green sectors can provide significant network benefits, particularly between the supply and demand side.

Second, rather than promoting self-sufficient innovation policies, domestic policies in emerging markets should provide incentives for cross-border collaborations. With rapid technological change and the associated increase in technological complexity, it becomes increasingly difficult for one country to master a full range of specialization. As the case of China's lead firms in the wind energy sector showed, cross-country collaborations provide a promising model to co-create new technologies and solutions alongside global partners and to build up highly advanced levels of innovation capability. As such, they provide a more efficient alternative to forced technology transfers that aim at duplicating existing rather than developing new technologies. In addition, grand challenges such as climate change can only be tackled on a global level. Hence, cross-border collaborations are imperative to accelerate the diffusion of low-carbon solutions (Köhler et al., 2019).

Besides the abovementioned policy implication, this thesis provides three-fold managerial implications for industry practitioners. First, to avoid catch-up traps, market and technology development must be balanced in the medium and long term. This requires latecomer firms to align their catch-up trajectories with country-specific factor endowments and sector-specific technology cycles. As the empirical cases of the wind and EV sector showed, low fluctuations in technology cycles provide significant path-skipping opportunities, whereas high fluctuations are associated to more risky path-creating strategies.

Second, to capture windows of opportunity resulting from technological shifts requires latecomer firms to respond in a timely and effectively way. For example, one of China's lead firms, Envision, became a first-mover in the development of digital products and business models and has accumulated highly advanced competencies in energy storage solutions, therein exemplifying an effective response to a technological shift. The digital transformation is likely to provide more upgrading opportunities of a similar nature for latecomer firms. India and China seem particularly equipped with the necessary knowledge base in new digital technologies, which provides them with a potential advantage over incumbent firms that move less quickly into new technologies.

Third, this thesis seeks to increase the awareness of the relationship between different upgrading mechanisms and the building of innovation capabilities. While conventional upgrading mechanisms such as licensing agreements are likely to spur the initial catch-up process, they are not suitable to enter into a beyond catch-up stage and they carry the risk of catch-up traps (e.g., market restrictions as a result of licensing agreements). Shifting to higher innovation capability levels requires increasing, diversifying, and effectively managing the innovation space through unconventional upgrading mechanisms e.g., externalized cross-border R&D. This highlights the need for purposely designed R&D partnerships and dedicated investments in the development of ODIP strategies to effectively absorb and integrate external knowledge.

6.4. Concluding remarks and future research

The underlying motivation of this dissertation was to investigate how changing conditions in the global economy affect the development of emerging market firms. It contributes to the literatures on catching up, technological learning, and the upgrading of innovation capabilities. The findings showed that recent technological change and the decomposition of innovation have profound consequences for upgrading dynamics. Drawing on the empirical case of latecomer firms in China's wind energy sector revealed important synergies between the green and digital transformation, and latecomer development. However, it also identified a high degree of firm-level heterogeneity in translating changing conditions into the accumulation of innovation capabilities.

Collectively, the findings open up several avenues for future research. First, as mentioned in Chapter 4.2., the thesis adopts appreciative theorizing based on China's wind energy sector as an *extreme case* of latecomer development. Hence, the objective of this thesis was to open the black box of causal mechanism underlying the upgrading of innovation capabilities, thereby placing higher priority on internal rather than external validity. To increase the transferability of the findings, future studies could further expand the approach to other empirical contexts beyond China's wind energy sector. For example, it would be very interesting to investigate the consequences of technological change and the decomposition of innovation for other emerging market firms from, for example, India, Brazil, and South Africa. Equally relevant would be to analyze these effects in lower-income and least-developed countries that are transitioning from production to innovation capabilities.

Second, this thesis has focused on how changing conditions in the global economy affect upgrading dynamics (*outcome*) and the accumulation of innovation capabilities in emerging market firms (*impact*), with the latter comprising both a technological and organizational dimension. Further research could benefit from two main directions: Despite highlighting the crucial role of organizational capabilities in effectively managing these changing conditions, additional research is needed to disentangle the specific functions of organizational capabilities. Furthermore, the exact extent to which the outcome of innovation capabilities is the result of exogenous change vs. other endogenous factors could also be subject of future studies. Third, this thesis alludes to a dual functionality of some conventional upgrading mechanisms (e.g., licensing agreements) that can shift from catch-up triggers into catch-up traps. Future studies could further investigate the assumed inverted u-shaped function of upgrading mechanisms given its heightened relevance for the upgrading process.

The findings of this thesis are linked to a broader set of questions on China's growing innovation capabilities and its consequences for the global economy: How is China's growing innovation capability transforming patterns of cooperation between countries? Is there growing competition or collaboration between Chinese and foreign firms? Do Chinese firms compete in the same technologies or specialize in complementary niche technologies? What role do Chinese firms play in addressing grand challenges and sustainable development goals, particularly in the face of the Belt and Road Initiative? And finally, is it still appropriate to refer to Chinese firms as 'latecomers' despite many of them forging ahead?

There is no doubt that China's rise in green and digital technologies entails significant geopolitical implications (see Scholten et al., 2020; IRENA, 2019b). As concerns green leadership, Chinese firms are taking over both market and technological leadership in a growing number of industries. China's wind turbine manufacturers are currently at an important juncture of providing world-class technology in global markets and are likely to follow suit with other green sectors such as biomass, solar PV, concentrated solar power, and hydro (see Special Issue, Lema et al., 2021). This leads, on the one hand, to growing competition with incumbent countries and firms: 'efforts to rein in climate change will up-end the geopolitics of power [...] to China's advantage' (The Economist, 2020: 3). On the other hand, it makes an important contribution to the transition to a global low-carbon economy. For example, China's rapid scale-up of wind turbines has led to a massive reduction in costs that make these technologies not only more accessible to other countries around the world, but also accelerates the attainment of grid parity in a number of countries, i.e., renewables becoming cheaper than conventional energy sources based on fossil fuels.

With regard to digital leadership, China has already developed world-leading capabilities in big data and artificial intelligence and is rapidly strengthening its path-creating position in the digital sphere (Lucas and Waters, 2018). Since traditional manufacturing sectors are increasingly digitalized, this technological widening opens significant leapfrogging opportunities for Chinese firms that seem to move faster into these new technologies than incumbent firms. However, it has also been shown that though this does not automatically lead to zero-sum competition between Chinese and foreign firms, it does open up new collaboration opportunities to develop new digital solutions for green industries in global R&D projects. This is of ever-growing importance in the light of rapid technological change and the new solutions required to tackle grand challenges.

Overall, these questions can neither be answered unambiguously nor with simple explanations. However, this thesis aimed to provide a new perspective on these topics, based on the empirical case of Chinese wind turbine manufacturers. This perspective would not have been able to unfold with a parsimonious theoretical and empirical lens but required an approach from different analytical angles, as presented across the three research articles. However, rather than presenting a closed book, it underscores the need to constantly develop the conceptual frameworks in the existing literature in order to keep pace with emerging trends in the global economy.

References

Abramovitz, M. (1986), ‘Catching up, forging ahead, and falling behind’, *The Journal of Economic History*, **46**(2), 385–406. https://www.jstor.org/stable/2122171.

Adcock, R., & Collier, D. (2001), ‘Measurement validity: A shared standard for qualitative and quantitative research’, *American Political Science Review*, 529–546. https://www.jstor.org/stable/3118231.

Altenburg, T., Schmitz, H., & Stamm, A. (2008), ‘Breakthrough? China’s and India’s transition from production to innovation’, *World Development*, **36**(2), 325–344. doi:10.1016/j.worlddev.2007.06.011.

Altenburg, T., Sagar, A., Schmitz, H., & Xue, L. (2016a), ‘Guest editorial: Comparing low-carbon innovation paths in Asia and Europe’, *Science and Public Policy*, **43**(4), 451–453. https://doi.org/10.1093/scipol/scv073.

Altenburg, T., E. W. Schamp & A. Chaudhary (2016b), ‘The emergence of electromobility: comparing technological pathways in France, Germany, China and India’, *Science and Public Policy*, **43**(4), 464–475. https://doi.org/10.1093/scipol/scv054.

Amendolagine, V., Giuliani, E., Martinelli, A., & Rabellotti, R. (2020), Chinese multinational enterprises bridging technologies across home and host regions. In: McKelvey, M., & Jun, J. (Eds.), *Innovative Capabilities and the Globalization of Chinese Firms: Becoming a Leader in Innovation Spaces.* Edward Elgar Publishing: Cheltenham, UK.

Amin, A., & Cohendet, P. (2004), *Architectures of knowledge: Firms, capabilities, and communities.* Oxford University Press: Oxford.

Amsden, A.H. (1989), *Asia’s Next Giant: South Korea and Late Industrialisation.* Oxford University Press: New York.

Ariffin, N. (2000), *The internationalisation of innovative capabilities: the Malaysian electronics industry.* Unpublished PhD Thesis, SPRU. University of Sussex: Brighton.

Arthur, W. B. (1989), ‘Competing technologies, increasing returns, and lock-in by historical events’, *The Economic Journal*, **99**(394), 116–131. https://doi.org/10.2307/2234208.

Arts, S., Hou, J., & Gomez, J. C. (2021), ‘Natural language processing to identify the creation and impact of new technologies in patent text: Code, data, and new measures’, *Research Policy*, **50**(2), 104144. https://doi.org/10.1016/j.respol.2020.104144.

Atkinson, P., & Coffey, A. (2003), ‘Revisiting the relationship between participant observation and interviewing’, *Postmodern Interviewing*, 109–122. https://dx.doi.org/10.4135/9781412984492.n20.

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

Backwell, B. (2017), *Wind Power: The Struggle for Control of a New Global Industry.* Routledge: London.

Beach, D. (2017), Process-Tracing Methods in Social Science. In: *Oxford Research Encyclopedias of Politics.* Oxford University Press: Oxford.

Beach, D., & Pedersen, R. B. P. (2016), ‘Selecting Appropriate Cases When Tracing Causal Mechanisms’, *Sociological Methods & Research*, **47**(4),1–35. https://doi.org/10.1177/0049124115622510.

Beach, D., & Pedersen, R. B. (2019), *Process-Tracing Methods: Foundations and Guidelines*. University of Michigan Press: Ann Arbor.

Bell, M. (1984), Learning and the Accumulation of Industrial Technological Capacity in Developing Countries. In: *Technological Capability in the Third World*. Palgrave Macmillan: London: 187–209. https://doi.org/10.1007/978-1-349-17487-4_10

Bell, M., & Pavitt, K. (1993), ‘Technological accumulation and industrial growth: contrasts between developed and developing countries’, *Industrial and Corporate Change*, **2**(2), 157–210. https://doi.org/10.1093/icc/2.2.157.

Bell, M., & Pavitt, K. (1995), The Development of Technological Capabilities. In: *Trade, Technology and International Competitiveness*, *22*(4831), 69–101. The World Bank: Washington, DC.

Bell, M., & Figueiredo, P. N. (2012a), ‘Innovation capability building and learning mechanisms in latecomer firms: recent empirical contributions and implications for research’, *Canadian Journal of Development Studies/Revue Canadienne d'études du Développement*, **33**(1), 14–40. doi:10.1080/02255189.2012.677168.

Bell, M., & Figueiredo, P. N. (2012b), Building Innovative Capabilities in Latecomer Emerging Firms: Some Key Issues. In: E. Amann & J. Cantwell (eds.), *Innovative Firms in Emerging Market Countries*. Oxford Scholarship Online: Oxford. doi:10.1093/acprof:oso/9780199646005.003.0002.

Bennett, A., & Checkel, J. T. (Eds.) (2015), *Process Tracing*. Cambridge University Press: Cambridge.

Berg, B. B. (2007), *Qualitative Research Methods for the Social Sciences* (6th ed.). Pearson Education: Boston, MA.

Berry, J. M. (2002), ‘Validity and reliability issues in elite interviewing’, *PS: Political Science and Politics*, **35**(4), 679–682. https://www.jstor.org/stable/1554809.

Binz, C. & B. Truffer (2017), ‘Global innovation systems - a conceptual framework for innovation dynamics in transnational contexts’, *Research Policy*, **46**(7), 1284–1298. https://doi.org/10.1016/j.respol.2017.05.012.

Binz, C., Gosens, J., Hansen, T., & Hansen, U. E. (2017), ‘Toward technology-sensitive catching-up policies: insights from renewable energy in China’, *World Development*, **96**, 418–437. doi:10.1016/j.respol.2017.05.012.

Blomström, M., & Kokko, A. (1998), ‘Multinational corporations and spillovers’, *Journal of Economic Surveys*, **12**(3), 247–277. https://doi.org/10.1111/1467-6419.00056.

BNEF (2019), *The world will get half its power from wind, solar by 2050,* Bloomberg New Energy Finance. Retrieved from https://www.bloomberg.com/news/articles/2019-06-18/.

BNEF (2020), *Top-10 OEMS in China*, Bloomberg New Energy Finance. Retrieved from https://energyiceberg.com/china-wind-oems-2019/.

Bogner, A., Littig, B., & Menz, W. (Eds.) (2009), *Interviewing Experts*. Palgrave Macmillan: London.

Borgatti, S. P., Mehra, A., Brass, D. J., & Labianca, G. (2009), 'Network analysis in the social sciences', *Science*, **323**(5916), 892–895. doi:10.1126/science.1165821.

Borgatti, S. P., Everett, M. G., & Johnson, J. C. (2013), *Analyzing Social Networks*. SAGE: London.

Breschi, S., L. Orsenigo & F. Malerba (2000), 'Technological regimes and Schumpeterian patterns of innovation', *Economic Journal*, **110**(463), 388–410.

Brusoni, S. (2005), 'The limits to specialization: problem solving and coordination in 'modular networks'', *Organization Studies*, **26**(12), 1885–1907. https://doi.org/10.1177/0170840605059161.

Bryman, A. (2016), *Social Research Methods*. Oxford University Press: Oxford.

Bueger, C., & Gadinger, F. (2014), *International Practice Theory: New Perspectives*. Palgrave Macmillan: London.

Cantner, U., & Graf, H. (2006), 'The network of innovators in Jena: An application of social network analysis', *Research Policy*, **35**(4), 463–480. https://doi.org/10.1016/j.respol.2006.01.002.

Cantwell, J., & Mudambi, R. (2005), 'MNE competence-creating subsidiary mandates', *Strategic Management Journal*, **26**(12), 1109–1128. https://doi.org/10.1002/smj.497.

Capone, G., Li, D. & F. Malerba (2021), 'Catch-up and the entry strategies of latecomers: Chinese firms in the mobile phone sector', *Industrial and Corporate Change*, dtaa061, https://doi.org/10.1093/icc/dtaa061.

Chandy, R. K. & Tellis G. J. (2000), 'The incumbent's curse? Incumbency, size, and radical product innovation', *Journal of Marketing*, **64**(3), 1–17. https://doi.org/10.1509/jmkg.64.3.1.18033.

Chesbrough, H. W. (2003), *Open Innovation: The New Imperative for Creating and Profiting From Technology*. Harvard Business Press: Boston, MA.

Chesbrough, H. W. (2006), 'The era of open innovation', *Managing innovation and change*, ***127***(3), 34–41.

Chesbrough, H. (2017), 'The future of open innovation: The future of open innovation is more extensive, more collaborative, and more engaged with a wider variety of participants', *Research-Technology Management*, **60**(1), 35–38. doi:10.1080/08956308.2017.1255054.

Chesbrough, H., & Bogers, M. (2014), *Explicating Open Innovation: Clarifying an Emerging Paradigm for Understanding Innovation. New Frontiers in Open Innovation.* Oxford University Press: Oxford.

Coenen, L., Hansen, T., & Rekers, J. V. (2015), 'Innovation policy for grand challenges. An economic geography perspective', *Geography Compass*, **9**(9), 483–496. https://doi.org/10.1111/gec3.12231.

Cohen, W. M., & Levinthal, D. A. (1990), 'Absorptive capacity: A new perspective on learning and innovation', *Administrative Science Quarterly*, 128–152. https://doi.org/10.2307/2393553.

Creswell, J. W. (2003), *Research Design: Qualitative, Quantitative, and Mixed methods*. SAGE: Thousand Oaks, CA.

Creswell, J. W., & Plano Clark, V. L. (2018), *Designing and Conducting Mixed Methods Research* (third edition). SAGE Publications: Thousand Oaks, CA.

Curley, M., & Salmelin, B. (2018), O*pen Innovation 2.0: The New Mode Of Digital Innovation For Prosperity And Sustainability.* Springer: Washington, DC.

CWEA (2020), *Ranking and Market Share of China's Wind Turbine Manufacturers in 2019.* [In Chinese] Chinese Wind Energy Association: Beijing.

Czarniawska, B. (2007), *Shadowing and other Techniques for Doing Fieldwork in Modern Societies.* Copenhagen Business School Press DK: Frederiksberg.

Dahlander, L., & Gann, D. M. (2010), 'How open is innovation?', *Research Policy*, **39**(6), 699–709. https://doi.org/10.1016/j.respol.2010.01.013.

Dahlman, C. J., Ross-Larson, B., & Westphal, L. E. (1987), 'Managing technological development: lessons from the newly industrializing countries', *World Development*, ***15***(6), 759–775. https://doi.org/10.1016/0305-750X(87)90058-1.

Dai, Y. & L. Xue (2015), 'China's policy initiatives for the development of wind energy technology', *Climate Policy*, 15(1), 30–57. https://doi.org/10.1080/14693062.2014.863549.

Dai, Y., Haakonsson, S., & Oehler, L. (2021), '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*, forthcoming.

Dang, J., & Motohashi, K. (2015), 'Patent statistics: A good indicator for innovation in China? Patent subsidy program impacts on patent quality', *China Economic Review*, **35**, 137–155. https://doi.org/10.1016/j.chieco.2015.03.012.

Dantas, E., & Bell, M. (2009), 'Latecomer firms and the emergence and development of knowledge networks: The case of Petrobras in Brazil', *Research Policy*, **38**(5), 829–844. doi:10.1016/j.respol.2009.01.007.

Davis, J. P., & Eisenhardt, K. M. (2011), 'Rotating leadership and collaborative innovation: Recombination processes in symbiotic relationships', *Administrative Science Quarterly*, **56**(2), 159–201. https://doi.org/10.1177/0001839211428131.

De Rassenfosse, G., Kozak, J., & Seliger, F. (2019), 'Geocoding of worldwide patent data', *Scientific Data*, **6**(1), 1–15. https://doi.org/10.1038/s41597-019-0264-6.

deGrazia, C. A., Frumkin, J. P., & Pairolero, N. A. (2020), 'Embracing invention similarity for the measurement of vertically overlapping claims', *Economics of Innovation and New Technology*, **29**(2), 113–146. https://doi.org/10.1080/10438599.2019.1593035.

Deng, L., & Liu, Y. (2018), A joint introduction to natural language processing and to deep learning. In: *Deep learning in natural language processing*, 1-22. Springer: Singapore.

Derfus, P. J., Maggitti, P. G., Grimm, C. M., & Smith, K. G. (2008), 'The Red Queen effect: Competitive actions and firm performance', *Academy of Management Journal*, **51**(1), 61–80. https://doi.org/10.5465/amj.2008.30708624.

Dexter, L. A. (2006), *Elite and Specialized Interviewing.* ECPR Press: Essex.

Dosi, G. (1982), 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change', *Research Policy*, **11**(3), 147–162.

Dosi, G. (1984), *Technical Change and Industrial Transformation: The Theory and an Application to the Semiconductor Industry.* Macmillan Press: London and Basingstoke.

Dosi, G. (1997), 'Opportunities, incentives and the collective patterns of technological change', *The Economic Journal*, **107**(444), 1530–1547. https://doi.org/10.1111/j.1468-0297.1997.tb00064.x.

Du, J., Leten, B., & Vanhaverbeke, W. (2014), 'Managing open innovation projects with science-based and market-based partners', *Research Policy*, **43**(5), 828–840. doi:10.1016/j.respol.2013.12.008.

Dutrénit, G. (2000), *Learning and Knowledge Management in the Firm: From Knowledge Accumulation to Strategic Capabilities.* Edward Elgar Publishing: Cheltenham, UK.

Dutrénit, G. (2004), 'Building technological capabilities in latecomer firms: a review essay', *Science, Technology and Society*, **9**(2), 209–241. https://doi.org/10.1177/097172180400900202.

Dutrénit, G. (2007), 'The transition from building-up innovative technological capabilities to leadership by latecomer firms', *Asian Journal of Technology Innovation*, **15**(2), 125–149. https://doi.org/10.1080/19761597.2007.9668640.

Dutrénit, G., Vera-Cruz, A. O., & Navarro, A. A. (2003), 'Diferencias en el perfil de acumulación de capacidades tecnológicas en tres empresas mexicanas', *El trimestre económico*, 109–165. https://www.jstor.org/stable/20856771.

Dutz, M. A., Kessides, I., O'Connell, S., & Willig, R. D. (2011), *Competition and Innovation-Driven Inclusive Growth*. The World Bank: Washington DC.

Eisenhardt, K. M., Graebner, M. E., & Sonenshein, S. (2016), 'Grand challenges and inductive methods: Rigor without rigor mortis', *Academy of Management Journal*, **59**(4). https://doi.org/10.5465/amj.2016.4004

Elias, N. (2001), *Society of Individuals*. The Continuum International Publishing Group: London.

Ellersgaard, C. H., Larsen, A. G., & Munk, M. D. (2013), 'A very economic elite: The case of the Danish top CEOs', *Sociology*, **47**(6), 1051–1071. https://doi.org/10.1177/0038038512454349.

Enkel, E., Gassmann, O., & Chesbrough, H. (2009), 'Open R&D and open innovation: exploring the phenomenon', *R&D Management*, **39**(4), 311–316. doi:10.1111/j.1467-9310.2009.00570.x

EPO (2020), *European Patent Register*. European Patent Office: Munich. Retrieved from https://www.epo.org/index.html.

Ernst, D., & Kim, L. (2002), 'Global production networks, knowledge diffusion, and local capability formation', *Research Policy*, **31**(8–9), 1417–1429. doi:10.1016/s0048-7333(02)00072-0.

Fagerberg, J. (2003), 'Schumpeter and the revival of evolutionary economics', *Journal of Evolutionary Economics*, **13**(2), 125–159. https://doi.org/10.1007/s00191-003-0144-1.

Fagerberg, J. & M. Godinho (2004), Innovation and catch-up. In: J. Fagerberg, D. Moweryand R. Nelson (eds), *Handbook of Innovation, 1-26.* Oxford University Press: Oxford.

Figueiredo, P. N. (2001), *Technological learning and competitive performance*. Edward Elgar Publishing: Cheltenham, UK.

Figueiredo, P. N. (2003), 'Learning, capability accumulation and firms differences: evidence from latecomer steel', *Industrial and Corporate Change*, **12**(3), 607–643. https://doi.org/10.1093/icc/12.3.607.

Figueiredo, P. N., & Piana, J. (2018), 'Innovative capability building and learning linkages in knowledge-intensive service SMEs in Brazil's mining industry', *Resources Policy*, **58**, 21–33. doi:10.1016/j.resourpol.2017.10.012.

Figueiredo, P. N., & Cohen, M. (2019), 'Explaining early entry into path-creation technological catch-up in the forestry and pulp industry: Evidence from Brazil', *Research Policy*, **48**(7), 1694–1713. doi:10.1016/j.respol.2019.03.017.

Flyvbjerg, B. (2006), 'Five misunderstandings about case-study research', *Qualitative Inquiry*, **12**(2), 219–245. https://doi.org/10.1177/1077800405284363.

Freeman, C. (1982), Innovation and long cycles of economic development. In: *Seminário Internacional. Universidade Estadual de Campinas, Campinas*, 1–13.

Freeman, C. (1987), *Technology Policy and Economic Performance: Lessons from Japan.* Frances Pinter: London.

Freeman, C. (1989), 'New technology and catching up', *The European Journal of Development Research*, ***1***(1), 85–99. doi: 10.1080/09578818908426503.

Freeman, L. (2004), 'The development of social network analysis', *A Study in the Sociology of Science*, *1*, 687. Empirical Press: Vancouver, BC.

Freeman, C. (2009), Schumpeter's Business Cycles and Techno-Economic Paradigms. In: Drechsler, W., Kattel, R., & Reinert, E. S. (Eds.). *Techno-economic paradigms: Essays in Honour of Carlota Perez*, 125-144. Anthem Press: London.

Freeman, C. and Perez, C. (1988), Structural crises of adjustment, business cycles and investment behavior, In: G. Dosi, C. Freeman, R Nelson, G. Silverberg and L. Soete (eds), *Technical Change and Economic Theory*, 38-66. Pinter: London.

Freeman, C., Louçã, F., Louçã, F., Louça̧, F., & Louçâ, F. (2001), *As time goes by: from the industrial revolutions to the information revolution.* Oxford University Press: Oxford.

FSFM (2018), *Certified Expert in Climate and Renewable Energy Finance. Unit 2: Climate Finance* (Unpublished Course Manuscript). Frankfurt School of Finance & Management: Frankfurt a. M.

Fu, X. (2015), *China's Path to Innovation.* Cambridge University Press: Cambridge, UK. https://doi.org/10.1017/CBO9781107110953.

Fu, X., Pietrobelli, C., & Soete, L. (2011), 'The role of foreign technology and indigenous innovation in the emerging economies: technological change and catching-up', *World Development*, **39**(7), 1204–1212. doi:10.1016/j.worlddev.2010.05.009.

Fu, X., Luo, J. D., & Boos, M. (Eds.). (2017), *Social Network Analysis: Interdisciplinary Approaches and Case Studies.* CRC Press: Boca Raton, FL.

Fu, X., Fu, X. M., Romero, C. C., & Pan, J. (2020), 'Exploring new opportunities through collaboration within and beyond sectoral systems of innovation in the fourth industrial revolution', *Industrial and Corporate Change.* https://doi.org/10.1093/icc/dtaa058.

Gassmann, O., & Enkel, E. (2006), 'Open innovation', *Zeitschrift Führung+ Organisation*, **75**(3), 132–138. https://www.alexandria.unisg.ch/publications/8567.

Gammeltoft, P., & Kokko, A. (2013), 'Introduction: Outward foreign direct investment from emerging economies and national development strategies: three regimes', *International Journal of Technological Learning, Innovation and Development*, **6**(1–2), 1–20. https://doi.org/10.1504/IJTLID.2013.051695.

Gebauer, H., Worch, H., & Truffer, B. (2012), 'Absorptive capacity, learning processes and combinative capabilities as determinants of strategic innovation', *European Management Journal*, ***30***(1), 57–73. https://doi.org/10.1016/j.emj.2011.10.004.

George, A. L., & Bennett, A. (2005), *Case Study and Theory Development in the Social Sciences.* MIT Press: Cambridge, MA.

Gerschenkron, A. (1962), *Economic Backwardness in Historical Perspective.* Harvard University Press: Cambridge, MA.

Gerybadze, A., & Stephan, M. (2003), *Growth strategies of multinational corporations: An empirical analysis of corporate growth in the 1983–1997 period.* Discussion Paper on International Management and Innovation 02–02, Stuttgart, Dezember 2003.

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

Granovetter, M. S. (1973), 'The strength of weak ties', *American Journal of Sociology*, **78**(6), 1360–1380.

Greco, M., Grimaldi, M., & Cricelli, L. (2016), 'An analysis of the open innovation effect on firm performance', *European Management Journal*, **34**(5), 501–516. https://doi.org/10.1016/j.emj.2016.02.008.

Greene, J. (2007), *Mixed Methods in Social Inquiry.* Wiley: San Francisco.

Greenspan, A. (2004), *Globalization and Innovation* (Conference on Bank Structure and Competition, May 6, 2004). Retrieved from https://www.federalreserve.gov/boarddocs/speeches/2004/200405062/default.htm.

Gross, N. (2018), 'The Structure of Causal Chains', *Sociological Theory*, **36**(4). https://doi.org/10.1177/0735275118811377.

Gui, Q., Liu, C., Du, D., & Duan, D. (2019), 'The changing geography of global science', *Environment and Planning A: Economy and Space,* **51**(8), 1615–1617. https://doi.org/10.1177/0308518X18816694.

Guo, Y., & Zheng, G. (2019), 'How do firms upgrade capabilities for systemic catch-up in the open innovation context? A multiple-case study of three leading home appliance companies in China', *Technological Forecasting and Social Change*, **144**, 36–48. https://doi.org/10.1016/j.techfore.2019.04.001.

GWEC. (2011), *Global Wind Report: Annual Market Update 2011.* Global Wind Energy Council: Brussels.

GWEC (2020), *Wind Turbine Sized Keep Growing As Industry Consolidation Continues.* Global Wind Energy Council. Retrieved from https://gwec.net/wind-turbine-sizes-keep-growing-as-industry-consolidation-continues/.

Haakonsson, S. (2020), 'Changing geography of clean tech', *Nature Energy*, **5**, 735-735. https://doi.org/10.1038/s41560-020-00690-9.

Haakonsson, S. J., & 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), 281–299. https://doi.org/10.1504/IJTM.2016.075892.

Haakonsson, S. J., & 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), 462–480. https://doi.org/10.1057/s41287-018-0128-5.

Haakonsson, S., Kirkegaard, J. K., & 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*, Vol. 28, Issue 11. https://doi.org/10.1080/09654313.2020.1712329.

Hain, D., R. Jurowetzki, P. Konda & L. Oehler (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,* dtaa021, https://doi.org/10.1093/icc/dtaa021.

Hansen, M. T. (1999), 'The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits', *Administrative Science Quarterly*, **44**(1), 82–111. https://doi.org/10.2307/2667032.

Hansen, U. E., & Lema, R. (2019), 'The co-evolution of learning mechanisms and technological capabilities: Lessons from energy technologies in emerging economies', *Technological Forecasting and Social Change*, **140**, 241–257. doi:10.1016/j.techfore.2018.12.007.

Hansen, U. E., Larsen, T. H., Bhasin, S., Burgers, R., & Larsen, H. (2020), 'Innovation capability building in subsidiaries of multinational companies in emerging economies: Insights from the wind turbine industry', *Journal of Cleaner Production*, **244**, 118746. https://doi.org/10.1016/j.jclepro.2019.118746.

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*. https://doi.org/10.1093/icc/dtaa008.

Hayashi, D., Huenteler, J., & Lewis, J. I. (2018), 'Gone with the wind: A learning curve analysis of China's wind power industry', *Energy Policy*, **120**, 38–51. https://doi.org/10.1016/j.enpol.2018.05.012.

He, D. X. (2016), 'Coping with climate change and China's wind energy sustainable development', *Advances in Climate Change Research*, **7**(1–2), 3–9. https://doi.org/10.1016/j.accre.2016.06.003.

Hine, C. (2008), Virtual ethnography: Modes, varieties, affordances. In: Fielding, N, Lee, R.M., Blank, G (Eds.) *The SAGE handbook of online research methods*. SAGE: Thousand Oaks, CA: 257–270.

Hirschberg, J., & Manning, C. D. (2015), 'Advances in natural language processing', *Science*, **349**(6245), 261–266. DOI: 10.1126/science.aaa8685.

Hirschman, A. O. (1981), *Essays in Trespassing: Economics to Politics and Beyond.* Cambridge University Press: Cambridge, UK.

Hobday M. (1995), *Innovation in East Asia: The Challenge to Japan.* Edward Elgar: Cheltenham.

Hobday, M., Rush, H., & Bessant, J. (2004), 'Approaching the innovation frontier in Korea: the transition phase to leadership', *Research Policy*, **33**(10), 1433–1457. https://doi.org/10.1016/j.respol.2004.05.005.

Horner, R. (2017), 'Beyond facilitator? State roles in global value chains and global production networks', *Geography Compass*, **11**(2), e12307.

Hu, R., Skea, J., & Hannon, M. J. (2018), 'Measuring the energy innovation process: An indicator framework and a case study of wind energy in China', *Technological Forecasting and Social Change*, **127,** 227–244. https://doi.org/10.1016/j.techfore.2017.09.025.

Huenteler, J., Ossenbrink, J., Schmidt, T. S., & Hoffmann, V. H. (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), 1195–1217. https://doi.org/10.1016/j.respol.2016.03.014.

IEA (2019), *Global Energy & CO2 Status Report 2019. The Latest Trends in Energy and Emission in 2018.* International Energy Agency: Paris. Retrieved from https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions.

IRENA (2012), *Renewable Energy Technologies: Cost Analysis Series. Wind Power.* International Renewable Energy Agency: Abu Dhabi. Retrieved from: https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-wind_power.pdf.

IRENA (2013), *30 Years of Policies for Wind Energy: Lessons from 12 Wind Energy Markets.* International Renewable Energy Agency: Abu Dhabi. Retrieved from: https://www.irena.org/publications/2013/Jan/30-Years-of-Policies-for-Wind-Energy-Lessons-from-12-Wind-Energy-Markets.

IRENA (2018), *Global Energy Transformation. A Roadmap to 2050.* International Renewable Energy Agency: Abu Dhabi. Retrieved from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf.

IRENA (2019a), *Renewable Energy Generation Cost in 2019.* International Renewable Energy Agency: Abu Dhabi. Retrieved from: https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019.

IRENA (2019b), *A New World. The Geopolitics of the energy Transformation.* International Renewable Energy Agency: Abu Dhabi. Retrieved from https://irena.org/publications/2019/Jan/A-New-World-The-Geopolitics-of-the-Energy-Transformation.

IRENA (2020), *Progress has been made but more needs to be done. International* Renewable Energy Agency: Abu Dhabi. Retrieved from https://www.irena.org/DigitalArticles/2019/Apr/How-To-Transform-Energy-System-And-Reduce-Carbon-Emissions.

Jackson, P. T. (2016), *The Conduct of Inquiry in International Relations: Philosophy of Science and its Implications for the Study of World Politics.* Routledge: London.

Jaffe, A. M. (2018), ‘Green giant: Renewable energy and Chinese power’, *Foreign Affairs*, **97**, 83.

Jimenez, J. R. P. (2019), ‘Mainstream and evolutionary views of technology, economic growth and catching up’, *Journal of Evolutionary Economics*, **29**(3), 823–852. https://doi.org/10.1007/s00191-019-00606-1.

Jung, M. & K. Lee (2010), ‘Sectoral systems of innovation and productivity catch-up: determinants of the productivity gap between Korean and Japanese firms’, *Industrial and Corporate Change*, **19**(4), 1037–1069. https://doi.org/10.1093/icc/dtp054.

Kang, H., & Song, J. (2017), ‘Innovation and recurring shifts in industrial leadership: Three phases of change and persistence in the camera industry’, *Research Policy*, **46**(2), 376–387. https://doi.org/10.1016/j.respol.2016.09.004.

Kaplinsky, R. (2011), ‘Schumacher meets Schumpeter: Appropriate technology below the radar’, *Research Policy*, **40**(2), 193–203. https://doi.org/10.1016/j.respol.2010.10.003

Katz, J., (1987), *Technology Generation in Latin American Manufacturing Industries.* Macmillan Press: Basingstoke.

Khan, A. A. (2014), ‘Qualitative research: A case for a multi-angle view to enhance ‘validity’’, *International Journal of Business and Management*, **9**(9), 29. http://dx.doi.org/10.5539/ijbm.v9n9p29.

Kim, L. (1997), *Imitation to Innovation: The Dynamics of Korea's Technological Learning.* Harvard Business Press: Boston, MA.

Kirkegaard, J. K. (2017), ‘Tackling Chinese Upgrading through Experimentalism and Pragmatism: The Case of China's Wind Turbine Industry’, *Journal of Current Chinese Affairs*, **46**(2), 7–39. https://doi.org/10.1177/186810261704600202.

Kondratieff N. D. (1925), ‘Long Economic Cycles’, *Voprosy konyunktury*, I, **1**, 1925.

Korsnes, Marius (2014), ‘Fragmentation, Centralisation and Policy Learning: An Example from China’s Wind Industry’, *Journal of Current Chinese Affairs*, **43**(3), 175–205. https://doi.org/10.1177/186810261404300308.

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., ... & Wells, P. (2019), ‘An agenda for sustainability transitions research: State of the art and future directions’, *Environmental Innovation and Societal Transitions*, **31**, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Lall, S. (1992), ‘Technological capabilities and industrialization’, *World Development*, **20**(2), 165–186. https://doi.org/10.1016/0305-750X(92)90097-F.

Latour, B. (2005), *Reassembling the Social—An Introduction to Actor Network Theory.* Oxford University Press: Oxford.

Laursen, K., & Salter, A. (2006), ‘Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms’, *Strategic Management Journal*, **27**(2), 131–150. doi:10.1002/smj.507.

Lazonick, W. (2010), ‘The Chandlerian corporation and the theory of innovative enterprise’, *Industrial and Corporate Change*, **19(**2), 317–349. https://doi.org/10.1093/icc/dtq005.

Lee, K. (2019), *The Art of Economic Catch-Up: Barriers, Detours and Leapfrogging in Innovation Systems.* Cambridge University Press: Cambridge.

Lee, K. and C. Lim (2001), 'Technological regimes, catching-up and leapfrogging: findings from the Korean Industries', *Research Policy*, **30**(3), 459–483. https://doi.org/10.1016/S0048-7333(00)00088-3.

Lee, A. S., & Baskerville, R. L. (2003), 'Generalizing generalizability in information systems research', *Information Systems Research*, **14**(3), 221–243. https://doi.org/10.1287/isre.14.3.221.16560.

Lee, K., & Malerba, F. (2017), 'Catch-up cycles and changes in industrial leadership: windows of opportunity and responses of firms and countries in the evolution of sectoral systems', *Research Policy*, **46**(2), 338–351. doi:10.1016/j.respol.2016.09.006.

Lema, R., Berger, A., Schmitz, H., & Song, H. (2011), *Competition and cooperation between Europe and China in the wind power sector* (IDS Working Papers, 377, 1–45). https://doi.org/10.1111/j.2040-0209.2011.00377_2.x.

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

Lema, R., Quadros, R., & Schmitz, H. (2015), 'Reorganising global value chains and building innovation capabilities in Brazil and India', *Research Policy*, **44**(7), 1376–1386. https://doi.org/10.1504/IJTLID.2009.026816.

Lema, R., X. Fu & R. Rabellotti (2021), 'Green Windows of Opportunity: Latecomer Development in the Age of Transformation towards Sustainability', *Industrial and Corporate Change*, **29**(5), doi: 10.1093/icc/dtaa044.

Lewis, J. I. (2007), 'Technology acquisition and innovation in the developing world: Wind turbine development in China and India', *Studies in Comparative International Development*, **42**(3–4), 208–232.

Lewis, J. I. (2011), 'Building a national wind turbine industry: experiences from China, India and South Korea', *International Journal of Technology and Globalisation*, ***5***(3–4), 281–305. https://doi.org/10.1504/IJTG.2011.039768.

Lewis, J. I. (2013), *Green Innovation in China: China's Wind Power Industry and the Global* Transition to a Low-Carbon Economy. Columbia University Press: New York.

Lichtenthaler, U. (2011), 'Open innovation: Past research, current debates, and future directions', *Academy of Management Perspectives*, **25**(1), 75–93. doi:10.5465/amp.25.1.75.

Lin, N. (2001), Guanxi: A Conceptual Analysis, In: A. So, N. Lin, and D. Poston (eds.), *The Chinese Triangle of Mainland China, Taiwan, and Hong Kong: Comparative Institutional Analysis*. Greenwood Press: London: 153–166.

Lim, K. (2004), 'The relationship between research and innovation in the semiconductor and pharmaceutical industries (1981–1997)', *Research policy*, **33**(2), 287–321. https://doi.org/10.1016/j.respol.2003.08.001.

Lindkvist, L. (2005), 'Knowledge communities and knowledge collectivities: A typology of knowledge work in groups', *Journal of Management studies*, **42**(6), 1189–1210. https://doi.org/10.1111/j.1467-6486.2005.00538.x.

List, F. (1841), *The National System of Political Economy* [English translation, 1904]. Longmans: London.

Lønsmann, D. (2016), Negotiating Positionality in Ethnographic Investigations of Workplace Settings: Student, Consultant or Confidante? In: Alessi, G. M., Jacobs, G, *The Ins and Outs of Business and Professional Discourse Research: Reflections on Interacting with the Workplace.* Palgrave Macmillan: Basingstoke.

Lucas, L., & Waters, R. (2018), *China and US compete to dominate big data.* Financial Times, Retrieved from: https://www.ft.com/content/e33a6994-447e-11e8-93cf-67ac3a6482fd.

Malerba, F. (2002), 'Sectoral systems of innovation and production', *Research Policy*, **31**(2), 247–264.

Malerba, F. (2005), 'Sectoral systems of innovation: a framework for linking innovation to the knowledge base, structure and dynamics of sectors', *Economics of Innovation and New Technology*, **14**(1–2), 63–82.

Malerba, F., & Orsenigo, L. (1995), 'Schumpeterian patterns of innovation', *Cambridge Journal of Economics*, **19**(1), 47–65. https://doi.org/10.1093/oxfordjournals.cje.a035308.

Malerba, F. & Orsenigo L. (2000), 'Knowledge, innovative activities and industrial evolution', *Industrial and Corporate Change,* **9**(2), 289–314. https://doi.org/10.1093/icc/9.2.289.

Malerba, F. & Nelson R. (2011), 'Learning and catching up in different sectoral systems: evidence from six industries', *Industrial and Corporate Change*, **20**(6), 1645–1675. https://doi.org/10.1093/icc/dtr062.

Mallapaty, S. (2020), 'How China could be carbon neutral by mid-century', *Nature*, **586** (7830), 482–483. https://doi.org/10.1038/d41586-020-02927-9.

Marshall, C., & Rossman, G. B. (2016), *Designing Qualitative Research.* SAGE Publications: Newbury Park, CA.

Marx, K. (1867), *Das Kapital Bd. 1: Der Produktionsprozess des Kapitals.* Dietz Verlag: Berlin.

Mathews, J. A. (2002), 'Competitive advantages of the latecomer firm: A resource-based account of industrial catch-up strategies', *Asia Pacific Journal of Management*, **19**(4), 467–488. https://doi.org/10.1023/A:1020586223665.

Mathews, J. A. (2006), 'Dragon multinationals: New players in 21 st century globalization', *Asia Pacific Journal of Management*, **23**(1), 5–27. doi:10.1007/s10490-006-6113-0.

Mathews, J. A. (2017), 'Dragon multinationals powered by linkage, leverage and learning: A review and development', *Asia Pacific Journal of Management*, **34**(4), 769–775. doi:10.1007/s10490-017-9543-y.

Mathews, J. A. (2020), 'Schumpeterian economic dynamics of greening: propagation of green eco-platforms', *Journal of Evolutionary Economics*, 1–20. https://doi.org/10.1007/s00191-020-00669-5.

Mathews, J. A., & Cho, D. S. (1999), 'Combinative capabilities and organizational learning in latecomer firms: The case of the Korean semiconductor industry', *Journal of World Business*, **34**(2), 139–156. https://doi.org/10.1016/S1090-9516(99)00013-9.

Mazzoleni, R., & Nelson, R. R. (2007), 'Public research institutions and economic catch-up', *Research Policy*, **36**(10), 1512–1528. https://doi.org/10.1016/j.respol.2007.06.007.

Mazzucato, M., & Perez, C. (2014), Innovation as Growth Policy. In: *The Triple Challenge for Europe: Economic Development, Climate Change, and Governance*. Oxford University Press: Oxford: 229–64.

Meijer, P. C., Verloop, N., & Beijaard, D. (2002), ‘Multi-method triangulation in a qualitative study on teachers' practical knowledge: An attempt to increase internal validity’, *Quality and Quantity*, **36**(2), 145–167. https://doi.org/10.1023/A:1014984232147.

Miles, M. B., & Huberman, M. (1994), *Qualitative Data Analysis: An expanded Sourcebook* (2nd ed.). SAGE: Thousand Oaks, CA.

Mina, A., Bascavusoglu-Moreau, E., & Hughes, A. (2014), ‘Open service innovation and the firm's search for external knowledge’, *Research Policy*, **43**(5), 853–866. doi:10.5465/ambpp.2012.1576.

Mingers, J. (2006), Philosophical Foundations: Critical Realism. In: *Realising Systems Thinking: Knowledge and Action in Management Science. Contemporary Systems Thinking.* Springer: Boston, MA. https://doi.org/10.1007/0-387-29841-X_2.

Morrison, A., Pietrobelli, C., & Rabellotti, R. (2008), ‘Global value chains and technological capabilities: a framework to study learning and innovation in developing countries’, *Oxford Development Studies*, **36**(1), 39–58. https://doi.org/10.1080/13600810701848144.

Morrison, A., & Rabellotti, R. (2017), ‘Gradual catch up and enduring leadership in the global wine industry’, *Research Policy*, **46**(2), 417–430. https://doi.org/10.1016/j.respol.2016.09.007.

Motohashi, K., & Zhu, C. (2020), *Technological Competitiveness of China's Internet Platforms: Comparison of Google and Baidu Using Patent Text Information* (Discussion Paper Series 20-E-045). Research Institute of Economy, Trade and Industry (RIETI): Tokyo.

Murdock, H. E., Gibb, D., André, T., Appavou, F., Brown, A., Epp, B., ... & Sawin, J. L. (2019), *Renewables 2019 Global Status Report.* Retrieved from: https://www.ren21.net.

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

Nambisan, S., Wright, M., & Feldman, M. (2019), ‘The digital transformation of innovation and entrepreneurship: Progress, challenges and key themes’, *Research Policy*, **48**(8), 103773. https://doi.org/10.1016/j.respol.2019.03.018.

Narula, R. & Zanfei, A. (2003), *Globalisation of Innovation The Role of Multinational Enterprises* (DRUID Working Papers, No 03–15). Copenhagen Business School: Frederiksberg.

Nelson, R. R. (1994), ‘The co-evolution of technology, industrial structure, and supporting institutions’, *Industrial and Corporate Change*, **3**(1), 47–63. https://doi.org/10.1093/icc/3.1.47.

Nelson, R. R. (2008), ‘What enables rapid economic progress: What are the needed institutions?’, *Research Policy*, **37**(1), 1–11. https://doi.org/10.1016/j.respol.2007.10.008.

Nelson, R. R. (2020), ‘A perspective on the evolution of evolutionary economics’, *Industrial and Corporate Change*, dtaa045, https://doi.org/10.1093/icc/dtaa045.

Nelson, R. R., & Winter, S. G. (1977), In search of a useful theory of innovation. In: *Innovation, Economic Change and Technology Policies*. Birkhäuser: Basel: 215–245. https://doi.org/10.1007/978-3-0348-5867-0_14.

Nelson, R. R. & S. Winter (1982), *An Evolutionary Theory of Economic Change.* Harvard University Press: Cambridge, MA.

Nelson, R. R., & Winter, S. G. (2002), 'Evolutionary theorizing in economics', *Journal of Economic Perspectives*, **16**(2), 23–46. doi: 10.1257/0895330027247.

Neuman, W. L. (2016), *Understanding Research.* Pearson: Boston.

Newman, I., Benz, C. R., & Ridenour, C. S. (1998), *Qualitative-quantitative research methodology: Exploring the interactive continuum.* SIU Press: Carbondale, Illinois.

Ngai, C., Raimonde, O., Longley, A. (2020, April 20), Oil Plunged Below Zero for First Time in Unprecedented Wipeout, *Bloomberg,* Retrieved from: https://www.bloomberg.com/news/articles/2020-04-19/oil-drops-to-18-year-low-on-global-demand-crunch-storage-woes.

Nobel Media (1987), *Press release.* 17 Dec 2020. Retrieved from: https://www.nobelprize.org/prizes/economic-sciences/1987/press-release.

Noy, C. (2008), 'Sampling knowledge: The hermeneutics of snowball sampling in qualitative research', *International Journal of Social Research Methodology*, **11**(4), 327–344. https://doi.org/10.1080/13645570701401305.

OECD (2015), *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development.* Organization for Economic Co-operation and Development: Paris. Retrieved from https://www.oecd.org/sti/frascati-manual-2015-9789264239012-en.htm.

OECD (2017), *The Next Production Revolution. Implications for Government and Business.* Organization for Economic Co-operation and Development Paris. Retrieved from https://www.oecd.org/governance/the-next-production-revolution-9789264271036-en.htm

OECD (2018), *Oslo Manual 2018: The Measurement of Scientific, Technological and Innovation Activities. Guidelines for Collecting, Reporting and Using Data on Innovation*, 4th Edition. Organization for Economic Co-operation and Development: Paris. Retrieved from https://www.oecd.org/science/oslo-manual-2018-9789264304604-en.htm.

OECD (2020), *Results in development cooperation: What are results?* Organization for Economic Co-operation and Development: Paris. Retrieved from https://www.oecd.org/dac/results-development/what-are-results.htm.

Olsen, W. (2007), 'Critical realist explorations in methodology', *Methodological Innovations Online*, **2**(2), 1–5. doi: 10.4256/mio.2007.0007.

Overland, I. (2019), 'The geopolitics of renewable energy: Debunking four emerging myths', *Energy Research & Social Science*, **49**, 36–40. https://doi.org/10.1016/j.erss.2018.10.018.

Owens, F. E. B. N. (2019), *China's Wind Power Surge. The Wind Power Story: A Century of Innovation that Reshaped the Global Energy Landscape.* IEEE Press: Piscataway, NJ.

Paavola, S., Lipponen, L., & Hakkarainen, K. (2004), 'Models of innovative knowledge communities and three metaphors of learning', *Review of Educational Research*, **74**(4), 557–576. https://doi.org/10.3102/00346543074004557.

Pack, H., & Nelson, R. R. (1999), *The Asian Miracle and Modern Growth Theory.* The World Bank: Washington DC. https://doi.org/10.1596/1813-9450-1881.

Parrilli, M. D., Nadvi, K., & Yeung, H. W. C. (2013), 'Local and regional development in global value chains, production networks and innovation networks: A comparative review and the challenges for future research', *European Planning Studies*, **21**(7), 967–988. https://doi.org/10.1080/09654313.2013.733849.

Patomäki, H., & Wight, C. (2000), 'After postpositivism? The promises of critical realism', *International Studies Quarterly*, **44**(2), 213–237. doi: 10.1111/0020-8833.00156.

Patton, M. Q. (2015), *Qualitative Research & Evaluation Methods* (4th ed.). SAGE: Thousand Oaks, CA.

Pavitt, K. (2005), Innovation Processes, In: J. Fagerberg, D. C. Mowery and R. R. Nelson (eds) *The Oxford Handbook of Innovation,* Oxford University Press: Oxford: 86–114.

Peng, X., Zheng, S., Collinson, S., Wu, X., & Wu, D. (2020), 'Sustained upgrading of technological capability through ambidextrous learning for latecomer firms', *Asian Journal of Technology Innovation*, 1–22. https://doi.org/10.1080/19761597.2020.1810084.

Perez, C. (1983), 'Structural change and assimilation of new technologies in the economic and social systems', *Futures*, **15**(5), 357–375. https://doi.org/10.1016/0016-3287(83)90050-2.

Perez, C. (1985), 'Microelectronics, long waves and world structural change: New perspectives for developing countries', *World Development*, **13**(3), 441–463. https://doi.org/10.1016/0305-750X(85)90140-8.

Perez, C. (2003), *Technological Revolutions and Financial Capital.* Edward Elgar Publishing: Northampton.

Perez, C. (2010), 'Technological revolutions and techno-economic paradigms', *Cambridge Journal of Economics*, **34**(1), 185–202. https://doi.org/10.1093/cje/bep051.

Perez, C. (2016), 'Capitalism, Technology and a Green Golden Global Age: The Role of History in Helping to Shape the Future', *Political Quarterly,* **86**(2016), 191–217. https://doi.org/10.1111/1467-923X.12240.

Perez, C. & Soete L. (1988), Catching up in technology: entry barriers and windows of opportunity, In: G.Dosi et al. (eds.) *Technical Change and Economic Theory*, Francis Pinter: London: 458–479.

Perkmann, M., & Walsh, K. (2007), 'University–industry relationships and open innovation: Towards a research agenda', *International Journal of Management Reviews*, **9**(4), 259–280. https://doi.org/10.1111/j.1468-2370.2007.00225.x.

Pizer, W. A., & Popp, D. (2008), 'Endogenizing technological change: Matching empirical evidence to modeling needs', *Energy Economics*, **30**(6), 2754–2770. https://doi.org/10.1016/j.eneco.2008.02.006.

Popa, S., Soto-Acosta, P., & Martinez-Conesa, I. (2017), 'Antecedents, moderators, and outcomes of innovation climate and open innovation: An empirical study in SMEs', *Technological Forecasting and Social Change*, *118*, 134–142. https://doi.org/10.1016/j.techfore.2017.02.014.

Posner, M. V. (1961), 'International trade and technical change', *Oxford Economic Papers*, **13**(3), 323–341. https://www.jstor.org/stable/2662034

Powell, W.W. & Grodal, S. (2005), Networks of Innovators, In: Fagerberg, J., Mowery, D.C. and Nelson, R.R. (Eds). *The Oxford Handbook of Innovation*, Oxford University Press: Oxford/New York: 56–85.

Prud'homme, D., & von Zedtwitz, M. (2019), 'Managing "forced" technology transfer in emerging markets: The case of China', *Journal of International Management*, **25**(3), 100670. https://doi.org/10.1016/j.intman.2019.04.003.

Quadros, R., & Consoni, F. (2009), 'Innovation capabilities in the Brazilian automobile industry: a study of vehicle assemblers' technological strategies and policy recommendations', *International Journal of Technological Learning, Innovation and Development*, **2**(1–2), 53–75. https://doi.org/10.1504/IJTLID.2009.021956.

Quah, D. (2011), 'The global economy's shifting centre of gravity', *Global Policy*, **2**(1), 3–9. https://doi.org/10.1111/j.1758-5899.2010.00066.x.

Quitzow, R., Huenteler, J., & Asmussen, H. (2017), 'Development Trajectories in China's Wind and Solar Energy Industries: How Technology-Related Differences Shape the Dynamics of Industry Localization and Catching Up', *Journal of Cleaner Production*, **158**, 122–133. https://doi.org/10.1016/j.jclepro.2017.04.130.

Reichertz, J. (2004), Abduction, deduction and induction in qualitative research. In: Dans U. Flick, E. von Kardorff, & I. Steinke (Eds), *A Companion to Qualitative Research*. SAGE: London: 159–164.

Ritchie, H., & Roser, M. (2017), *CO_2 and Greenhouse Gas Emissions*. Published online at OurWorldInData.org, Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

Rock, M. T. & Toman M. (2015), *China's Technological Catch-Up Strategy: Industrial Development, Energy Efficiency, and CO2 Emissions*. Oxford University Press: New York.

Rodrik, D. (2004), *Industrial Policy for the Twenty-First Century*. Harvard University: Cambridge, MA.

Rosiello, A., & Maleki, A. (2021), 'A dynamic multi-sector analysis of technological catch-up: The impact of technology cycle times, knowledge base complexity and variety', *Research Policy*, **50**(3), 104194. https://doi.org/10.1016/j.respol.2020.104194.

Ru, P., Zhi, Q., Zhang, F., Zhong, X., Li, J., & Su, J. (2012), 'Behind the development of technology: The transition of innovation modes in China's wind turbine manufacturing industry', *Energy Policy*, **43**, 58–69. https://doi.org/10.1016/j.enpol.2011.12.025.

Sahal, D. (1985), 'Technological guideposts and innovation avenues', *Research Policy*, **14**(2), 61–82. https://doi.org/10.1016/0048-7333(85)90015-0.

Saunders, M. N., & Lewis, P. (2012), *Doing Research in Business & Management: An Essential Guide to Planning Your Project*. Pearson: Boston, MA.

Saunders, M., Lewis, P., & Thornhill, A. (2016), *Research Methods for Business Students (7th ed.)*. Pearson Education: Boston, MA.

Sayer, A. (2000), Key features of critical realism in practice: a brief outline. In: *Realism and Social Science*. SAGE Publications: Thousand Oaks, CA. https://doi.org/10.4135/9781446218730.

Schmidt, T. S., & Huenteler, J. (2016), ‘Anticipating industry localization effects of clean technology deployment policies in developing countries’, *Global Environmental Change*, **38**, 8–20. https://doi.org/10.1016/j.gloenvcha.2016.02.005.

Schmitz, H. (2007), ‘Transitions and trajectories in the build-up of innovation capabilities: Insights from the global value chain approach’, *Asian Journal of Technology Innovation*, **15**(2), 151–160. https://doi.org/10.1080/19761597.2007.9668641.

Schmitz, H., & Strambach, S. (2009), ‘The organisational decomposition of innovation and global distribution of innovative activities: Insights and research agenda’, *International Journal of Technological Learning, Innovation and Development*, **2**(4), 231. doi:10.1504/IJTLID.2009.026816.

Schmitz, H. & Altenburg T. (2016), ‘Innovation paths in Europe and Asia: divergence or convergence?’, *Science and Public Policy*, **43**(4), 454–463.

Scholten, D., Bazilian, M., Overland, I., & Westphal, K. (2020), ‘The geopolitics of renewables: New board, new game’, *Energy Policy*, **138**, 111059. https://doi.org/10.1016/j.enpol.2019.111059.

Schot, J., & Steinmueller, W. E. (2018), ‘Three frames for innovation policy: R&D, systems of innovation and transformative change’, *Research Policy*, **47**(9), 1554–1567. https://doi.org/10.1016/j.respol.2018.08.011.

Schumpeter J. A. (1939), *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process*, 1st edition. McGraw-Hill Book Company: New York and London.

Schumpeter, J. A. (1954), *History of Economic Analysis.* Oxford University Press: New York.

Schreier, M., Stamann, C., Janssen, M., Dahl, T., & Whittal, A. (2019), Qualitative Content Analysis: Conceptualizations and Challenges in Research Practice—Introduction to the FQS Special Issue ‘Qualitative Content Analysis I’, In: *Forum Qualitative Sozialforschung/Forum: Qualitative Social Research* **20**(3).

Scott, J. (2011), ‘Social network analysis: developments, advances, and prospects’, *Social Network Analysis and Mining*, **1**(1), 21–26. doi:10.1007/s13278-010-0012-6.

Scott-Kemmis, D. and M. Bell (1985), *Technological Capacity and Technical Change: Case Studies. Report on a study of technology transfer in the manufacturing industry in Thailand* (Working paper, Science Policy Research Unit). University of Sussex: Brighton.

Seawright, J., & Gerring, J. (2008), ‘Case selection techniques in case study research: A menu of qualitative and quantitative options’, *Political Research Quarterly*, **61**(2), 294–308. https://doi.org/10.1177/1065912907313077.

Shin, J. S. (2017), ‘Dynamic catch-up strategy, capability expansion and changing windows of opportunity in the memory industry’, *Research Policy*, **46**(2), 404–416. https://doi.org/10.1016/j.respol.2016.09.009.

Sianaki, O. A., Yousefi, A., Tabesh, A. R., & Mahdavi, M. (2018), *Internet of everything and machine learning applications: issues and challenges* (32nd International Conference on Advanced Information Networking and Applications Workshops, WAINA: 704–708. doi:10.1109/WAINA.2018.00171.

Sil, R., & Katzenstein, P. J. (2010), *Beyond Paradigms: Analytic Eclecticism in the Study of World Politics*. Macmillan International Higher Education: London.

Silva, P. C., & Klagge, B. (2013), 'The evolution of the wind industry and the rise of Chinese firms: From industrial policies to global innovation networks', *European Planning Studies*, **21**(9), 1341–1356. https://doi.org/10.1080/09654313.2012.756203.

Simmie, J., & Strambach, S. (2006), 'The contribution of KIBS to innovation in cities: an evolutionary and institutional perspective', *Journal of Knowledge Management*, **10**(5), 26–40. https://doi.org/10.1108/13673270610691152.

Slepniov, D., Lassen, A. H., Haakonsson, S. J., & McKelvey, M. (2015), Understanding Innovation Spaces Through Emerging Multinational Enterprises in China: An Explorative Case Study of a Chinese Wind Turbine Manufacturer. In: *Innovation Spaces in Asia*. Edward Elgar Publishing: Cheltenham, UK.

Solow, R. M. (1956), 'A contribution to the theory of economic growth', *The Quarterly Journal of Economics*, **70**(1), 65–94. https://doi.org/10.2307/1884513.

Stake, R. E. (1995), *The Art of Case Study Research.* SAGE: Thousand Oaks, CA.

Steen, M., & Weaver, T. (2017), 'Incumbents' diversification and cross-sectorial energy industry dynamics', *Research Policy*, **46**(6), 1071–1086. https://doi.org/10.1016/j.respol.2017.04.001.

Stephan, A., Schmidt, T. S., Bening, C. R., & Hoffmann, V. H. (2017), 'The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan', *Research Policy*, **46**(4), 709–723. doi:10.1016/j.respol.2017.01.009.

Sudhahar, S., Veltri, G. A., & Cristianini, N. (2015), 'Automated analysis of the US presidential elections using Big Data and network analysis', *Big Data & Society*, **2**(1), 2053951715572916. https://doi.org/10.1177/2053951715572916.

Sun, S. L. &. Yang, X. (2013), Transformative Capacity and Absorptive Capacity. In: P. P. Li (ed.), *Disruptive Innovation in Chinese and Indian Business: The Strategic Implications for Local and Global Incumbents*. Routledge: New York.

Suri, H. (2011), 'Purposeful sampling in qualitative research synthesis', *Qualitative Research Journal*, **11**(2), 63. doi:10.3316/qrj1102063.

Sutton, J. (2012), *Competing in Capabilities: The Globalization Process.* Oxford University Press: Oxford. doi:10.1093/acprof:oso/9780199274536.001.0001.

Tan, H., & Mathews, J. A. (2015), 'Accelerated internationalization and resource leverage strategizing: The case of Chinese wind turbine manufacturers', *Journal of World Business*, **50**(3), 417–427. https://doi.org/10.1016/j.jwb.2014.05.005.

Tashakkori, A., & Creswell, J. W. (2007), 'Exploring the nature of research questions in mixed methods research', *Journal of Mixed Methods Research*, **1**(3), 207–2011. doi:10.1177/1558689807302814.

The Economist (2020, September 19), Power in the 21st century: efforts to rein in climate change will up-end the geopolitics of energy. *The Economist*: 9.

Torrisi, S., Gambardella A., Giuri P., Harhoff D., Hoisl K. & Mariani M. (2016), 'Used, blocking and sleeping patents: empirical evidence from a large-scale inventor survey', *Research Policy*, **45**(7), 1374–1385. https://doi.org/10.1016/j.respol.2016.03.021.

Tsekouras, G. (2006), 'Gaining competitive advantage through knowledge integration in a European industrialising economy', *International Journal of Technology Management*, **36**(1–3), 126–147. https://doi.org/10.1504/IJTM.2006.009965.

Tushman, M. L., & Anderson, P. (1986), 'Technological discontinuities and organizational environments', *Administrative Science Quarterly*, 439–465. https://doi.org/10.2307/2392832.

Ufuah, A. N. & J. Utterback (1997), 'Responding to structural industry changes: a technological evolution perspective', *Industrial and Corporate Change*, **6**(1), 183–202. https://doi.org/10.1093/icc/6.1.183.

UNCTAD (2019), *Digital Economy Report 2019: Value Creation and Capture; Implications for Developing Countries.* United Nations Conference on Trade and Development: Geneva. Retrieved from: https://unctad.org/en/pages/PublicationWebflyer.aspx?publicationid=2466.

UNCTAD (2019), *The Impact of Rapid Technological change on Sustainable Development.* United Nations Conference on Trade and Development: Geneva. Retrieved from: https://unctad.org/webflyer/impact-rapid-technological-change-sustainable-development.

Van Ark, B. (2001), *The renewal of the old economy: An international comparative perspective.* Organization for Economic Cooperation and Development: Paris. Retrieved from https://www.stat.go.jp/english/info/meetings/iaos/pdf/ark.pdf.

Van Dijk, M. (2000), 'Technological regime and industrial dynamics: the evidence from Dutch manufacturing', *Industrial and Corporate Change*, **9**(2), 173–194. https://doi.org/10.1093/icc/9.2.173.

Van Mossel, A., van Rijnsoever, F. J., & Hekkert, M. P. (2018), 'Navigators through the storm: A review of organization theories and the behavior of incumbent firms during transitions', *Environmental Innovation and Societal Transitions*, **26**, 44–63. https://doi.org/10.1016/j.eist.2017.07.001.

Vanhaverbeke, W. (2017), *Managing Open Innovation in SMEs.* Cambridge University Press: Cambridge.

Veblen, T. (1915), 'The opportunity of Japan', *J. Race Dev.*, **6**, 23.

Von Zedtwitz, M., & Gassmann, O. (2016), Global Corporate R&D to and from Emerging Economies. In: *The Global Innovation Index 2016, 125–131.* Geneva, Switzerland: Cornell University, INSEAD, and the World Intellectual Property Organization.

Wang, Z., H. Qin & J. I. Lewis (2012), 'China's wind power industry: policy support, technological achievements, and emerging challenges', *Energy Policy*, **51**, 80–88. https://doi.org/10.1016/j.enpol.2012.06.067.

Wang, Q., Li, S., & Pisarenko, Z. (2020), 'Modeling carbon emission trajectory of China, US and India', *Journal of Cleaner Production*, **258**, 120723. https://doi.org/10.1016/j.jclepro.2020.120723.

Weaver, G. R., & Gioia, D. A. (1994), 'Paradigms lost: incommensurability vs structurationist inquiry', *Organization Studies*, **15**(4), 565–589. doi: 10.1177/017084069401500404.

West, J., & Bogers, M. (2014), 'Leveraging external sources of innovation: a review of research on open innovation', *Journal of Product Innovation Management*, **31**(4), 814–831. https://doi.org/10.1111/jpim.12125.

Westphal, L., L. Kim & C. Dahlman (1985), Reflections on the Republic of Korea's Acquisition of Technological Capability', In N. Rosenberg and C. Frischtak, (eds.), *International Technology.* Praeger Publishers: New York: 167–221.

Whittaker, D. H., Zhu, T., Sturgeon, T., Tsai, M. H., & Okita, T. (2010), 'Compressed development', *Studies in Comparative International Development*, **45**(4), 439–467. doi:10.1007/s12116-010-9074-8.

Woodside, A. G., & Wilson, E. J. (2003), 'Case study research methods for theory building', *Journal of Business & Industrial Marketing*, Vol. 18, No. 6/7. doi:10.1108/08858620310491274

Xi, J. (2020, September, 22). *Statement by H.E. Xi Jinping President of the People's Republic of China.* At the General Debate of the 75th Session of The United Nations General Assembly. Retrieved from https://www.fmprc.gov.cn/mfa_eng/zxxx_662805/t1817098.shtml.

Yin, R. K. (2009), *Case study research: Design and methods*. SAGE Publications: London.

Yin, R. K. (2013), 'Validity and generalization in future case study evaluations', *Evaluation*, **19**(3), 321–332. https://doi.org/10.1177/1356389013497081.

Yoon, B. & Park Y. (2004), 'A text-mining-based patent network: analytical tool for high-technology trend', *The Journal of High Technology Management Research*, **15**(1), 37–50. https://doi.org/10.1016/j.hitech.2003.09.003.

Yousefi Nooraie, R., Sale, J. E., Marin, A., & Ross, L. E. (2020), 'Social network analysis: An example of fusion between quantitative and qualitative methods', *Journal of Mixed Methods Research*, **14**(1), 110–124. https://doi.org/10.1177/1558689818804060.

Zander, I. (2002), 'The formation of international innovation networks in the multinational corporation: an evolutionary perspective', *Industrial and Corporate Change*, **11**(2), 327–353. https://doi.org/10.1093/icc/11.2.327.

Zhou, Y., X. Li, R. Lema & F. Urban (2016), 'Comparing the knowledge bases of wind turbine Firms in Asia and Europe: patent trajectories, networks, and globalisation', *Science and Public Policy*, **43**(4), 476–491. https://doi.org/10.1093/scipol/scv055.

Zhou, Y., Pan, M., & Urban, F. (2018), 'Comparing the international knowledge flow of China's wind and solar photovoltaic (PV) industries: Patent analysis and implications for sustainable development', *Sustainability*, **10**(6), 1883. https://doi.org/10.3390/su10061883.

Zhu, M., Qi, Y., Belis, D., Lu, J., & Kerremans, B. (2019), 'The China wind paradox: The role of state-owned enterprises in wind power investment versus wind curtailment', *Energy Policy*, **127**, 200–212. https://doi.org/10.1016/j.enpol.2018.10.059.

Appendix

A1. Overview of five successive technological revolutions (1770s–2000s)

No.	Year	Name	Industrial leader	New technologies	Key event
1	1771	The Industrial Revolution	GB	Mechanized cotton; wrought iron; machinery	Arkwright's mill opens (Cromford, UK)
2	1829	Age of Steam and Railways	GB (spreading to US)	Steam engines; iron and coal mining; railway construction	Rocket steam engine (Liverpool-Manchester, UK)
3	1875	Age of Steel, Electricity, and Heavy Engineering	US and DE (forging ahead of GB)	Steel; heavy chemistry and civil engineering; electrical equipment; canned and bottled food	Carnegie Bessemer steel plant opens (Pittsburg, US)
4	1908	Age of Oil, the Automobile, and Mass Production	US and DE (spreading to rest of Europe)	Mass-produced automobiles; petrochemicals; home electrical appliances	First Ford Model-T (Detroit)
5	1971	Age of Information and Telecommunications	US (spreading to Europe and Asia)	Computers; software; microelectronics; telecommunications	Intel microprocessor launched (Santa Clara, US)

Source: Adapted from Perez (2003)

A2. Perspectives on latecomer firm learning and upgrading

Concept	Description	Examples of knowledge sources	References
Technology transfer	Learning through knowledge flows between OECD and emerging countries	- Conventional (Trade, FDI, licensing, joint venture) - Unconventional (R&D partnerships, R&D hubs, M&A of foreign firms) - Knowledge-intensive business services (KIBS)	Lema and Lema (2012), Haakonsson et al. (2020), Gammeltoft and Kokko (2013)
Learning linkages	Learning through linkages across the value chain between stakeholders within and across natural-resource related industries	- Backward linkages (upstream) - Forward linkages (downstream)	Hirschman (1981), Figueiredo and Piana (2018)
Knowledge/learning networks & innovation systems	Learning within innovation systems/spaces comprised of building blocks, i.e., actors, networks, technologies, and institutions	- Actors: firms, universities, scientific and technological institutes - Learning network types: passive, active, innovation, strategic innovation - System boundaries: geographies, sectors, technologies	Malerba (2002, 2005), Dantas and Bell (2009), Slepniov et al. (2015), Lewis (2013)
Linkage, leverage, learning	Learning understood as overseas capability seeking through asset augmentation (rather than asset exploitation)	- Joint ventures, supply chain contracts, technology licensing, market-entry partnerships	Mathews (2006, 2017)
Learning mechanisms	Learning through the purposive accumulation of external and internal knowledge to create innovation capabilities	- Hiring expertise, training/R&D with suppliers, training/R&D with local institutions, learning from users, codified knowledge acquisition, internal knowledge sharing	Dutrénit (2000, 2004, 2007), Figueiredo (2003), Hansen and Lema (2019)
Knowledge spillovers	Learning understood as domestic industry development through inward FDI to broader domestic industry development	- Labor mobility, supplier relationships, demonstration effects, university – industry collaboration	Hansen and Hansen (2020), Fu et al. (2011), Blomström and Kokko (2002)
Global production networks	Learning through global outsourcing networks, i.e., in lower-cost locations	- Dispersed supply and customer bases, e.g., from multinational enterprises to lower-tier network suppliers	Ernst and Kim (2002), Horner (2017)

Source: Author's compilation.

A3. Overview of interviewed organizations per category

Interview partner	# interviews
Industry Associations	**6**
GWEC - Global Wind Energy Council	
WWEA - World Wind Energy Association	
CWEA - Chinese Wind Energy Association	
IEA – International Energy Agency	
Wind Turbine Manufacturers	**39**
Goldwind	
Envision Energy	
Ming Yang	
CSIC Haizhuang	
Suzlon	
Sinovel	
Vestas	
Siemens Gamesa	
General Electric	
Senvion	
Nordex	
AMSC Windtec	
Component Suppliers	**4**
Titan Wind Energy	
Sinoma Blades	
ABB	
LM Wind Power	
Licensing, Engineering, Design firms	**6**
Aerodyn	
Vensys	
Norwin	
WINDnovation	
Project Development & Utilities	**3**
Longyuan	
Ørsted	
Power China	
Consulting Firms	**7**
FTI Consulting	
Aventage	
McKinsey & Co.	
Mott MacDonald	
PwC	
CECL - Consolidated Energy Consultants	
Beijing OHW Tech	
Policymakers, Regulatory Bodies	**4**
CASTED - Ministry of Science and Technology, Chinese Academy of Science and Technology for Development	
ERI - Energy Research Institute of China's National Development and Reform Commission (NDRC)	
CNREC - China National Renewable Energy Center	
International Organizations	**3**
UNEP – United Nations Environment Programme	
World Bank	
OECD – Organization for Economic Cooperation and Development	
Other Industry Experts	**9**
Georgetown University	
IEEFA - Institute for Energy Economics and Financial Analysis	
GGGI – Global Green Growth Institute	
GIZ - German Corporation for International Cooperation	
AHK - German Industry and Commerce	
World Economic Forum	
Fos4X (Wind Analytics Startup)	
Greenovation Hub	
Innovation House China-Denmark	
	81

A4. Chronological list of interviews

Round	#	Organization	Category	Position	Country Interviewee	Date	Duration (min)
1							
	1	FTI Consulting	Consulting Firm	Head of Dep.	Denmark	20.12.2017	75
	2	German Corporation for Int. Cooperation	Industry Expert	Senior Manager	China	18.01.2018	60
	3	Ministry of Science and Technology, CASTED	Policymakers, Regulatory Bodies	Director	China	23.01.2018	90
	4	German Industry and Commerce	Industry Expert	Head of Dep.	China	24.01.2018	60
2							
	5	Siemens Gamesa	Wind Turbine Manufacturer	Manager	Germany	02.03.2018	25
	6	AMSC Windtec	Wind Turbine Manufacturer	[Area] Director	Germany	05.03.2018	55
	7	Norwin	Licensing, Engineering, Design Firm	Executive Director	Denmark	06.03.2018	135
	8	Institute for Energy Economics & Fin. Analysis	Industry Expert	Director	Australia	07.03.2018	60
	9	Vestas	Wind Turbine Manufacturer	Senior VP	Denmark	09.03.2018	60
	10	Envision	Wind Turbine Manufacturer	Head of Dep.	Germany	16.03.2018	60
	11	Vensys	Licensing, Engineering, Design Firm	Deputy Head	Germany	21.03.2018	30
	12	Senvion	Wind Turbine Manufacturer	Managing Director	Germany	22.03.2018	45
	13	Aerodyn	Licensing, Engineering, Design Firm	Head of Unit	Germany	23.03.2018	70
	14	Innovation House China-Denmark	Industry Expert	General Manager	Denmark	27.03.2018	55
3							
	15	Energy Research Institute	Policymakers, Regulatory Bodies	Director	China	03.04.2018	70
	16	World Economic Forum	Industry Expert	Senior Analyst	China	04.04.2018	50
	17	China National Renewable Energy Center	Policymakers, Regulatory Bodies	Senior Researcher	China	05.04.2018	60
	18	China National Renewable Energy Center	Policymakers, Regulatory Bodies	Chief Expert	Denmark	10.04.2018	85
	19	Georgetown	Industry Expert	Professor	United States	16.04.2018	50
	20	Titan Wind Energy	Component Supplier	Vice President	China	23.04.2018	60
	21	Envision	Wind Turbine Manufacturer	[Area] Director	China	23.04.2018	105
	22	Siemens Gamesa	Wind Turbine Manufacturer	Head of Dep.	China	23.04.2018	150
	23	Envision	Wind Turbine Manufacturer	Head of Dep.	China	24.04.2018	90
	24	GWEC	Industry Association	China Director	China	25.04.2018	75
	25	Goldwind	Wind Turbine Manufacturer	IP Director	China	25.04.2018	175
4							
	26	McKinsey and Company	Consulting Firm	Associate Partner	China	22.03.2019	70
	27	Envision	Wind Turbine Manufacturer	C-Level	China	22.03.2019	60
	28	Goldwind	Wind Turbine Manufacturer	Senior Analyst	China	27.03.2019	110
	29	Goldwind	Wind Turbine Manufacturer	Manager	China	27.03.2019	120
	30	Goldwind	Wind Turbine Manufacturer	Manager	China	01.04.2019	120
	31	Ming Yang International	Wind Turbine Manufacturer	C-Level (f)	China	03.04.2019	150
	32	Goldwind	Wind Turbine Manufacturer	Chief Engineer (rd)	Denmark	03.04.2019	40
	33	Fos4X	Industry Expert	C-Level	Germany	04.04.2019	60
	34	Goldwind	Wind Turbine Manufacturer	General Manager (rd)	Denmark	04.04.2019	55
	35	Ørsted	Project Development & Utility	Senior Analyst	Denmark	08.04.2019	90
	36	Envision	Wind Turbine Manufacturer	Head of Dep.	China	09.04.2019	55
	37	Goldwind	Wind Turbine Manufacturer	Deputy GM	China	10.04.2019	60
	38	Goldwind	Wind Turbine Manufacturer	Senior Engineer	China	10.04.2019	30
	39	Goldwind	Wind Turbine Manufacturer	Senior Engineer (f)	China	11.04.2019	100
	40	Sinoma	Component Supplier	Project Manager	China	12.04.2019	75
	41	Envision	Wind Turbine Manufacturer	Team Leader (rd)	United States	12.04.2019	65
	42	Goldwind	Wind Turbine Manufacturer	Team Leader	China	15.04.2019	75

	43	Envision	Wind Turbine Manufacturer	Project Manager (rd)	Denmark	15.04.2019	50
	44	Ming Yang	Wind Turbine Manufacturer	Senior Manager	China	16.04.2019	35
	45	Power China	Project Development & Utility	C-Level	China	16.04.2019	75
	46	Suzlon	Wind Turbine Manufacturer	Senior Manager	India	16.04.2019	55
	47	LM Wind Power	Component Supplier	Director	China	17.04.2019	35
	48	General Electric	Wind Turbine Manufacturer	Project Manager	China	17.04.2019	60
	49	Ming Yang	Wind Turbine Manufacturer	R&D Manager	China	18.04.2019	70
	50	Goldwind	Wind Turbine Manufacturer	R&D Manager	China	18.04.2019	55
	51	Envision	Wind Turbine Manufacturer	Head of Dep.	China	18.04.2019	75
	52	Beijing OHW Tech	Consulting Firm	Managing Director	China	19.04.2019	70
	53	Ming Yang	Wind Turbine Manufacturer	Chief Scientist (f)	China	19.04.2019	40
	54	Aventage Consulting	Consulting Firm	Partner	United Kingdom	19.04.2019	45
	55	CSIC Haizhuang	Wind Turbine Manufacturer	Project Manager	China	20.04.2019	70
	56	Goldwind	Wind Turbine Manufacturer	Manager	China	21.05.2019	60
	57	ABB	Component Supplier	Project Engineer	China	23.05.2019	55
	58	Sinovel	Wind Turbine Manufacturer	Manager (f)	China	23.05.2019	70
	59	Consolidated Energy Consultants	Consulting Firm	Executive Director	India	20.04.2019	60
	60	WWEA	Industry Association	Vice President	India	24.04.2019	50
	61	WINDnovation	Licensing, Engineering, Design Firm	Project Manager	Germany	24.04.2019	75
	62	Ming Yang	Wind Turbine Manufacturer	Manager (f)	China	24.04.2019	25
	63	Aerodyn	Licensing, Engineering, Design Firm	Head of Unit	Germany	25.04.2019	70
	64	Greenovation Hub	Industry Expert	Program Officer	China	26.04.2019	45
	65	Mot MacDonald	Consulting Firm	Partner	China	26.04.2019	35
	66	Nordex	Wind Turbine Manufacturer	Director (f)	China	27.04.2019	100
	67	Longyuan	Project Development & Utility	Manager	China	29.04.2019	80
	68	PwC	Consulting Firm	Partner	China	02.05.2019	65
	69	WWEA	Industry Association	Director General	Germany	03.05.2019	70
	70	Nordex	Wind Turbine Manufacturer	Director (f)	China	24.10.2019	55
	71	Global Wind Energy Council	Industry Association	Director	China	24.10.2019	65
5							
	72	International Energy Agency	Industry Association	Senior Researcher	United States	06.04.2020	50
	73	Envision	Wind Turbine Manufacturer	Project Manager	China	06.04.2020	70
	74	Chinese Wind Energy Association	Industry Association	Secretary General	China	08.04.2020	30
	75	Goldwind	Wind Turbine Manufacturer	Chief Engineer	China	09.04.2020	45
	76	Envision	Wind Turbine Manufacturer	Line Manager	China	13.04.2020	85
	77	Global Green Growth Institute	Industry Expert	Head of Division	South Korea	21.04.2020	60
	78	United Nations Environmental Program	International Organization	Project Officer	China	23.04.2020	25
	79	World Bank	International Organization	Economist	China	24.04.2020	40
	80	Organization for Econ. Cooperation & Dev.	International Organization	Head of Unit	France	28.04.2020	65
	81	Aerodyn	Licensing, Engineering, Design Firm	Head of Unit	Germany	25.08.2020	70
							3,550

Note: (f) stands for 'former employee'; (rd) for 'R&D hub'. Position titles are generalized for anonymization purposes. Interview durations are rounded up. 3,550 minutes are equivalent to 59 hours or 2.5 days.

A5. Example interview questions per category

Global wind industry evolution and key trends

- What have been the key trends in the global wind turbine industry in the past ten years?
- What are the key trends currently? What key trends do you expect in the near and long-term future?
- What have been the most important changes/transformations in the industry? Why were they important?
- What are the most important changes/transformations currently?
- How does industry 4.0/digitalization/industry hybridization influence the industry?

Chinese wind industry evolution and key trends

- What have been the most important milestones in the Chinese vis-à-vis global industry?
- What have been the main drivers for China's rapid industry development?
- Why has China rapidly taken over global market share?
- Why has the market share of foreign firms in China dropped significantly over time?
- How have incumbent firms reacted to China's growing competitiveness in the industry?
- How would you describe the relationship between Western and Chinese wind turbine manufacturers?
- In what terms would you describe it as collaborative? Or competitive?
- Why is the level of internationalization/number of exported wind turbines still low?
- Why was it so difficult to scale-up the offshore market at the beginning?
- To what extent do you expect Chinese firms to become innovation leaders/technological first movers? Where? How?
- What is their competitive advantage (e.g., certain sub-components)?
- In what terms are they still catching up with global industry leaders?

Public policies and their impact on the industry

- What have been the most important global/national policies (in recent years)?
- How have they impacted the technological capabilities of Chinese wind turbine manufacturers?
- What can policymakers in other countries learn from China's rapid market scale-up?
- What policies turned out to be more/less effective?
- What is the role of central/local industrial policies and government support schemes for industry development?

Technological learning and upgrading

- To what extent have Chinese manufacturers developed new-to-the-sector/new-to-the-world technologies? Examples?
- Why are some Chinese firms more successful in developing new technologies than others?
- Who are the technology leaders? What are the commonalities and differences between them?
- What are second and third tier companies doing differently?
- Are there certain areas/segments/subcomponents in the wind turbine sector where Chinese companies have become particularly strong?
- To what extent have Chinese companies become contributors to rather than recipients of wind turbine technology (e.g., through technology transfers)?

Firm-specific questions

- When did you establish subsidiary [x]? What is the subsidiaries' main function? What type of tasks are delegated from HQ to subsidiary?
- Please describe the structure of the R&D department. How has it changed?
- Do you have internal knowledge communities? Which ones? What do they work on?
- Do you work with universities/research institutes? Since when and how do you work with them?
- How do you work with your suppliers? Examples of successful product/process co-development?
- How do you work with licensing firms or other external service providers?
- Do you work with other external partners? Which ones? How?
- Who are your most important R&D partners nationally and internationally?
- How do you collaborate with them? Examples?

	• How do you develop new technologies? • Could you describe your R&D processes? • How do you test and develop ideas? • How do you make sure you produce cutting-edge technology? • Where do you look for inspiration/market trends? • What differentiates your firm from others? • What are your competitive advantages? • What are your key challenges currently? • In what ways can your organization learn and improve? • What is your company's roadmap for the next five years (e.g., key projects, technology development, partnerships)? • How is your relationship with central/local government? • Which policies/support schemes are most relevant?
Project-specific questions	
	• What are currently the most important innovation projects in your company? • What projects are you responsible for? • What are the objectives of the project? • What is new about the project? • What methods are being used to implement the project? • What types of employees are working on the project? • What external partners are involved in the project? How are they involved exactly? • To what extent are the findings of the project generally applicable? • Did you have to deal with unexpected events during the project? What were they?

Research articles

Article I:	Hain, D. S., Jurowetzki, R., Konda, P., & Oehler, L. (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*, Published 15 October 2020, doi:10.1093/icc/dtaa021
Article II:	Dai, Y., Haakonsson, S., & Oehler, L. (2021). 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*, Forthcoming, doi:10.1093/icc/dtaa034
Article III:	How do R&D networks change? The upgrading of innovation capabilities in emerging market firms. Insights from China's wind energy sector. *Submitted for publication.*

Article I

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

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Abstract

Studies on catching up and industrial leadership have often used market-related variables to evaluate the catch-up trajectories of latecomer countries and firms. In this study, we aim to enhance our understanding of these concepts by presenting an integrated market-technology framework. Using natural language processing techniques allows us to go beyond patent numbers and analyze patent novelty and impact as well as technological changes over time. In empirical case studies on wind energy and electric vehicles in China, Japan, and South Korea, we compare and identify country and sector-specific catch-up trajectories and potential catch-up traps.

Keywords: Catching up, industrial leadership, technological capability building, patent data, natural language processing, vector space modeling, wind power, electric vehicles

JEL codes: O31 (Innovation and Invention: Processes and Incentives), O32 (Management of Technological Innovation and R&D), O33 (Technological Change: Choices and Consequences), Q20 (Renewable Resources and Conservation), Q55 (Technological Innovation), L10 (Market Structure, Firm Strategy, and Market Performance), L60 (Industry Studies Manufacturing), L62 (Automobiles, Other Transport Equipment)

1. Introduction

Over the last two decades, a growing number of emerging economies have adopted industrial policies to incentivize the catch up and development of green economy sectors (Rodrik, 2014; Capozza and Samson, 2019). China, in particular, has shown an unprecedented catch up and become a "green giant" (Jaffe, 2018), taking over an increasing number of green sectors previously led by incumbent countries such as solar photovoltaics (PVs; Fu and Gong, 2011), wind power (Lewis, 2012), and electric vehicles (EVs; Li *et al.*, 2018). As it relates to sustainability transition, this green transformation is paramount, considering China remains the world's largest polluter, emitting more greenhouse gases than the European Union and USA combined (UN, 2019). Besides, its catch up, leapfrogging and leadership in green industries can serve as a model for other emerging economies (Fu, 2015).

However, China's market leadership in green technologies does not necessarily correlate with its technological capabilities. Despite this, the existing literature often measures catch up and industrial leadership in terms of market quantities (Mowery and Nelson, 1999; Lee and Malerba, 2017a; Morrison and Rabellotti, 2017; Shin, 2017) to the neglect of assessing technological novelty and impact. Only a few studies have tried to provide a more nuanced view of catching up, comprising both market- and technology-related indicators on firm and sectoral levels (Jung and Lee, 2010). Using patent quantities as a measure for technological innovation (e.g. as done by Fu *et al.*, 2011; Awate *et al.*, 2012) can be misleading, given the significant imbalance between patent quantity and quality with regard to novelty and impact (Torrisi *et al.*, 2016). Similarly, despite acknowledging its benefits, patent citation analysis is not able to reveal insights into overall relationships among patents, thereby overlooking valuable insights into technology development paths (Yoon and Park, 2004). Nevertheless, especially in the context of green sectors, both market scale up and technological novelty and impact are imperative to reach efficiency levels where low-carbon technologies become cheaper than conventional alternatives, based on fossil fuels (Geels, 2014).

In this article, we seek to address this shortcoming. Conceptually, we propose an integrated market-technology (MT) framework. Methodologically, we create patent quality indicators (Basberg, 1987) and use natural language processing and lead-lag estimation techniques (e.g. Shi *et al.*, 2010) to determine technological novelty and impact. Text similarity-based methodologies have recently performed well on patent data when matching technological similarity (Arts *et al.*, 2018), providing an alternative to established approaches that are leveraging citation structures. Deploying the methodology developed by Hain *et al.* (2020), we draw upon the rich but, up to now, under-utilized textual information in patent abstracts. Using the inventor level of patents, we gain further valuable insights into the geographies of technological innovation and knowledge networks. By contrasting wind energy and EV catch up in China as compared with South Korea and Japan, we discover heterogeneous country- and sector-specific patterns of technology life-cycles, technological regimes, and windows of opportunity that have considerable implications for catch-up strategies.
Against this background, we aim to answer the following research questions:

> *What implications does sector-specificity have for market vs technology catch up and leadership? What should latecomer countries consider when entering a new sector? Which trajectories and detours can latecomers take to avoid market and technology traps*?

This article is organized as follows. In Section 2, we review the existing literature on catching up and industrial leadership and integrate these insights to propose a new MT framework. In Section 3, we present the methodology developed to analyze technological novelty and impact based on semantic patent-to-patent similarity scores. In Section 4, we analyze the empirical cases and discuss our findings in Section 5. In Section 6, this article concludes with a summary of our key findings and their relevance for policymakers and practitioners in the green catch up context.

2. Theoretical and conceptual considerations

2.1 Existing perspectives on catching up and industrial leadership—drivers, strategies, and barriers

2.1.1 Catching up through windows of opportunities

Two of the most prominent and controversial questions in innovation, development, and economics literature have been: under what conditions do latecomer economies (Abramovitz, 1986; Bell and Pavitt, 1993; Dosi et al., 1994; Fagerberg et al., 2007) and firms (Hobday, 1995; Mathews, 2002; Dutrénit, 2004) catch up and why are some more successful than others? In order to understand the drivers and barriers of catching up, it is necessary to take a dynamic view of technological change (Perez and Soete, 1988). In this article, we understand catching up in the Schumpeterian evolutionary tradition rather than in the neoclassical model (Fagerberg, 2003; Rock and Toman, 2015). In this line, catching up means learning and capability building. This process comprises costly, risky, and path-dependent activities that require significant coordination between various actors to overcome market and systems failures (Nelson, 1982; Fu and Gong, 2011). Consequently, every country and sector requires a different catch-up strategy—depending on the respective market, technology and knowledge regimes (Malerba and Orsenigo, 2000; Lee and Lim, 2001; Castellacci, 2007; Jung and Lee, 2010; Lema and Fu, 2020). However, not all factors influencing the catch-up process are endogenous to the country. There are significant links at the global sectoral level (Malerba, 2005), as described in Section 2.1.3.

These endogenous and exogenous factors, affecting a country's catching up, are referred to as "windows of opportunity" (WOO) in the literature. In their influential article, Perez and Soete (1988) introduced the concept of temporary and non-automatic WOO as enablers for "effective" technological catch up. They understood these WOO as shifts in the underlying techno-economic paradigm, thereby providing leapfrogging opportunities as the cases of Japan and South Korea illustrated at that time. Recently, the notion of WOO gained renewed attention in the context of industrial leadership changes (Lee and Malerba, 2017b). Introducing the concept of "catch-up cycles," Lee and Malerba (2017a) explain the phenomenon of successive changes in industrial leadership by WOO and firm responses. Here, WOO concerns changes in (i) technology and the related knowledge base, for example, through significant technological innovations, (ii) market demand, for example, through new user preferences or business cycles, and (iii) institutional settings, for example, through public policies and regulations. A prominent example of such a catch-up cycle is the mobile phones sector, where industrial leadership shifted from Motorola (USA) to Nokia (FI) in 1998 and from Nokia to Samsung (KR) in 2012 (Giachetti and Marchi, 2017). The degree to which such geographic leadership changes occur depends on the sequence, type and scope of the WOO as well as the respective responses by the incumbent and latecomer (Lee and Lim, 2001; Guennif and Ramani, 2012; Lee and Malerba, 2017b).

2.1.2 Catch-up strategies

Interestingly, case studies have shown that latecomers do often not follow the footsteps of advanced economies but seek to skip stages or create their own paths. Lee and Lim (2001) identify three types of catch-up strategies that latecomers can pursue: *path following* (adopting first-generation technology), *stage skipping* (adopting up-to-date technology), and *path-creating* (exploiting new technological trajectories). Although the first strategy is cheaper and safer, it bears the risk of middle-income traps where latecomers remain in a *path-follower* position (Lee, 2019). Particularly, in the context of green technologies with typically high path-dependencies, asset-specificity and upfront investments, first-generation technologies are in most cases not suitable to compete with the lower price-levels of conventional technologies based on coal, oil or gas. These structural patterns have been extensively discussed in the literature on *sustainability transitions* (e.g. Markard et al., 2012). *Stage skipping* can be considered the most common strategy, in which latecomers follow the incumbent path to a certain extent, but use the latest technology through conventional technology transfer mechanisms such as licensing, joint ventures or inbound foreign direct investment (Lema and Lema, 2013). Yet, intellectual property protection (e.g. patents or trade secrets) can pose challenges to this strategy. *Path-creating*, also referred to as "leapfrogging" (Perez and Soete, 1988), describes the most advanced form of catching up where latecomers turn to create new paths and detour from the forerunners. This strategy is associated with high levels of uncertainty and risk, but also significant advantages if successful.

Contrary to Lee and Lim (2001), we consider these strategies not as mutually exclusive but rather as temporary and sequential (Lee et al., 2016). In his recent book, Lee (2019) stresses the importance of the third strategy for overcoming the "catch-up paradox," positing that latecomers cannot close the catch-up gap by merely following previous paths. This is in line with Malerba and Nelson (2011), who consider effective catching up as tailoring practices to local circumstances rather than cloning them. To understand the multifaceted processes involved in catching up, we have to introduce the wider innovation ecosystem as "enabling constraints" for catch-up processes (Nooteboom, 2000).

2.1.3 Catching up in sectoral vs. national systems of innovation

The direction and rate of catching up is significantly affected by the surrounding innovation system (IS). When entering a new sector, latecomers' catch-up trajectories are largely influenced by the characteristics of the IS—both on a sectoral and national level. The IS defines the environment, where agents—individual or organizational—undergo learning processes through interactions with one another (Malerba, 2002, 2005). In line with evolutionary theory, the system boundaries in an IS are not static but dynamic as its systemic elements—technologies and knowledge, actors and networks and institutions—change over time. Regulative and cognitive institutions can concurrently enable and constrain interactions within a system.

In the context of catching up and latecomer trajectories, both the sectoral innovation system (SSI) and the national innovation system (NIS) framework provide useful analytical insights. Although the SSI analyzes innovation and technological change along sectoral[68] lines, the NIS focuses on innovation capabilities across national boundaries (Freeman, 1987; Lundvall, 1992; Nelson, 1993; Malerba,

[68] With 'sector' being defined as 'related product groups for a given or emerging demand' (Malerba, 2005: 65).

2005; Coenen and López, 2010; Mu and Fan, 2011). Hence, the SSI determines the overall pace and direction of technological change in a given sector and is often dominated by advanced economies. In turn, the NIS defines the innovation capability of a latecomer country, which constitutes an important enabler and/or constraint for effective catch up. In order to develop the "right" catch-up strategy (see Section 2.1.2), latecomer countries have to take into account sector-specificity as well as their national endowments and capabilities. Jung and Lee (2010) found that catch up is more likely in sectors with explicit and easily embodied knowledge regimes (e.g. electronics) than sectors with higher tacit knowledge regimes (e.g. automobile sector). Similarly, Malerba and Nelson (2011) found significant sectoral differences in terms of learning and catching up among six sectors, according to variations in industry structures. Although acknowledging that setting strict boundaries in times of globalization of innovation and hybridization of sectors can raise the question of "*who appropriates the innovation rents*" (Schmitz and Altenburg, 2016: 6), we consider that applying the SSI and NIS framework can be useful in the context of this study for analyzing the implications of sector-specificity for country-level catch-up processes.

2.1.4 Measuring catching up and industrial leadership

In order to evaluate the catch-up level of a latecomer, it is crucial to operationalize the concepts. Generally, studies on catching up and industrial leadership can be divided into two different strands, the market- vs. technology-oriented view. The market-oriented literature, following the epistemological tradition of Mowery and Nelson (1999), understands industrial leadership as superior production or marketing strategies, measured by global market or production shares of a country's lead firm. This research stream often adopts a sectoral systems approach to understand the sources of leadership. In contrast, the technology-oriented literature, following Lall (1992) and Bell and Pavitt (1993), understands industry leadership in terms of a firm's superior technology and innovation capabilities, categorized by four different capability levels: *basic, intermediate, advanced*, and *world-leading*. This epistemological tradition focuses more on the internal, technological capability building and upgrading processes than on the firm level to understand the sources of catching up, yet recognizing that "a substantial part of a firm's innovative capability lies in other organizations" (Figueiredo and Piana, 2016: 23).

Both approaches have their advantages and drawbacks. Although the first approach provides an indicator that is easy to measure, thereby allowing for cross-sectoral analysis (Malerba and Nelson, 2011), it neglects a differentiated view of production vs. technology-related innovation capabilities. However, as the cases of India and China have shown, capturing large—often domestic—market share does not necessarily correlate with developing novel technologies. By extension, smaller countries such as South Korea and Japan might have the technological capabilities to produce new-to-the-world technologies but face considerable barriers in terms of scale up and commercialization. In contrast, the second approach gives detailed insights into the evolution and accumulation of a firm's indigenous innovation capabilities. However, the classification method provides limited opportunities for cross-sectoral comparisons (Hansen and Lema, 2019). We consider the MT dichotomy a considerable shortcoming in the existing catch-up literature, which needs to be addressed. Jung and Lee (2010) established a good entry point, using sectoral- and firm-level variables to identify which factors in the market and technology regime influenced the productivity catch up in Korean and Japanese firms.

2.2 Towards an integrated perspective: market vs. technology catch up and leadership

2.2.1 The MT matrix

In this article, we understand catching up as a combination of market and technology development, as shown in Figure 1. When entering a new sector, for example, due to favorable policies, a latecomer country can go in two different directions and focus on becoming either a market or technology forerunner—depending on a variety of factors. These originate from the latecomer's existing knowledge base and technological capabilities within its NIS, on the one hand, and the properties of the new SSI, on the other. Although market catch up and development is primarily driven by the institutional (e.g. government policies) and market regime (e.g. country size, market structure), technology catch up and development largely depends on the technology (e.g. complexity, technological cycle), and knowledge regime (e.g. appropriability and transferability of existing knowledge).

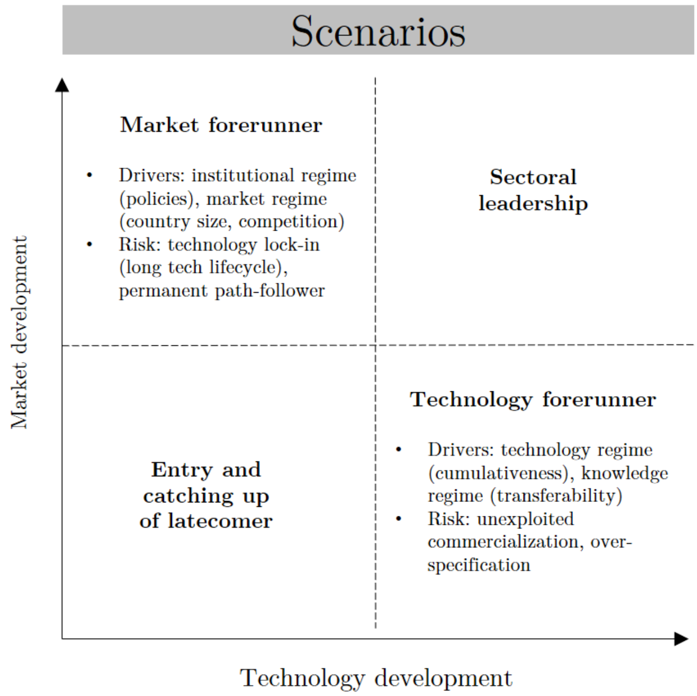

Figure 1. The MT matrix

Consequently, horizontal technological catch up and indigenous knowledge creation require much higher levels of pre-existing knowledge and technological capabilities, for example, from adjacent industries compared with vertical market catch up (Awate et al., 2012). However, latecomers with a relatively low level of technological capabilities and knowledge appropriability can still enter the sector and even become market leaders when the institutional and market regime are favorable, and latecomer firms find strategies to skip stages, for example, through effective technology transfer mechanisms. However, this catch-up strategy is only sustained when technology follows market development as institutional support, especially in the context of green sectors, is likely to fade away at a certain point.

2.2.2 MT trajectories and traps

Figure 2 shows two paths to sectoral leadership, the MT trajectory and the technology market (TM) trajectory. Although both trajectories eventually lead to sectoral leadership, the MT trajectory describes a potential detour: latecomers manage to capture substantial market share, but also gradually improve their capabilities and knowledge base on the technological side, for example, China's catching up in the mobile phone sector (Liu, 2008). Hence, process innovation is followed by product innovation. In line with Schmidt and Huenteler (2016), this process of "industry localization" is technology specific and depends on the country's endowments with technological capabilities. If the ladder remains scarce, there is the risk of a *market trap* where latecomers stay in the technology-follower position. As soon as institutional support fades out, catch up is aborted. Another risk of the MT trajectory arises when market scale up based on outdated, first-generation technology occurs too fast. As green sectors typically involve significant asset-specific investments with very long product life-cycles (e.g. 20–25 years for wind turbines), there is an additional risk of technology lock-in.

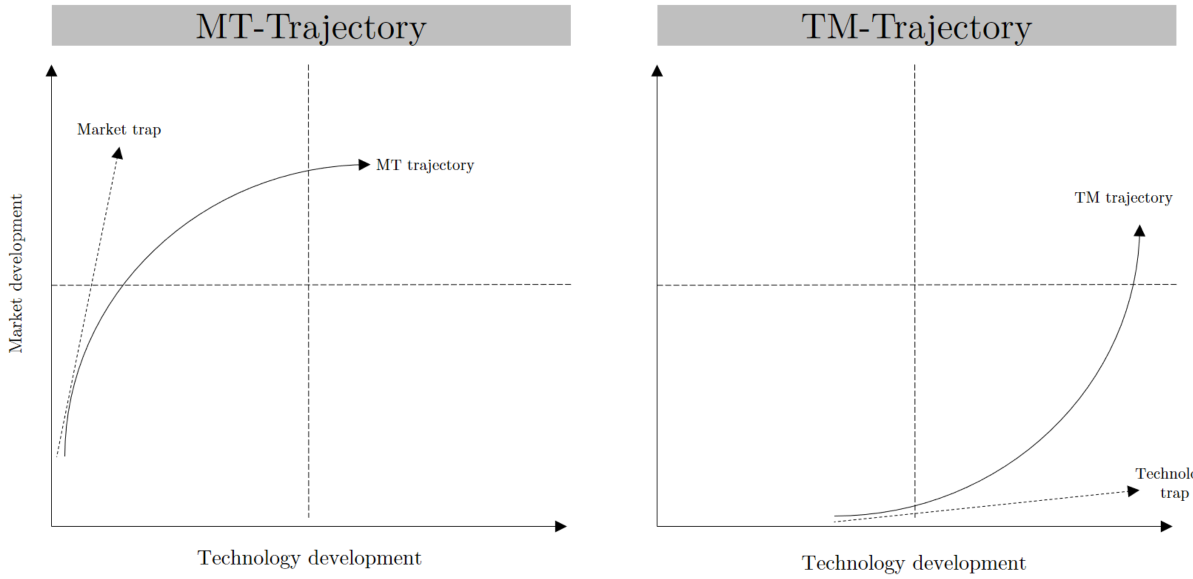

Figure 2. Trajectories and potential traps in the MT matrix

In turn, the TM trajectory describes a situation where countries with a strong pre-existing set of technological capabilities and developed industrial knowledge base enter a new sector. Although enhancing and upgrading technological capabilities occurs relatively fast, for example, through crosscutting capabilities (Nahm and Steinfeld, 2014), the challenge here is scaling up the commercialization and gaining market share. If the market does not follow technology development, there is the risk of a *technology trap* where strong technological capabilities inhere to the latecomer but remain insufficiently commercialized. This bears two risks: first, financial bottlenecks lead to an aborted catch up. Second, knowledge regimes become over-specified, thereby neglecting significant innovation potentials within the SSI. By taking the TM trajectory, Taiwan managed to catch up in semiconductors, by accumulating knowledge, and with strategic alliances through research and development (R&D), providing advanced products to global markets (Rasiah et al., 2012; Hoeren et al., 2015).

3. Methods

3.1 Measuring market development

Various metrics are used to evaluate the market development of a latecomer, as shown in Table 1. Especially global market share has become a popular indicator, mostly based on the single share of a country's lead firm (Mowery and Nelson, 1999; Giachetti and Marchi, 2017; Landini et al., 2017; Lee and Malerba, 2017b; Morrison and Rabellotti, 2017; Shin, 2017). We adapt our definition of market catch up and development in this study for two main reasons. First, the lead firm's share might not sufficiently represent a country's total market contribution to a sector (favoring market regimes with monopolistic structures). Second, the market share is useful to evaluate a country's positioning in the context of the overall sectoral development. However, as green technologies not only compete with conventional but also with other green technologies, we consider the relative output (e.g. wind capacity relative to the overall energy mix) a more suitable metric in the green context. As data availability significantly differs among green technologies and countries—depending on their respective maturity levels—we approach market development differently for wind and EVs. For wind, we use a country's installed capacity (−imports/+exports) as a percentage of the overall energy mix, whereas for EVs, we use a country's stock in EVs (−imports/+exports) as a percentage of the overall automotive sector.

Table 1. Key market development indicators

Market development indicator	Sector	Advantage	Drawback
Installed capacity (GW)	Wind	Easy to compare across countries due to aggregated data availability	(1) Does not reflect the connected capacity or (2) the country's production capability (due to imports/exports)
Units registered	EV	Easy to compare across countries due to aggregated data availability	(1) Registrations may be limited through quotas (2) does not reflect the country's production capability (due to imports/exports)
Manufacturing capacity (GW/number of units)	Wind and EV	Easy to compare across firms	(1) Does not reflect the actual production and commercialization; (2) needs to be aggregated for cross-country comparison; (3) manufacturing can be spread across countries; (4) technologies (e.g. EV) can be defined differently across countries
Global market or production share (GW/number of units)	Wind and EV	Easy to compare across firms; indicates country's proportion of sectoral market development	(1) Needs to be aggregated for cross-country comparison; (2) does not reflect domestic vs. international market share; (3) manufacturing can be spread across countries
Export / imports (GW/number of units)	Wind and EV	Easy to compare across countries; indicates dependence on foreign vs. domestic market	Does not reflect the reasons for importing/exporting and is only expedient in conjunction with other indicators (e.g. country size)

Source: Authors' elaboration based on Hu et al. (2018), Robinson (2018), and IRENA (2014).

3.2 Measuring technology development

Although most studies to date have focused on indicators of markets catching up, we are aiming to complement this stream of research by emphasizing the technology dimension of catching up.

Besides in-depth technology development case studies, more generic indicators of technological development and catching up broadly utilize patent data. Generally, an extensive body of literature in economics and other areas of the broader literature on innovation studies has long embraced patents as a measure of the rate as well as the direction of technological change. Indeed, the correlation between the number of patent applications and various measures of innovation output and success have been empirically investigated and established at various levels, such as countries, sectors and firms (Pavitt, 1985, 1988). However, the meaningfulness of patents to map the pattern as well as measure the rate of technological change is also perceived to be limited by the fact that: (i) not all inventions are patentable, (ii) not all patentable inventions are patented, (iii) not everything patented represents an invention, and (iv) the importance of patents as a mean of intellectual property protection varies broadly across jurisdictions, industries, and over time (Pavitt, 1985, 1988).

It has also been recognized that the technological and economic significance of patents vary broadly (Basberg, 1987). Although all patents must meet objective criteria in terms of novelty and utility in order to be granted, this can still be an incremental and narrow improvement to existing technology, invisible in its impact on technological progress. Even when radically novel and theoretically of broad technological scope and broadly applicable, a patent's economic value is contingent on firm-, technology-, market-, and timing-related factors.

Existing approaches to derive indicators of patent quality include the number or composition of a patent's International Patent Classification (IPC) assignments (Lerner, 1994), backward (Trajtenberg et al., 1997; Lanjouw and Schankerman, 2001; Shane, 2001) and forward citations (Trajtenberg et al., 1997; Harhoff et al., 2003).

In order to measure technology development over time, we base our approach on the micro-level identification of technological similarity between patents. Thereby, we center our analysis around the structure of technologies, and how certain patents exhibit technological similarity to others, and how these similarity patterns are distributed across technologies, geography, and over time. Such a patent-to-patent similarity mapping enables us to derive and construct nuanced measures of patent novelty and impact, which can be aggregated on the level of technologies as well as geography. To create such a measure of technological similarity, we follow a vector space modeling approach, where we first create a high-dimensional "signature vector" that captures the technological features of the corresponding patent. These vectors are in turn composed of individual term vectors, which we obtain from training a custom Word2Vec embedding model (Mikolov et al., 2013). In contrast to numerical representation of text that is based on simple (co)-occurrence of terms, this method aims to capture the meaning of terms in textual data and thus it helps overcome the challenges posed by synonyms as well as technical jargon. We describe the approach and further validation exercises carried out (such as the prediction of a patent's IPC classes based on the created vectors) in detail in the Supplementary Appendix SA. All this enables us to leverage unstructured textual data in patent titles and abstracts. Based on technological signature vectors, we derive an indicator of technological similarity between patents.

A similar approach has been developed by Arts et al. (2018), who use keyword similarity to approximate technological similarity between patents. The main argument for the use of text rather than citations in this project is the following.

When using citations, one generally relies on explicit expressions of relatedness. However, this also means accepting that one does not capture similarity unless it is explicitly stated. By using numerical representation of the patent from text rather than citation patterns, we circumvent potential issues attributed to patenting strategy or the absence of explicit similarity attribution. Thus calculated vectors capture similarity regardless of the presence of explicit links. First, evaluations of the relationship between our similarity measure and the presence of a citation between two patents (to be found in Supplementary Appendix SA) tentatively confirm this argumentation. Here, the presence of a citation was loosely associated with increased similarity between two patents. Yet, there are many patent pairs with high similarity scores that do not cite each other (and *vice versa*), supporting our argument that citations may offer a too restrictive measure for technological similarity. It further raises the question, what exactly is the information regarding the relationship of two patents represented in a citation.

Our semantics-based technological similarity is independent of time. Therefore, patents can exhibit similarity to other patents which are published earlier as well as later in time. We exploit the temporal distribution of technological similarity, where we compute an *ex ante* indicator of *novelty* (sim_{past}) as measured by the similarity (or the lack of) to patents published in the past, and likewise an *ex post* measure of *technology potential* as measured the similarity to patents published in the future (sim_{future}). When aggregating these to temporal similarity measures on technology level, we are able to capture the development of their technology life-cycle. In Supplementary Appendix SA, we describe the distinct steps, methodological choices, and technical details of the outlined approach.[69]

3.3 Patent data and methodological choices

The patent data we used for our study were retrieved from the EPO's PATSTAT (autumn 2018 edition) worldwide patent database which covers bibliographic patent data from more than 100 patent offices over a period of several decades. Although we perform the above described semantic similarity mapping for all patents where English-language abstracts are available (~48 million), we only store similarity edgelists (patent-to-patent) for a subset of those.

First of all, for our analysis, we include only patent applications that have been granted. This already applies a first quality filter, yet also induces a time lag between the filing of the application and the inclusion of the application in our analysis, preventing us from analyzing post-2017 data. We further limit ourselves to patent applications in the period 1980–2017. Our measure for a patent's similarity to the future refers to patents granted in the next 5 years following the original patent's granting date. Thus, for analyses utilizing this measure we are only able to use patents up to 2012. Since patents filed in different legislations imply a certain degree of heterogeneity with respect to patent scope, timing and quality of applications at

[69] Also consider (Hain et al., 2020) for an exhaustive description of the method, workflow, options and choices, and a thorough evaluation of the resulting indicators. Also consider Hain and Jurowetzki (2020) for an application of this data for patent impact prediction.

different patent offices, many studies include only applications at a single (e.g. EPO, USTPO) or selected (e.g. triadic applications jointly at the EPO, USTPO, and JPO) patent offices. Furthermore, patents filed only in the domestic patent office are often said to be of lower quality and without commercial potential on the global market. However, a catching-up country may decide to follow a MT trajectory and first create a sufficiently large domestic market before ramping up technology development. Such patents targeting the domestic market could be an important signal that is not captured when only considering single office or triadic filings. Consequently, we include filings at all patent office, but apply the following measures to mitigate the resulting heterogeneity.

Since a single invention can in many cases lead to multiple patent applications at different patent offices and over time, to avoid the inclusion of double-counting applications at multiple offices we follow De Rassenfosse et al. (2013) and only include priority filings. We further include only one patent per extended (INPADOC) patent family, which contains patents directly or indirectly connected via at least one shared priority filing.[70]

Here, we select the earliest priority filing per extended patent family, which by now has been granted and where an English-language abstract is available. This reduces the number of patent applications considered roughly by a factor of 6 (~12 million).

Having generated the final patent-to-patent similarity edge list, we first compute our patent quality indicators (sim_{past}) and (sim_{future}) on the whole universe of patents, before we select a set of technology fields for our case studies to follow. Consequently, our indicators represent the patent's general technology novelty and potential which is not limited to a specific field. To identify the relevant patents for the technologies under study, we rely for the most part on IPC codes. Our classification of technologies is typically performed at the class or subclass level.[71]

Although much of previous research analyzed the geographical distribution of patents as well as the development of country-level patenting activity over time using applicant addresses to assign patents to geographical locations, we use inventor level data instead. Our reason here is that we aim to capture the location of inventive activity rather than the location of intellectual property right ownership (Squicciarini et al., 2013). We thereby focus on local research capacity building, knowledge production, collective learning, and knowledge spillover within a NIS, which for catching-up countries is in many cases to a large extent influenced by national policy measures (cf. Supplementary Appendix Table SB3 for a summary). This can be done by domestic but also foreign firms or other research facilities. However, as a consequence, we do not capture firm-level responses to technological WOOs in terms of international knowledge sourcing.

PATSTAT data are known to incompletely capture inventor addresses correct and complete (~30% of patents cannot be clearly assigned to any geographical location), a problem which is amplified in Asian countries in particular. Therefore, in this research, we leverage recent efforts by De Rassenfosse et al. (2019) to provide more comprehensive geo-information for

[70] Due to different regulations, in some cases applicants have an incentive to vary the scope of their patent when applying to different offices. For instance, the Japanese Patent Office is known to prefer narrower patents, and until the 1990s also included the number of claims in the application fees. Consequently, more narrow patents at the JPO have often been consolidated to one broader application at the USTPO and EPO. Including only one INPADOC family member mitigates the resulting bias, since direct as well as indirect priority linkages are included in the same family.

[71] This relates to the observation that the labels at the subclass level are more static, whereas group and subgroup labels are revised more often (WIPO, 2017).

PATSTAT data, covering >90% of global patenting activity. Since most patents have multiple inventors listed, we assign every geolocation a fractionalized number representing the share of inventors of a particular patent in a particular location.[72]

3.3.1 Technology cases: wind energy and EV

In the following, we present and define the selected green technologies, wind energy and EV. First, the two sectors represent different technology regimes, as shown in Table 2.

Although the former represents a technology directly related to renewable energy production, the latter can be seen as a greener alternative to the current fossil fuel-based mobility paradigm in the automotive industry. Second, the two sectors are complementary, which allows for analyzing potential spillovers and network externalities among green sectors. For instance, EV can be seen as both a technology and market demand WOO for wind, providing energy storage and increasing the demand for clean electricity through the shift from fossil-fuel to electricity-driven mobility. We also observe the first wind turbine OEMs diversifying into the production of EVs. Third, the two sectors are at different maturity levels, which allow us to gain valuable insights into different catch-up patterns alongside different levels of industrial development.

Table 2. Comparing technology regimes

Sector	Technological complexity	Unit costs	Lifetime	Technology domain change	Stylized technology classification
EV	Low-medium *150 subcomponents*	Medium *€20-100k*	High *180,000 km/8-10 years*	Medium *5-10 years between hybrid, full EV, fuel cells*	Process-intensive products *High scale, low-medium complexity*
Wind	High *8,000 subcomponents*	Very high *€1-2 m/MW*	Very high *20-25 years*	Low *10-15 years between onshore, offshore, hybrid/digital*	Design-intensive products *Medium-scale, medium-high complexity*

Note: Wind turbine costs include transportation and installation.
Source: Authors' own elaboration based on Nielsen (2017), IRENA (2012), Larminie and Lowry (2012), and Huenteler et al. (2016).

The selection process is based on purposive sampling focusing on China as an *extreme case* (Flyvbjerg, 2006), constituting the market leader in both sectors. Japan and South Korea were selected as benchmarking cases along the following four dimensions: (i) industry relevance (for both sectors, see Table 3), (ii) geographical proximity, (iii) stages of industrial development, and (iv) market regimes (size and competition, see Table 4). Comparing heterogeneous cross-country cases within geographical proximity and high sectoral relevance provide valuable insights into country-specific catch-up determinants along different stages of development. The two selected industries—wind energy and EV—are arguably at the forefront of the low-carbon transformation (Altenburg et al., 2016).

[72] However, international labor mobility might be a confounding factor in our analysis, since foreign inventors in most patent offices can choose to report their domestic or foreign address. Potential bias could be mitigated by identifying foreign inventors by their nationality, as done by Montobbio and Sterzi (2013). Furthermore, for USTPO applications, the WIPO-PCT database on inventors' nationalities (Fink and Miguélez, 2017; Ferrucci and Lissoni, 2019) could be used. However, since the worldwide geocoding data by De Rassenfosse et al. (2019) also includes additional inventor data provided by national patent offices on inventors unreported in PATSTAT, we do not include such an attempt in our analysis.

EV technologies: "EVs" constitute a relatively broad concept comprising several EV types and technologies. Generally, we can distinguish between four types of EV: battery-EVs (BEVs), hybrid-EVs (HEVs), range-extended EVs (REEVs), and fuel-cell vehicles (FCEVs) (Proff and Kilian, 2012). Although the HEV and REEV include both a combustion and an electric engine, the BEV includes only the latter (Larminie and Lowry, 2012). However, the REEV only uses the combustion engine to recharge the battery upon depletion. Instead of the combustion engine, the FCEV uses hydrogen based on fuel-cell stacks to produce electricity.

This study defines EV in the narrow sense. Hence, our analysis focuses on electric propulsion as a key technology of BEVs. We follow Pilkington et al. (2002) and use the class B60L11/-IPC, which represents the electric propulsion and power supplied within the vehicle. However, we need to bear in mind that the class covers not only electric cars but also other EVs such as marine vehicles. Thus, for this analysis, the class B60L 11/00 and its subclasses were used, as they can be determined as a "likely home for EV patents" (Pilkington and Dyerson, 2006: 85). A list of all used IPC classes and their description is given in Supplementary Appendix Table SB1. Overall, we identify 22,285 patent families related to these technologies.

Wind technologies: In the same vein as EV, "wind technology" encompasses different technology fields that need to be purposefully defined for analysis purposes. Contrary to EV, the wind sector is a second-generation green technology that has been deployed for several decades. Wind technology can be generally divided into onshore, offshore and, since very recently, hybrid technologies that is, combining wind and energy storage with other renewables such as solar PV (GWEC, 2019).

As wind technology develops fast and new sub-technologies emerge, it becomes increasingly difficult to delineate wind technology along with static IPC categories. Consequently, besides utilizing the core wind technology class "F03D-*," we further include various subgroups (Supplementary Appendix Table SB2) in line with WIPO (2019). For instance, the installation of offshore turbines requires technology innovations originating from the maritime industry, listed in subgroup B63B as *water vessel equipment* (Chang and Fan, 2014). Overall, we analyze a total number of 25,095 patent families related to wind technologies.

Table 3. Market and technology figures

	Wind		**EV**	
	Global market share (2018)	Global patent share (2017)	Global market share (2018)	Global patent share (2017)
CN	35.7%	2.8%	45.0%	1.6%
JP	0.9%	5.4%	5.0%	31.4%
KR	0.2%	15.5%	1.2%	16.9%

Note: Global market share for wind and EV measured in installed capacity (MW) and in EVs stock, respectively.
Source: Bunsen et al. (2019) and GWEC (2019).

Table 4. Comparing market regimes

Sector	Country	No. of OEMS	Lead firms	Cumulative capacity (GW/stock in k)	Top-1 market share (% domestic)
Wind	CN	19	Goldwind, Envision, Ming Yang	188.3 GW	26%
	KR	4	Doosan, Unison, Hanjin, and Hyundai	1.1 GW	58%
	JP	2	Hitachi, Mitsubishi	3.5 GW	37%
EV	CN	16	BYD, Geely, Jiangang, BAIC, and SAIC	1,227.7 k	30%
	KR	<5	Hyundai, Kia, and RSM	25.9 k	40%
	JP	<5	Toyota, Mitsubishi, Nissan, and Honda	205.3 k	N/A

Note: Data as in 2017. No exact data available for number of OEMs EV in JP and KR as EV is not listed separately. Market share of largest KR wind turbine OEM Hyundai is <10%; listed share by Danish Vestas. In Japan, the largest local wind OEM Mitsubishi accounts for <15%, yet formed a joint venture with Vestas in 2013. Listed share by MHI Vestas.
Source: FTI (2018), Ou et al. (2017), and GWEC (2018).

4. Analysis

In the following section, we analyze the market and technology development of the two sectors. We will start to provide an overview of the overall industry evolution, which is followed by a cross-country comparison of China, Japan, and South Korea. Table 3 indicates the countries' relevance to the overall market and technology development of the two sectors in terms of market and patent quantities. As we can see from the table, the global market and patent share in the wind energy sector are inversely proportional. China constitutes more than one-third of the world's installed capacity, but only account for 2.8% of global patent share. In contrast, South Korea's market share is 0.2%, while the patent share is above 15%. In the EV sector, China accounts for almost half global market share, yet holds only 1.6% of global patent share, with Japan and South Korea at 31% and 17%, respectively. Despite providing a good point of departure, these market and technology figures indicate quantity-based tendencies. However, in this article, we aim to analyze the technological quality of patents beyond conventional approaches focusing on overall counts. We nevertheless include them to illustrate the extent to which patent quantity and quality can diverge over time. In line with the theoretical framework as presented in Section 2, the objective of this analysis is to identify sector and country-specific patterns of market vs. technology catch up. More precisely, we examine the determinants and potential traps along the catch-up paths toward sectoral leadership.

4.1 A first glance at industrial evolution: comparing market and patenting activity

We start our analysis with an overview of the sectoral evolution in wind and EV from a global perspective. First, we compare market and technology development, with the latter based on overall patent activity, which will be complemented with technological novelty and impact in the subsequent section.

Figure 3 shows the worldwide annual production as well as the number of patents by technology over time. Although around 1980, we see slightly more patenting activity in wind power, and EV patenting activity starts to overtake wind power between 1992 and 2005. Post-2005, wind again experiences a higher patenting activity than EV. Noticeably, both EV and wind power indicate a rapid growth between 2005 and 2010, peaking shortly after.[6] When comparing patent activity with market development, we see that wind—despite similar levels of patent activity—started to develop 15 years before EV, with the latter taking off post-2010. This implies that EV-related knowledge and technology remained unutilized for a relatively extended period. To gain a better understanding of the reasons for this evolution, we take a closer look at the respective sectoral level.

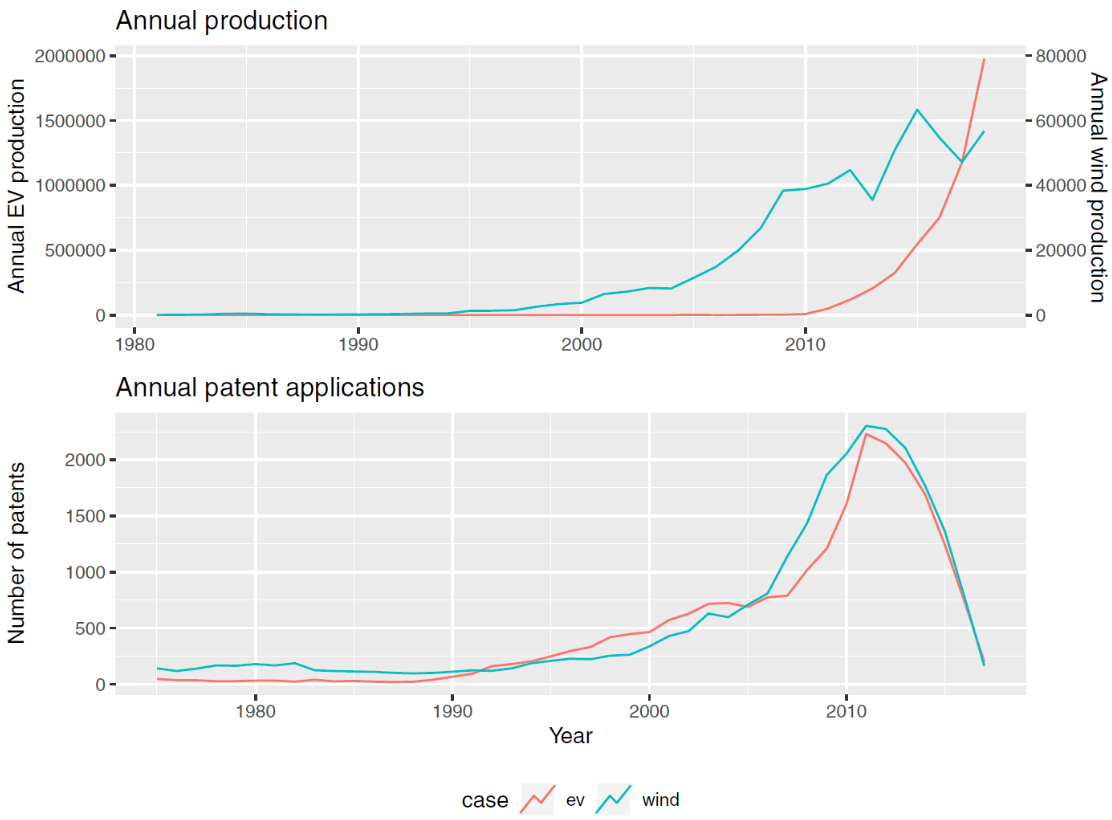

Figure 3. Production and technology development over time

Although the development of infant EVs technology dates back to the 19th century (Larminie and Lowry, 2012), it took until 2010 to launch mass production. There are several reasons for the considerable time lag between R&D activity and market development. First, the development of EV technology, despite its relatively low level of complexity (Table 2), is subject to an *science-based* innovation mode, which requires longer time-to-market periods than technologies developing through *doing, using, and interacting* (DUI) modes such as early wind power (Binz and Truffer, 2017). Hence, technology was not mature enough to open a technological WOO.

Furthermore, despite having the potential assets to exploit innovations, incumbent countries leading the conventional automotive sector had relatively few incentives to introduce novel technology at the risk of potential market cannibalization (Chandy and Tellis, 2000). Previous research has shown that large car manufacturers accounted for notable parts of EV R&D activities, yet without exploiting the acquired knowledge (Wesseling et al., 2014). Possibly, incumbents also used their patent activity for strategic non-use purposes, for example, to block other parties (Torrisi et al., 2016). This suggests that institutional and technological WOO have to be leveraged to overcome such potential barriers.

Within 8 years from starting commercialization, the production of EVs ramped up from a few thousand to 2 million in 2018 (Bunsen et al., 2019). In this phase, both the development and production phases experienced strong institutional support (Supplementary Appendix Table SB3). To increase technological legitimacy and lower the cost pressure on the market price, national governments provided a wide range of subsidies for manufacturers and customers, and also for the development of public infrastructure (Helveston et al., 2015; He et al., 2018). However, these policies not only stimulated production growth but also led to the emergence of different EV solutions. For example, in 2016, due to the different subsidy regimes, top European countries in EV commercialization—Norway and the Netherlands—had different shares of plug-in hybrids as of total EVs, namely 27% and 88%, respectively. For latecomer countries of interest for this study, the same observation holds: China 25%, Japan 42%, and Korea 4% (Bunsen et al., 2019). Consequently, the emergence of new technology domains did not automatically replace previous ones but led to coexistence among them.

Although small-scale wind energy had been used for thousands of years transcending different geographies and cultures, the oil shortages of the 1970s paved the way for increased R&D interest in this technology (EIA, 2020), thereby opening a first yet small institutional WOO. Figure 3 shows a slight increase in patent activity in the aftermath of the oil crisis, yet slowing down after 1982. The signing of the Kyoto protocol in 1997 led to a recurring increase in patent activity, which was followed by a series of national policy mixes in the following years to boost the growth of renewable energies as part of a general shift toward a new energy transition paradigm (IRENA, 2014). When comparing patent activity with market development (Supplementary Appendix Table SB4), we can observe that technology mostly followed market development, which is in line with the aforementioned exploratory innovation mode of early wind technology, exploiting high degrees of DUI (Binz and Truffer, 2017). Since wind technology is design-intensive with high degrees of customization and comprising several thousand sub-components (Table 2), its technological development has been based on incremental changes rather than breakthrough innovations (Huenteler et al., 2016; Binz et al., 2017). However, as relatively small configurations (mainly related to size) can already have major impacts on the efficiency of wind turbines, wind has already reached a tipping point and entered into a stage where it is more price-competitive than conventional sources, reaching grid parity in a number of markets (Backwell, 2017). In 2018, the world's cumulative installed capacity in wind reached 591 GW, thereby representing the second-largest source of renewable energy after hydro (GWEC, 2019; IRENA, 2019).

4.2 Bringing in the novelty and impact perspective: technology cycles and temporal similarity

In the next step, we go beyond interpreting quantities of patents and analyze the technological evolution over time—from a novelty and impact perspective. To do so, we utilize the temporal patent-to-patent similarity measures to analyze static technology characteristics as well as technology evolution and life-cycle dynamics.

Table 5 provides descriptive statistics for our core technology indicators. We can see that EV technology patents display a substantially higher amount of overall similarity to other patents compared with wind power. This can be explained by the narrow technology definition of EV as a sub-sector of the automotive industry with one key technology—propulsion. In contrast, wind technology comprises multiple key technologies, which display technologically dissimilar properties (e.g. tower, rotor blades, gearbox, generator).

After computing temporal similarity scores for every patent, we continue analyzing the development of temporal similarity over time, which provides valuable insights into the evolution of technological change. The joint development of similarity to the future and past enables us to identify technological WOO, which appears at times where promising technology development is taking place (high similarity to the future), while similarity to the past remains relatively low. In Figure 4, we can observe various of such—sector-specific—patterns.

Table 5. Descriptive statistics: similarities

Statistic	N	Mean	SD	Min	25th percentile	75th percentile	Max
All patent (EV and wind)							
sim^{all}	47,380	0.88	3.24	0	0	0	64
sim^{past}	47,380	0.34	1.57	0	0	0	42
$sim^{present}$	47,380	0.20	0.83	0	0	0	18
sim^{future}	47,380	0.34	1.55	0	0	0	38
EV patents							
sim^{all}	22,285	1.40	4.33	0	0	1	64
sim^{past}	22,285	0.55	2.10	0	0	0	42
$sim^{present}$	22,285	0.30	1.09	0	0	0	18
sim^{future}	22,285	0.55	2.07	0	0	0	38
wind patents							
sim^{all}	25,095	0.42	1.65	0	0	0	41
sim^{past}	25,095	0.16	0.81	0	0	0	25
$sim^{present}$	25,095	0.11	0.50	0	0	0	10
sim^{future}	25,095	0.16	0.81	0	0	0	21

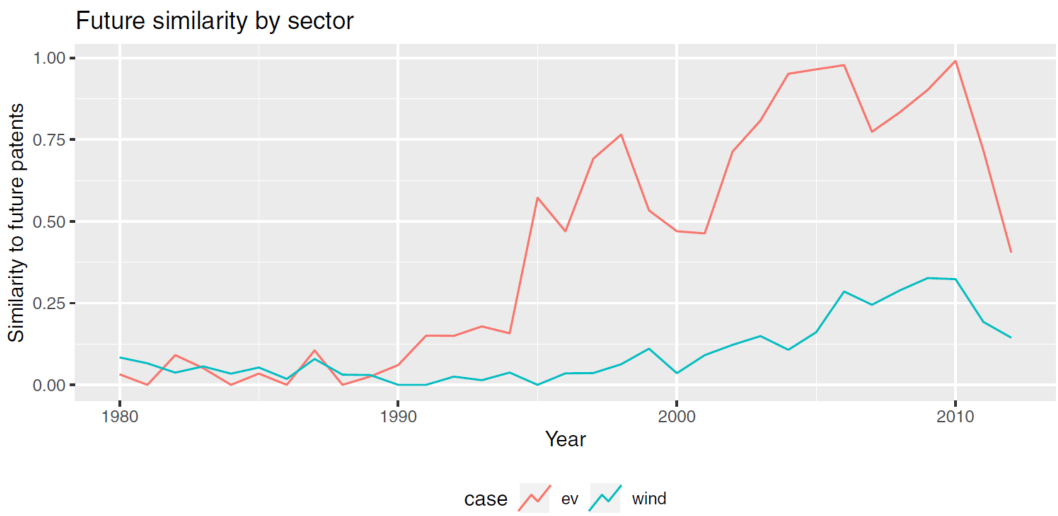

Figure 4. Development of temporal similarity

First, technology cycles *fluctuations* are much more pronounced in EV than in wind, undergoing several peaks of exploration. This can be explained by different maturity levels. Although wind is considered an advanced green sector with a high degree of dominant design,[73] EV is still in the exploratory phase where multiple competing designs co-exist, as described in the previous section. In EV, the first spike in the 1990s relates to the development of hybrid engines, which are charged by using regenerative braking systems. The increase of future similarities in the mid-2000s presents research on plug-in solutions that is, new battery types and infrastructure. In general, all plug-in solutions can use the same charging station; however, the commercialization of the next type of EVs (fuel cell) requires a different infrastructure (Larminie and Lowry, 2012). The development of fuel-cell solutions and supporting elements corresponds with the third cycle. In wind, we can see an increase in sim^{future} between 1995 and 2009, which strongly correlates with the emergence and growth of offshore technology, gaining momentum post-2000 (IRENA, 2018). The decline in future similarity in wind after 2009 is not to be confused with a decline in offshore technology. Rather, it shows stabilization of offshore technology in terms of maturity levels.

Second, technology cycle *intervals* between technology domains are substantially shorter in EV, ranging from 5 to 10 years. In contrast, changes in technology domains in wind occur over 10- to 15-year time periods (Table 2). This can be considered another sign of disparity in technological maturity. However, technology cycles also vary across sectors and over time in terms of the speed of innovation and level of disruption (Perez, 2003). This is important to take into account to develop the right catch-up strategy. In summary, bringing in the temporal similarity perspective allowed us to identify technology cycles as potential WOO. Catch-up countries seeking to adopt up-to-date technology should consider the size and duration of technological cycles and either wait until the technology regime has stabilized or take the opportunity to exploit new trajectories. In the next section, we go one level deeper to analyze country-specific patterns of technological catch up.

4.3 A closer look at novelty and impact at country level: technology vs. market catchup

After investigating the technological development in both EV and wind and identifying potential technological WOO through technology cycles, we now turn our analysis toward the country level to see how the countries under study responded to the technological WOO on a sectoral level. In the following, we compare market development and technology development.

First, we contrast *patent impact* to the overall *patenting activity* (Figure 5), which reveals interesting differences. In the case of EV, we clearly see the industrial dominance of Japan in terms of patent applications. This is, however, to a considerably lesser extent reflected in terms of technology impact. On the contrary, South Korea indicates high levels of technology impact with various peaks in similarity to the future, which does not appear in its overall patenting activity before 2005. Although Chinese patent applications remain at very modest levels, it shows the first sharp increase in similarity to the future in 2010, getting close to the level of Japan.

[73] Competing designs mainly concern the wind turbine's drive, for example, conventional drive (69%), hybrid drive (3%), direct drive (28; FTI, 2018).

In the case of wind, we generally see less cumulative but cyclic developments. Like EV, patent applications and technology impact speak somewhat different languages. South Korea caused the first spike in the mid-1990s, followed by high-impact events throughout the 2000s. In the case of China, we can observe the country intensifying its patenting activities in mid-2000, particularly in the aftermath of 2006 when the Renewable Energy Law was passed, which broadly correlates with technology impact. However, it is important to note that the vast majority of Chinese patents in wind was filed at the national patent office (SIPO), registering an increase by a factor five between 2005 and 2011 (Hu et al., 2018).

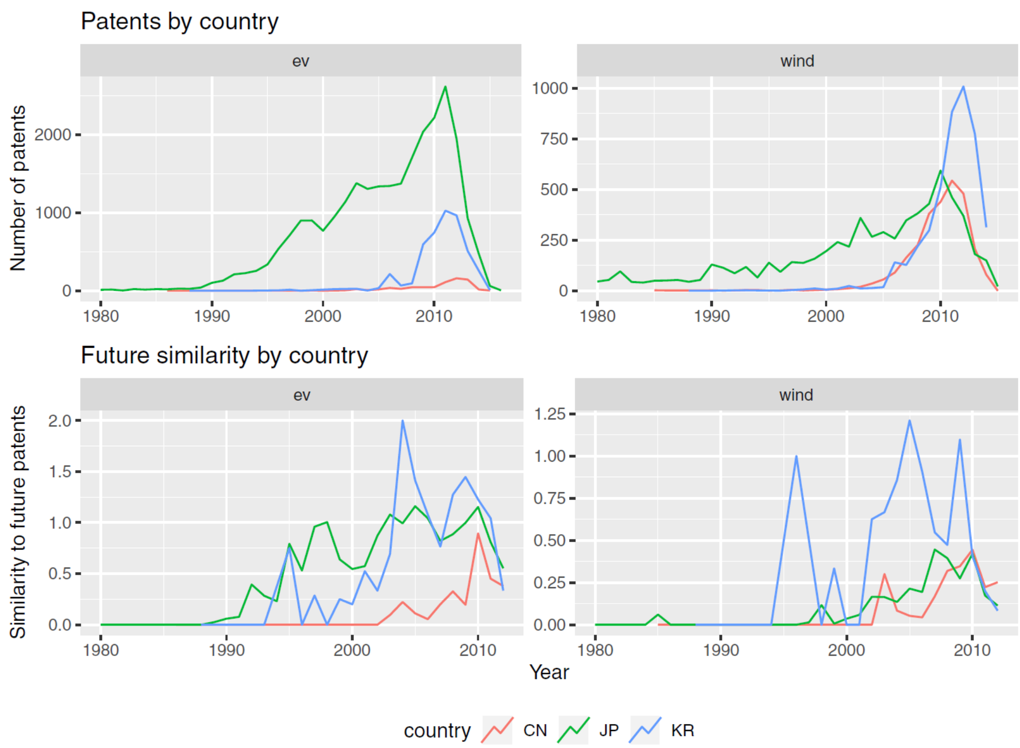

Figure 5. Number of patents and future similarity by country over time

Interestingly, China also shows a first peak in similarity to the future around 2003, which can be seen as an attempt to capture the technological WOO opening on a sectoral level around the same time. The same holds for South Korea, which seemed to be more successful than China in capturing this opportunity. Besides having a more developed industrial base, South Korea also had to rely on the development of offshore technology due to its limited land areas (Lewis, 2012). In a second step, besides technology activity and impact, we turn to compare their relationships with *market development*, which reveals the mix of the countries' catch-up strategies. As stated in Supplementary Appendix SB, institutional support is mainly effective in boosting market development in the short term, while developing and implementing efficient R&D programs requires more systematic and long-term coordination efforts within the NIS. Therefore, based on a country's overall positioning and existing endowments upon entering a new sector, it either focuses on becoming a market or technology forerunner as an initial strategy.

In both sectors, South Korea provided major contributions in terms of high-impact patent knowledge, yet did not really enter the market development and commercialization stage. In EV, Japan—like South Korea—had already an advanced knowledge regime in the mid-1990s and later started the production of the first hybrid solution. With the second spike and opening of a new technological WOO, they entered the market in 2009 and slowly built up their market capacities. Four years later, production started to increase exponentially, reaching 2.3 million EV stock in 2018 (45% global share).

In wind, in contrast, Japan did not manage to create the same level of impact as in EV, despite relatively high levels of patent applications, particularly post-1997. Both Japan and South Korea entered the wind market in the early 2000s. Although Japan had reached the 1 GW threshold 5 years later, South Korea still had minimal market traction (~100 MW). By 2018, Japan had slowly grown to 3.6 GW, while South Korea was still at 1.3 GW. Thus, both countries belong to the group of slowest growing countries among the 30 countries in the world with more than 1 GW cumulative installed wind capacity in 2018 (GWEC, 2019). In contrast, China focused on rapid market growth through a series of institutional support schemes (Lewis, 2012), yet without creating substantial amounts of high-impact knowledge. China tentatively entered the sector in the late 1990s but started its market ramp-up post-2006 with the Renewable Energy Law, which set medium- to long-term targets for wind and provided financial support by setting up the Renewable Energy Fund (IRENA, 2013). Within 4 years after the Renewable Energy law became effective, China had already overtaken incumbent countries such as Denmark, Spain, Germany, and the USA. In 2018, China reached the by far highest levels of installed capacity of 211.3 GW, accounting for 35.7% global market share of (GWEC, 2019).

In summary, all three countries had different strategies with regard to market and technology development. Based on their industrial knowledge endowments when entering the sector, they took either an MT (China) or a TM trajectory (Japan, South Korea).

5. Discussion

In this section, we discuss our key findings, answer the research questions and state some limitations of our article. As we can see in Figure 6, China is pursuing a fast-paced MT trajectory in wind. Particularly post-2012, China has managed to build up its technological capabilities in addition to its rapid market scale up in the previous years. As a result, China has been successfully avoiding the risk of a market trap. However, in order to become a market and technology leader, China needs to further enhance its technological base (e.g. through path creation). At the same time, Japan and South Korea have been quickly building up their technology base (TM trajectory), yet without translating their knowledge into market development. Hence, both countries, especially South Korea, run the risk of tapping into a technology trap and ultimately aborted catch up. According to a recent policy roadmap, South Korea plans to triple the share of renewables in the country's power mix by 2030 (47 GW added capacity), which may constitute a promising institutional WOO for South Korea's wind sector. Meanwhile, Japan's market development is still slowed due unclear and inconsistent policies (GWEC, 2019).

In the EV sector, production started later than in wind. In 2012, only Japan had started its production. Although Korea had accumulated advanced knowledge in this sector, production started later (TM trajectory) and, in 2017, reached a share of 1%. South Korea's decrease in technology development after 2012 can be explained by the sector's fast technology development that is, advanced knowledge became quickly obsolete, thereby allowing for path-creating opportunities. In contrast to South Korea, China's MT trajectory was production-oriented and achieved a high share in 2017, without having advanced technology. Hence, China needs to further increase its technology base to avoid the risk of falling into a market trap.

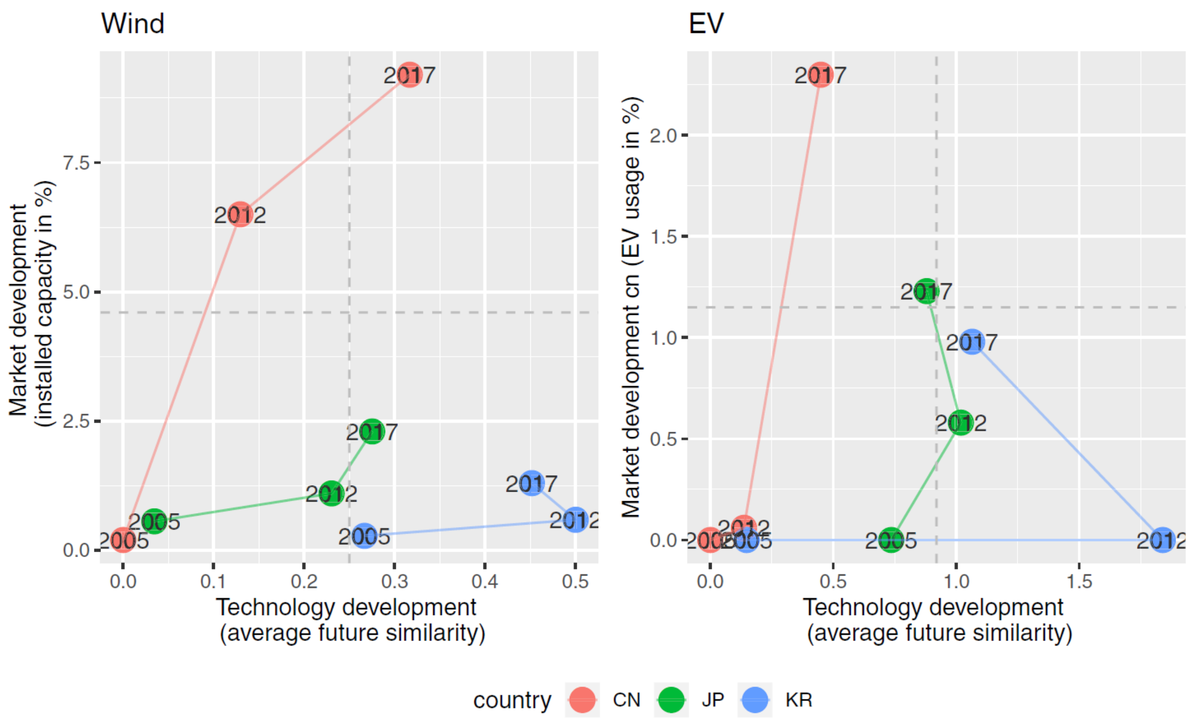

Figure 6. Market vs. technology development in China, Japan and South Korea.

Note. This figure visualizes the market vs. technology development at country level and over time. Market development is operationalized as the share of domestic deployment (EV, electric vehicles to all vehicles; Wind: Wind energy to overall capacity). Technology development represents the average patent sim^{future} over the last 5 years.

One direction could be to build up similar conglomerate structures as have Japan and South Korea. In this way, China could reconfigure its composition of endogenous knowledge sources and shift toward a more enterprise-driven innovation mode, which allows for faster feedback of market needs into the NIS. At the same time, China should strengthen the linkages between scientific knowledge and industrial application. As we can see, Japan and South Korea possess a large amount of high-impact knowledge in both sectors—yet in the wind sector they are not able to exploit them due to limitations in their institutional and market regimes. This calls for more collaboration between the countries under study to leverage market availability and knowledge accumulation for the development of green technologies. Otherwise, countries such as South Korea face a potential technology trap, where strong technological capabilities inhere to the sectoral latecomer but remain insufficiently commercialized.

Our analysis has shown that sector-specificity has important implications for market vs. technology catch up (RQ1). First, sectors vary in terms of innovation modes. Market scale up of a science-based sector (e.g. EV) requires longer ramp-up periods than sectors innovating through DUI modes (e.g. wind). Hence, it is easier for latecomers to create short-term market demand WOO for DUI sectors, particularly in combination with appropriate market regimes (e.g. large domestic markets). In order to enter science-based sectors, systematic and coordinated R&D efforts are required. Second, sectors vary in terms of maturity that is, fluctuations and intervals of technology cycles. Although relatively mature sectors (e.g. wind) allow for path-following and/or stage-skipping catch-up strategies, they also bear the risk of market traps based on outdated technologies. In turn, relatively immature sectors (e.g. EV) may allow for path-creating trajectories reflected in high similarity to the future patents, yet at the risk of aborted catch up and considerable sunk costs if other competing designs prevail. Third, sectors vary in terms of entry barriers. As green sectors compete with conventional technologies (e.g. wind and EV with fossil fuel-based technologies) and are often perceived as high investment risk (e.g. due to high upfront investments and high dependence on policy support schemes), they require stable and long-term institutional WOOs to overcome potential entry barriers.

When entering a new sector, latecomers should consider a number of factors (RQ2). Depending on the factor endowments available within a latecomer's NIS (e.g. institutional, market, technology, and knowledge regimes (Figure 1), either a MT or TM trajectory should be pursued to strive for industrial leadership (Figure 2). In order to avoid aborted catch up, market and technology development must be balanced. We also found that green sectors display (positive) network externalities. The more technologies emerge on the demand (e.g. EV) and supply side (e.g. wind), the more likely new WOO will open. Although EVs provides a technological and market demand WOO for wind, the latter can be considered an important legitimizing technology for EVs, which would otherwise depend on high-emission technologies for electricity generation.

Finally, latecomers should avoid the risk of market and technology traps (RQ3). Latecomer countries considering entrance into a new sector should align their catch-up strategies to the technology cycle and innovation mode of the underlying sector. For instance, when adopting a stage-skipping strategy, technology cycles have to reach a certain level of stabilization. If catch-up countries scale up their market development too fast, yet novel technology cycles unfold within short time intervals, they face the risk of technology lock-in based on outdated technologies. This is of particular importance in the green energy sector (wind), which is characterized by very high asset-specificity and large upfront investments. For sectors such as EV with high fluctuations and co-existing technology regimes, latecomers could opt for the most advanced catch-up strategy, namely creating new paths.

Our analysis also comes with some limitations. In respect of empirical findings, we have to acknowledge that China is in a unique position that allowed the country to employ a catch-up strategy that leveraged the domestic market. Countries that build up a considerable technological knowledge stock but lack a sizable home market can exploit foreign markets and their respective national institutional support schemes. Here, Korean EV exports to western countries are a good illustration. Although its domestic market is just starting to develop, the country has been able to become the world's third-biggest EV net exporter (Supplementary Appendix Table SB5). Such an export-driven strategy relies in part on constant knowledge upgrades to remain competitive as well as being able to adjust to changing contexts in various markets.

This study uses patent data for the technological analysis, and we acknowledge the limitations associated with this data source. The assumption that knowledge encoded in patents is available and used in the respective country is not negligible. In the case of China, it is furthermore important to emphasize an often observed disconnect between substantial (mostly academic) patenting activity and commercialization.

The interpretation of the quantitative analysis relies on reviewing of individual representative patents with high *similarity to the future* scores to qualify observed spikes, and thereby “novel knowledge bases.” This is so far performed manually and thereby the number of patents that can be examined is limited. Future work may go beyond that by incorporating clustering as well as topic modeling techniques to extend and support the qualitative analysis.

Finally, other directions for further methodological expansion include the more detailed evaluation of the signature vector “quality” as well as comparison with other vectorization techniques. Such an evaluation would need to draw on technology expertise to construct a representative baseline dataset of technological relatedness against which it would be able to test different algorithmic language vectorization strategies.

6. Conclusion

This article’s contributions can be summarized in three main points. First, methodologically, we propose a new approach to measure novelty and impact that can be applied to a wide array of empirical contexts. Being built on text data, the approach can be adapted to other types of documents than patents, allowing to draw on broader and more fine-grained data foundations. Second, we propose a nuanced view of catching up, integrating both market and technology development. This perspective allows us to go beyond traditional market leadership inspection and so explore antecedents of industrial catch up. We are able to identify technological WOO as well as the effectiveness of institutional WOO, thus providing a more holistic picture. Finally, we map different catch-up trajectories and identify potential catch-up traps. Based on these novel insights, we are able to provide recommendations on catch-up strategies. There is arguably no one-size-fits-all solution to catching up. Awareness of technology cycles helps us to find the right timing for catch up as well as the right strategy.

As green sectors face considerable entry barriers (e.g. due to perceived investment risk, initially higher energy prices than conventional alternatives) as well as relatively high risk of market traps and technology lock-ins (e.g. deployment of outdated technology), they require substantial government support. Hence, the NIS plays a key role as an enabling constraint in the creation of “Green Windows of opportunity” (GWO) that is, endogenously created support schemes that are stable, strategic and transparent. These should cover both short-term market creation as well as medium to long-term technological capability building (e.g. in the form of mission-guided R&D programs). The success of capturing GWOs depends on how effectively market and technology development can be balanced along catch-up trajectories. If one side is neglected, there is a risk of falling into a market or technology trap and aborted catch up. As the cases of Japan and South Korea have shown, an existing technological base needs to be leveraged with strong market incentives to avoid an aborted catch up. Cross-country collaboration (e.g. “market for technology”) can help balance these catch-up trajectories. If public policy interventions manage to create an enabling environment for green technologies, countries can benefit from considerable network externalities on the supply and demand side, as the cases of wind energy and EV have shown.

The Chinese case shows how successful detours can look like. Nevertheless, due the unique set-up of the country, it does not necessarily illustrate a viable option for other latecomers. There are potential advantages when entering various green sectors due to positive network externalities and the complementary of some green technologies.

Although we can clearly delineate distinct catch-up trajectories, many important questions remain unresolved, which represent limitations regarding the generalization of our findings, but also provide potentially fruitful avenues for future research. First, by carrying out our patent analysis on the inventor level, we focused on the origin of technological competencies as reflected by activity within a specific geography, assuming that such competencies are developed domestically. However, domestic firms might also source knowledge internationally, for example, via cross-border mergers and acquisitions or the establishment of research facilities abroad. Consequently, a comparable examination of patent applicants could augment our analysis by including firm-level responses to technological WOO in terms of international knowledge sourcing. In a similar vein, while we focus on the production of technological knowledge as measured by patent applications, to date we have not analyzed the effect of cross-national knowledge flows and learning in the process of catching up. Our main indicators based on temporal patent-to-patent similarity are by nature relational and therefore could also be used for a network analysis of technological similarity at the country level. This could, for example, give us insights if catching-up countries follow different technological trajectories, and where this knowledge originates.

Acknowledgments

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References

Abramovitz, M. (1986), 'Catching up, forging ahead, and falling behind,' *The Journal of Economic History*, 46(2), 385–406.

Altenburg, T., Schamp E. W. and Chaudhary A. (2016), 'The emergence of electro mobility: comparing technological pathways in France, Germany, China and India,' *Science and Public Policy*, 43(4), 464–475.

Arts, S., Cassiman B. and Gomez J. C. (2018), 'Text matching to measure patent similarity,' *Strategic Management Journal*, 39(1), 62–84.

Awate, S., Larsen M. M. and Mudambi R. (2012), 'Emne catch-up strategies in the wind turbine industry: is there a trade-off between output and innovation capabilities?,' *Global Strategy Journal*, 2(3), 205–223.

Backwell, B. (2017), *Wind Power: The Struggle for Control of a New Global Industry.* Routledge: London.

Basberg, B. L. (1987), 'Patents and the measurement of technological change: a survey of the literature,' *Research Policy*, 16(2–4), 131–141.

Bell, M. and Pavitt K. (1993), 'Technological accumulation and industrial growth: contrasts between developed and developing countries,' *Industrial and Corporate Change*, 2(2), 157–210.

Bernhardsson, E. (2017), 'Annoy: approximate nearest neighbors in c++/python optimized for memory usage and loading/saving to disk,' Python package version 1(0). Retrieved from *https://github.com/spotify/annoy*

Binz, C., Gosens J., Hansen T. and Hansen U. E. (2017), 'Toward technology-sensitive catching-up policies: insights from renewable energy in China,' *World Development*, 96, 418–437.

Binz, C. and Truffer B. (2017), 'Global innovation systems - a conceptual framework for innovation dynamics in transnational contexts,' *Research Policy*, 46(7), 1284–1298.

Bunsen, T., Cazzola P., D'Amore L., Gorner M., Scheffer S., Schuitmaker R., Signollet H., Tattini J. and Teter J. (2019), 'Global EV Outlook 2019: scaling-up the transition to electric mobility,' Technical report, *International Energy Agency.*

Capozza, I. and Samson R. (2019), 'Towards Green Growth in Emerging Market Economies: Evidence from Environmental Performance Reviews. *Organization for Economic Cooperation and Development*, Retrieved from https://www.oecd-ilibrary.org/environment/towards-green-growth-in-emerging-market-economies_d5e5b5d7-en

Castellacci, F. (2007), 'Evolution and new growth theories. Are they converging?,' *Journal of Economic Surveys*, 21(3), 585–627.

Chandy, R. K. and Tellis G. J. (2000), 'The incumbent's curse? incumbency, size, and radical product innovation,' *Journal of Marketing*, 64(3), 1–17.

Chang, S.-H. and Fan C.-Y. (2014), 'Analyzing offshore wind power patent portfolios by using data clustering,' *Industrial Engineering and Management Systems*, 13(1), 107–115.

Coenen, L. and López F. J. D. (2010), 'Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities,' *Journal of Cleaner Production*, 18(12), 1149–1160.

De Rassenfosse, G., Dernis H., Guellec D., Picci L. and de la Potterie B. V P. (2013), 'The worldwide count of priority patents: a new indicator of inventive activity,' *Research Policy*, 42(3), 720–737.

De Rassenfosse, G., Kozak J. and Seliger F. (2019), ‘Geocoding of worldwide patent data,’ *Scientific Data*, 6(1), 1–15.

Deerwester, S., Dumais S. T., Furnas G. W., Landauer T. K. and Harshman R. (1990), ‘Indexing by latent semantic analysis,’ *Journal of the American Society for Information Science*, 41(6), 391–407.

Dosi, G., Freeman C. and Fabiani S. (1994), ‘The process of economic development: introducing some stylized facts and theories on technologies, firms and institutions,’ *Industrial and Corporate Change*, 3(1), 1–45.

Dumais, S. T., Furnas G. W., Landauer T. K., Deerwester S. and Harshman R. (1988), ‘Using latent semantic analysis to improve access to textual information,’ *Proceedings of the SIGCHI conference on Human factors in computing systems.* ACM, pp. 281–285.

Dutrénit, G. (2004), ‘Building technological capabilities in latecomer firms: a review essay,’ *Science, Technology and Society*, 9(2), 209–241.

EIA. (2020), 'History of wind power - energy explained,' *U.S. Energy Information Administration.* Retrieved from https://www.eia.gov/energyexplained/index.php?page=wind_history

Fagerberg, J. (2003), ‘Schumpeter and the revival of evolutionary economics,’ *Journal of Evolutionary Economics,* 13(2), 125–159.

Fagerberg, J., Srholec M. and Knell M. (2007), ‘The competitiveness of nations: why some countries prosper while others fall behind,’ *World Development*, 35(10), 1595–1620.

Ferrucci, E. and Lissoni F. (2019), ‘Foreign inventors in Europe and the United States: diversity and patent quality,’ *Research Policy*, 48(9), 103774–103771.

Figueiredo, P. N. and Piana J. (2016), ‘When one thing (almost) leads to another: a micro-level exploration of learning linkages in Brazil’s mining industry,’ *Resources Policy*, 49, 405–414.

Fink, C. and Miguélez E. (2017), *The International Mobility of Talent and Innovation.* Cambridge University Press: Cambridge.

Flyvbjerg, B. (2006), ‘Five misunderstandings about case-study research,’ *Qualitative Inquiry*, 12(2), 219–245.

Freeman, C. (1987), *Technology Policy and Economic Performance: Lessons from Japan.* Frances Pinter: London.

FTI. (2018), ‘Global wind market update - demand & supply 2017,’ *FTI Intelligence.* Retrieved from https://fti-intelligenceresearch.com/gwmu2017-demand-side-analysis/

Fu, X. (2015), *China’s Path to Innovation.* Cambridge University Press: Cambridge.

Fu, X. and Gong Y. (2011), ‘Indigenous and foreign innovation efforts and drivers of technological upgrading: evidence from China,’ *World Development*, 39(7), 1213–1225.

Fu, X., Pietrobelli C. and Soete L. (2011), ‘The role of foreign technology and indigenous innovation in the emerging economies: technological change and catching-up,’ *World Development*, 39(7), 1204–1212.

Geels, F. W. (2014), ‘Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective,’ *Theory, Culture & Society*, 31(5), 21–40.

Giachetti, C. and Marchi G. (2017), ‘Successive changes in leadership in the worldwide mobile phone industry: the role of windows of opportunity and firms’ competitive action,’ *Research Policy*, 46(2), 352–364.

Guennif, S. and Ramani S. V. (2012), ‘Explaining divergence in catching-up in Pharma between India and Brazil using the NSI framework,’ *Research Policy*, 41(2), 430–441.

GWEC. (2018), ‘Global wind statistics 2017,’ *Global Wind Energy Council.* Retrieved from https://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf

GWEC. (2019), ‘Global wind report 2018,’ *Global Wind Energy Council.* Retrieved from https://gwec.net/global-wind-report-2019/

Hain, D. and Jurowetzki R. (2020), 'Introduction to rare-event predictive modeling for inferential statisticians – a hands-on application in the prediction of breakthrough patents,' *arXiv e-prints*, page arXiv : 2003.13441.

Hain, D., Jurowetzki R., Buchmann T. and Wolf P. (2020), 'Text-based technological signatures and similarities: how to create them and what to do with them,' *arXiv e-prints*, arXiv: 2003.12303.

Hansen, U. E. and Lema R. (2019), 'The co-evolution of learning mechanisms and technological capabilities: lessons from energy technologies in emerging economies,' *Technological Forecasting and Social Change*, 140, 241–257.

Harhoff, D., Scherer F. M. and Vopel K. (2003), 'Citations, family size, opposition and the value of patent rights,' *Research Policy*, 32(8), 1343–1363.

He, H., Jin L., Cui H. and Zhou H. (2018), 'Assessment of electric car promotion policies in Chinese cities,' *International Council on Clean Transportation.*

Helveston, J. P., Liu Y., Feit E. M., Fuchs E., Klampfl E. and Michalek J. J. (2015), 'Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the US and China,' *Transportation Research Part A-Policy and Practice*, 73, 96–112.

Hobday, M. (1995), 'East Asian latecomer firms: learning the technology of electronics,' *World Development*, 23(7), 1171–1193.

Hoeren, T., Guadagno F., Wunsch-Vincent S., (2015), Breakthrough Technologies–Semiconductor, Innovation and Intellectual Property, *WIPO Working Paper No. 27.*

Hu, R., Skea J. and Hannon M. J. (2018), 'Measuring the energy innovation process: an indicator framework and a case study of wind energy in China,' *Technological Forecasting and Social Change*, 127, 227–244.

Huenteler, J., Schmidt T. S., Ossenbrink J. and Hoffmann V. H. (2016), 'Technology life-cycles in the energy sector - technological characteristics and the role of deployment for innovation,' *Technological Forecasting and Social Change,* 104, 102–121.

IRENA. (2012), 'Renewable energy cost analysis - wind power,' *International Renewable Energy Agency.* Retrieved from https://www.irena.org/publications/2012/Jun/Renewable-Energy-Cost-Analysis---Wind-Power

IRENA. (2013), '30 years of policies for wind energy - lessons from 12 wind energy markets,' *International Renewable Energy Agency.* Retrieved from https://www.irena.org/documentdownloads/publications/irena_gwec_windreport_full.pdf

IRENA. (2014), 'Evaluating renewable energy policy: a review of criteria and indicators for assessment,' *International Renewable Energy Agency.* Retrieved from https://www.irena.org/documentdownloads/publications/evaluating_re_policy.pdf

IRENA. (2018), 'Offshore innovation widens renewable energy options: opportunities, challenges and the vital role of international co-operation to spur the global energy transformation,' *International Renewable Energy Agency.* Retrieved from https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_offshore_wind_brief_G7_2018.pdf

IRENA. (2019), 'Renewable capacity statistics 2019,' *International Renewable Energy Agency.* Retrieved from https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019

Jaffe, A. M. (2018), 'Green giant: renewable energy and Chinese power,' *Foreign Affairs*, 97, 83.

Jung, M. and Lee K. (2010), 'Sectoral systems of innovation and productivity catch-up: determinants of the productivity gap between Korean and Japanese firms,' *Industrial and Corporate Change*, 19(4), 1037–1069.

Lall, S. (1992), 'Technological capabilities and industrialization,' *World Development*, 20(2), 165–186.

Landini, F., Lee K. and Malerba F. (2017), 'A history-friendly model of the successive changes in industrial leadership and the catch-up by latecomers,' *Research Policy*, 46(2), 431–446.

Lanjouw, J. O. and Schankerman M. (2001), 'Characteristics of patent litigation: a window on competition,' *RAND Journal of Economics*, 32(1), 129–151.

Larminie, J. and Lowry J. (2012), *Electric Vehicle Technology Explained.* John Wiley & Sons: Chichester, UK.

Lee, K. (2019), *The Art of Economic Catch-Up: Barriers, Detours and Leapfrogging in Innovation Systems.* Cambridge University Press: Cambridge.

Lee, K., Gao X. and Li X. (2016), 'Industrial catch-up in China: a sectoral systems of innovation perspective,' Cambridge Journal of Regions, *Economy and Society*, 10(1), 59–76.

Lee, K. and Lim C. (2001), 'Technological regimes, catching-up and leapfrogging: findings from the Korean industries,' *Research Policy*, 30(3), 459–483.

Lee, K. and Malerba F. (2017a), 'Catch-up cycles and changes in industrial leadership: windows of opportunity and responses of firms and countries in the evolution of sectoral systems,' *Research Policy*, 46(2), 338–351.

Lee, K. and Malerba F. (2017b), 'Theory and empirical evidence of catch-up cycles and changes in industrial leadership,' *Research Policy*, 46(2), 337.

Lema, A. and Lema R. (2013), 'Technology transfer in the clean development mechanism: insights from wind power,' *Global Environmental Change*, 23(1), 301–313.

Lema, R. and Fu X. R. R. (2020), 'Green windows of opportunity? Latecomer development in the age of transformations towards sustainability,' *Industrial and Corporate Change*, 29(5), in press.

Lerner, J. (1994), 'The importance of patent scope: an empirical analysis,' *The RAND Journal of Economics*, 25(2), 319–333.

Lewis, J. I. (2012), *Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low-Carbon Economy.* Columbia University Press: New York.

Li, W., Yang M. and Sandu S. (2018), 'Electric vehicles in China: a review of current policies,' *Energy & Environment*, 29(8), 1512–1524.

Liu, X. (2008), 'China's development model: An alternative strategy for technological catch-up.' *Research Institute of Economy, Trade and Industry.*

Lundvall, B.-A. (1992), *National Systems of Innovation: An Analytical Framework.* Pinter: London.

Malerba, F. (2002), 'Sectoral systems of innovation and production,' *Research Policy*, 31(2), 247–264.

Malerba, F. (2005), 'Sectoral systems of innovation: a framework for linking innovation to the knowledge base, structure and dynamics of sectors,' *Economics of Innovation and New Technology*, 14(1–2), 63–82.

Malerba, F. and Nelson R. (2011), 'Learning and catching up in different sectoral systems: evidence from six industries,' *Industrial and Corporate Change*, 20(6), 1645–1675.

Malerba, F. and Orsenigo L. (2000), 'Knowledge, innovative activities and industrial evolution,' *Industrial and Corporate Change,* 9(2), 289–314.

Markard, J., Raven R. and Truffer B. (2012), 'Sustainability transitions: an emerging field of research and its prospects,' *Research Policy*, 41(6), 955–967.

Mathews, J. A. (2002), 'Competitive advantages of the latecomer firm: a resource-based account of industrial catch-up strategies,' *Asia Pacific Journal of Management*, 19(4), 467–488.

Mikolov, T., Sutskever I., Chen K., Corrado G. S. and Dean J. (2013), 'Distributed representations of words and phrases and their compositionality,' *Advances in Neural Information Processing Systems*, pp. 3111–3119. http://papers.nips.cc/paper/5021-distributed-representations-of-words-and-phrases-and NIPS.

Montobbio, F. and Sterzi V. (2013), 'The globalization of technology in emerging markets: a gravity model on the determinants of international patent collaborations,' *World Development*, 44, 281–299.

Morrison, A. and Rabellotti R. (2017), 'Gradual catch up and enduring leadership in the global wine industry,' *Research Policy*, 46(2), 417–430.

Mowery, D. and Nelson R. (1999), *Sources of Industrial Leadership: Studies of Seven Industries.* Cambridge University Press: Cambridge.

Mu, R. and Fan Y. (2011), 'Framework for building national innovation capacity in China,' *Journal of Chinese Economic and Business Studies*, 9(4), 317–327.

Nahm, J. and Steinfeld E. S. (2014), 'Scale-up nation: China's specialization in innovative manufacturing,' *World Development*, 54, 288–300.

Nelson, R. R. (1982), *An Evolutionary Theory of Economic Change.* Harvard University Press: Boston.

Nelson, R. R. (1993), *National Innovation Systems: A Comparative Analysis.* Oxford University Press: New York.

Nielsen, V. (2017), 'The Danish wind cluster: the microeconomics of competitiveness,' *Harvard Business School.* Retrieved from https://www.isc.hbs.edu/resources/courses/moc-course-at-harvard/Documents/pdf/student-projects/Denmark_Wind_2017.pdf

Nooteboom, B. (2000), 'Learning by interaction: absorptive capacity, cognitive distance and governance,' *Journal of Management & Governance*, 4(1/2), 69–92.

Ou, S., Lin Z., Wu Z., Zheng J., Lyu R., Przesmitzki S. and He X. (2017), *A Study of China's Explosive Growth in the Plug-in Electric Vehicle Market.* US Department of Energy: Oak Ridge, TN, pp. 37831–6283.

Pavitt, K. (1985), 'Patent statistics as indicators of innovative activities: possibilities and problems,' *Scientometrics*, 7(1–2), 77–99.

Pavitt, K. (1988), 'Uses and abuses of patent statistics,' in van Raan, A. (Ed.), *Handbook of Quantitative Studies of Science Policy.* North-Holland, Amsterdam., pp. 509–536.

Pennington, J., Socher R. and Manning C. (2014), Glove: Global Vectors for Word Representation. In *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*, pp. 1532–1543, Doha, Qatar. Association for Computational Linguistics.

Perez, C. (2003), *Technological Revolutions and Financial Capital.* Edward Elgar Publishing: Northampton.

Perez, C. and Soete L. (1988), 'Catching up in technology: entry barriers and windows of opportunity". In G.Dosi et al. eds. *Technical Change and Economic Theory*, London: Francis Pinter, pp. 458-479.

Pilkington, A. and Dyerson R. (2006), 'Innovation in disruptive regulatory environments: a patent study of electric vehicle technology development,' *European Journal of Innovation Management*, 9(1), 79–91.

Pilkington, A., Dyerson R. and Tissier O. (2002), 'The electric vehicle: patent data as indicators of technological development,' *World Patent Information*, 24(1), 5–12.

Proff, H. and Kilian D.. (2012), 'Competitiveness of the EU automotive industry in electric vehicles: final report - study,' *EU publications.* Retrieved from https://op.europa.eu/en/publication-detail/-/publication/a2ea34db-8154-4d3d-9075-e97bf0329e3f

Rasiah, R., Kong X., Lin Y. and Song J. (2012), Variations in the catch up experience in the semiconductor industry in China, Korea, Malaysia and Taiwan in Malerba, F. and Nelson, R. (eds), *Economic Development as a Learning Process: Differences across Sectoral Systems.* Edward Elgar Publishing: Cheltenham.

Robinson, D. (2018), 'Electric vehicles and electricity,' *Oxford Energy Insight*, 36, 1-19.

Rock, M. T. and Toman M. (2015), *China's Technological Catch-Up Strategy: Industrial Development, Energy Efficiency, and CO2 Emissions.* Oxford University Press: New York.

Rodrik, D. (2014), 'Green industrial policy,' *Oxford Review of Economic Policy*, 30(3), 469–491.

Salton, G. and Buckley C. (1988), 'Term-weighting approaches in automatic text retrieval,' *Information Processing & Management,* 24(5), 513–523.

Schmidt, T. S. and Huenteler J. (2016), ‘Anticipating industry localization effects of clean technology deployment policies in developing countries,’ *Global Environmental Change*, 38, 8–20.

Schmitz, H. and Altenburg T. (2016), ‘Innovation paths in Europe and Asia: divergence or convergence?,’ *Science and Public Policy*, 43(4), 454–463.

Shane, S. (2001), ‘Technological opportunities and new firm creation,’ *Management Science*, 47(2), 205–220.

Shi, X., Nallapati R., Leskovec J., McFarland D. and Jurafsky D. (2010), ‘Who leads whom: Topical lead-lag analysis across corpora,’ *NIPS Workshop*.

Shin, J.-S. (2017), ‘Dynamic catch-up strategy, capability expansion and changing windows of opportunity in the memory industry,’ *Research Policy*, 46(2), 404–416.

Squicciarini, M., Dernis H. and Criscuolo C. (2013), ‘Measuring patent quality: indicators of technological and economic value.’ *OECD Publishing*.

Sutskever, I., Vinyals O. and Le Q. V. (2014), ‘Sequence to sequence learning with neural networks,’ *Advances in Neural Information Processing Systems*, pp. 3104–3112.

Torrisi, S., Gambardella A., Giuri P., Harhoff D., Hoisl K. and Mariani M. (2016), ‘Used, blocking and sleeping patents: empirical evidence from a large-scale inventor survey,’ *Research Policy*, 45(7), 1374–1385.

Trajtenberg, M., Henderson R. and Jaffe A. (1997), ‘University versus corporate patents: a window on the basicness of invention,’ *Economics of Innovation and New Technology*, 5(1), 19–50.

UNEP. (2019), 'Emissions gap report 2019,’ United Nations Environment Programme. Retrieved from https://www.unenvironment.org/resources/emissions-gap-report-2019

Wesseling, J., Faber J. and Hekkert M. (2014), ‘How competitive forces sustain electric vehicle development,’ *Technological Forecasting and Social Change*, 81, 154–164.

WIPO. (2017), 'Guide to the international patent classification,’ *World Intellectual Property Organization*. Retrieved from https://www.wipo.int/publications/en/series/index.jsp?id=183

WIPO. (2019), 'IPC green inventory,’ *World Intellectual Property Organization*. Retrieved from https://www.wipo.int/classifications/ipc/en/green_inventory/index.html

Yoon, B. and Park Y. (2004), ‘A text-mining-based patent network: analytical tool for high-technology trend,’ *The Journal of High Technology Management Research*, 15(1), 37–50.

Supplementary Appendix

A: Methodological Appendix (SA)

This section provides a detailed technical description of the text vectorization, largescale semantic similarity and indicator calculation. The method is exhaustively described and verified in Hain et al. (2020), to which refer for further information.

From patent to vector: Natural Language Processing

To express the technological signature of a patent based on textual data in a way that is suitable for our analysis, we have to assume that every patent can be represented as a vector v in some vector space $V \in \mathrm{R}^n$ such that the vectors satisfy two properties: composability and comparability. Vectors must be composable so that we can compute a signature vector for every patent, which can be manipulated using vector algebra, for instance, to compute an average vector for an aggregated higher-level entity such as a firm, technology, or country. In addition, such vectors need to be comparable, so that for any pair of vectors $\vec{\imath}$ and $\vec{\jmath}$, a robust similarity score $s(\vec{\imath},\vec{\jmath})$ can be computed. If such a vector indeed represents the technological properties of a patent accurately, the resulting similarity score $S_{i,j}$ provides a dyadic measure of technological relatedness, which can be used for static mapping but also dynamic analysis.

Given a relatively high number of patent abstracts, we need to identify an efficient approach to generating numeric representations of the patent text that preserve its semantic features. There are several approaches to doing this, thanks to the rapid development of new methods in recent years. The most basic approach would be to represent individual abstracts as bag-of-words or word-co-occurrence vectors, i.e. an array of dummies, or weighted for generality and specificity of the utilized terms, e.g. by using TF-IDF (Salton and Buckley, 1988). Even now, such a simple weighting scheme and the representation of patent abstracts as a sparse matrix can be powerful. While scholars and industry have for some time been utilizing dimensionality reduction techniques such as latent semantic indexing (LSI, Deerwester et al. (1990); Dumais et al. (1988)) to get useful document representations, more recently word embedding approaches, e.g. Word2Vec (Mikolov et al., 2013) or GloVe (Pennington et al., 2014) have gained traction. Here, the model learns term meanings from the context that surrounds the term rather than merely within-document co-occurrence. Training of such models on large datasets enables us to account for syntax and to extract higher-level meaning structures for terms. Summing and averaging such word vectors has proven to generate good document representations. While we are aware of and have been experimenting with more advanced approaches such as Sequence2Sequence models based on auto encoder architectures composed of recurrent neural networks (e.g. Sutskever et al., 2014), in this paper we use a simpler approach that we expect to emphasize semantics, i.e. technological content over other linguistic features. This choice is in part motivated by the assumption that patent text, being formal and aiming at codification of contents rather than writing style, carries less information in its syntax.[74]

[74] In machine learning and related domains, new methods that are meant to automate some human tasks are usually evaluated in comparison with human performance. Computer vision methods are, for instance, evaluated on the basis of image datasets

For the present analysis, we represent patent abstracts as TF-IDF weighted word embedding averages, which means that each patent is represented as the average vector of contained terms, accounting for their specificity or generality. To calculate such abstract representations, we first train a custom word embedding model using the Word2Vec approach[75] on approximately 48m English patent abstracts found in PATSTAT.
We train this custom model instead of using generic word embeddings due to the arguably specific language found in patent descriptions. In addition, we train a simple TF-IDF model on the whole corpus of patent abstracts. Abstract embeddings are obtained by taking the dot product of the word-embedding matrix with the dense TF-IDF weighted bag-of-word representations of the abstracts.

We evaluated the produced vectors on the task of automated IPC symbol classification on sub-class level for the first mentioned class—a multiclass prediction problem with 637 outcome classes in our sample. We trained an artificial neural network on 9,471,069 observations that explicitly mention one of the symbols as "first" and evaluated on 100,000. The classifier achieved a weighted accuracy of 54% and weighted recall of 53% meaning that it was able to detect the right sub-class out of 637 possible answers for over half of the patents in the test set. Since we only fitted the model on the first symbol, there is a chance that the misclassified vectors belong to other symbols mentioned for a given patent. However, we did not further investigate that, as the results were convincing given the complexity of the task and the fact that the created vector representations were not intended to be used for classification.

From vector to similarity: Approximate Nearest Neighbor Search

After creating a signature vector for every patent, we attempt to identify for every one of those the patents that exhibit the highest (semantic) technological similarity. The most precise but also naive approach is a brute-force nearest neighbor search where a similarity score (e.g. Euclidean distance) for each pair of observation is calculated for instance by taking the dot product of the document matrix and its transpose.

In the present case, such an approach would be technically infeasible. Efficient nearest neighbors computation is an active area of research in machine learning and one of the common approaches to this problem is using k-d trees that partition the space to reduce the required number of distance calculations. Search of nearest neighbors is then performed by traversing the resulting tree structure. Utilizing such an approach can reduce complexity to $O[DNlog(N)]$ and more. In our case, this would leads to an efficiency increase by a factor of at least $1.12e^4$. We utilize the efficient *annoy* (Approximate Nearest Neighbor Oh Yeah!, Bernhardsson (2017))[76] implementation that constructs a forest of trees (100) using random projections. In the next step we calculate the cosine similarity between focal patent and all other patents to be found in neighboring leaves of the search tree, where we discard patents-pairs with a cosine similarity beyond the threshold of 0.35.

annotated by humans. To evaluate the performance of text representation methods in the present case, one would similarly need an expert annotated dataset that goes beyond existing classifications. Unfortunately, for now, such a benchmark dataset does not exist.

[75] Python's Gensim library (Rehurek, 2010) is used for the training https://radimrehurek.com/gensim/

[76] Extensive documentation of the *annoy* package can be found here: https://github.com/spotify/annoy

$$sim^{cosine}(x, y) = \frac{x^T y}{||x|| \cdot ||y||} \tag{A.1}$$

We evaluate the comparability of the embedding vectors, and consequently the quality of the calculated dyadic measure of technological similarity between patents, in multiple ways. First, we compare different samples of patent-parts that could intuitively be expected to display on average a higher (lower) similarity. To start with, we assume that technological similarity should be more pronounced within technological domains, as approximated by technological classifications such as technological fields, IPC or CPC categories. On average, patents within the same IPC class display a significantly higher similarity than patents from different classes. This has been evaluated by randomly matching every patent with another one within the same IPC class as well as one in a different IPC class. As a result, patents sharing an IPC class display an increased magnitude of similarity by a factor of roughly 3, which increases when repeating the same exercise on subclass (5), group (7) and subgroup (8) level. Similar results are obtained when using the CPC classification scheme instead. Sharing multiple classes further increases our similarity score. Repeating this procedure on inventor and applicant level leads to similar results. Within IPC classes, similarity is also higher for patents applied closer in time, where similarity sharply drops by around 30% comparing patent applications in the same year with the following one. This effect continues over time, making patents within the same IPC class published more than seven years apart not significantly more similar than patents from different classes.

In addition, we investigate the relationship between patents linked by forward or backward citations with their similarity. Backward citations refer to relevant prior art, consequently a pair where one patent cites the other should on average display a higher technological similarity than the pair where this is not the case. We therefore retrieve all citations to prior art, and compare the similarity scores of the resulting patent pairs with a random sample of equal size where the patents do not cite each other. The results indeed show that patent pairs connected by a backward citation show on average a 50 times higher similarity score. However, the average similarity of citing patents is with ca 7% still low and highly skewed, where around 70% of patents citing each others do not display meaningful similarity. Likewise, the Pearson correlation coefficient between citation and similarity of a patent pair is with 0.05 low but statistically significant at the 1% level.[77] Yet there are many patent pairs with high similarity scores that do not cite each other (and *vice versa*), supporting our argument that citations may offer a too restrictive measure for technological similarity. It further raises the question, what exactly is the information regarding the relationship of two patents represented in a citation.

From similarity to patent-level indicators

Our resulting similarity index between patents based on the semantic of the patent abstracts appears valuable in its own right, since it offers a nuanced measure of relatedness which is in contrast to citations not dependent on explicit mentioning by the author or patent office. As a

[77] Similar results with slightly higher average similarity and higher correlation are obtained when only limiting ourselves to X and Y tag citations, and citations added by the examiner.

dyadic measure, the derived semantic similarity can also be used to create patent networks, as we demonstrate later. Such a relational representation offers the potential to visually map technological fields and their development, derive further network related measures such as degree centrality, betweenness, and perform relational clustering exercises.

However, to develop a measure of patent quality, novelty and impact, we exploit the temporal properties of our similarity measure. Therefore, for every patent i, the set of mostly semantically similar patents $Ji[1 : m]$ will contain patents j with earlier as well as later application dates. With that information, we construct a temporal similarity index on patent level as follows:

$$sim_i^{future} = \sum_{j=1}^{m} \frac{\{\Delta t_{j,i} > \tau\}\ s_{i,j}}{m} \tag{A.2}$$

Consequently, sim_i^{future} represents patent i's share of similar patents with application date in the future, weighted by their similarity $s_{i,j}$. The parameter r represents the time delay after which a patent j is considered to be in the future. To offset the delay between patent application and the official publication of 6 to 12 months (Squicciarini et al., 2013), we set $r = 1$, meaning that patents with application date more that a year after the focal patent are considered as laying in the future. Likewise, sim_i^{past} represents patent i's share of similar patents with application date in the past, weighted by their similarity $s_{i,j}$.

$$sim_i^{past} = \sum_{j=1}^{m} \frac{\{\Delta t_{i,j} > \tau\}\ s_{i,j}}{m} \tag{A.3}$$

B: Supplementary Tables (SB)

Table SB1. IPC classes EV

IPC class	Level	Description
B60L 11/00	Subgroup	Electric propulsion with power supplied within the vehicle
B60L 11/02	Subgroup	Using engine-driven generators
B60L 11/04	Subgroup	Using dc generators and motors
B60L 11/06	Subgroup	Using ac generators and dc motors
B60L 11/08	Subgroup	Using ac generators and motors
B60L 11/10	Subgroup	Using dc generators and ac motors
B60L 11/12	Subgroup	With additional electric power supply, e.g. accumulator
B60L 11/14	Subgroup	With provision for direct mechanical propulsion
B60L 11/16	Subgroup	Using power stored mechanically, e.g. in flywheel
B60L 11/18	Subgroup	Using power supplied from primary cells, secondary cells, or fuel cells

Table SB2. IPC classes wind

IPC class	Level	Description
F03D	Class	Wind energy
H02K 7/18	Subgroup	Structural association of electric generator.
B63B 35/00	Subgroup	Structural aspects of wind turbines.
E04H 12/00	Subgroup	Structural aspects of wind turbines.
F03D 11/04	Subgroup	Structural aspects of wind turbines.
B60K 16/00	Subgroup	Propulsion of vehicles using wind power.
B60L 8/00	Subgroup	Electric propulsion of vehicles using wind power.
B63H 13/00	Subgroup	Propulsion of marine vessels by wind-powered motors.

Table SB3. Main policies by country

	CN	JP	KR
WIND	Plan for Science and Technology (1991) Plan for Renewable Energy Development (1996, 2001) National Renewable Energy Law (2005) 863 Wind Program (2006) Plan for Wind Power Science and Technology (2011)	Long-term purchase menus for renewable power by electric company (1997) Kyoto Protocol (1997) Voluntary "green power fund" (2000) Renewable Portfolio Standard law (2002)	NRE Development, Utilization, and Deployment (1972) National energy plan (2006) Green New Deal (2009)
	TIF: USD 0.051 - 0.06 KWh (2003-09)	TIF: USD 0.23 - 0.61 KWh (2012)	TIF: USD 0.105 KWh (2001-10)
EV	Research on the Key Technologies of EVs (1991) National Clean Vehicle Action program (1995) EV Key Project - 863 (2001) Alternative Fuel Vehicles Key Project-863 (2006) Plan on Shaping and Revitalizing the Auto Industry (2009) The Ten Cities, Thousand Vehicles Program (2009) NEV Industry Development Plan (2012)	Government-industry RD programme (1971) Internal company RD (1978) New Sunshine Programme (1992) Public procuremenet (1995) Clean-Energy Vehicles Introduction Programme (1998)	Law for Eco Friendly Cars RD (2004) Eco-Friendly Car Master Plan (2005) Law for Low Carbon Green Growth (2010) Green car Industry Stimulating plan (2010) Law for Sustainable Transport Development (2011)

Source: Åhman (2006); Chen et al. (2014); He et al. (2018); Kyu Hwang et al. (2015); Lewis (2011)

Table SB4. Wind market figures

	Installed Capacities (MW)			Global share		
	2006	2012	2018	2006	2012	2018
China	2599	75564	211392	3.5%	26.8%	35.7%
Japan	1309	2614	3661	1.8%	0.9%	0.6%
Korea	176	483	1302	0.2%	0.2%	0.2%
World	74151	282482	591549			

Source: EPI - Earth Policy Institute (2016); GWEC (2019)

Table SB5. EV market figures

	EVs stock			EVs sale			EVs share		Trade in 2018*		
	2009	2012	2018	2009	2012	2018	2012	2018	Im	Ex	Net EX
China	0.48	16.88	2306.30	0.48	9.90	1078.53	0.16%	4.74%	$1200	$129.8	-$1070.2
Japan	1.08	40.58	255.10	1.08	24.44	49.75	0.58%	1.13%	$69.8	$389.4	$319.6
Korea	NA	0.85	59.60	NA	0.51	33.68	NA	2.21%	$231	$1100	$869
World	7.48	182.82	5122.46	2.32	118.68	1975.18	0.09%	1.21%			

Note: In thousand EVs. *In million USD

Source: Bunsen et al. (2019); Workman (2019)

Article II

Catching up through green windows of opportunity in an era of technological transformation: Empirical evidence from the Chinese wind energy sector

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Abstract

Recent transformations in the global wind energy industry have considerable implications for firms to catch up as the sectoral frontier advances from on- and offshore wind turbines towards digital/hybrid systems. These technological shifts potentially precipitate new green windows of opportunity. This article finds that latecomer firms show different capabilities in responding to technological transformation at the global level, which explains variations in catch-up trajectories under the same framework conditions.

Keywords: Catch-up trajectories, windows of opportunity, technological transformation, wind power, latecomer firms, China

JEL codes: O31 (Innovation and Invention: Processes and Incentives), O33 (Technological Change: Choices and Consequences), Q20 (Renewable Resources and Conservation), Q55 (Technological Innovation), L10 (Market Structure, Firm Strategy, and Market Performance), L60 (Industry Studies: Manufacturing), R58 (Regional Development Planning and Policy)

1. Introduction

The global economy is experiencing profound transformation. In light of environmental degradation associated with massive economic growth, especially the threat of climate change, many countries around the world are shifting their energy systems towards low-carbon technologies. Along with this green transformation, the fourth industrial revolution is shaking up sectoral boundaries and business models. Traditional industry classifications are increasingly challenged by new hybrid forms such as smart cities, the industrial Internet of Things (IoT), and additive manufacturing. Green and digital transformations are moving technological frontiers and opening up new windows of opportunity both for firms specialized in renewable energies and for new entrants (Lema et al., 2021).

The wind energy sector provides a good example of both transformations in play. The production and deployment of wind turbines has grown exponentially since the 2000s, from a niche to a mainstream and even least-cost energy source in two-thirds of the world (Global Wind Energy Council [GWEC], 2019a). By 2050, wind is expected to supply half of the world's electricity needs together with solar photovoltaics (PV; International Renewable Energy Agency [IRENA], 2018)). Yet, the global wind turbine sector is transitioning to a techno-economic paradigm characterized by digitalization and hybridization, thus fundamentally challenging previous industry dynamics (IRENA, 2019; UNCTAD, 2019). Data analytics and other software-as-a-service (SaaS) solutions based on machine learning, artificial intelligence (AI), and the IoT represent the new technological frontier in the wind turbine industry. The number of wind patents filed using words like "big data," "deep learning," or "algorithm" have soared in recent years. In order to realign their technological in-house capabilities, lead firms have acquired analytics start-ups and initiated strategic collaborations with leading tech and digital consulting firms such as Apple, Microsoft, and Accenture.

This redirection of the economy provides significant opportunities for latecomer countries and firms. Since the 2000s, large developing and emerging economies have been rapidly catching up in renewable energy industries like wind (Zhou et al., 2016; Quitzow et al., 2017; IRENA, 2019). Chinese firms especially have been at the forefront, challenging incumbents from Europe and the USA in unprecedented ways. Although Chinese firms were absent from the global top 15 wind turbine manufacturers in 2000, they held eight of the top 15 positions in 2018 (see Appendix Table A1). Existing scholarship has largely attributed China's rise in wind power to windows of opportunity related to industrial policies for market creation (Jiang, 2007; Lewis, 2013; Lema et al., 2013; Ding and Li, 2015; Fu, 2015; Mathews and Tan, 2015; Chung-Fung Chen, 2016; Daisuke et al., 2018; Haakonsson and Slepniov, 2018; Haakonsson et al., 2020). Yet, market expansion does not necessarily lead to indigenous technological learning (Altenburg et al., 2008; Hain et al., 2020; Quitzow et al., 2017). It may take much longer for emerging market firms to gain technological capabilities. It is no surprise then that China's catch-up predominantly builds on known technologies within the well-established market segment for small- and medium-sized turbines (Appendix Table A2 shows market leaders per size of turbines). In addition, Chinese firms mainly supply the domestic market, which is the largest since 2009 and represents 35% of the world's installed capacity today (GWEC, 2018). However, some Chinese firms have also managed to narrow the technology gap with incumbent firms by following different strategies as a response to technological shifts at a global level.

This article empirically investigates the relationship between technological change at the global level and varieties of catch-up responses by latecomer firms. It analyses how different types of firm operating under the same framework conditions follow different catch-up trajectories, thereby highlighting inter-firm diversity. The recent transformations and their implications for emerging market firms to move from a path-following or path-skipping to a path-creating catch-up trajectory have not been thoroughly investigated in the existing literature. Against this background, this article addresses the following research questions:

> *How does technological transformation open green windows of opportunity that affect latecomers' possibilities for catching up? What strategies can latecomer firms develop to respond effectively to technological shifts?*

The article is organized as follows. Section 2 reviews the literature and introduces the concepts of windows of opportunity and technological regime to analyze the implications of technological transformation for firm-level catchup. Section 3 presents the data collection and research methods for the present study. Section 4 gives an overview of China's wind energy policies as institutional responses to windows of opportunity in the wind turbine industry. Section 5 presents the empirical evidence of how incumbent and Chinese wind turbine manufacturers are responding to the new technological frontier. It identifies different firm-level trajectories for technological catch-up due to a combination of company strategy, sectoral evolution, and technological innovation. Section 6 draws conclusions and identifies future research needs.

2. Implications of technological change for latecomer development and industrial leadership

Technological change is a continuous process that can trigger deep structural transformations (Perez and Soete, 1988). The degree of technological change and level of disruption to an existing knowledge base is closely linked to the notion of "technological (learning) regimes" (Breschi et al. 2000). The factors underpinning a technological regime in which innovative activities are organized and structured can change both across and within industrial sectors (Pavitt, 1984; Mu and Lee, 2005; Malerba and Nelson, 2011). Profound changes within technological regimes can trigger changes to the technological frontier and, in case of major change, new techno-economic paradigms, which constitute "radical discontinuities in overall technological evolution" (Perez and Soete, 1988: 460). Hence, sectoral shifts in the technological frontier are highly relevant events in the context of catch-up and industrial leadership change since they may open new windows of opportunity for latecomers. Profound and competence-destroying technological shifts are likely to change the position of key actors in a given industry and can even lead to a situation where incumbents and latecomers find themselves at the same starting line (Lee, 2019). This section introduces the theoretical and conceptual framework for understanding how technological shifts and an accelerating technological frontier affect catch-up opportunities and what strategies latecomer firms can develop to respond effectively to them.

2.1 Catch-up cycles and industrial leadership changes

The reasons why some established firms lose their market dominance to industry latecomers has been subject to a plethora of scientific studies and debates (Perez and Soete, 1988; Lee, 2005; Mathews, 2006; Christensen, 2016; Lee and Malerba, 2017). In order to analyze the conditions under which effective technological catch-up of latecomers takes place, we have to first understand the driving forces behind the process of catch-up (Perez and Soete, 1988). Lee and Malerba (2017) developed a framework for understanding why and how successive changes in industrial leadership occur among different geographies over time. They define catching up as "the process of closing the gap in global market share between firms in leading countries and firms in latecomer countries" (p. 339). A prominent example of such a change in industrial leadership is the memory chips industry, where leadership shifted from the USA to Japan in 1982 and from Japan to South Korea in 1993 (Shin, 2017).

According to the catch-up cycle literature, there are three conditions under which catching up and potential changes in industrial leadership are likely to occur, also referred to as "windows of opportunity." These windows are temporary openings and constitute changes in technology, in market demand, and/or in institutional regimes (Lee and Malerba, 2017; see also Perez and Soete, 1988; Lee and Ki, 2017). Windows vary in scope and often occur unexpectedly. Consequently, there is no guarantee that latecomer firms will catch up once a window appears (Malerba and Nelson, 2011; Landini et al., 2017; Lee and Malerba, 2017). More precisely, the ability to capture a window of opportunity depends on responses at the national and firm levels as well as the capabilities of the wider innovation ecosystem (Freeman, 1987; Lundvall, 1992; Malerba, 2005). In this context, Sun and Yang (2013) emphasize the superior learning abilities of latecomer firms. They view firms' absorptive and transformative capabilities through effective learning processes as the driving forces behind effective catch-up. This aligns with Malerba and Nelson (2011), who view catch-up inherently as a learning and capability-forming process. Analogous to Lee (2018), they argue that latecomers have to reach a stage in which they create and export new types of knowledge, products, and technologies in order to successfully close the catch-up gap.

Depending on national responses and firm capabilities, latecomers can pursue a path-following (adopting first generation technology), path-skipping (adopting up-to-date technology), or path-creating (exploring new technological trajectories) strategy (Lee, 2019; Lee and Lim, 2001). Hence, latecomers can have advantages over incumbent firms as the "arrival of a new techno-economic paradigm can serve as a pull factor for leapfrogging" (Lee, 2005: 97). Leapfrogging (used here synonymously with path creating) occurs when emerging market firms have the opportunity to jump to the technological frontier and create new paths as they may "bypass heavy investments in previous technology systems" (Lee and Lim, 2001: 460). Besides these endogenous responses at national and firm levels, the ability to effectively respond to windows of opportunity opening at a global level is highly sector-specific. As elaborated in Section 2.2, sectors show considerable differences in their underlying innovation patterns, which have important implications for the catch-up potential of latecomer firms.

2.2 Sector-specificity of catching up: technological regimes and Schumpeterian patterns of innovation

Innovation patterns vary across industrial sectors. This can be explained using the concept of "technological regimes" (Breschi et al., 2000), herein defined as the "particular combination of the knowledge base, common to specific activities of innovation and production and shared by the population of firms undertaking those activities" (van Dijk, 2000: 173). Consequently, each industrial sector consists of an idiosyncratic combination of knowledge. The literature on technological regimes is concerned with the relationship between the nature of the technological (knowledge) environment and the intensity of innovation (Nelson and Winter, 1982; Breschi et al., 2000).

Four factors underpin a technological regime: technological opportunities (ease of innovation with a given amount of resources), cumulativeness of knowledge (likelihood of innovating along specific trajectories), appropriability of innovations (ease of extracting profits from innovative activities), and the knowledge base (relevance of existing knowledge; Breschi et al., 2000). These vary across industries, but more importantly they can change over time within a given industry (Ufuah and Utterback, 1997), thereby providing new catch-up opportunities for latecomers. For example, cumulativeness of knowledge is a result of time and experience by intensifying research and development (R&D) into specific technologies. The higher the cumulativeness of knowledge, the harder it becomes for latecomers to reach the technological frontier. However, if cumulativeness is low, it is easier to leapfrog into a path-creating catch-up trajectory. With regard to the knowledge base, the more generic the characteristics of the technological regime, the easier firms from other industries can diversify into the given sector. If the knowledge base of an industry is very specific, it takes time for latecomers to build the ecosystem of innovation required for path-creating catch-up—especially if the technological complexity is high as it is in wind turbines (Huenteler et al., 2016).

Building on the Schumpeterian tradition, two distinct patterns of sectoral innovation have been identified: Schumpeter Mark I (SM-I) and Schumpeter Mark II (SM-II) (Breschi et al., 2000). SM-I is characterized by innovation patterns that lead to creative destruction. Here, innovation predominantly comes from firms that were not previously involved in innovation in the industry. Therefore, this form of industrial innovation leads to a “widening” as new firms take over the technological frontier. In SM-II the opposite is the case. Innovation is generated through a continuous specialization of existing lead firms within the industry engaged in continuous development of innovative activities. This process is referred to as “deepening” (Malerba and Orsenigo, 2000).

The technological regime underlying a specific sector sets the framework conditions for catch-up possibilities of latecomer firms (Jung and Lee, 2010; Malerba and Nelson, 2011). Industries within the SM-I innovation pattern see new entrants moving into lead positions more regularly, which allows for path-creating catch-up. In turn, technological specialization in SM-II is much higher. Here, established lead firms tend to be the drivers of technological change and the position of the lead firm is closely linked to this “deepening” pattern of innovation. Hence, in SM-II industries, catch-up trajectories are dominated by path-following and path-skipping catch-up strategies.

2.3 The heterogeneity of catching up: inter-firm variations of latecomer responses

The responses of latecomer firms to global technological shifts evolve differently across geographies and time due to differences in institutional responses and firm capabilities. Yet as the technological frontier moves, technologies are often not mutually exclusive, but rather co-existing elements, particularly in industries characterized by high levels of cumulative knowledge. Consequently, a sector may encounter multiple generations of co-existing technologies. For example, a shift in the technological frontier may open a new window of opportunity for latecomer firms to take leadership in an established technology while incumbents move into a new one. However, the time lag between shifts at the global level and responses by latecomer firms may decrease over time due to increased technological firm capabilities and potentially higher appropriability of the latecomers (Malerba and Orsenigo, 2000). Latecomers may also catch up into a newly emerging technology as the technological frontier advances, yet follow different innovation paths to other firms, for example, by focusing on product and/or service niches. Therefore, latecomer firm responses within the same country and under the same framework conditions can be highly heterogeneous. For example, while some firms may pursue a path-skipping strategy and adopt technology from a preceding technology, other firms within the same national economy may focus on creating their own paths along the technological frontier. Likewise, firms developing capabilities within the same technology may not follow similar innovation paths (Dosi, 1982; Leiponen and Drejer, 2007).

2.4 Analytical framework: technological shifts and latecomer responses

The catch-up trajectories of emerging market firms are embedded at different levels and over time. Global and exogenous dynamics of technology shifts generate technological windows of opportunity for catch-up. However, realizing catch-up depends on endogenous industrial dynamics; that is, the responses at the national and firm levels—here, a combination of policies and dynamic capabilities. Windows of opportunity related to technologies emerge at the global level as the technological frontier changes. Whether the catch-up strategy is to follow, skip, or create paths is linked to the technological regime and the specific underlying factors found therein for a given technology. These factors are likely to change across paradigms and within a paradigm over time.

Figure 1 illustrates how shifts in technologies and the changes in technological frontier from one technology to another (vertical axis) opens windows of opportunity for latecomers to take different catch-up trajectories (still requiring effective responses). The solid line illustrates the sectoral evolution through the maturing processes of three consecutive technological frontiers (T1–3). The three catch-up paths are illustrated: following, skipping, and creating. Catch-up is seen where latecomers close in on sectoral evolution timewise (horizontal axis). An additional trajectory relates to firms that did not react to changes and are not on the catch-up path (aborted catch-up). The shifts can be different in nature as the degree of change in the four underlying factors differs (see Section 2.2). Moreover, some technological shifts are more radically changing the conditions in a given technological regime. Although a shift in the technological trajectory constitutes a change within a given cluster of possible technological directions, a shift in the technological paradigm redefines the outer sectoral boundaries (Dosi, 1982). Hence, the latter represents a radical change to the technological frontier that potentially links to a new techno-economic paradigm (Perez and Soete, 1988). This is highly relevant, since understanding catch-up as radical change in these factors challenges sectoral boundaries and requires extra-sectoral knowledge (see Fu et al., 2011).

For green sectors the evolution of the technological frontier and the opening of technological windows of opportunity are largely shaped by strong institutional support for a green transition. Therefore, they are not exclusively technological but also "green windows of opportunity" (see introduction to this special issue, Lema et al., 2021). Nevertheless, the green technologies compete with conventional technologies and face strong entry barriers. For example, renewable energy technologies require considerable upfront investment and concurrently benefit from relatively low and stable operating costs, which diverges from traditional business models in the energy sector (Ajadi et al., 2019).

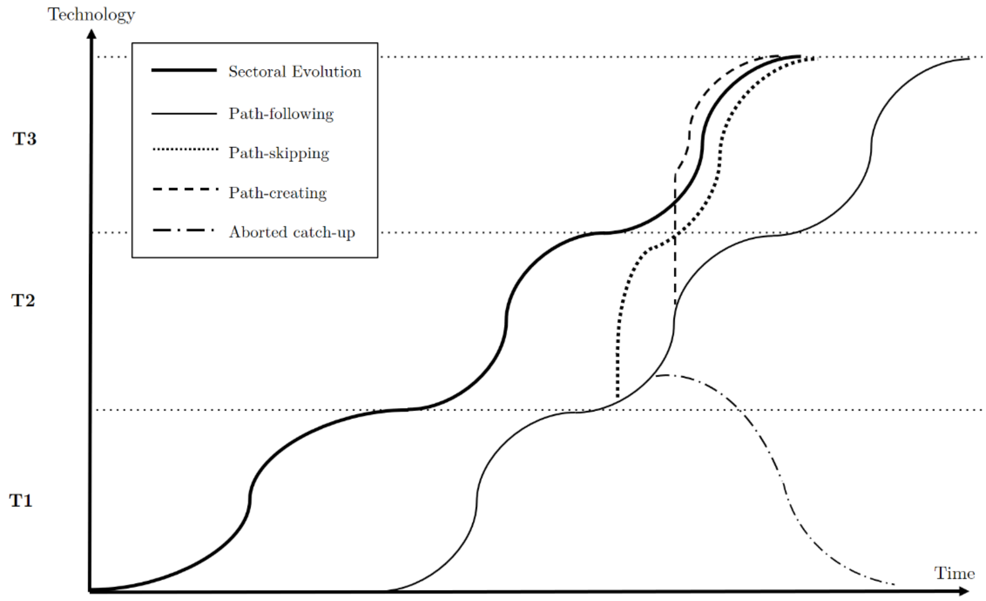

Figure 1. Catch-up trajectories in shifting technologies (T1-3)

3. Data collection and research methods

For our empirical study, primary data were collected in the form of 178 semi-structured interviews in several rounds of fieldwork between 2014 and 2019 in Denmark, Germany, and China with wind turbine original equipment manufacturers (OEMs), component suppliers, utilities, project developers, licensing and engineering firms, government agencies, research institutes, industry associations, and consultancies. All wind turbine OEMs and suppliers interviewed are either headquartered in China or have a Chinese branch. To gain a balanced view between different firms and their subunits, we interviewed different departments and at different locations, including international subsidiaries and R&D hubs. In addition, we discussed interview observations with multiple experts from industrial associations and consultancies, as well as specialized engineers and researchers in the field. Questions covered both macro-level topics such as industry trends and public policies and specific micro-level questions on the firms' market, technology and innovation strategies, R&D collaboration, main challenges, and future prospects. To enhance internal validity, the authors independently analyzed the interview material before discussing it. Reliability of our findings was ensured as all interviews were transcribed, coded, and triangulated with external sources.

Secondary data were collected and analyzed at different stages and with different objectives. In order to identify technological shifts, we systematically scrutinized a wide range of both qualitative and quantitative data: patent applications, onshore/offshore statistics, mergers and acquisitions (M&A) activities, and industry and company reports. Relevant data sources were the European Patent Office (EPO), Bloomberg Terminal, FTI Intelligence, GWEC, IRENA, Chinese Wind Energy Association (CWEA), and Crunchbase.

As the development of digital/hybrid technologies in the wind sector (T3) is still in its nascent stage, we could not draw upon deployment statistics as we could for onshore and offshore wind. Therefore, we retrieved patent data from EPO's Espacenet (version 1.10.0) and created a search code based on the International Patent Classification (IPC) for T3 (see Table 1). In line with our definition of T3, we include all patents related to both "wind motors" (IPC class F03D) and "computing, calculating, counting" (IPC class G06) or "wind motors" and "energy storage" (IPC class H01M), as well as all "hybrid wind-PV energy systems" (IPC class H02S10/12). For our patent analysis, we included all pending and granted patent applications to minimize the time lag since the filing of the application. We consider patent applications from all patent offices in the period 1980–2020 and use the priority date per extended patent family (INPADOC) to avoid double-counting. In total, we identified 8115 patent applications and 5313 patent families in T3. The Espacenet database covers 110 million patent documents from worldwide patent offices and is updated on a weekly basis, allowing for an analysis of the progress of emerging and state-of-the-art technologies (EPO, 2020).

In order to analyze how firms can respond effectively to technological shifts under the same framework conditions, we selected a single-case design with China being an *extreme case* with multiple units of analysis, namely latecomer firms pursuing different catch-up trajectories (Yin, 2003; Flyvbjerg, 2006). In selecting latecomer firms, we applied *purposeful sampling* (Suri, 2011) to identify a small number of information-rich cases along the different catch-up trajectories.

Table 1. Definition and patent search codes of T3

	Technologies	IPC Searching codes
T3	Digital, hybrid and storage-related wind technologies	(cl = "F03D" AND (cl = "G06" OR cl = "H01M")) OR cl = "H02S10/12"
	Wind motors	cl = "F03D"
	Computing, calculating, counting	cl = "G06“
	Energy storage	cl = "H01M"
	Hybrid wind-PV energy systems	cl = "H02S10/12"

4. China's catch-up: overview of the Chinese wind industry

The first wind farm in China was built in the early 1980s. At that time turbines were produced and installed by European firms for demonstration and technology transfer. During the mid to late 1990s Chinese companies initiated domestic production of wind turbines (Dai and Xue, 2015). Previous research has attributed China's fast wind development to industrial and energy policies (Lewis, 2007; Wang et al., 2012). Central milestones in the industrial development that followed were the local content requirements introduced in 2003 and the Renewable Energy Law from 2006. By setting long-term targets and prioritizing renewable energy in the national grid system, the Renewable Energy Law marked the beginning of an unprecedented growth of the domestic market and industrial catch-up. Although there were only a few domestic small-scale turbine manufacturers at the beginning of 2005, the number of new firms entering the market reached 40 in 2007 and almost doubled again by 2008 (IRENA, 2013; Quitzow et al., 2017). At the same time, foreign wind turbine manufacturers experienced a dramatic drop, from a 79% market share in China in 2004 to 12% in 2009 (Sun and Yang, 2013).

In the following 5 years, China's installed capacity grew from one gigawatt (GW) to 44.7GW and the global market share of China reached 22.6% (GWEC, 2011, 2017, 2019b). Strong national support schemes formed the market and institutional base of the industry, paving the way for a rapid market increase in installed wind power capacity. Until 2010, these schemes focused on establishing a national base for onshore wind. When this was established, focus shifted to include offshore projects. Policies since 2017/2018 have moved again, towards energy transition and increased use of renewables in the energy mix more broadly. Table 2 outlines the responses in the Chinese institutional framework for wind turbine development. By the end of 2017, China accounted for 35% (188 out of 539GW) of the cumulative installed capacity in the world, double that of the USA, the second largest market (GWEC, 2017). Today, wind has surpassed nuclear power to become the third largest source of China's growing electricity consumption, accounting for 5% of national electricity supply, following fossil fuels (71%) and hydropower (19%; Dai and Xue, 2015; GWEC, 2017). In 2018, 19 Chinese OEMs remained in the market, with the three leading firms, Goldwind, Envision, and Ming Yang, accounting for over 50% of the domestic market share (FTI Intelligence, 2018).

Table 2. Key institutional responses driving China's catch-up (2003-2018)

	Year	Policy	Description		Cum. installed capacity (GW)	% world
T1	2003	Wind Concessions Program (local content requirements)	50% (2003) / 70% (after 2004) of turbine components' purchasing value had to be produced domestically; repealed in 2009	Onshore	0.5	1.4
	2005	Renewable Energy Law (implemented 2006)	Setting of mid- and long-term targets, creation of the Renewable Energy (RE) Fund		1.2	2.1
	2009	Feed-in-tariff (FIT) for Onshore Wind	NDRC introduced regionalized FIT policies for onshore wind, valid for lifecycle of a wind farm (20 years)		25.8	16.3
T2	2010	Interim Offshore Measures (12th 5-year plan)	China sets offshore target at 5 GW by 2015 and 30 GW by 2020	Offshore	0.1	3.4
	2014	Notice on Offshore Wind Power On-Grid	Shanghai, Fujian and Zhejiang provinces selected for key pilot offshore projects; introduction of offshore FIT plus regional subsidies		0.6	6.8
	2016	13th 5-year plan	Restatement of offshore target by 2020 (5 GW installed capacity / 10 GW cumulative construction)		1.9	10.2
	2017	Development Plan Beibu Gulf	Approval to build offshore wind park in southwestern Beibu Gulf region		2.7	14.8
T3	2018	Clean Energy Accommodation Action Plan (2018-2020)	Set up national goal to increase in the wind availability hours to 95% by 2020, and drop national curtailment rate to around 5%	Hybrid	N/A	N/A
	2018	Notice on the issuance of the energy work guidance (2018)	Set up monitoring system for renewable energy curtailment, and promote renewable energy to have competitive market price via electricity trading market mechanism		N/A	N/A

Source: Author's own elaboration based on Lewis (2007), GWEC (2011–2018), IRENA (2013), and Zhang et al. (2018).

Despite the rapid catch-up in market share, Chinese manufacturers produce mainly onshore turbines for the domestic market. In 2018 only 1.8% of total Chinese production was installed outside China (FTI Intelligence, 2018). Many Chinese firms have not yet acquired certifications from internationally recognized bodies (Backwell, 2017). With an initially slow and hesitating evolution in the Chinese market for offshore wind power, it is not surprising that the top-tier companies are largely competing in the onshore medium-sized turbine segment of 1.5–2.5 megawatts (MW) and only recently in the more advanced offshore wind power markets in terms of average turbine size (see Appendix Table A2). Hence, Chinese companies are approaching the technological frontier but do not yet belong to the group of international frontrunners, consisting of Siemens Gamesa, Vestas, and GE (Backwell, 2017). The domestic industry is dealing with problems of disorder, overproduction, and imbalance, for example, by reducing curtailment rates and lowering wind energy prices (Zhu et al., 2019). In light of the presence of strong institutional support schemes at the national level, Chinese wind firms show a variety of different catch-up patterns, which will be elaborated on in the next section.

5. Latecomer responses to technological shifts

Different types of firm are maneuvering, balancing, and evolving through a shifting, competing, and progressing technological frontier in the wind turbine industry. The technological frontier in China has evolved from a paradigm of onshore wind turbines to offshore wind to a more fundamental shift towards digital/hybrid transition. This section examines the responses and strategies of Chinese latecomer firms to the technological windows of opportunity created, paying close attention to the dynamics of incumbent and latecomer firms and how strategies shift with the evolution of the three emerging technologies. It looks first at how incumbent firms responded to global technological transformation and potential paradigm shifts, before turning to how Chinese latecomers caught up.

Onshore (T1) and offshore (T2) technologies are situated within an SM-II technological regime and characterized by deepening innovation patterns and a spatially sticky global innovation system (Binz et al., forthcoming). At the technological frontier, the global wind turbine lead firms are currently operating across three different technologies (T1–3) as defined by their innovation and technology focus (see Table 3). The share of F03D (core wind tech) patents decreases from T1 to T2 and from T2 to T3 when looking at the top-5 IPCs. Hence, there is a widening of the technological regime which may eventually lead to a paradigm shift from SM-II towards SM-I.

Although the technological frontier has changed along two major shifts, the three technologies co-exist, since the new technologies constitute add-ons to products developed in the previous one(s) and the markets for all three are still expanding. However, the incumbent lead firms have largely moved their technological focus downstream towards more value-added segments in their value chain. Along with these technological changes, windows of opportunity to follow or skip the path have opened up for latecomer firms.

Table 3. Overview of T1-3

	Emergence	Tech category	Description
T1	Since 1980	Low tech	Small/medium turbines, normally used for onshore wind energy generation. T1 technology becomes increasingly commodified and standardized.
T2	Since 2000	High tech	Large turbines, normally used for offshore wind energy generation. T2 technology requires high customization and integrates technology from the maritime industry.
T3	Since 2010	New tech	Digital/hybrid technologies used for the digitalization and integration of energy systems. T3 technology comprises digital solutions (SaaS, IoT, AI) for wind turbines and various up and downstream renewable technologies (wind, solar PV, and storage).

5.1 Path-creating incumbent firms shaping the technological frontier

The incumbent lead firms are undergoing what they call a disruption and are strategizing their technological investments and engagement accordingly. Given that the industry has reached the point of grid parity, where energy from new wind parks is cheaper than conventional sources, mainly coal, a complete shift is occurring in the energy market. One European lead firm explained:

> "We are selling unsubsidized turbines in New Zealand. The market trend is that the average cost of electricity is on grid parity in many markets. By 2030, wind and solar energy will be by far the cheapest sources of energy."

This occurred as national feed-in-tariffs were gradually decreased or fully removed. At the firm level, market strategies and business models are increasingly adjusting to this shift, in particular as the wind energy markets in advanced economies shift to an auction-based system. In such a market design, the production of energy is the focus, not the wind turbine itself. At the same time, wind turbines as products have been largely commodified and incumbent firms have externalized production through outsourcing while increasingly focusing on downstream activities as they relate to, for instance, systems integration and park development. Table 4 shows how Vestas, the world's largest wind turbine manufacturer, changed its strategic focus to downstream integration while also investing in acquisitions of and partnerships with specialized actors, for example in digitalization technology.

Similar developments were found in Siemens and General Electric. For example, in 2016, Siemens Wind Power developed the product Sinalytics in for advanced data analytics and General Electric introduced the Predix Platform, a cloud-based software system for digital wind farm management. Among the Chinese firms, Envision stands out in developing software systems for advanced analytics and forecasting, EnOS and Ensight.

The incumbent firms are undergoing a major change in shifting technologies. As noted by one incumbent firm manager, "You don't make money by just selling commodities." Consequently, these firms are expanding the wind turbine business towards sustainable wind energy solutions encompassing full grid systems applications by providing complementary types of energy sources such as solar power, energy storage, smart grid solutions, or hybrid systems (combining solar and wind) that are holistic from an energy mix perspective. Another incumbent firm reflected:

"We are in a process of restructuring. In India and elsewhere, we do the whole wind park development (downstream integration), whereas in Australia we have integrated new storage systems into the wind park."

As shown in Table 4, in 2017 Vestas built the world's first complete utility on-grid energy park in Australia, integrating solar, wind, and battery technologies. This integration trend is also reflected in changes to product warranties, from a standard warranty of five years for the turbine in the previous system, to the production of energy in most current markets.

Table 4. Vestas' changing priorities entering digital and hybrid solutions (2014-2018)

2014	-	Focus on the 'Business Service Area'
	-	Joint Venture with Mitsubishi Heavy Industries for off-shore segment
	-	Reduction of in-house production capacity
2015	-	Focus on 'Wind energy solutions'
	-	Acquisition of 'Upwind Solutions' in US for downstream service delivery
2016	-	Focus on systems for integrating energy sources
	-	Establishing strong supplier base
	-	Integration into the energy grid is described as key
	-	Investments into digitalization and the use of data at all stages
	-	Investments into supercomputing, analytical capabilities, and diagnostics technology
2017	-	Focus on 'Decarbonized energy sector' and energy solutions
	-	Investments into digital solutions development
	-	Collaboration with WindLab Ltd on integrating wind, solar, and battery energy storage
	-	Strategic partnership with Northvolt AB on battery storage solutions and grid integration
	-	Strategic partnership with Arise Windpower AB and Infigen Energy to outsource service operations
	-	Australia: world's first on-grid energy system wind, solar, battery storage with WindLab ltd.
2018	-	Establishing a market of offering full-scope solutions
	-	Digital solutions to lower the cost of energy in mixed systems
	-	Acquisition of Utopus Insights, data analytics and digital solutions
	-	Partnership with EDP Renewables in Spain on integrating wind and solar through hybrid solutions
	-	New services introduced on digital and flexible solutions
	-	New platform introduced to the market 'EnVentus' for next generation of wind turbines
	-	Investments in robotics
	-	Introduced power plant controller for integration of multiple energy sources and storage
	-	Offshore turbine 9.5MW received the final certification, installation started in September 2019
	-	Development of floating solutions for offshore

Source: Annual reports and company websites.

The market change requires radical technological innovation. To make production of green energy stable and sustainable, turbines have to be able to adjust in how much energy is produced. Digital technologies such as SaaS, advanced analytics, and failure prediction, and other forms of AI, are integrated into the design and operation of wind parks. This is also reflected in the patents files by the incumbent firms. For example, back in 2008 Siemens filed a patent for predictive modeling which predicts the production of the wind turbines to allow for the energy grid to adjust. Vestas (2011) and General Electric (2012) filed patents for similar tools; computer programs for power system stabilization and dynamic role engine, respectively. In 2016, Goldwind filed a patent for monitoring followed by Ming Yang in 2018 and Envision in 2019 (for a control system for energy storage; EPO, 2020). Figure 2 illustrates the annual filing of patents within T3 by incumbents and Chinese firms. As with the examples above, this graph shows a delay in response by the Chinese firms. Although in the previous paradigms of onshore and offshore turbines, lead firms competed in designing larger turbines and dominating the market, in this paradigm they have broadened their innovation beyond the turbine itself. Table 5 shows how large incumbent lead firms have acquired specialized technology in T3 since 2008. This has also been the case for Chinese firms, starting in 2016.

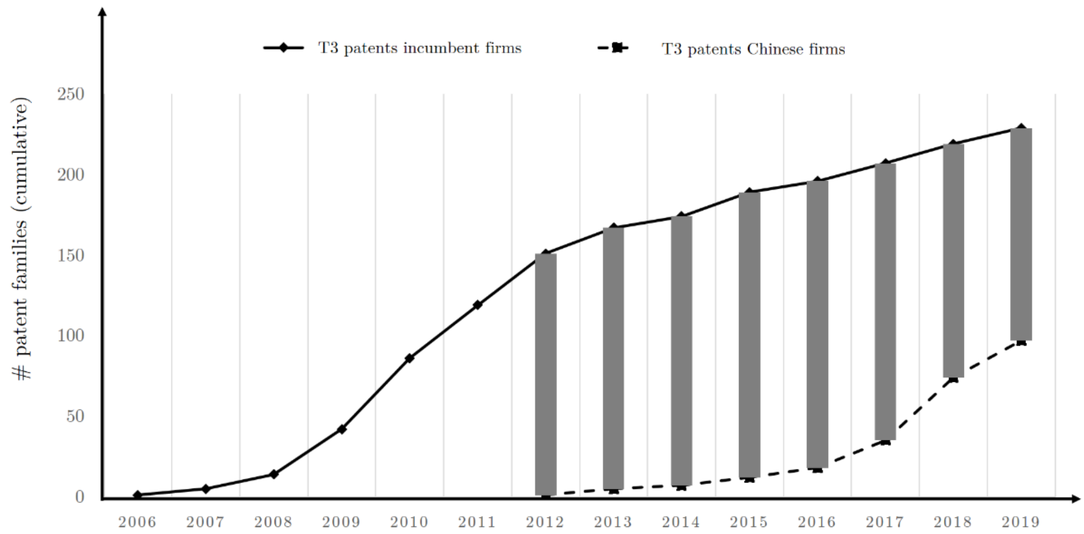

Figure 2. Development of T3 patents filed by incumbent versus Chinese lead firms (2005-2019)

Software is key in the new digitalized and hybridized paradigm, moving the industry towards a more ICT-based system of innovation. As one interviewee noted:

> “We can make the turbines produce more power when the electricity price is higher, so the turbine itself understands when to produce more; the load consumption turbine specific software increases the wind turbine’s ability to use itself.”

Therefore, path-creating incumbent firms are broadening their scope to focus on new developments beyond turbines, such as digitalized control, systems integration, power plant controllers, transmission technologies, storage solutions, and energy mix. The competitive dynamics are transforming from a race for larger turbines to delivering downstream activities. However, radical technological capacity can be gained through either in-house innovation or M&As. As noted by a leading European manufacturer, “Our M&A section is very busy acquiring and buying companies downstream.” Obviously, there is a major shift in the fundamental factors of the industry’s innovation patterns and no guarantee that traditional lead firms will maintain their position.

With climate change-related policies being implemented across the world and the emergence of new technologies such as electric vehicles, more national energy systems are being electrified. But, the deployment of renewable energy goes far beyond electricity; it goes into new sectors such as transport, agriculture, and even water and sanitation. The incumbent lead firms are first movers in responding to the green windows of opportunity, yet they experience a loss in global market share when measured as installed capacity. According to one such firm, "When we are not performing in market share, it is China, since the Chinese market is the largest." However, in terms of creating technological trajectories, incumbent firms are still defining and developing the technological frontier. These companies remain important actors in offshore turbines even if their focus has shifted to understanding downstream segments and system integration as well as finding new methods for optimizing this integration.

Table 5. Digital and hybrid M&A activities of Chinese versus incumbent firms by year (2007–2019)

	Firm	Country (HQ)	Acquired company	Industry	Year
Chinese firms	Envision	CN	Nissan Motor (electric battery production facility)	Automotive (lithium-ion batteries)	2019
	Goldwind	CN	Oxford PV, UK/DE	Solar (perovskite cells)	2019
	Envision	CN	Automotive Energy Supply Corporation (AESC), JP	Automotive (lithium-ion batteries)	2018
	Envision	CN	Sonnen, DE	Battery, energy storage (lithium-based storage)	2016
	Envision	CN	Autogrid, US	Big Data, Analytics (SaaS)	2016
Incumbent firms	Siemens	DE	MultiMechanics, US	Computer-aided engineering (CAE) software	2019
	Vestas	DK	Utopus Insights, US	Data Analytics	2017
	GE	US	IQP Corporation, JP	IoT Apps	2017
	GE	US	Wise.io, US	Machine Learning Applications	2016
	Siemens	DE	CD-adapco Group, US	Engineering simulation software	2016
	Vestas	DK	OCAS AS, NO	IT/radar tech (obstacle collision avoidance for wind farms)	2011
	GE	US	Sensicore, US	Sensor networks, analytics	2008
	Gamesa	ES	NEM Solutions (50%)	Predictive maintenance, advanced analytics	2007

Source: Author's elaboration based on company websites, newspaper articles, annual reports and M&A databases (Crunchbase).

5.2 Chinese wind turbine manufacturers catching up through different trajectories

Chinese firms have responded to the window of opportunity related to the most recent technological shift in the past decade. Since technological change in this industry is particularly cumulative in T1 and T2, the technologies co-exist. This provides latecomer firms the opportunity to catch up in existing technologies through path-following or path-skipping catch-up trajectories. The trajectories of catch-up in emerging markets differ according to institutional settings, market responses, and firm levels.

Chinese wind firms accumulated technological capacity in onshore turbines (T1) as they gradually caught up via imported components, licensing, M&As, building overseas research centers, and investing in in-house innovation. More recently, a number of Chinese firms, including Sinovel, Shanghai Electric, Goldwind, and Envision, have invested in offshore technology on 4–6MW turbines and have built capabilities in offshore technologies either internally (based on the R&D capacity gained in onshore experience) or externally (internalizing technological capabilities through licensing and M&As). When the latest shift in the technological frontier emerged at the global level, the domestic market for onshore wind was still highly profitable compared with markets abroad. Yet, installed onshore wind capacity in China presents a decreasing trend since 2015 due to the high curtailment rate (CWEA, 2018).

As shown in Section 4, the development of wind technology had major responses at the policy level in China, most recently, after 2017, targeting an increase in the overall integration of wind energy. The *Clean Energy Accommodation Action Plan* (2018–2020; NDRC, 2018) set a requirement for a 3-year continuous increase in the wind availability hours with 95% as the 2020s goal. The plan also set a national curtailment rate (loss of energy) drop to around 5%. This is just one example where policy focus has been shifted from the installation of wind energy per se to energy production. The other regulatory change affected the price of wind energy. Whereas China's renewable energy feed-in-tariff policy served as an effective institutional response to onshore (T1) and offshore (T2) technological shifts, the gap between payable subsidies and actual subsidies continued to widen. In its requirement that wind energy prices be determined through market competition, the *Relevant Requirements of Wind Power Construction Management in 2018* (NEA, 2018) changed the marketplace. These policy responses pushed Chinese companies to actively adapt new technologies in their search for market; that is, to focus more on combined energy production and integration rather than on selling wind turbines as a commodity. Chinese firms have responded differently to both the exogenous sectoral dynamics shifting towards technologies for systems integration, and to the endogenous responses in the market and institutional framework specific to the Chinese context. Consequently, they have followed different catch-up trajectories and responded differently to technological change.

5.2.1 Path-following firms' response to technological change

Path-following Chinese wind turbine manufacturers are long-established players who maintain a high degree of similarity with incumbent firms in terms of technology roadmap and market development strategies. These firms have mature technological capacity within onshore technology, and occupy a good share of the domestic market. During their initial catch-up, they also initiated investments in offshore technology and market exploration. One example is Goldwind, a market leader in China, which produced 26.6% of the installed capacity in 2017. Although its main products are 2, 2.5, and 3MW onshore turbines, Goldwind released a 6.7MW turbine product in 2018 for offshore. Currently, Goldwind holds the third largest offshore market share in China (after Shanghai Electric and Envision; GWEC, 2020).

When technological change occurs, path-following firms have two choices: continue their R&D and market expansion in offshore turbines or respond to the windows of opportunity created by the new technology and redirect to digitalization and energy integration. Unlike the catch-up speed into offshore turbines, which is still ongoing, the Chinese path-following firms recognized the shift towards hybrid technologies and digital solutions much earlier and followed the path of the incumbent firms closely (see Section 5.1). In 2016, Goldwind proposed a new slogan, "Innovation—Leading the future of the global energy," to illustrate its vision to become a leader in the global renewable energy sector. It is expanding its strategic portfolio in wind turbine manufacturing while diversifying into related technologies such as water projects, energy saving, smart grid, smart agriculture, health, solar PV, and financial services. Technologically, Goldwind is expanding into in digitalization, smart grids, and AI due to the national priority to develop those industries. Path-following firms also invest upstream in the design and development of turbines where new innovation projects are taking place through European specialized suppliers and, in one case, through an acquired design hub in Europe. As a manager in a path-following company noted, international connections helps the company "focus on wind operation digitalization, energy integration, and smart solutions for the energy system, hoping to make the wind production chain green and smart via diversified innovation, and to explore new emerging business areas other than wind."

Developing a catch-up strategy towards the latest shift does not crowd out path-following firms' efforts to catch up in offshore turbine technology. Goldwind, for example, after decades of catch-up in wind turbine technology, has released its 6MW offshore turbine, and currently 8 and 10MW offshore turbines are under development. The technological readiness in offshore wind turbines, however, has to give away to an unexpected slow development of the offshore market in China. Instead, these actors are integrating vertically and investing in specialized component suppliers to ensure access to financially stable and profitable offshore technologies. This is contrary to the incumbent firms, which are increasingly externalizing their manufacturing processes, yet helps firms to ensure supply as well as lower the overall cost of the turbine in response to the reducing subsidy.

Institutional responses that helped path-following firms ensure their domestic market share in onshore turbines (T1) may become institutional barriers in moving towards offshore (T2) and digital/hybrid technologies (T3). Benefiting mainly from the cost-out strategy in the domestic market, path-following firms are having a hard time entering the international offshore market that is extremely competitive where product quality and energy production during the lifetime of the turbine are key competitive parameters. Even for firms working hard to gain a larger international offshore market share, it takes decades to build an international reputation.

The path followers in our study mentioned possible institutional barriers to following incumbent along the technological frontier, especially in international markets. For example, international technology transfer agreements with specialized engineering and design firms usually include geographic market restrictions, leaving Chinese companies limited room to exploit international markets. The firms also encountered high institutional transaction costs in international markets, especially compared with domestic market exploration costs. Therefore, although these firms regard international market exploitation as the ultimate goal, they are not actively pursuing it for now. In summary, the path-following firms catch up by narrowing the gap with the incumbents. With the help of a national technological base that is developed in software and AI, Chinese firms are in the process of bridging the technological gap at speed as the technological regime develops towards a less cumulative and specialized nature.

5.2.2 Path-skipping firms' response to technological change

The path-skipping firms are either latecomers who entered directly into offshore or hybrid/digital solutions—for example, Shanghai Electric—or followers in onshore technologies that skipped large-size turbine development and put the company's focus directly into hybrid/digital solutions—such as Envision. Shanghai Electric pursued its catch-up via technology licensing targeting the advanced offshore technology. The firm used to be an energy supplier, but in 2012, it established two joint ventures with Siemens Wind Power for offshore turbines for the Chinese market. Shanghai Electric successfully installed the first 4MW offshore wind turbine using Siemens licensing in 2014. In 2015 Shanghai Electric took full control of this technology through acquisition and obtained a manufacturing license to produce 6MW Siemens wind turbine. This partnership helped Shanghai Electric gain the largest offshore market share in China in 2018, accounting for 44% of newly installed offshore capacity (CWEA, 2019) and, although dependent on the technology available from its partners, it became a lead firm in the offshore market in China by skipping technology accumulation in onshore turbines.

Envision represents another kind of path-skipping pattern. The firm emerged in 2007, shortly after the Renewable Energy Law and market take-off of the Chinese wind sector. From the beginning, Envision positioned itself as a company with broad international technological collaborations and insisted on also building indigenous innovation and maintaining its advantages in software development. In China, this positioning has shaped its image of "incrementally improved quality" and gained its market share. In 2018, Envision occupied 25% of the Chinese onshore and offshore market respectively (CWEA, 2019).Yet, the company does not develop wind turbines above 4.5MW. According to a manager, the rationale behind this is that Envision uses very similar turbines for onshore and offshore markets, thereby keeping technological adjustments at a minimum level. Instead it started to invest in various new energy-related product areas, including batteries, electric vehicle charging, smart grids, electricity generation insurance, and IoT in the energy sector. Technologically, this strategy represents a path-skipping catch-up from T1 to T3.

The main window of opportunity for these companies to path-skip is technological. For Shanghai Electric, the joint venture with Siemens upgraded its domestic research when it licensed 6 and 8MW technology. For Envision, which has defined itself as a high-tech company from the beginning, the strategy and technological ambition relate to software technology. The company sees many potential opportunities in the most recent technology shift:

> "We already have the software for solar and wind. Basically, the idea is to become the Google in energy control software. In internet business the winner takes it all, so we need to be the winner of all this software for energy."

Operating in the Chinese context provides advantages in integrating with the software industry to acquire technical talent.

Path-skipping companies face market challenges similar to path-following companies. Their responses are similar: the domestic market is still very attractive after path-skipping catch-up since profit margins outside China are smaller. Meanwhile, institutional responses towards new technologies, particularly the mixed energy trading trend, makes energy integration and digitalization increasingly important to the industry both for price reduction and for smooth production output—and this indirectly pushes the path-skipping strategy.

5.2.3 Aborted catch-up by latecomer firms' failed responses

Not all Chinese manufacturers have experienced a successful catch-up. Because institutional responses are so tightly connected to the establishment and growth of demand in the domestic market, some companies have managed to obtain significant market share but have fallen behind because their business strategy was not sustainable or because their products were revealed as having quality issues. Sinovel, for example, used to be a leader in China in both market share and technological capacity. It released the first Chinese 1.5MW turbine in 2010, year before Goldwind released its 1.2MW turbine (Sinovel, n.d.). However, Sinovel mainly relied on the institutional framework that emphasized localization in a market characterized by a race to the bottom through cost-out strategies: "This protection (*tendering system*) faded away in 2010," which reduced Sinovel's profit. Meanwhile, large-scale wind curtailment in China raised the technological upgrading costs of the firm, meaning it was unable to invest in its turbine R&D and lost the technological capacity to catch up. Even though it released China's first 6MW turbine in 2011, Sinovel lost its leading position and fell out of the top 22 in 2017 (CWEA, 2018) as government subsidies started to decrease at a faster speed and wind energy was pushed further into electricity market competition. Similarly, some of the early Chinese turbine manufacturers followed a learning-by-doing strategy through technology licensing without building in-house innovation capacity. As a result, most have failed to respond to the new technologies and rigorous institutional changes and have subsequently dropped out of the market. Their catch-ups were aborted in onshore technology. Some experimented with new materials (e.g. bamboo blades), bore the innovation risk, and fell behind.

5.3 Three responses to technological shifts with different characteristics

Our analysis confirms the three consecutive technologies dominating the wind turbine sectoral system of innovation, namely: small- and medium-sized *onshore turbines*; larger *offshore turbines*; and downstream integration with *digital and hybrid technologies*. The recent downstream changes in the technological frontier are largely attributed to the fact that "green transition" is a broad umbrella that covers various sectors and offers cross-sectoral and global green windows of opportunity. Therefore, the technological roadmap and sectoral boundaries are all likely to extend and integrate further during the green energy transition. The consequences of global trends in policy towards green and sustainable solutions are particularly clear in the wind energy sector, encountering a technological shift.

As illustrated in Figure 3, this evolutionary development from onshore (T1) to offshore (T2) to digital/hybrid (T3) was led by the incumbent firms in Europe and the USA. Chinese firms are currently strongest in the area of small and medium-sized turbines (T1) and moving into offshore (T2). Due to their experience and capability development, the response time of Chinese firms to technological windows of opportunity has reduced throughout the three technological shifts. For onshore technology the response time was almost two decades, for offshore one decade, and for hybrid/digital technological shift much shorter (see Table 6). Meanwhile, incumbent firms are still dominating the global market for large turbines while increasingly moving towards downstream integration and hybrid solutions. This is visible through their M&A activities, business priorities, product launches, and patents. Moreover, Chinese firms are catching up in size and capacity, making still larger and better turbines, also recently with offshore technology. Yet for wind turbines, one technology is not replacing another.

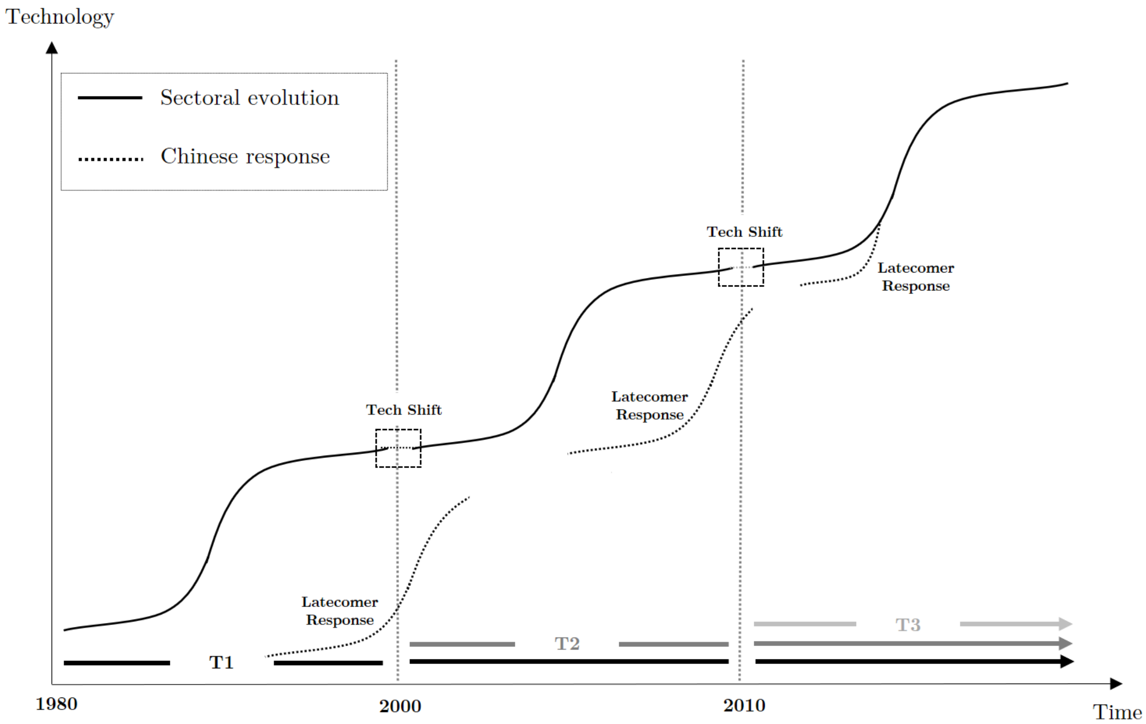

Figure 3. Global technological shifts and the responses of China's wind energy sector

Our analysis shows that new windows of opportunity emerge along with technological shifts. New technologies, market opportunities, and institutional settings enable Chinese follower firms to catch up via a path-following or path-skipping strategy. The gap is narrowing since the current change in the technological frontier is less conditioned by cumulativeness and is not reliant on a knowledge base established throughout the industrial development (see Table 7).

Although institutional responses supported the catch-up of the industry, they also generated barriers that now prevent many Chinese firms from moving into path-creating catch-up. When existing institutional support for the national industry fades away, firms relying on support schemes rapidly lose their competitive advantages. Building national innovation capabilities is crucial for moving into a path-creating catch-up trajectory. The emerging technologies within energy integration are an illustrative example of this since it requires advanced technological capacity that cannot be acquired by international M&A alone. To respond to the green window of opportunity of sustainable energy integration, firms must be familiar with wind turbines, and additional technologies also need to be integrated, such as energy transmission, storage, distribution, and usage optimization. The incumbent companies have internalized these key technologies while externalizing turbine component technologies, which hint at a trend towards a widening of the technological regime through changes in the conditions. Further catch-up in market share of onshore and offshore technologies is very likely as the incumbent firms are increasingly outsourcing parts of turbine production; however, catching up in digital/hybrid technologies will relate to the extent to which followers can gain new market share internationally.

Table 6. Overview of T1–3 emergence and China's response time

	T1	**T2**	**T3**
World	1980	2000	2010
China	2000	2010	2015
Response time	*~20 years*	*~10 years*	*~5 years*

Note: All years are based on initial market development that is, when the first commercial T1–3 technologies were installed. This is not necessarily linked to institutional responses and/or technological R&D (e.g. filed patents).

6. Conclusion: wind technologies and firm-level responses to green windows of opportunity

As green and techno-economic windows of opportunity emerge with the global policy focus on energy transformation, the wind turbine industry is undergoing massive change. Since the 1980s, the industry has evolved to become a core actor in addressing climate change by reducing global carbon emissions. In order to make wind a sustainable and reliable source of energy the industry has moved through three technological shifts: onshore, offshore, and digital/ hybrid. Emerging market actors, predominantly from China, have entered the market since the 2000s and are today among the largest in the world for small- and medium-sized turbines.

Combined with the construction of an institutional framework forming the domestic market, the Chinese industry has experienced immense catch-up in market share. Chinese firms have moved into onshore and offshore technologies via path-following and path-skipping trajectories. They have established themselves as competitors in the global wind turbine industry mainly lowering the costs of turbines. However, their technological catch-up efforts vary widely. The incumbent firms are losing market positions in installed capacity because they are moving beyond the turbine into the new paradigm of energy systems integration, energy mix, storage, and digital solutions.

At the company level, the analysis identified different responses to technological windows of opportunity. Three different types of strategies were identified at the firm level. (i) Path-following firms succeeded in catching up with existing technology, allowing them to expand their market share in installed capacity but also to closely follow leaders' efforts into technological change. These path-followers aim to integrate into the new technologies as part of their firm strategy but do not yet have the capacity to forge a path-creating strategy. (ii) Path-skipping firms are also successful because they keep narrowing the technology gap with incumbent sector leaders, which may lead to continuous market share increase. These firms also experienced market catch-up, as defined in the catch-up cycle framework. In the long term, path-following and path-skipping firms may risk becoming uncompetitive, leaving them trapped in the mid-segment market. (iii) Catch-up aborting firms failed due to their dependency on policy- driven domestic market demand. As they have not managed to build the technological capabilities needed for an enduring catch-up strategy, these firms experienced aborted catch-up cycles.

Although we found successful path-followers and path-skippers in the Chinese industry, this applied only to the domestic market. Their competitive capacity in the international market is quite different. Although in China, market share depends on prices, cost-out strategies, flexible design, quick response in service provision, integrating capacity suppliers, and quality, international market exploration requires technological capacity in large offshore wind turbines and high-quality manufacturing along with major investments in technological capacity for energy integration. Hence, these firms still lack the enabling factors needed to respond to green windows of opportunity through path-creating strategies that relate to the international market.

Table 7. Technological regime (TR) conditions of T1–3 in the wind energy sector

TR conditions	T1	T2	T3
Opportunity Ease of innovating with given amount of resources	**Low** dominant designs of onshore turbines	**Medium** emerging designs of offshore turbines (e.g. floating)	**High** no dominant designs of digital and hybrid products
Cumulativeness Likelihood of innovating along specific trajectories	**High** narrow along turbine subcomponents	**Medium** influences from adjacent industries e.g. the maritime industry	**Low** cross-sectorial influences from multiple digital and manufacturing industries (e.g. solar PV, energy storage)
Approproability Ease of extracting profits from innovative activities e.g. through IP protection	**Low** sale of commodified turbines	**Medium** sale of electricity over lifetime (LCOE)	**High** sale of electricity and software-as-a-service (e.g. data analytics)
Knowledge base Relevance of existing knowledge	**Consolidated** vertically integrated and fixed supply chains	**Maturing** complex systems of subcontracting and downstream integration	**New** tacit interfaces (e.g. with startups and tech firms)

Note: TR conditions of T1–3 are characterized from today's evolutionary perspective.
Source: Author's own elaboration based on Malerba and Orsenigo (2000).

In conclusion, this article has two main implications. First, recent transformations in the global economy may change the factors underpinning the technological regime of a sector and open new green and technological windows of opportunity for latecomer firms. Especially if industrial innovation leads to sectoral widening, latecomer firms have the advantage of lower transaction costs as the technological frontier is shifting from one technology to another.

The digital transformation and adaptation of technologies such as machine learning and AI is happening very quickly in China and latecomer firms seem to be more agile than incumbent firms in moving into completely new technologies. Second, we found that latecomer firms under the same framework conditions show different responses to technological transformation. Hence, catch-up (and catch-up failures) can only partly be attributed to the innovation ecosystem and institutional environment but strongly depend on the dynamic capabilities at firm level.

This article constitutes an empirical contribution to the catch-up literature connecting the ongoing and relevant discussions of (green) windows of opportunity and evolutionary sectoral change in an era of technological transformation (for sectoral comparison, see Lema et al., 2020). However, our findings open up for new research avenues into catch-up opportunities in times of technological change. First, as digitalization and hybridization are likely to have profound implications of catch-up and industrial leadership across industrial sectors, these implications need further exploration. The relationship between industry characteristics and implications of technological shifts calls for in-depth and comparative analyses. Second, in this article, we focused on latecomer firms' responses within the same national framework conditions. China constitutes an extreme and unique case and to further develop the concepts and frameworks of technological regimes and catch-up cycles, it is relevant to systematically test our findings in cross-country analyses. Third, our article shows that the nature of technological change is fundamentally changing. As it becomes increasingly difficult to delineate sectors along conventional boundaries due to industry digitalization/hybridization, the existing literature on catching up and industrial leadership changes could benefit from conceptually integrating these changes.

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References

Ajadi, T., R. Boyle, D. Strahan, M. Kimmel, B. Collins, A. Cheung and L. Becker (2019), '*Global Trends in Renewable*

Energy Investment 2019', Frankfurt School - UNEP Collaborating Center for Climate & Sustainable Energy Finance, Frankfurt am Main.

Altenburg, T., H. Schmitz and A. Stamm (2008), 'Breakthrough? China's and India's transition from production to innovation,' *World Development*, 36(2), 325–344.

Backwell, B. (2017), *Wind Power: The Struggle for Control of a New Global Industry* (2nd edn). Routledge: London.

Binz, C., J. Gosens, X. Yap and Z. Yu (forthcoming). 'Catch-up cycles in global innovation systems – a typology of catch-up dynamics in four emerging clean-tech industries,' *Industrial and Corporate Change.*

Breschi, S., L. Orsenigo and F. Malerba (2000), 'Technological regimes and schumpeterian patterns of innovation,' *Economic Journal*, 110(463), 388–410.

Chun-Fung Chen, G. (2016), *Governing Sustainable Energies in China*. Springer: Cham.

Christensen, C. M. (2016), *The Innovator's Dilemma. When New Technologies Cause Great Firms to Fail.* Harvard Business Review Press: Boston, MA.

CWEA. (2018), *Ranking and Market Share of China's Wind Turbine Manufacturers in 2017 [in Chinese].* Chinese Wind Energy Association: Beijing.

CWEA. (2019), *Ranking and Market Share of China's Wind Turbine Manufacturers in 2018 [in Chinese].* Chinese Wind Energy Association: Beijing.

Dai, Y. and L. Xue (2015), 'China's policy initiatives for the development of wind energy technology,' *Climate Policy*, 15(1), 30–57.

Daisuke, H., J. Huenteler and J. I. Lewis (2018), 'Gone with the wind: a learning curve analysis of China's wind power industry,' *Energy Policy*, 120, 38–51.

Ding, X. and J. Li (2015), *Incentives for Innovation in China: Building an Innovative Economy.* Routledge: London.

Dosi, G. (1982), 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change,' *Research Policy*, 11(3), 147–162.

European Patent Office (EPO). (2020), 'Espacenet Patent Search,' https://worldwide.espacenet.com/.

Flyvbjerg, B. (2006), 'Five misunderstandings about case-study research,' *Qualitative Inquiry,* 12(2), 219–245.

FTI Intelligence. (2018), *Global Wind Market Update—Demand and Supply 2017*. FTI Intelligence: London/Copenhagen/Denver.

Freeman, C. (1987), *Technology, Policy, and Economic Performance: Lessons from Japan.* Frances Printer Publishers: London/New York.

Fu, X. (2015), *China's Path to Innovation.* Cambridge University Press: Cambridge.

Fu, X., C. Pietrobelli and L. Soete (2011), 'The role of foreign technology and indigenous innovation in the emerging economies: technological change and catching-up,' *World Development*, 39(7), 1204–1212.

GWEC. (2011), *Global Wind Report: Annual Market Update 2011.* Global Wind Energy Council: Brussels.

GWEC. (2017), *Global Wind Report: Annual Market Update 2017.* Global Wind Energy Council: Brussels.

GWEC. (2018), *Global Wind Report: Annual Market Update 2018.* Global Wind Energy Council: Brussels.

GWEC. (2019a), *Global Wind Report 2019.* Global Wind Energy Council: Brussels.

GWEC. (2019b), *Supply Side Data 2018 Report.* Global Wind Energy Council: Brussels.

GWEC. (2020), *Wind Turbine Sizes Keep Growing as Industry Consolidation Continues.* Global wind Energy Council: Brussels. https://gwec.net/.

Haakonsson, S. and D. Slepniov (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), 462–480.

Haakonsson, S., J. K. Kirkegaard and R. Lema (2020), 'The decomposition of innovation in Europe and China's catch-up in wind power technology: the role of KIBS,' *European Planning Studies*, Published online 7 January 2020: doi: 10.1080/09654313.2020.1712329.

Hain, D., R. Jurowetzki, P. Konda and L. Oehler (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,* dtaa021, https://doi.org/10.1093/icc/dtaa021

Huenteler, J., T. S. Schmidt, J. Ossenbrink and V. H. Hoffmann (2016), 'Technology life-cycles in the energy sector: technological characteristics and the role of deployment for innovation,' *Technological Forecasting and Social Change*, 104, 102–121.

IRENA. (2013), *China: 30 Years of Policies for Wind Energy. International Renewable Energy Agency.* https://www.irena.org/404?item¼%2fdocumentdownloads%2fpublications%2fgwec_china.pdf&user ¼extranet%5cAnonymous&site¼IrenaLive.

IRENA. (2018), *Global Energy Transformation: A Roadmap to 2050.* International Renewable Energy Agency: Abu Dhabi.

IRENA. (2019), *Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects.* International Renewable Energy Agency: Abu Dhabi.

Jiang, K. (2007), 'Energy Technology Research in China', in L. Jakobson (ed.), *Innovation with Chinese Characteristics* (pp. 99–133). Palgrave Macmillan: London.

Jung, M. and K. Lee (2010), 'Sectoral systems of innovation and productivity catch-up: determinants of the productivity gap between Korean and Japanese firms,' *Industrial and Corporate Change*, 19(4), 1037–1069.

Landini, F., K. Lee and F. Malerba (2017), 'A history-friendly model of successive changes in industrial leadership and the catch-up by latecomers,' *Research Policy*, 46(2), 431–446.

Lee, K. (2019), *The Art of Economic Catch-Up: Barriers, Detour, and Leapfrogging.* Cambridge University Press: Cambridge.

Lee, K. (2005), 'Making a Technological Catch-up: barriers and opportunities,' *Asian Journal of Technology Innovation*, 13(2), 97–131.

Lee, K. and J-h Ki (2017), 'Rise of latecomers and catch-up cycles in the world steel industry,' *Research Policy*, 46(2), 365–375.

Lee, K. and C. Lim (2001), 'Technological regimes, catching-up and leapfrogging: findings from the Korean Industries,' *Research Policy*, 30(3), 459–483.

Lee, K. and F. Malerba (2017), 'Catch-Up cycles and changes in industrial leadership: WOO and responses of firms and countries in the evolution of sectoral systems,' *Research Policy,* 46(2), 338–351.

Leiponen, A. and I. Drejer (2007), 'What exactly are technological regimes? Intra-industry heterogeneity in the organization of innovation activities,' *Research Policy*, 36(8), 1221–1238.

Lema, R., X. Fu and R. Rabellotti (2021), 'Green Windows of Opportunity: Latecomer Development in the Age of Transformation towards Sustainability,' *Industrial and Corporate Change*, 29(5), DOI: 10.1093/icc/dtaa044.

Lema, R., A. Berger and H. Schmitz (2013), 'China's impact on the global wind power industry,' *Journal of Current Chinese* Affairs, 42(1), 37–69.

Lewis, J. I. (2007), 'Technology acquisition and innovation in the developing world: Wind turbine development in China and India,' *Studies in Comparative International Development*, 42(3–4), 208–232.

Lewis, J. I. (2013), *Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low-Carbon Economy.* Columbia University Press: New York.

Lundvall, B.A. (1992). *National systems of innovation: towards a theory of innovation and interactive learning.* Pinter, London.

Malerba, F. (2005), 'Sectoral systems: how and why innovation differs across sectors', in J. Fagerberg, D. C. Mowery, & R. R. Nelson (eds), *The Oxford Handbook of Innovation.* Oxford University Press: Oxford.

Malerba, F. and R. Nelson (2011), 'Learning and catching up in different sectoral systems: evidence from six industries,' *Industrial and Corporate Change*, 20(6), 1645–1675.

Malerba, F. and L. Orsenigo (2000), 'Knowledge, innovative activities and industrial evolution,' *Industrial and Corporate Change*, 9(2), 289–314.

Mathews, J. A. (2006), 'Catch-up strategies and the latecomer effect in industrial development,' *New Political Economy*, 11(3), 313–335.

Mathews, J. and H. Tan (2015), *China's Renewable Energy Revolution.* Palsgrave Macmillan: Basingstoke.

Mu, Q. and K. Lee (2005), 'Knowledge diffusion, market segmentation and technological catch-up: the case of the telecommunication industry in China,' *Research Policy*, 34(6), 759–783.

NDRC. (2018), *Clean Energy Accommodation Action Plan (2018–2020) [in Chinese].* National Development and Reform Commission. https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201812/t20181204_960958.html.

NEA. (2018), *Notice on the Relevant Requirements of Wind Power Construction Management in 2018 [in Chinese].* National Energy Commission. http://coalcap.nrdc.cn/policy/info? id¼308&type¼1.

Nelson, R. R. and S. Winter (1982), *An Evolutionary Theory of Economic Change.* Harvard University Press: Cambridge, MA.

Pavitt, K. (1984), 'Sectoral patterns of technical change: towards a taxonomy and a theory,' *Research Policy*, 13(6), 343–373.

Perez, C. and L. Soete (1988), 'Catching Up in Technology: entry Barriers and WOO', in G. Dosi (ed.), *Technical Change and Economic Theory.* Pinter: London.

Quitzow, R., J. Huenteler and H. Asmussen (2017), 'Development trajectories in China's wind and solar energy industries: how technology-related differences shape the dynamics of industry localization and catching up,' *Journal of Cleaner Production*, 158, 122–133.

Shin, J.-S. (2017), 'Dynamic catch-up strategy, capability expansion and changing windows of opportunity in the memory industry,' *Research Policy*, 46(2), 404–416.

Sinovel (n.d.), 'Milestones' Accessed from http://www.sinovel.com/english/about/?31.html, 28 July 2020.

Sun, S. L. and X. Yang (2013), 'Transformative capacity and absorptive capacity,' in P. P. Li (ed.), *Disruptive Innovation in Chinese and Indian Business: The Strategic Implications for Local and Global Incumbents.* Routledge: New York.

Suri, H. (2011), 'Purposeful sampling in qualitative research synthesis,' *Qualitative Research Journal*, 11(2), 63–75.

Ufuah, A. N. and J. Utterback (1997), ‘Responding to structural industry changes: a technological evolution perspective,’ *Industrial and Corporate Change*, 6(1), 183–202.

UNCTAD. (2019), *Digital Economy Report 2019: Value Creation and Capture; Implications for Developing Countries.* United Nations Conference on Trade and Development. https://www.un-ilibrary.org/democracy-and-governance/digital-economy-report-2019_c7dc937a-en

Van Dijk, M. (2000), ‘Technological regime and industrial dynamics: the evidence from Dutch manufacturing,’ *Industrial and Corporate Change*, 9(2), 173–194.

Wang, Z., H. Qin and J. I. Lewis (2012), ‘China’s wind power industry: policy support, technological achievements, and emerging challenges,’ *Energy Policy*, 51, 80–88.

Yin, R. K. (2003), *Case Study Research: Design and Methods.* SAGE: Thousand Oaks, CA.

Zhang, H., Y. Zheng, D. Zhou and X. Long (2018), ‘Selection of key technology policies for Chinese offshore wind power: a perspective on patent maps,’ *Marine Policy*, 93, 47–53.

Zhou, Y., X. Li, R. Lema and F. Urban (2016), ‘Comparing the knowledge bases of wind turbine Firms in Asia and Europe: patent trajectories, networks, and globalisation,’ *Science and Public Policy*, 43(4), 476–491. https://doi.org/10.1093/scipol/scv055.

Zhu, M., Y. Qi, D. Belis, J. Lu and B. Kerremans (2019), ‘The China wind paradox: the role of state-owned enterprises in wind power investment versus wind curtailment,’ *Energy Policy*, 127, 200–212.

Appendix

Table A1. Top 10 wind turbine manufacturers with country of origin and global market share

Chinese firms

2000				2006				2018			
1	Vestas	DK	17.9	1	Vestas	DK	28.2	1	Vestas	DK	20.3
2	Gamesa	ES	13.9	2	Gamesa	ES	15.6	**2**	**Goldwind**	**CN**	**13.8**
3	Enercon	DE	13.7	3	GE Wind	US	15.5	3	Siemens Gamesa	DE, ES	12.3
4	Neg Micon	DK	13.4	4	Enercon	DE	15.4	4	GE Renewable Energy	US	10
5	Bonus	DK	11.5	5	Suzlon	IN	7.7	**5**	**Envision**	**CN**	**8.4**
6	Nordex	DE	8.3	6	Siemens	DE	7.3	6	Enercon	DE	5.5
7	Enron	US	6	7	Nordex	DE	3.4	**7**	**Mingyang**	**CN**	**5.2**
8	Ecotecnica	ES	3.9	8	REPower	CH	3.2	8	Nordex Acciona	DE, ES	5
9	Suzlon	IN	2.3	9	Acciona	ES	2.8	**9**	**United Power**	**CN**	**2.5**
10	Dewind	DE	2.1	**10**	**Goldwind**	**CN**	**2.8**	**10**	**Sewind**	**CN**	**2.3**
	Other		*7*		*Other*		*3.5*		*Other*		*14.7*

11	**Suzlon**	**IN**
12	**Senvion**	**DE**
13	**Windey**	**CN**
14	**CSIC Haizhuang**	**CN**
15	**XEMC**	**CN**

Source: Author's own elaboration based on FTI, GWEC and Bloomberg reports.

Table A2. Top 5 wind turbine manufacturers according to turbine size

Turbine size range (MW)	1	2	3	4	5
0 – 0.49	Shiram	Enercon	EWT	–	–
0.5 – 0.74	RRB Energy	Pioneer	EWT	–	–
0.75 – 0.99	Enercon	Siemens Ga.	Wind World India	EWT	–
1 – 1.3	Leitwind	–	–	–	–
1.5	Goldwind	CCWE	Regen Power Tech	CSR	Windey
1.5 – 1.99	GE Ren.	Vestas	Envision	Hyundai	–
2	Goldwind	Vestas	Ming Yang	Siemens Ga.	United Power
2.01 – 2.49	Envision	Siemens Ga.	Ge Ren.	Enercon	Suzlon
2.5	Goldwind	Envision	Dongfang	GE Ren.	Nordex Acciona
2.5 – 2.99	GE Ren.	Siemens Ga.	Goldwind	–	–
3	Enercon	Nordex Acciona	Siemens Ga.	Ming Yang	Vestas
3.01 – 3.59	Vestas	Siemens Ga.	Senvion	Nordex Acciona	MHI Vestas
3.6 – 3.99	Nordex Acciona	Siemens Ga.	Senvion	–	–
4 – 5	Siemens Ga.	SEwind[a]	Enercon	Envision	CSIC Haizhuang
5.1 – 6	Siemens Ga.	–	–	–	–
> 6	MHI Vestas	Senvion	Siemens Ga.	Enercon	Goldwind[b]

[a]SEwind (Shanghai Electric) purchased a license from Siemens Wind Power to manufacture their offshore designs for the Chinese market.
[b]Goldwind recently entered the test stage for offshore installations. These turbines are still at the development level.
Note: The dark grey shade denotes Chinese firms.
Source: FTI Intelligence (2018).

Article III

How do R&D networks change? The upgrading of innovation capabilities in emerging market firms. Insights from China's wind energy sector

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Abstract

Innovative activities are increasingly decentralized and globally dispersed, which provides new upgrading opportunities for emerging market firms. However, little is known about how latecomer firms (re-)organize their research and development (R&D) over time as conditions for upgrading change. This paper systematically maps the R&D networks of China's lead firms in the wind turbine industry. The empirical findings reveal that latecomer firms not only exploit but increasingly co-create vanguard knowledge in global R&D networks through organizational diversification. Taking an evolutionary perspective, the paper extends our understanding of the changing nature of upgrading mechanisms and provides new insights into the reorganization of innovation processes in an era of technological change.

Keywords: latecomer firms, upgrading of innovation capabilities, technological change, decomposition of innovation, global R&D networks, wind energy, China

JEL codes: O31 (Innovation and Invention: Processes and Incentives), O32 (Management of Technological Innovation and R&D), O33 (Technological Change: Choices and Consequences), Q20 (Renewable Resources and Conservation), Q55 (Technological Innovation), L10 (Market Structure, Firm Strategy, and Market Performance), L60 (Industry Studies Manufacturing), D83 (Search, Learning, Information & Knowledge)

1. Introduction

The way companies organize for innovation is undergoing a fundamental shift. In light of rapid technological change, firms are increasingly decentralizing their innovation and globally distributing their research and development (R&D) activities (Von Zedtwitz and Gassmann, 2002; Du et al., 2014; Lazonick, 2010; Cricelli et al., 2016; Popa et al., 2017; Muhammad, 2013).[78] The

[78] While R&D constitutes the part in the innovation cycle where financial resources are turned into new knowledge, innovation is described as the first attempt to turn ideas on a new product or process into practice, e.g., by implementing a new process or bringing a new product/service to the market. All types of R&D constitute innovative activities, but not all innovative activities

idea of transferring innovative activities from internal units to external networks has been referred to as 'open' innovation.[79] Incentives for decentralizing innovative activities and conducting joint R&D along with external partners are manifold: besides financial benefits such as shared commercial returns and R&D savings, access to exogenous competencies enables faster innovation cycles, enhances flexibility, and reduces risk (Lichtenthaler, 2011; Enkel at al., 2009; Ritala et al., 2017; Lee et al., 2010).

While it has been recognized that the geography of the decomposing of innovation goes well beyond OECD countries (Schmitz and Strambach, 2009; Lema et al., 2015; Fu, 2015), the open innovation and strategic management literature has been predominantly concerned with advanced economy multinational enterprises (MNEs) (see, e.g., Gassmann and Enkel, 2006; Dodgson et al., 2006; Mina et al., 2014; Vanhaverbeke, 2017; Laursen and Salter, 2006; Cantwell and Mudambi, 2005). Much less is known about how open and diversifying innovation dynamics affect the upgrading process of newly industrialized economies, specifically industrial latecomers firms. By contrast, the latecomer development literature has significantly enhanced our understanding of technological learning and upgrading mechanisms of latecomer firms at basic to intermediate levels of innovation capabilities (Bell, 2006; Bell and Figueiredo, 2012b; Hansen and Lema, 2019).[80] Yet, despite recognizing the growing significance of *unconventional* upgrading mechanisms (Lema and Lema, 2012, 2016) such as acquisitions of foreign firms and overseas collaborative R&D, existing concepts have not sufficiently focused on how latecomer firms upgrade to higher levels of innovation capabilities. In particular, little is known about how the decomposition of innovation provides new upgrading opportunities (Dai et al., 2021) to facilitate the transition to a beyond catch-up stage (Peng et al., 2020; Dutrénit, 2000, 2007).

This paper addresses this gap by bringing the two strands of literature together and exploring the following two research questions:

> *In the face of technological change and the global decomposition of innovation, (1) what strategies do latecomer firms adopt to upgrade their innovation capabilities, and (2) how does their R&D organization change?*

Empirically, the paper focuses on lead firms in China's wind turbine industry as an extreme case for compressed development (Whittaker at al., 2010) and rapid technological catch-up (Hansen and Lema, 2019). It draws on a firm-level dataset and adopts a network analysis approach to map systematically the evolution of R&D networks over the past two decades.

The remainder of the paper is organized as follows. Section 2 introduces the core concepts from the extant literature and combines it into an analytical framework. Section 3 presents the research methods. Section 4 analyzes the empirical firm cases, which are discussed in Section 5. Section 6 concludes and summarizes the key contributions.

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are R&D. The conceptualization of *innovation* and *R&D* is further described in Section 2 and described in detail in Supplementary Appendix A.

[79] 'Open Innovation' (Chesbrough, 2003, 2017; Chesbrough et al., 2006) and the 'Organizational Decomposition of Innovation' (Schmitz and Strambach, 2009) constitute two differently framed perspectives on the same underlying phenomenon.

[80] See Supplementary Table C1 for a detailed overview of key concepts on latecomer learning and upgrading mechanisms.

2. Framing perspectives on the changing conditions for latecomer firm upgrading

2.1 The decomposition of innovation and reorganization of R&D

Since the early 2000s, a growing number of studies have been concerned with the changing patterns of innovation. The underlying observation is that firms fundamentally reorganize their innovative activities by internationalizing their R&D (Awate et al., 2012; Chen et al., 2012; Von Zedtwitz and Gassmann, 2002), engaging in open innovation projects (Du et al., 2014; Chesbrough and Bogers, 2014), and establishing multi-scalar couplings in global systems of innovation (Binz and Truffer, 2017). This phenomenon can be summarized as the 'Organizational Decomposition of the Innovation Processes' (ODIP), which is reflected in the transformation of both intra- and inter-organizational R&D structures (Schmitz and Strambach, 2009).[81] Accordingly, innovative activities are not only decentralized within the firm headquarters (e.g., through separate R&D units and knowledge communities), but also increasingly delegated to globally dispersed subsidiaries/R&D centers or outsourced to external suppliers and providers of R&D and engineering services (Haakonsson et al., 2020; Lema et al., 2015).[82]

The ODIP typology by Schmitz and Strambach (2009) provides a good point of departure to explore this changing nature of the organization of innovative activities (see Table 1). It distills four types of ODIP along two dimensions, *internal/external* to the organization and *loose/tight* connection between innovation and production. Analogous to loosely/tightly connected external ODIP, this paper uses the more intuitively framed *market-based* and *science-based* distinction to classify external R&D partners (Du et al., 2014). While the first defines commercial actors with close links to an industry such as suppliers and startups, the latter refers to organizations that are primarily concerned with the creation of new knowledge such as universities and research institutes (Schmitz and Strambach, 2009). Both are highly relevant to generate new knowledge and turn this knowledge into new or improved products or processes. The following five criteria must be fulfilled to qualify as R&D: activities must be novel, creative, systematic, transferable and/or reproducible, and address an uncertain outcome (OECD, 2015, 2018a).[83] Supplementary Table A1 provides a detailed overview on the terminologies and delimitations.

Although it has been recognized that ODIP provides new upgrading opportunities for industrial latecomers (Haakonsson et al., 2020; Lema et al., 2015; Schmitz and Altenburg, 2016), the co-evolution of ODIP and the upgrading of innovation capabilities of latecomer firms remains

[81] Digital technologies allow firms to access external knowledge and collaborate with external partners at an unprecedented scale (Veugelers et al., 2010; Curley and Salmelin, 2018). In addition, given that open innovation occurs in multidisciplinary and cross-organizational R&D networks (Ritala et al., 2017), it increases the likelihood of generating more radical innovation (Chesbrough et al., 2006; Lee et al., 2010).

[82] *Decentralization* and *dispersion* describe activities related to the decomposition of innovation, with the first highlighting the organizational and the second the geographical dimensions.

[83] Despite recognizing that the intensity of 'research' versus 'development' varies across the different ODIP types, this paper understands 'R&D' broadly as a range of activities firms can undertake in pursuit of innovation, including prototyping, pilot testing, and other demonstration activities close to the market (but not there yet). The delegation of tasks to internal subsidiaries (*Type 2*) and external market-based partners (*Type 4*) is considered R&D as long as it involves development functions.

little explored.[84] An important entry point was established by Lema et al., (2015), who showed that ODIP provided significant opportunities for the build-up of innovation capabilities in latecomer firms in Brazil's auto and India's software industries. However, most studies in this field portray advanced economy firms ('old powers') as the dominant actors in producing knowledge and shaping global R&D networks. By contrast, latecomer firms are assumed to play a less active role by tapping into existing knowledge pools (Fu, 2015), thereby benefitting from the global decomposition of innovation rather than co-creating it. However, as a growing number of latecomer firms are building up sufficient innovation capabilities to enter a beyond catch-up stage and compete at or close to the technological frontier (Peng et al., 2020; Dutrénit, 2004, 2007), traditional technology transfer models become increasingly limited in their analytical value. In particular, Asian firms have witnessed a historically unprecedented rise in innovative activities and have become leaders in a number of high-tech sectors (Hain et al., 2020; Lee and Malerba, 2017; Giachetti and Marchi, 2017; Shin, 2017; Lee and Ki, 2017; Altenburg et al., 2016). With the world's center of economic and scientific gravity shifting further toward Asia, particularly China (Quah, 2011; Gui et al., 2019), latecomer firms are playing an increasingly proactive role in reshaping global R&D networks rather than only exploiting existing knowledge.[85] This highlights the relevance of further empirical investigation.

Table 1. The ODIP framework

Connection[(a)]	Internal	External
Loose	*Type 1* Decentralizing the R&D department; setting up internal knowledge communities	*Type 3 – Science-based partner* Commissioning research from universities or other organizations
Tight	*Type 2* Delegating the development of new products to subsidiaries; setting up internal centers of excellence	*Type 4 – Market-based partner* Engaging suppliers of products and services in developing new products or processes

Source: Adapted from Schmitz and Strambach (2009). *Note:* (a) Between innovation and production.

2.2 The upgrading of innovation capabilities

2.2.1 What is upgrading?

While the *catch-up cycle literature* (Lee and Malerba 2017) operationalizes upgrading based on a lead firm's market or production shares, the *technological learning* and *innovation capability building literature* considers upgrading as an accumulation of capabilities inherent to a latecomer firm (Lall, 1992; Bell and Figueiredo, 2012 a, 2012b). Hence, the latter understands upgrading as a process that is relatively detached from quantitative market outputs and rather focuses on the qualitative outcome of innovation capabilities or *revealed capabilities* (Sutton, 2012). This paper understands upgrading in relative terms by the rate of innovation as compared with competitors and defines it as enhancing a latecomer firm's innovation capabilities through effective learning, with the latter being defined as 'conscious, purposive and costly [...] mechanisms for acquiring

[84] Upgrading is herein defined as enhancing a latecomer firm's innovation capabilities through effective learning; it does not refer to the notion of upgrading as defined in the global value chains literature, i.e., increasing a firm's benefits by participating in global value chains.

[85] For example, China's value-added content in ICT and electronics has increased substantially over the last decade (OECD, 2018b).

and creating knowledge, skills and organizational arrangements for supporting innovation' (Bell and Figueiredo, 2012a: 19). Innovation capabilities comprise both a technological and an organizational dimension (Dutrénit, 2000, 2007). The underlying assumption is that external (technological) knowledge needs to be effectively integrated into and coordinated with a firm's existing knowledge base to increase innovation capability accumulation beyond improved production capabilities (Bell and Pavitt, 1992, 1995; Bell and Figueiredo, 2012b; Altenburg et al., 2008; Kim, 1997). The relative importance of organizational capabilities increases across different maturity levels: the more a latecomer firm transitions toward advanced levels of innovation capabilities, the more important the organizational dimension is to *orchestrate* the firm's internal innovative activity (Dutrénit, 2000; Bell and Figueiredo, 2012a; Lall, 1992). This co-orchestration capability becomes even more important as firms decentralize and globally distribute their R&D activities. For later analysis, this paper categorizes innovation capabilities as 'low,' 'medium,' and 'high,' corresponding to increasing degrees of novelty and impact as shown in Table 2.

Table 2. Three levels of innovation capabilities

Innovation	**Low**	**Medium**	**High**
Capabilities	Capability to produce new-to-the-firm innovations such as minor adaptions of imported products	Capability to produce new-to-the-country/sector innovations such as complex modifications of existing technologies	Capability to produce new-to-the-world innovations related to technology at the global frontier

Source: Adapted from OECD (2018a).

2.2.2 How do upgrading mechanisms change?

Previous studies have provided useful tools to analyze the changing sources of learning and upgrading mechanisms of latecomer firms as they advance from production to innovative activities (Hansen and Lema, 2019; Figueiredo and Cohen, 2019; Mathews, 2006). However, there has been much less focus on more advanced upgrading mechanisms as firms transition to higher levels, approaching the innovation frontier. Recent research has shown that latecomer firms have to build ambidextrous learning strategies to 'conquer the upgrading barriers in beyond catch-up stage and innovation frontier stage' (Peng et al., 2020: 2). By analyzing China's lead firms, this paper pays particular attention to the changing upgrading mechanisms once firms transition to the stage where they no longer only follow the paths of incumbent firms.

This study adopts an evolutionary perspective and draws on Lema and Lema's (2012) distinction between *conventional* and *unconventional* upgrading mechanisms to classify collaboration activities along their increasing degree of cross-border interaction and recipient effort.[86] Conventional upgrading mechanisms comprise international trade, foreign direct investment (FDI), technology licensing, and local joint ventures. These activities involve a relatively low degree of cross-border collaboration and recipient effort, which constitute a common upgrading mechanism for new industry entrants with lower degrees of innovation capabilities. In turn, unconventional upgrading mechanisms include overseas collaborative R&D, acquisition of

[86] The terms 'technology transfer,' as originally used by Lema and Lema (2012), and 'technology transmission' (Haakonsson and Slepniov, 2018) imply by convention knowledge flows from OECD to emerging market firms. This study understands *conventional* upgrading as largely unidirectional and *unconventional* upgrading as a largely multidirectional learning process.

foreign firms, and overseas R&D in the form of outward FDI. These are more difficult to coordinate and are typically adopted by firms that have accumulated a certain level of innovation capabilities.

In line with Slepniov et al. (2015), this study uses the concept of *innovation spaces* to describe the cross-border interaction in which the upgrading of innovation capabilities takes place. Accessing knowledge through globally dispersed innovation spaces is particularly important for latecomer firms as their home markets usually lack vanguard knowledge due to their latecomer status (Mathews, 2006, 2017; Kedia et al., 2012). Given the rapid pace of technological change, accessing global innovation spaces across geographies and sectors becomes increasingly important as one country alone can hardly master a full range of specialism. This underlines the growing need for intra- and inter-organizational decentralization and dispersion strategies to tap into complementary knowledge pools (Fu, 2015).

2.3 Analytical framework

Based on the framing perspectives discussed in this section, Figure 1 provides the analytical framework to guide the empirical analysis. It shows the two key dimensions in the upgrading of innovation capabilities, namely *innovation space* (indicating the degree of cross-border and cross-sector interaction) and *knowledge (co-)creation effort* (indicating the degree of effort and investment to co-create new knowledge). The underlying assumption is that in order to upgrade their innovation capabilities, latecomer firms have to increase the innovation space through organizational diversification and scale up their knowledge (co-)creation efforts to produce new knowledge (rather than only absorbing existing knowledge).[87] Neglecting one dimension can restrain the upgrading process and result in decelerated growth or a middle-income trap (Lee, 2013, 2019), in which innovation capabilities are not sufficient to compete in global markets and latecomer firms remain in a follower position.

As shown in Figure 1, conventional upgrading mechanisms cover the lower innovation capability spectrum, where latecomer firms produce new-to-the-firm innovation such as minor adaptions of imported products. To upgrade beyond this stage and produce increasingly complex innovations, latecomer firms must adopt unconventional upgrading mechanisms. While the analytical framework suggests that latecomers can evenly expand their innovation capabilities, it needs to be mentioned that the upgrading of innovation capabilities rarely follows a linear path (Figueiredo, 2010; Bell and Figueiredo, 2012b). Each latecomer firm's upgrading path is idiosyncratic and depends on a multitude of macro and micro factors such as the institutional environment, domestic market size, sectoral characteristics, and pre-existing technological capabilities (Hain et al., 2020; Awate et al., 2012; Lee and Malerba, 2017). Since this study analyzes firm cases within the same country and the same sector, it explicitly focuses on the varieties of firm-level strategies to upgrade innovation capabilities.

[87] Expanding the innovation space is important both to absorb knowledge in the home market and to gain access to vanguard knowledge in international markets.

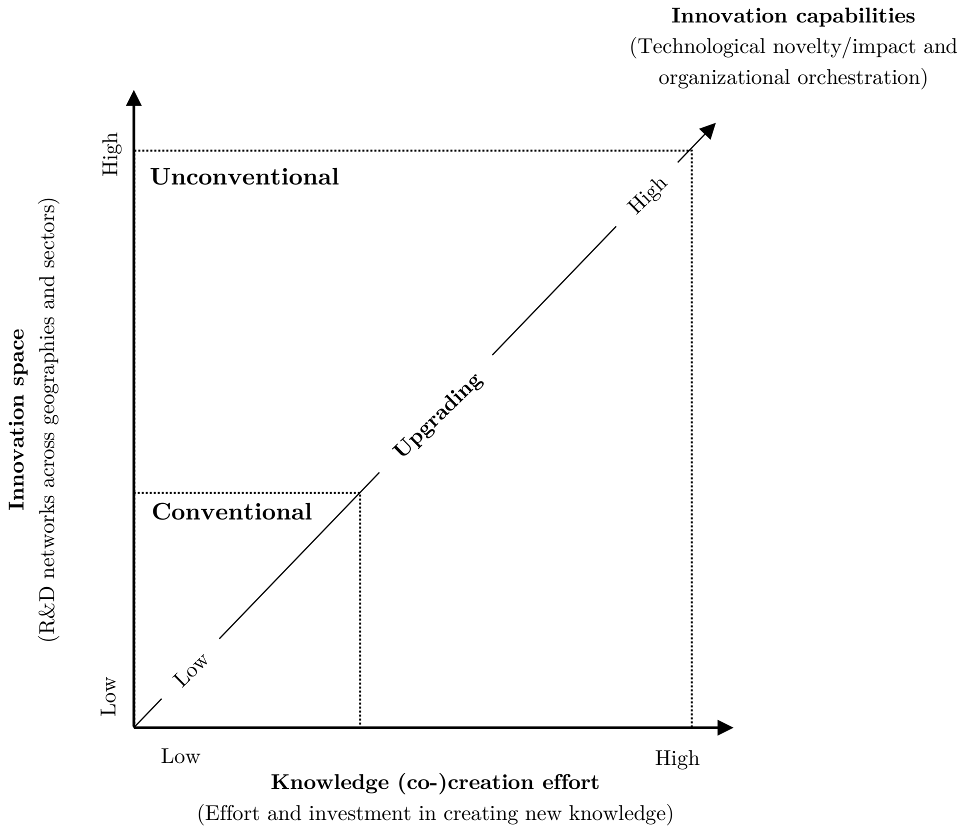

Figure 1. Upgrading of innovation capabilities along two dimensions
Source: Author's elaboration based on Lema and Lema (2012) and Bell and Figueiredo (2012a).
Note: The innovation space dimension constitutes a continuum based on the ODIP framework. Each of the four ODIP types represents one option to expand the innovation space internally (ODIP Type 1–2) and/or externally (ODIP Type 3–4).

3. Research methods

To reach a high level of internal validity and analytical generalization, this study combines within-case process tracing and cross-case comparative research techniques (Beach, 2017; Gerring, 2006; George and Bennett, 2005; Yin, 2009). Case studies are 'cumulatively contingent generalizations that apply to well-defined types or sub-types of cases with a high degree of explanatory richness' (George and Bennett, 2005: 31). Therefore, the conditions or mechanisms under which certain outcomes occur are of interest rather than their frequency. Information-rich cases (Suri, 2011) were selected as follows: First, given its high technological complexity, catching up in the *wind energy sector* requires particularly effective learning mechanisms (Hain et al., 2020; Binz et al., 2017; Huenteler et al., 2016). Second, with the accumulation of 'significant innovation capabilities [by] participating in globalized innovation processes' (Schmitz and Altenburg, 2016: 5), *China's* wind energy sector represents an *extreme case* (Flyvbjerg, 2006) of rapid latecomer catch-up. Third, *firm-level cases* in China's wind energy sector were selected in line with a most-similar case study design (Seawright and Gerring, 2008), displaying a very high similarity in terms of background conditions (country, sector, and market position), yet low similarity in terms of two key variables (upgrading strategies and innovation capabilities). As shown in Table 3, three firm cases were finally selected for two main reasons: They represent the top three Chinese wind turbine manufacturers in terms of market share, accounting for two-thirds of China's and almost 30% of global market output; yet they have developed very different technological foci (see *key technology* in Table 3; Dai et al., 2021).

Table 3. Top three Chinese wind turbine manufacturers by domestic and global market share (2019)

Firm	Founding year	Headquarters	Company type (% state-owned)	Domestic market share and rank	Global market share and rank			Key technology and global rank
					Total	Onshore	Offshore	
Goldwind	1998	Beijing*	Public (43%)**	28% (1)	13.2% (3)	13.6% (2)	9.4% (5)	PMG Direct Drive (1)
Envision	2007	Shanghai	Private (<10%)	19% (2)	8.6% (5)	8.5% (5)	9.5% (4)	Conventional Drive (4)
Ming Yang	2006	Zhongshan	Public (<10%)	16% (3)	5.7% (6)	5.5% (6)	7.3% (6)	Hybrid Drive (1)
				63%	**27.5%**	**27.6%**	**26.2%**	

Source: Author's own compilation based on GWEC (2012, 2020), BNEF (2020a), and CWEA (2018, 2020).
Note: (*) Goldwind later moved its headquarters from Urumqi (Xinjiang) to Beijing. (**) 43% are owned by state-owned China Three Gorges New Energy. The gray-hatched areas highlight a changed market ranking from first (dark gray) to third (white).

To operationalize the research questions, this paper draws on multiple data collection techniques and data sources. Data was iteratively collected through desk research (350 archival records and five databases) and extensive fieldwork (81 semi-structured interviews and 23 on-site observations) between 2017 and 2020 and includes 1.5 years of consecutive field research in China. Since publicly disclosed reports on the firms' R&D collaborations are scarce, drawing upon different data collection techniques was important to identify a wide range of R&D partnerships, get a better understanding of their respective relevance for upgrading, and triangulate different data sources. The combination of qualitative and quantified relation data was important to investigate the relationship between upgrading strategies and R&D networks over time. The collected dataset contains detailed information on approximately 400 market- and science-based R&D partnerships of the case-study firms between 1998 and the first half of 2020. The dataset was analyzed with a longitudinal network approach (Stephan et al., 2017), clustering R&D partners into nodes and their inter-organizational relationships into edges. Widths of edges reflect intra- versus inter-organizational connections of the case-study firms in line with the ODIP framework.

As this study takes an evolutionary perspective on how networks change over time, various time intervals had to be chosen. In a recent study, Dai et al. (2021) identified three successive technology domains in the evolution of the global wind sector that entered China's wind industry with a certain time lag: (1) onshore technology (world: 1980, China: 2000), (2) offshore technology (world: 2000, China: 2010), and (3) digital/hybrid systems (world: 2010, China: 2015). This periodical classification was useful to see how the Chinese firms reorganized their R&D networks in the face of technological change. The methodological choices and consecutive steps of collecting and analyzing data are described in detail in Supplementary Appendix A.

4. Shifting upgrading strategies in China's wind energy sector

4.1 Phase I: Emergence and fast market scale-up (until 2009)

Existing scholarship has dealt extensively with the emergence of China's wind turbine industry, which was driven by industrial policies and different forms of conventional technology transfers such as licensing agreements with European design firms (Lewis, 2012; Fu, 2015; Hansen and Lema, 2019; Haakonsson et al., 2020; Nahm, 2017; Mathews and Tan, 2015; Backwell, 2017). Figure 2a shows the early-stage R&D networks of the three firms.

While Goldwind (GOL) and Ming Yang (MNG) had already established collaborations with licensing firms,[88] suppliers,[89] and universities,[90] Envision (ENV) only started commercial operations in 2009. In contrast to GOL and MNG, which had been building experience in the manufacturing industry since the 1990s,[91] ENV started the manufacturing business from scratch. This is reflected in the almost nonexistent partnership network. Hence, unlike the other two firms, which could crowd in capabilities from other sectors, ENV did not have the existing manufacturing base to technologically leapfrog through licensing agreements with European design firms. Instead, it hired engineers from global lead firms who had gained in-depth industry experience. As the R&D director of a European licensing firm noted: 'Envision is the only one I know of that is really self-developed […] the boss hired people on the world market who have an idea about wind power.' While GOL was collaborating with both market- and science-based R&D partners for rapid market scale-up, MNG's early network mainly comprised science-based partnerships with local universities and research institutes. It hired a professor who had gained considerable engineering experience in Europe as a chief scientist: 'I tried to bring my background from academic research into the industry.' A first step toward opening up the innovation process during that time concerned the licensing agreements of GOL and MNG. Rather than keeping their collaboration closed, GOL encouraged Vensys to offer licensing services to competitors across Latin America, Europe, and India for learning purposes (Lewis, 2012). Similarly, MNG financed its early R&D by reselling the licensing agreements it had obtained from aerodyn to other Chinese firms in the market.

However, in general, the first period was largely dominated by an organizationally closed paradigm with innovative activities being concentrated at or near the headquarters. External knowledge sourcing occurred conventionally from a few proven, foreign industry partners (mainly licensing firms and suppliers). Chinese wind energy firms were mainly recipients of technology transfers, which is also reflected in the dearth of patenting activity before 2010 (Hu et al., 2018).[92]

[88] GOL licensed first from Jacobs Energie/REpower (DE) and later from Vensys (DE), where it acquired a majority stake of 70% in 2008. MNG licensed from aerodyn (DE) and General Electric (US).
[89] E.g., GOL with Hebei Electric Equipment (CN), CSR Electric (CN), and Beijing Tianrun (CN); MNG with Nanjing Gearbox Corporate (CN) and ABB (CH).
[90] E.g., GOL with Xinjiang Agriculture University (CN), the National Wind Technology Center (CN), and Delft University (NL); MNG with the Guangdong Wind Power Research Institute (CN), Xiamen University (CN), and Risø-DTU (DK).
[91] GOL as Xinjiang Wind Energy Company and MNG as Ming Yang Electric.
[92] No patents were filed during the first phase as GOL and MNG were buying complete turbine designs through licensing agreements; ENV only became operational at the end of the first phase.

4.2 Phase II: Technological consolidation and divergence (2010–2014)

In the course of the second phase, the three firms gradually built up their partner networks (Figure 2b). During this period, the focus shifted from technological licensing to mergers and acquisitions (M&A), collaborative R&D, and joint research with universities. At the same time, the firms gradually decentralized their internal organization and delegated R&D-related tasks to globally dispersed hubs. Each of the firms inaugurated overseas subsidiaries (width gray edges), yet with different knowledge sourcing strategies. Besides setting up an R&D center in Denmark for 'developing and testing wind turbines [through] highly skilled engineers' and a sales office in Germany, ENV established a digital hub in Singapore to collaborate with 'software companies than can drive disruptions in the internet-of-things, big data and cloud security.' Furthermore, it started a partnership with US-based Pattern Energy to test ENV's wind software in its operating fleet. MNG opened a local laboratory for wind power in Guangdong and a global R&D center on the campus of North Carolina State University, aiming at 'exploring local market opportunities [and] lowering the cost of electricity of offshore wind turbines.' In terms of market-based partnerships, it formed a joint venture with India's Reliance Group to 'capture and grow in India and South Asian markets' and signed a framework agreement with a Romanian engineering, procurement, and construction (EPC) contractor.

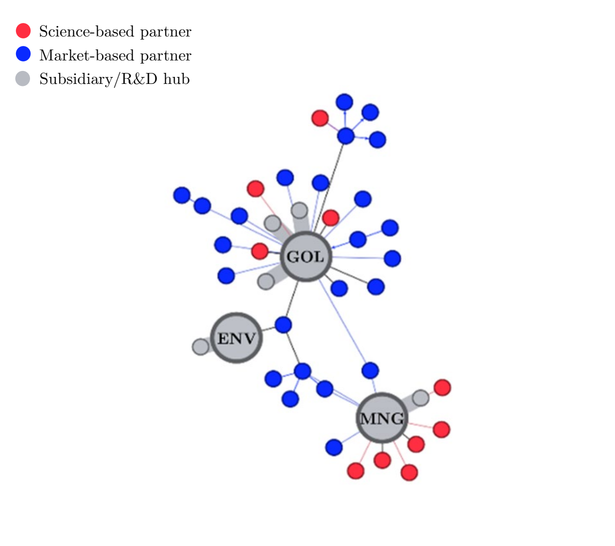

Figure 2a. R&D networks, phase I (until 2009)

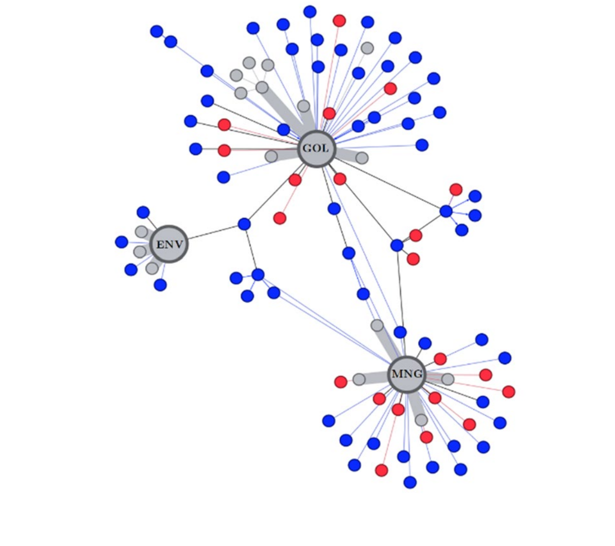

Figure 2b. R&D networks, phase II (2010–2014)

GOL opened a US center in Chicago and founded its own university, mainly for internal training but also for R&D collaboration purposes, with academic advisors from leading universities in the United States and China such as Stanford, Peking, and Tsinghua universities. In addition, it sponsored a professorship at the German HTW Saar for wind energy, where Vensys had emerged as a university spin-off. With regard to industry partners, GOL focused on localizing its supply chain through various acquisitions and vertically integrated various upstream (component and equipment suppliers) and downstream (project development) companies.[93] To expand in the overseas market, GOL entered into different kinds of agreements with utilities and project developers in Latin America,[94] and with a power grid company in Australia. It started overseas R&D collaborations with German firms such as Infineon and Semikron to 'introduce semiconductor technology into the company.'

During the second phase, the three firms' divergent technological directions became increasingly pronounced. First, each of the firms opted for a different core wind turbine technology: GOL used the gearless permanent-magnet direct drive through Vensys (license), MNG the slow-rotating hybrid drive developed by aerodyn (license),[95] and ENV followed the conventional drive model used by incumbents such as Vestas, General Electric (GE), and Nordex (see Table 3). Second, the three firms started to diversify into industrial sectors beyond the core wind turbine business. GOL invested in various domestic water treatment companies. MNG partnered with the China National Nuclear Corporation to 'join forces to develop [...] solar projects in China.'[96] ENV started an alliance with New Zealand's Infrantil to 'build smart infrastructure in Christchurch.' ENV also initiated two innovation projects with market- and science-based partners: one demonstration project with the Massachusetts Institute of Technology (MIT) and Tsinghua University to 'create an ecosystem of innovation for both generation and conservation of renewable energy,' and a unified testing alliance (UniTTE) with multiple university (Danish Technical University and the University of Stuttgart) and industry partners (Vattenfall, DNV GL), including incumbent firms (Siemens Gamesa and Vestas). Starting in 2014, the project's objective was to 'form a sound scientific basis for the next generation of international standards for wind turbine power measurement and loads assessment.' This can be considered one of the first global innovation alliances involving a Chinese wind turbine manufacturer.

In sum, this second phase was characterized by a transition from conventional to unconventional upgrading mechanisms, which allowed the firms to shift from low to medium innovation capabilities. To increase their innovation space and collaborate with external partners, all three firms delegated some internal R&D operations to globally dispersed units. These units often had a dual R&D/sales function. However, the main R&D activity was still housed at the headquarters. External partnerships were increasingly diversified across countries and sectors yet mainly with the objective to exploit existing rather than co-create new knowledge.

4.3 Phase III: Technological transformation (2015–today)

The third phase saw a major transformation of the global wind energy sector (Dai et al., 2021). With rapidly falling prices for wind energy and the commoditization of wind turbines, firms in the wind sector sought to shift their business models toward new hybrid and digital business models as well as ancillary services.[97] As the manager of a global lead firm summarized it, 'we

[93] E.g., Xiexin Wind Power (CN), China Machinery and Equipment (CN), and Yiwu Tianrun Wind Power (CN).
[94] E.g., with CELEC in Ecuador, Mainstream Renewable Power in Chile, and InterEnergy and UEP Penome in Panama.
[95] Referring to the Rendsburg-based (DE) aerodyne Energiesysteme GmbH.
[96] This window of opportunity was opened as the Chinese government required conventional power plant constructors and operators to invest a certain percentage (*ca.* 12%) into renewable energies.
[97] 'Hybrid' refers to the combination of renewable energy technologies (often wind and solar PV) and storage solutions.

have to provide more than just the turbine, we have to develop more holistic solutions beyond the incremental increase of the wind turbine size.' As a consequence, firms in the industry had to quickly open up their R&D organization and shift toward more flexible and decentralized collaboration modes.

As shown in Figure 3, this had significant implications for the Chinese lead firms, especially GOL and ENV. Within five years they had transformed their own R&D organization in three important ways: (1) they shared a growing number of R&D partners, (2) they expanded their R&D reach from bilateral R&D partnerships to multilateral, externalized R&D projects, and (3) they shifted from acquiring existing knowledge to co-developing new knowledge. In addition, R&D partnerships were mostly formed for a limited period, with a specific innovation purpose, and comprised various market- and science-based partners.

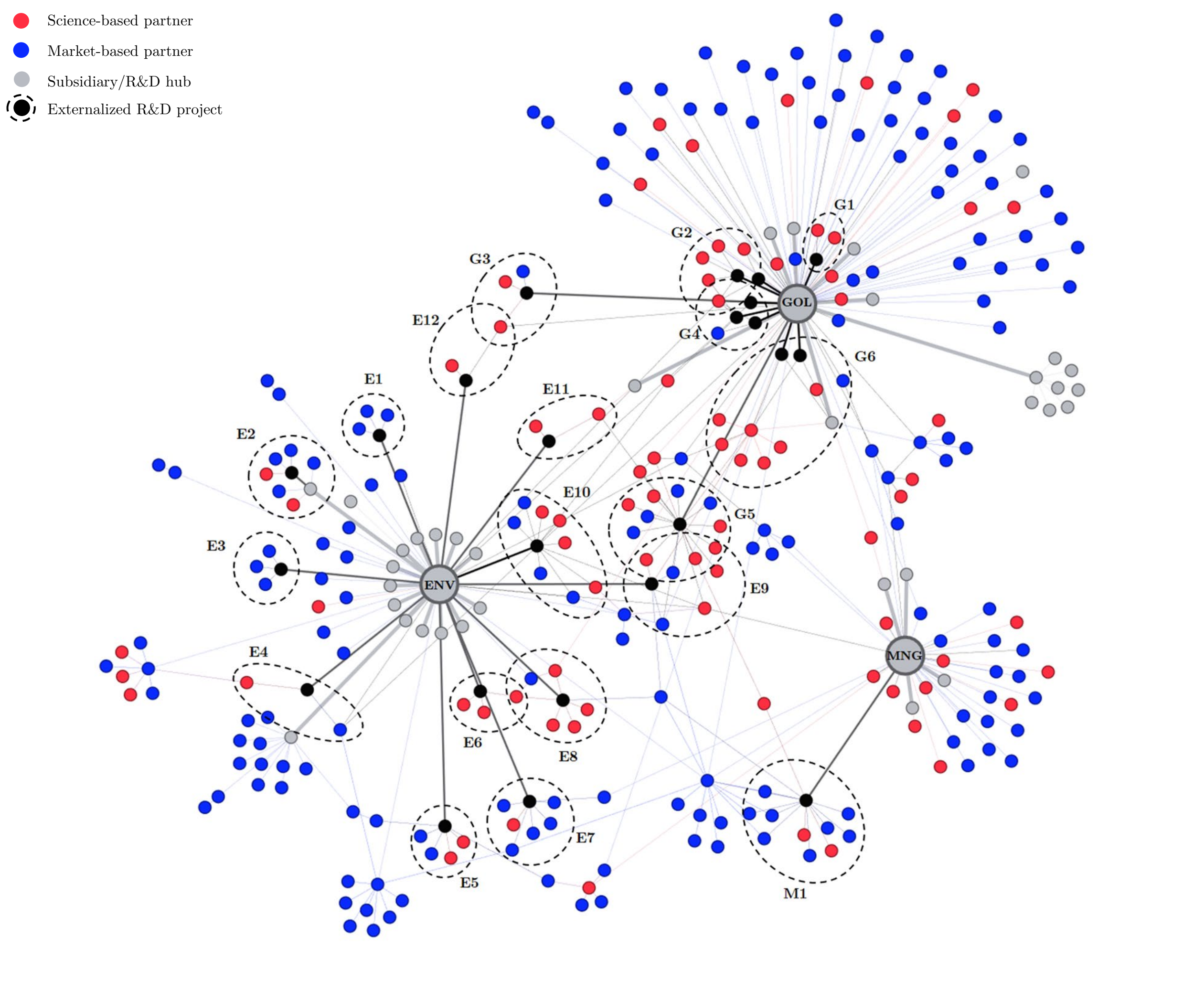

Figure 3. R&D networks, phase III (2015–2020)

Note: E1 and E3 are marked as externalized R&D projects because they have very close contact with science-based partners, even if they are not formally categorized as such.

Particularly striking is ENV's transformation in the course of the third phase. While ENV had long lagged behind the two other firms in terms of external partner networks, it now established more externalized R&D projects than the other two firms combined (see Annex A for a detailed overview of the R&D projects). Many of these collaborations had been initiated by a small European team, who acted as a partnerships task force. As the head of this team explained, 'I don't even know the number of collaborations we have, we are engaged in so many collaborations with third parties like research partners and startups [...] otherwise we would not be able to do all the things.' After establishing a venture capital program in Silicon Valley in 2015, ENV had acquired various startups to advance its digital analytics and energy management platform EnOS.[98] Besides software development, ENV put a major focus on e-mobility (see Annex A, E5–6), smart infrastructure (E2–3), and storage solutions, mainly lithium-ion batteries (E7). In 2018, ENV acquired Nissan's battery manufacturing business. Besides battery storage, ENV has been partnering with research institutes on hydrogen as an alternative storage and e-mobility application, especially for heavy-duty transport. One of ENV's flagship R&D projects is the EU-funded EcoSwing Superconductor project (E10) in collaboration with a number of European market- and science-based partners.[99] Various industry experts described the project as new-to-the-world and potentially path-creating for the wind energy sector: 'They are really pushing new technologies [...] this superconductor generator is like super rocket science technology and super risky but it has a proper chance to be our future' (Senior Wind Turbine Engineer), and 'this is not the technology of today, but tomorrow' (R&D Director, European licensing firm). During the third phase, ENV outsourced many manufacturing tasks to external partners but continued prototyping many components in-house for learning purposes.

Like ENV, GOL increasingly expanded its R&D to the external project level but with a different technological focus and collaboration mode. Despite having various market- and science-based partners in common,[100] GOL used external R&D partnerships mainly to advance in downstream activities such as microgrids (see Annex A, G2, 4, 6) and wind farm optimization (G5). This was part of GOL's larger strategy to shift from an EPC to an integrated industry chain service provider. Compared with ENV, GOL used external R&D networks mostly for research rather than co-development purposes. One exception is the Big Data Innovation Platform in Qinghai (G3), which was jointly developed with domestic research institutes.[101] During the third phase, GOL intensified its focus on water treatment by acquiring over ten domestic firms in the sector. In addition, it acquired a few international firms in the solar photovoltaics (PV), blade design, and energy storage sectors.[102] In 2018, GOL opened a renewable energy test lab at Australia's University of New South Wales. To improve learning among its suppliers, GOL set up an open innovation island platform where different suppliers can 'share data, best practices, interact and learn from each other.' However, despite recognizing its

[98] E.g., ProtectWise, Vidder, Onion ID, PubNub, and Baffle in the field of cloud security/computing and Orbital Insight and ZingBox in the field of big data analytics.
[99] E.g., Eco 5 (DE), Delta Energy (DE), DNV GL (NO), University Twente (NL), Frauenhofer IWES (DE).
[100] E.g., Tsinghua University (CN), National Renewable Energy Laboratory (US), Frauenhofer Institute (DE), University of Stuttgart (DE), Technical University of Denmark (DK).
[101] State Grid Qinghai Electric Power Company, Innovation Center for Industrial Big Data, and Tsinghua University.
[102] Oxford PV (GB), an Oxford University spin-off, for solar PV, Best Blades (DE) for blade design, and SaltX (SE) for large-scale energy storage.

potential, some Chinese suppliers also expressed skepticism due to trust issues in the Chinese market, commenting, for example, that 'such a platform will not help the suppliers to really trust each other' and 'it's kind of risky, people are afraid of disclosing their data.'

After enhancing its global network reach and tripling its partnerships between the first and second phases, MNG's global presence saw a slowdown in the third phase—in terms of both global sales and R&D partnerships.[103] Compared with the other two firms, MNG is still highly dependent on a few global partners and its local market (see global maps in Annex B).[104] Most of the firm's R&D takes place in-house with little exploration of external networks. A longtime consultant described it as follows: 'We [gave] them a list, every year, with the most innovative clean-tech startups. So, we told them to research more. I don't think they have done it.' A company manager emphasized that '[universities] don't have the ability to create products.' Therefore, the majority of partnerships today are still related to 'very mature technology and product design such as the ones acquired from aerodyn.' The only international R&D project where MNG is engaged in joint research is the Ocean Renewable Energy Action Coalition (OREAC) to support the firm's offshore capabilities (see Annex A, M1). Like GOL, MNG recently became a board member of the Global Wind Energy Association (GWEC) for knowledge exchange purposes.[105]

Table 4. Descriptive statistics of structural centrality

Phase	Firm	Degree	Eigenvector*	Closeness	Betweenness
1	GOL	21	1.00	0.54	0.82
	ENV	2	0.06	0.31	0.04
	MNG	10	0.23	0.39	0.37
2	GOL	44	1.00	0.50	0.71
	ENV	8	0.05	0.30	0.13
	MNG	32	0.48	0.42	0.52
3	GOL	95	1.00	0.42	0.54
	ENV	50	0.34	0.40	0.49
	MNG	38	0.19	0.34	0.20

Note: *Degree* shows the number of direct connections (direct influence); *eigenvector* shows connectedness to most influential nodes (quality of influence); *closeness* shows the average of the shortest distance to all other nodes (speed of influence); *betweenness* shows the extent to which a particular node lies on the shortest path between other nodes (control of influence); (*) 100 iterations. While GOL's number of direct connections (degree) grew linearly from 21 to 95, ENV shows an exponential growth after the second phase whereas MNG's degree only grew slightly. As the eigenvector centrality shows, the two lead firms GOL and ENV strengthened their ties during the third phase, while MNG was increasingly marginalized. This is also reflected in the network betweenness, where MNG lost and ENV gained considerable control during the third phase.

In sum, the third phase saw a considerable expansion in the innovation space, not only to exploit existing but also to co-create new knowledge. GOL and ENV shifted their R&D increasingly from the headquarters to globally dispersed units and externalized R&D projects. These external R&D projects differed from unconventional upgrading mechanisms in the second phase in three key dimensions: first, they consisted of at least three actors; second, they comprised at least one science- and one market-based partner (including the respective case-study firm); and third, they had a very specific innovation purpose, which is why they were usually formed for a limited period of time. In addition, these projects were formed to create significantly

[103] See Supplementary Annex B for a detailed overview of the market development of the three case-study firms.

[104] Global partners include aerodyn (DE), Frauenhofer Institute (DE), and ECN (NL).

[105] Besides GOL and MNG, other board members are GE Renewable Energy (since 2019), ENERCON (since 2019), ACWA Power (since 2019), and Shell (since 2018).

improved or new-to-the-world products or processes. Consequently, the degree of knowledge co-creation tends to be significantly higher than in previous unconventional upgrading mechanisms.

It was also found that the three firms varied considerably in their R&D partnership strategies. Table 4 provides an overview of the changing structural network centrality of the three case-study firms across the three phases. While GOL's number of direct connections (*degree*) grew linearly from 21 to 95, ENV shows an exponential growth after the second phase, whereas MNG's degree only grew slightly. As the eigenvector centrality shows, the two lead firms GOL and ENV strengthened their ties during the third phase, while MNG was increasingly marginalized. This is also reflected in the network betweenness, where MNG lost and ENV gained considerable control during the third phase.

5. Distilling the key findings

This section presents the two key findings of this paper. The first concerns the strategies latecomer firms adopt to upgrade their innovation capabilities in the face of technological change and the global decomposition of innovation. As the analysis showed, the type and relative importance of learning and upgrading mechanisms change across development stages. Two of the three firms used conventional upgrading mechanisms such as licensing agreements with established design firms to enter the wind energy sector. This enabled them to leapfrog first-generation technology. ENV did not have the same in-house manufacturing capabilities and had to gradually build up its R&D networks. As the firms transitioned to higher innovation capability levels, conventional upgrading mechanisms were gradually complemented or substituted by unconventional ones such as M&A and collaborative R&D activities. This was particularly important to complement the firms' technology base and diversify into new technologies beyond the core business. More recently in phase three, as a result of rapid technological change—that is, digitalization, hybridization, and servitization at the sectoral level—the firms have shifted their R&D to externalized projects. These offer new opportunities to upgrade toward higher levels of innovation capabilities and (co-)develop new-to-the-world products, services, and business models in collaboration with international market- and science-based partners. It was also shown that some conventional upgrading mechanisms such as licensing agreements can spur catching up in early development stages, yet they bear the risk of development traps once firms upgrade to higher innovation capability levels. In the case of GOL, licensing agreements constitute catch-up traps in the form of market restrictions due to its licensing agreement with Vensys, whereas for MNG, licensing agreements long represented a closed R&D trap, that is, over-reliance on a low number of intra-industry R&D sources. Latecomer firms should be aware of this inverted u-shape in which catch-up triggers can potentially turn into catch-up traps.[106] The empirical analysis further revealed that latecomer firms not only benefit by exploiting knowledge through the decomposition of innovation originating from advanced-country firms, but increasingly appropriate ODIP strategies themselves as part of their upgrading process. It was shown that constant upgrading requires expanding the innovation space by establishing diversified networks

[106] The inverted u-shape describes the rapid market/technology growth in early development stages (e.g., due to conventional upgrading mechanisms such as technological licensing), followed by a rapid decline in market/technology growth (e.g., due to market restrictions or expiring access to technological designs through licensing agreement).

across geographies and sectors. Hence, in order to upgrade to higher levels of innovation capabilities, latecomer firms have to design and develop R&D partnership strategies and concurrently become organizational orchestrators to effectively integrate new knowledge and improve existing competencies.

Table 5 shows how the case-study firms decentralized their innovative activities across the three phases. While GOL gradually increased its innovation space by shifting its R&D functions to globally dispersed units, ENV and MNG display two extreme cases: the first demonstrates extreme catch-up and the second restrained catch-up after the second phase. ENV has created the largest number of externalized networks, mainly outside its home market China. Today, almost half of ENV's priority patents are filed outside China (<3% for the other two firms; see Supplementary Table C2) and 93% of its R&D partnerships are global. In contrast, MNG gave up its global market reach and only marginally developed its global R&D networks after the second phase. It still depends heavily on a few licensing partners in Europe and the United States (see Supplementary Annex B for a detailed overview of the case-study firms' market development).[107]

Table 5. Shaded matrix of intensity showing the growing innovation space across the three phases

INNOVATION SPACE	GOL			ENV[(a)]			MNG		
	1	2	3	1	2	3	1	2	3
Internal R&D Organization									
R&D hubs, subsidiaries and centers of excellence									
External R&D Partnerships									
Science-based partners									
Market-based partners									
Externalized R&D projects									

Note: Network reach is graduated according to a five-level scale, with darker shades indicating a higher reach. The gray shades are based on the actual network numbers. (a) ENV was founded in 2007 but started operations in 2009, which explains why the first column is not shaded. A more detailed overview is provided in Supplementary Appendix C3.

The second key finding of this paper concerns a broader question, namely why some firms within the same sector and the same institutional environment are more successful in upgrading their innovation capabilities. Using a most-similar case design revealed relevant insights. On the one hand, the firms' background played an important role in terms of both pre-knowledge base and geographic location. While GOL and MNG already had an existing manufacturing-related technology base before entering the wind energy sector through licensing agreements, ENV was built from scratch and therefore faced comparatively lower technological switching costs. Consequently, the firm focused on niche tech competencies beyond the core manufacturing business. Today, ENV has become a first mover in the development of digital products and

[107] Licensing strategies between the firms varied considerably in terms of technology (1) control and (2) novelty. GOL exerted a relatively high level of control due to its majority stake in Vensys and licensed a novel technology (PMDD) that was rarely used by the incumbent firms. In turn, MNG did not acquire stakes in aerodyn and licensed the less novel slow-rotating hybrid drive. ENV did not license any technology, which is why it focused on developing new digital technology in the absence of technological path-dependencies.

business models (e.g., SCADA systems,[108] software-as-a-service) and has developed world-leading competencies in energy storage solutions after acquiring various business units from incumbent firms and startups in Silicon Valley. ENV's digital products are even used by incumbent firms. In terms of the firms' technological core competencies, the respective geographic location was an important determinant, too. Given their coastal proximity, MNG and ENV have become leading players in China's offshore market.

On the other hand, even more importantly, organizational capabilities to expand their innovation space in combination with the firms' efforts (and willingness) to invest in risky activities with the purpose to (co-)create new knowledge have been found to be crucial factors for the upgrading of innovation capabilities. To develop sufficient innovation capabilities to compete in global markets and respond effectively to technological change, firms have to diversify their R&D partnerships and become organizational orchestrators (Bell and Figueiredo, 2012a, 2012b). This requires building up strong intra- and inter-organizational links with market- and science-based partners across geographies and taking strategic positions in global R&D networks. Successful ODIP strategies are associated with clear leadership, targeted investments, and a willingness to take certain risks. The three case-study firms show very different risk appetites, with GOL on the conservative and ENV on the experimental end of the spectrum. As open innovation is generally associated with high levels of risk (e.g., potential loss of intellectual property), both firms had to develop strategies to build trust with and among their partners. ENV built trust by sharing data with external partners and managing most partnerships from its European R&D center. GOL focused more on encouraging dense network structures among its suppliers (without sharing data itself) and managed most partnerships from its HQ. Both strategies have been successful in terms of market leadership. Yet in terms of technological leadership, ENV has been exploring new paths through its energy management platform EnOS and superconductor technology, whereas GOL has largely remained in a technological follower position with global market leader Vestas as the benchmark. Hence, ENV has opted for a higher risk but also potentially path-creating strategy. In contrast, MNG is lagging behind the other two firms in terms of innovation capabilities.

In summary, the case studies show that upgrading is an inherently firm-specific process, where different upgrading dimensions (*innovation space* and *knowledge co-creation efforts*) lead to diverse upgrading outcomes (*innovation capabilities*). As upgrading to higher innovation capability levels is associated with a growing number of ODIP options, developing purposively managed R&D strategies (beyond conventional technology transfer) becomes even more relevant. Otherwise, there is a risk of missing significant upgrading potential through new upgrading mechanisms. Externalized R&D projects provide such a new strategy tool to shift toward knowledge co-creating. Table 6 provides an overview of the changing upgrading mechanisms across different levels of innovation capability. It summarizes the key findings as discussed in this paper. The light gray-shaded column on the right has not been covered by the extant literature and constitutes the main contribution of this paper.

[108] Supervisory control and data acquisition (SCADA) comprises both hardware (e.g., sensors) and software components for the remote and real-time supervision and control of energy plants.

Table 6. Changing upgrading mechanisms across innovation capability levels

	Phase I	Phase II	Phase III
Upgrading mechanism	**Internal**		
	R&D concentration close to HQ	R&D activities loosely distributed to exploit ODIP	R&D activities globally dispersed and coordinated
	Low co-orchestration of new knowledge and existing competencies required	Intermediate co-orchestration of new knowledge and existing competencies required	High co-orchestration of new knowledge and existing competencies required
	External		
	Conventional	Unconventional (bilateral partnerships)	Unconventional (multilateral partnerships)
	Acquiring proven knowledge from a few experienced intra-industry sources, e.g., licensing firms, suppliers	Acquiring new knowledge from individual intra- and inter-industry market- and science-based partners, e.g., universities, tech firms	Co-creating new knowledge through externalized R&D projects
	Low level of R&D network reach and diversification	Medium level of R&D network reach and diversification	High level of R&D network reach and diversification
Innovation Capabilities	**Low**	**Medium**	**High**
	Capability to produce new-to-the-firm innovations such as minor adaptions of imported products	Capability to produce new-to-the-country/sector innovations such as complex modifications of existing technologies	Capability to produce new-to-the-world innovations related to technology at the global frontier

Source: Author's own elaboration based on Lema and Lema (2012), Dutrénit (2000, 2004, 2007), Schmitz and Strambach (2012), OECD (2018a), Bell (2009).

6. Conclusion

This paper provides new empirical insights into the changing conditions and strategies for latecomer firm upgrading. It finds that technological change and the decomposition of innovations lead to a reorganization of global R&D networks, in which latecomer firms play an increasingly proactive role. As firms progress to higher capability levels, innovating through externalized R&D projects provides significant means to shift from exploiting existing to co-creating new knowledge. In addition, this paper shows that decentralizing R&D strategies are not only reserved to advanced country firms but are also appropriated by latecomer firms as part of their upgrading process. Yet there are significant firm-level differences in regard to the willingness and readiness to organize R&D through globally dispersed networks. While the firms' respective factor conditions (e.g., pre-knowledge base, geographical location) and initial conventional technology transfer mechanisms (e.g., licensing) played a crucial role in setting a general technological direction, organizational capabilities were found to be key to identifying the right R&D partners and orchestrating the integration of external knowledge.

These insights have several policy and managerial implications. Domestic policies in emerging markets should foster cross-border collaborations rather than reinforcing self-sufficient innovation policies. With rapid technological change and the digitalization of manufacturing industries, it becomes increasingly difficult for one country to master a full range of specialism. At the same time, grand challenges such as climate change can only be tackled on a global level. This provides a new imperative for global collaboration, with externalized R&D projects providing a good example of how to accelerate the creation of new knowledge rather than duplicating existing knowledge. Particularly when firms reach higher maturity levels, cross-border collaborations provide more promising upgrading opportunities for innovation capabilities than do forced technology transfers.

Firm (R&D) managers need to be aware of the changing mechanisms underlying the upgrading of innovation capabilities. While conventional mechanisms can provide leapfrogging opportunities in early stages, shifting toward higher levels of innovation capabilities requires expanding the innovation space and knowledge co-creation efforts. This implies targeted investments and the development of conscious and purposively managed R&D partnership strategies. The increase of innovation space and network reach through decentralizing strategies requires increasing degrees of organizational co-orchestration to effectively absorb external knowledge and accumulate innovation capabilities.

Conceptually, these conclusions open up avenues for future research. First, the extent to which latecomer firms' innovation capabilities can be compensated by other factors such as privileged access to decision-makers in local governments and financing, especially in the mid- and long term, requires more research. For example, Oehler et al. (2020) found that ownership structure correlates with access to overseas financing in China's energy sector. Second, the focus here has been on R&D partnerships at a relatively formalized stage, thereby potentially neglecting more informal types of upgrading. Future studies could benefit from further specifying the degree to which specific externalized R&D projects contribute to the upgrading of latecomers. Particular attention could be paid to the interactive nature of various externalized R&D projects and their potential network effects. Third, future research could deepen the analysis of the dual functionality or u-shape function of some (conventional) upgrading mechanisms such as licensing agreements that can precipitate catch-up traps at later development stages. Fourth, in light of industry hybridization and digitalization, the literature on catching up and innovation capability building of industrial latecomer firms should incorporate these recent transformations in the global economy. The paper seeks to contribute to this literature by introducing externalized R&D projects as a new and highly relevant strategy tool for emerging market firms to reach global competitiveness. Finally, this study analyzed the changing upgrading mechanisms of latecomer firms in the face of open innovation and ODIP, based on the empirical case of Chinese lead firms in the wind energy sector. This provides a good point of departure for more comparative studies. In particular, it will be important to explore country-specific factors that enable or prevent open innovation initiatives (e.g., indigenous innovation vs. open innovation policies).

Declaration of interests

The author declares that there has been no conflict of interests.

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References

Altenburg, T., Schamp, E. W., & Chaudhary, A. (2016). The emergence of electromobility: Comparing technological pathways in France, Germany, China and India. *Science and Public Policy*, 43(4), 464–475. doi:10.1093/scipol/scv054

Altenburg, T., Schmitz, H., & Stamm, A. (2008). Breakthrough? China's and India's transition from production to innovation. *World Development*, 36(2), 325–344. doi:10.1016/j.worlddev.2007.06.011

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

Backwell, B. (2017). *Wind Power: The Struggle for Control of a New Global Industry.* London, UK: Routledge. doi:10.4324/9781315112534

Beach, D. (2017). *Process-Tracing Methods in Social Science.* Oxford Research Encyclopedia of Politics. Oxford: Oxford University Press. doi:10.1093/acrefore/9780190228637.013.176

Bell, M. (2006). Time and technological learning in industrializing countries: how long does it take? How fast is it moving (if at all)? *International Journal of Technology Management*, 36(1–3), 25–39. doi:10.1504/ijtm.2006.009959

Bell, M. (2009). *Innovation capabilities and directions of development*, STEPS Working Paper 33, Brighton: STEPS Centre.

Bell, M., & Figueiredo, P. N. (2012a). Innovation capability building and learning mechanisms in latecomer firms: recent empirical contributions and implications for research. *Canadian Journal of Development Studies/Revue Canadienne D'études du Développement*, 33(1), 14–40. doi:10.1080/02255189.2012.677168

Bell, M., & Figueiredo, P. N. (2012b). Building Innovative Capabilities in Latecomer Emerging Firms: Some Key Issues. In E. Amann & J. Cantwell (eds.), *Innovative Firms in Emerging Market Countries.* Oxford: Oxford Scholarship Online. doi:10.1093/acprof:oso/9780199646005.003.0002

Bell, M., & Pavitt, K. (1992). Accumulating technological capability in developing countries. *The World Bank Economic Review*, 6(suppl_1), 257–281. doi:10.1093/wber/6.suppl_1.257

Bell, M., & Pavitt, K. (1995). The development of technological capabilities. *Trade, Technology and International Competitiveness*, 22(4831), 69–101. doi:10.1596/0-8213-3418-2

Binz, C., Gosens, J., Hansen, T., & Hansen, U. E. (2017). Toward technology-sensitive catching-up policies: insights from renewable energy in China. *World Development*, 96, 418–437. doi:10.1016/j.respol.2017.05.012

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

BNEF (2020a). *Top-10 OEMS in China.* [Online] Bloomberg New Energy Finance. Retrieved from https://energyiceberg.com/china-wind-oems-2019/

BNEF (2020b). *India's Top Wind Turbine Suppliers in 2019.* [Online] Bloomberg New Energy Finance. Retrieved from https://about.bnef.com/blog/indias-top-wind-suppliers-in-2019/

Cantwell, J., & Mudambi, R. (2005). MNE competence-creating subsidiary mandates. *Strategic Management Journal*, *26*(12), 1109-1128. https://doi.org/10.1002/smj.497

Chen, C. J., Huang, Y. F., & Lin, B. W. (2012). How firms innovate through R&D internationalization? An S-curve hypothesis. *Research Policy*, *41*(9), 1544-1554. https://doi.org/10.1016/j.respol.2012.06.008

Chesbrough, H. W. (2003). *Open Innovation: The New Imperative For Creating And Profiting From Technology.* Boston, MA: Harvard Business Press. doi:10.1108/14601060410565074

Chesbrough, H. (2017). The future of open innovation: The future of open innovation is more extensive, more collaborative, and more engaged with a wider variety of participants. *Research-Technology Management*, 60(1), 35–38. doi:10.1080/08956308.2017.1255054

Chesbrough, H., & Bogers, M. (2014). *Explicating Open Innovation: Clarifying an Emerging Paradigm for Understanding Innovation. New Frontiers in Open Innovation.* Oxford: Oxford University Press, 3–28. doi:10.1093/acprof:oso/9780199682461.003.0001

Chesbrough, H., Vanhaverbeke, W., & West, J. (2006). *Open Innovation: Researching a New Paradigm.* Oxford: Oxford University Press. doi:10.1111/j.1467-8691.2008.00502.x

Cricelli, L., Greco, M., & Grimaldi, M. (2016). Assessing the open innovation trends by means of the Eurostat Community Innovation Survey. *International Journal of Innovation Management*, 20(3), 1650039. doi:10.1142/s1363919616500390

Curley, M., & Salmelin, B. (2018). *Open Innovation 2.0: The New Mode Of Digital Innovation For Prosperity And Sustainability.* Washington, DC: Springer. doi:10.1007/978-3-319-62878-3

CWEA (2018). *Ranking and Market Share of China's Wind Turbine Manufacturers in 2017.* [In Chinese] Beijing: Chinese Wind Energy Association.

CWEA (2020). *Ranking and Market Share of China's Wind Turbine Manufacturers in 2019.* [In Chinese] Beijing: Chinese Wind Energy Association.

Dai, Y., Haakonsson, S., & Oehler, L. (2021). 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*, forthcoming.

Dantas, E., & Bell, M. (2009). Latecomer firms and the emergence and development of knowledge networks: The case of Petrobras in Brazil. *Research Policy*, 38(5), 829–844. doi:10.1016/j.respol.2009.01.007

Dodgson, M., Gann, D., & Salter, A. (2006). The role of technology in the shift towards open innovation: the case of Procter & Gamble. *R&D Management*, 36(3), 333–346. doi:10.1111/j.1467-9310.2006.00429.x

Du, J., Leten, B., & Vanhaverbeke, W. (2014). Managing open innovation projects with science-based and market-based partners. *Research Policy*, 43(5), 828–840. doi:10.1016/j.respol.2013.12.008

Dutrénit, G. (2000). *Learning and Knowledge Management in the Firm: From Knowledge Accumulation to Strategic Capabilities.* Cheltenham, UK: Edward Elgar Publishing.

Dutrénit, G. (2004). Building technological capabilities in latecomer firms: a review essay. *Science, Technology and Society*, *9*(2), 209-241. https://doi.org/10.1177/097172180400900202

Dutrénit, G. (2007). The transition from building-up innovative technological capabilities to leadership by latecomer firms. *Asian Journal of Technology Innovation*, *15*(2), 125-149. https://doi.org/10.1080/19761597.2007.9668640

Enkel, E., Gassmann, O., & Chesbrough, H. (2009). Open R&D and open innovation: exploring the phenomenon. *R&D Management*, 39(4), 311–316. doi:10.1111/j.1467-9310.2009.00570.x

Ernst, D., & Kim, L. (2002). Global production networks, knowledge diffusion, and local capability formation. *Research Policy*, 31(8–9), 1417–1429. doi:10.1016/s0048-7333(02)00072-0

Fagerberg, J., Mowery, D. C., & Nelson, R. R. (Eds.). (2005). *The Oxford handbook of innovation.* Oxford university press.

Fagerberg, J., Fosaas, M., & Sapprasert, K. (2012). Innovation: Exploring the knowledge base. *Research policy*, *41*(7), 1132-1153. https://doi.org/10.1016/j.respol.2012.03.008

Figueiredo, P. N. (2003). Learning, capability accumulation and firms differences: evidence from latecomer steel. *Industrial and Corporate Change*, 12(3), 607–643. doi:10.1093/icc/12.3.607

Figueiredo, P. N. (2010). Discontinuous innovation capability accumulation in latecomer natural resource-processing firms. *Technological Forecasting and Social Change*, 77(7), 1090-1108. https://doi.org/10.1016/j.techfore.2010.02.004

Figueiredo, P. N., & Cohen, M. (2019). Explaining early entry into path-creation technological catch-up in the forestry and pulp industry: Evidence from Brazil. *Research Policy*, 48(7), 1694–1713. doi:10.1016/j.respol.2019.03.017

Figueiredo, P. N., & Piana, J. (2018). Innovative capability building and learning linkages in knowledge-intensive service SMEs in Brazil's mining industry. *Resources Policy*, 58, 21–33. doi:10.1016/j.resourpol.2017.10.012

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, 12(2), 219–245. doi:10.1177/1077800405284363

Fu, X. (2015). *China's Path to Innovation.* Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9781107110953

Fu, X., Pietrobelli, C., & Soete, L. (2011). The role of foreign technology and indigenous innovation in the emerging economies: technological change and catching-up. *World Development*, 39(7), 1204–1212. doi:10.1016/j.worlddev.2010.05.009

Gassmann, O., & Enkel, E. (2006). Open Innovation: Externe Hebeleffekte in der Innovation erzielen. *Zeitschrift Führung + Organisation*, 75(3), 132–138.

Gassmann, O., & Von Zedtwitz, M. (1998). Organization of industrial R&D on a global scale. *R&D Management*, 28(3), 147-161. https://doi.org/10.1111/1467-9310.00092

Gault, F. (2018). Defining and measuring innovation in all sectors of the economy. *Research Policy*, 47(3), 617-622. https://doi.org/10.1016/j.respol.2018.01.007

George, A. L., & Bennett, A. (2005). *Case Study and Theory Development in the Social Sciences.* Cambridge, MA: MIT Press.

Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy*, 12(1), 78-104.

Gerring, J. (2006). *Case Study Research: Principles and Practices.* Cambridge, UK: Cambridge University Press. doi:10.1017/cbo9780511803123

Giachetti, C., & Marchi, G. (2017). Successive changes in leadership in the worldwide mobile phone industry: The role of windows of opportunity and firms' competitive action. *Research Policy*, *46*(2), 352-364. https://doi.org/10.1016/j.respol.2016.09.003

Gui, Q., Liu, C., Du, D., & Duan, D. (2019). The changing geography of global science. *Environment and Planning A: Economy and Space,* 51(8), 1615-1617. https://doi.org/10.1177/0308518X18816694

GWEC (2012). *China Wind Energy Outlook.* [Online] Global Wind Energy Association. Retrieved from http://gwec.net/wp-content/uploads/2012/11/China-Outlook-2012-EN.pdf

GWEC (2020). *Wind Turbine Sized Keep Growing As Industry Consolidation Continues.* [Online] Global Wind Energy Council. Retrieved from https://gwec.net/wind-turbine-sizes-keep-growing-as-industry-consolidation-continues/

Haakonsson, S. J. (2009). Learning by importing in global value chains: upgrading and South–South strategies in the Ugandan pharmaceutical industry. *Development Southern Africa*, 26(3), 499–516. doi:10.1080/03768350903086861

Haakonsson, S., Kirkegaard, J. K., & 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*, 1–19. doi:10.1080/09654313.2020.1712329

Haakonsson, S. J., & 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), 462-480. https://doi.org/10.1057/s41287-018-0128-5

Hain, D., Jurowetzki, R., Konda, P., & Oehler, L. (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*, dtaa021, https://doi.org/10.1093/icc/dtaa021

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*, dtaa08. doi:10.1093/icc/dtaa008

Hansen, U. E., & Lema, R. (2019). The co-evolution of learning mechanisms and technological capabilities: Lessons from energy technologies in emerging economies. *Technological Forecasting and Social Change*, 140, 241–257. doi:10.1016/j.techfore.2018.12.007

Hirschman, A. O. (1981). *Essays in Trespassing: Economics to Politics and Beyond.* Cambridge, UK: Cambridge University Press.

Horner, R. (2017). Beyond facilitator? State roles in global value chains and global production networks. *Geography Compass*, 11(2), e12307.

Hu, R., Skea, J., & Hannon, M. J. (2018). Measuring the energy innovation process: An indicator framework and a case study of wind energy in China. *Technological Forecasting and Social Change*, 127, 227–244.

Huenteler, J., Schmidt, T. S., Ossenbrink, J., & Hoffmann, V. H. (2016). Technology life-cycles in the energy sector—Technological characteristics and the role of deployment for innovation. *Technological Forecasting and Social Change*, 104, 102–121. doi:10.1016/j.techfore.2015.09.022

IRENA (2013). *China: 30 Years of Policies for Wind Energy.* [Online] International Renewable Energy Agency. Retrieved from https://www.irena.org/publications/2013/Jan/30-Years-of-Policies-for-Wind-Energy-Lessons-from-12-Wind-Energy-Markets

Kedia, B., Gaffney, N., & Clampit, J. (2012). EMNEs and knowledge-seeking FDI. *Management International Review*, 52(2), 155–173. doi:10.1007/s11575-012-0132-5

Kim, L. (1997). *Imitation to innovation: The dynamics of Korea's technological learning.* Harvard business press, Boston, MA.

Lall, S. (1992). Technological capabilities and industrialization. *World Development*, 20(2), 165–186. doi:10.1016/0305-750x(92)90097-f

Laursen, K., & Salter, A. (2006). Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms. *Strategic Management Journal*, 27(2), 131–150. doi:10.1002/smj.507

Lazonick, W. (2010). The Chandlerian corporation and the theory of innovative enterprise. *Industrial and Corporate Change*, 19(2), 317–349. doi:10.1093/icc/dtq005

Lee, K. (2013). *Schumpeterian Analysis of Economic Catch-Up: Knowledge, Path-Creation, and The Middle-Income Trap.* Cambridge, UK: Cambridge University Press. doi:10.1017/CBO9781107337244

Lee, K. (2019). *The Art of Economic Catch-Up: Barriers, Detours and Leapfrogging in Innovation Systems*. Cambridge, UK: Cambridge University Press. doi:10.1017/9781108588232

Lee, K., & Ki, J. H. (2017). Rise of latecomers and catch-up cycles in the world steel industry. *Research Policy*, *46*(2), 365-375. https://doi.org/10.1016/j.respol.2016.09.010

Lee, K., & Malerba, F. (2017). Catch-up cycles and changes in industrial leadership: windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research Policy*, 46(2), 338–351. doi:10.1016/j.respol.2016.09.006

Lee, S., Park, G., Yoon, B., & Park, J. (2010). Open Innovation in SMEs – An Intermediated Network Model. *Research Policy*, 39(2), 290–300. doi:10.1016/j.respol.2009.12.009

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

Lema, A., & Lema, R. (2016). Low-carbon innovation and technology transfer in latecomer countries: Insights from solar PV in the clean development mechanism. *Technological Forecasting and Social Change*, 104, 223–236.

Lema, R., Quadros, R., & Schmitz, H. (2015). Reorganising global value chains and building innovation capabilities in Brazil and India. *Research Policy*, *44*(7), 1376-1386. https://doi.org/10.1504/IJTLID.2009.026816

Lewis, J. I. (2012). *Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low-Carbon Economy*. New York: Columbia University Press.

Li, Z., Gallagher, K. P., & Mauzerall, D. L. (2020). China's global power: Estimating Chinese foreign direct investment in the electric power sector. *Energy Policy*, 136, 111056. doi:10.1016/j.enpol.2019.111056

Lichtenthaler, U. (2011). Open innovation: Past research, current debates, and future directions. *Academy of Management Perspectives*, 25(1), 75–93. doi:10.5465/amp.25.1.75

Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy*, 31(2), 247–264. doi:10.1016/s0048-7333(01)00139-1

Malerba, F. (Ed.). (2004). *Sectoral Systems of Innovation: Concepts, Issues and Analyses of Six Major Sectors in Europe.* Cambridge, UK: Cambridge University Press. doi:10.1017/cbo9780511493270.002

Malerba, F. (2005). Sectoral systems of innovation: a framework for linking innovation to the knowledge base, structure and dynamics of sectors. *Economics of Innovation and New Technology*, 14(1–2), 63–82. doi:10.1080/1043859042000228688

Mathews, J. A. (2006). Dragon multinationals: New players in 21st century globalization. *Asia Pacific Journal of Management*, 23(1), 5–27. doi:10.1007/s10490-006-6113-0

Mathews, J. A. (2017). Dragon multinationals powered by linkage, leverage and learning: A review and development. *Asia Pacific Journal of Management*, 34(4), 769–775. doi:10.1007/s10490-017-9543-y

Mathews, J. A., & Tan, H. (2015). *China's Renewable Energy Revolution.* Washington, DC: Springer. doi:10.1057/9781137546258

Mina, A., Bascavusoglu-Moreau, E., & Hughes, A. (2014). Open service innovation and the firm's search for external knowledge. *Research Policy*, 43(5), 853–866. doi:10.5465/ambpp.2012.1576

Muhammad, A. S. (2013). Exploring management issues of cross-border R&D alliances in the Australian biotechnology industry. *Innovation and Development*, Vol. 3, Issue 2, p. 317. doi: 10.1080/2157930X.2013.833774

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

OECD (2018a). *Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation*, 4th Edition. The Measurement of Scientific, Technological and Innovation Activities. [Online] Organization for Economic Co-operation and Development. Retrieved from https://www.oecd.org/science/oslo-manual-2018-9789264304604-en.htm

OECD (2018b). *Trade in Value Added: China.* [Online] Organization for Economic Co-operation and Development. Retrieved from https://www.oecd.org/sti/ind/measuring-trade-in-value-added.htm

OECD (2015). *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development.* [Online] Organization for Economic Co-operation and Development. Retrieved from https://www.oecd.org/sti/frascati-manual-2015-9789264239012-en.htm

Oehler, L.; Lund Larsen, M. & W. Yao (2020), 'Financing the global low-carbon energy transition: China's dual role domestically and overseas', Chapter 14, p. 110-118, In: *SDC International Report 2020, Cooperating for Energy Transition*, Copenhagen, Denmark. doi: 10.7146/aul.395.156

Olsen, W. (2004). Triangulation in social research: qualitative and quantitative methods can really be mixed. *Developments in Sociology*, 20, 103–118.

Peng, X., Zheng, S., Collinson, S., Wu, X., & Wu, D. (2020). Sustained upgrading of technological capability through ambidextrous learning for latecomer firms. *Asian Journal of Technology Innovation*, 1-22. https://doi.org/10.1080/19761597.2020.1810084

Popa, S., Soto-Acosta, P., & Martinez-Conesa, I. (2017). Antecedents, moderators, and outcomes of innovation climate and open innovation: An empirical study in SMEs. *Technological Forecasting and Social Change*, 118, 134–142.

Quah, D. (2011). The global economy's shifting centre of gravity. *Global Policy*, 2(1), 3-9. https://doi.org/10.1111/j.1758-5899.2010.00066.x

Ritala, P., Huizingh, E., Almpanopoulou, A., & Wijbenga, P. (2017). Tensions in R&D networks: Implications for knowledge search and integration. *Technological Forecasting and Social Change*, 120, 311–322. https://doi.org/10.1016/j.techfore.2016.12.020

Schmitz, H., & Altenburg, T. (2016). Innovation paths in Europe and Asia: Divergence or convergence? *Science and Public Policy*, 43(4), 454–463. doi:10.1093/scipol/scv053

Schmitz, H., & Strambach, S. (2009). The organisational decomposition of innovation and global distribution of innovative activities: Insights and research agenda. *International Journal of Technological Learning, Innovation and Development*, 2(4), 231. doi:10.1504/IJTLID.2009.026816

Seawright, J., & Gerring, J. (2008). Case selection techniques in case study research: A menu of qualitative and quantitative options. *Political Research Quarterly*, 61(2), 294-308.

Shin, J. S. (2017). Dynamic catch-up strategy, capability expansion and changing windows of opportunity in the memory industry. *Research Policy*, *46*(2), 404-416. https://doi.org/10.1016/j.respol.2016.09.009

Slepniov, D., Lassen, A. H., Haakonsson, S. J., & McKelvey, M. (2015). Understanding innovation spaces through emerging multinational enterprises in China: an explorative case study of a Chinese wind turbine manufacturer. In *Innovation Spaces in Asia*. Cheltenham, UK: Edward Elgar Publishing. doi:10.4337/9781783475681.00013

Stephan, A., Schmidt, T. S., Bening, C. R., & Hoffmann, V. H. (2017). The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy*, 46(4), 709–723. doi:10.1016/j.respol.2017.01.009

Sun, S. L. &. Yang, X. (2013). Transformative Capacity and Absorptive Capacity. In P. P. Li (ed.), *Disruptive Innovation in Chinese and Indian Business: The Strategic Implications for Local and Global Incumbents*. New York: Routledge.

Suri, H. (2011). Purposeful sampling in qualitative research synthesis. *Qualitative Research Journal*, 11(2), 63. doi:10.3316/qrj1102063

Sutton, J. (2012). *Competing in Capabilities: The Globalization Process.* Oxford: Oxford University Press. doi:10.1093/acprof:oso/9780199274536.001.0001

Veugelers, M., Bury, J., & Viaene, S. (2010). Linking technology intelligence to open innovation. *Technological Forecasting and Social Change*, 77(2), 335–343. https://doi.org/10.1016/j.techfore.2009.09.003

Von Zedtwitz, M., & Gassmann, O. (2002). Market versus technology drive in R&D internationalization: four different patterns of managing research and development. *Research Policy*, 31(4), 569–588. doi:10.1016/s0048-7333(01)00125-1

Whittaker, D.H., Zhu, T., Sturgeon, T. *et al.* Compressed Development. *St Comp Int Dev* **45,** 439–467 (2010). https://doi.org/10.1007/s12116-010-9074-8

Yang, C. (2013). From strategic coupling to recoupling and decoupling: Restructuring global production networks and regional evolution in China. *European Planning Studies*, 21(7), 1046–1063.

Yin, R. K. (2009). *Case Study Research: Design and Methods* (4th Edition). Thousand Oaks, CA: SAGE.

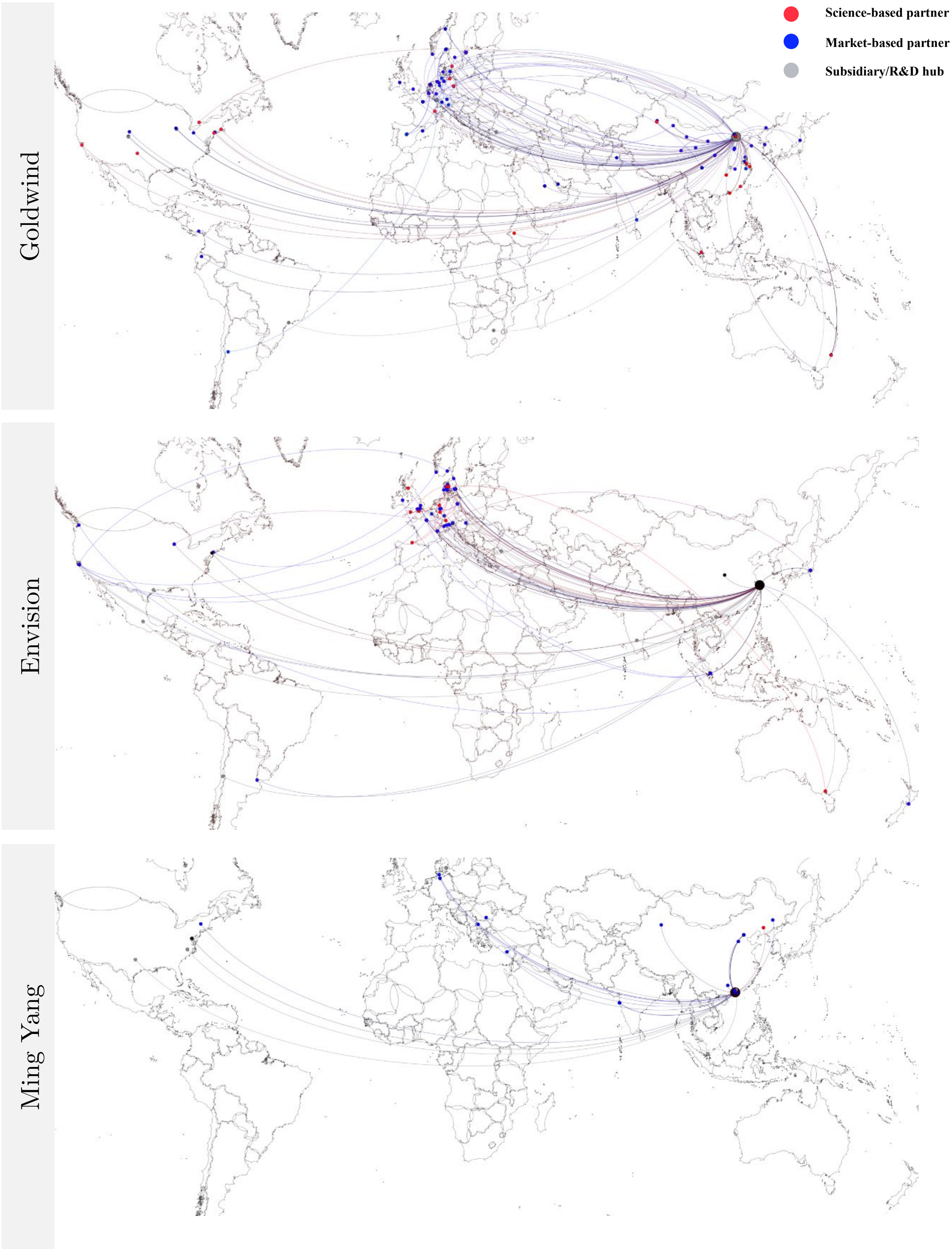
Annex

Annex A. Externalized R&D projects

Firm	Project	Year	Description	Collaboration type	Subsector	Partners	Partner countries
GOL	G1	2015	Storage for Hybrid RE Systems	Joint research	Hybrid	3	AU
	G2	2018	Energy Management Prediction	Joint research	Microgrid	6	PK, NO
	G3	2018	Big Data Innovation Platform	Joint development	IoT	5	CN
	G4	2017	Microgrid Optimization	Joint research	Microgrid	6	NO
	G5	2015	IEA Task Force	Joint research	O&M	19	DK, JP, KR, IT, NO, SE. DE, SG, FR, ES, NL, US
	G6	2019	Load Forecasting Aeroacoustics Prediction	Joint research	Microgrid, turbine acoustics	5	DK, ET
ENV	E1	2019	Multi-industry R&D Initiative	Joint R&D	Lubrication, gearboxes, services	4	US, SG
	E2	2020	Smart Infrastructure	Joint development	IoT, smart grid	8	TH
	E3	2017	Smart City Alliance	Joint R&D	IoT, smart city	4	US, GB, IE
	E4	2019	Financing/Risk-sharing Initiative	Joint financing	Finance	3	DK
	E5	2018	SET Innovation Platform	Joint development	Digital energy, e-mobility	7	DE, AT, FR, GB
	E6	2017	Forecasting Partnership	Joint research	Hybrid, grids, e-mobility	4	GB, DK
	E7	2017	Global Battery Alliance	Joint R&D	Battery	8	CH, DK, JP, DE
	E8	2019	Onshore Wind Atlas	Joint research	Resource assessment	7	DK, US, GB, DE, AU, FR
	E9	2014	Unified Turbine Testing (UniTTE)	Joint R&D	Turbine performance	12	DK, DE, ES, NO, GB
	E10	2019	EcoSwing Superconductor	Joint R&D	Wind turbine	11	DE, NL, GB, FR
	E11	2016	Weather Prediction Model	Joint research	Wind farm	3	US
	E12	2014	Smart Energy Campus	Joint research	Smart energy management	3	US
MNG	M1	2020	OREAC	Joint research	Offshore	14	IE, GB, JP, PT, US, FR, NO, DK, NL, BE, ES

Note: The number of partners includes the respective case-study firm. 'Hybrid' refers to hybrid wind–PV energy systems including energy storage solutions.

Annex B. Comparing global R&D reach, phase III (2015–2020)



Supplementary Appendix

A: Methodological Appendix

This section provides a detailed description of the methodological choices made throughout the data collection and analysis process.

(1) Key definitions and delimitations

Before describing the consecutive methodological steps, it is important to provide the context by defining and delimiting key terminology. First, R&D and innovation are understood in accordance with the *Frascati and Oslo Manual* published by the OECD (2015, 2018a).

Table A1. Definitions and delimitations of key terminologies

Terminology	Definition	Delimitation
R&D	Comprises creative and systematic work in the form of *basic research* (to enlarge a firm's knowledge stock), *applied research* (directed toward a specific practical aim), and *experimental development* (to produce new or improve existing products or processes).	While R&D constitutes the part in the innovation cycle where financial resources are turned into new knowledge, innovation is described as the first attempt to turn ideas on a new product or process into practice, e.g., by implementing a new process or bringing a new product/service to the market. All types of R&D constitute innovative activities, but not all innovative activities are R&D.
Innovation	Defined as a new or improved product or process (or a combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (*product*) or brought into use by the unit (*process*). Innovation is a nonlinear process.	
Market-based partners	Organizations not directly concerned with the creation of new knowledge but with the production of specific products or processes that, in turn, generate new knowledge.	While market-based partners constitute commercial actors that produce new knowledge by reviewing and combining existing knowledge or engaging in value-adding activities throughout the value chain (e.g., suppliers, customers, and project developers), science-based partners can be both profit and nonprofit actors that create new knowledge through dedicated research activities such as universities and research institutes.
Science-based partners	Organizations that are primarily concerned with the creation of new knowledge, but not necessarily with the commercialization or implementation thereof.	

Sources: OECD (2015, 2018a), Fagerberg et al. (2005, 2012), Chen et al. (2012), Schmitz and Strambach (2009), Du et al. (2014).

R&D constitutes a broad range of activities firms can undertake in pursuit of innovation (see Table A1). To qualify as (joint) R&D, activities must meet five criteria: they must be novel, creative, systematic, transferable and/or reproducible, and address an uncertain outcome. The following exemplary activities meet/do not meet the criteria. Classified as R&D activities: design, construction, and testing of prototypes with the objective to make further improvements; fundamental research with a range of potential fields of application; and the development of new applications software. Not classified as R&D activities: minor design changes; day-to-day quality control procedures; and employee training for the use of existing products or business processes. Split R&D activities: patent applications and licensing activities connected directly with innovation projects are considered R&D,[109] whereas the administration of intellectual property activities is per se not an R&D activity; trial production is only considered R&D if it applies full-scale testing and subsequent design improvements.

Second, market- and science-based partners are commonly distinguished in the open innovation (Du et al., 2014) and, albeit labeled differently, in the ODIP literature (Schmitz and Strambach, 2009). The rationale is to provide a simple classification of actors according to how closely/loosely they are positioned between the innovation and production processes. For example, science-based actors such as universities are loosely connected as they are primarily concerned with the creation of new knowledge but not necessarily with its implementation in industrial products or processes. In turn, market-based actors such as suppliers are closely connected as they generate new knowledge through their daily industry practice.

(2) Identifying R&D partnerships over time

In a first step, internal R&D units (including geographically dispersed R&D hubs) and their links to external market- and science-based partners had to be identified over a 20-year period. As there were no comprehensive, publicly disclosed reports on the case-study firms' R&D partnerships available, various primary and secondary data sources were iteratively combined over a period of two and a half years, including 18 months of field research in China. In total, 81 semi-structured interviews and 23 participant observations (e.g., conferences, summits, workshops, seminars, company visits) were conducted. Secondary data sources included the screening of five databases and over 350 documents, such as annual industry and company reports, company websites, social media announcements, newspaper articles, wind power magazines and newsletters, technical papers, and research articles (see Table A2 for a detailed overview).

The interviews and participant observations served a three-fold purpose: first, to identify undisclosed partnerships not previously identified through desk research; second, to get an in-depth understanding of the R&D partnerships in terms of collaboration modalities and innovation relevance; and third, to triangulate different statements by informants and secondary data sources (Olsen, 2004). To identify R&D projects, the following exemplary questions were asked as suggested by the OECD's (2015) *Frascati Manual*: What are the objectives of the project? What is new about this project? What methods are being used to carry out the project? How generally applicable are the findings or results of the project? What types of employees are working on the project?

The fact that partnerships are highly dynamic and change over time added another layer of complexity to the data collection. For example, science-based partners such as universities can become market partners once they spin off and create separate entities that are primarily concerned with commercial industry practice. In the same vein, external partners such as startups can become internal units of a firm through M&A activities. However, a level of internalization where all functional areas are fully integrated into the headquarters' organizational structures is

[109] Innovation projects are defined as a 'set for activities that are organized and managed for a specific purpose and with their own objectives, resources and expected outcomes, even at the lowest level of formal activity' (OECD, 2018a: 99).

rare and often not intended.[110] The same holds true for internal yet geographically dispersed units of a firm such as subsidiaries and R&D hubs that show highly diverging degrees of integration with the headquarters and between one another over time. Despite recognizing that the boundaries between internal and external as well as between market- and science-based can be blurred, this differentiation still provides useful insights. All fully owned units (corresponding to 100% headquarter ownership) are considered internal and all other units external to the firm. For example, despite the fact that 70% of the German licensing firm Vensys is owned by China's Goldwind, it is not considered an internal unit.

Table A2. Data collection techniques and data sources

Data collection technique	Number	Data sources
Semi-structured interviews(*)	81	- Group 1: case-study firms (R&D managers and engineers both at HQ and across subsidiaries/R&D hubs) - Group 2: market-based R&D partners (licensing and design firms, component suppliers, startups, tech firms, consulting firms) - Group 3: science-based R&D partners (universities, research institutes) - Group 4: external industry experts (industry associations, policymakers, competitors, international organizations)
Direct on-site observations	23	Observation of R&D-related presentations, conferences, workshops, and other intra-firm daily routines during 1.5 years of consecutive field research in China
Databases	5	- Bloomberg New Energy Finance (BNEF): industry and market statistics, e.g., market share, installed capacity, export data - EPO's PATSTAT: bibliographic patent data, e.g., co-patents between one of the case-study firms and external organizations - EBSCOhost: academic journal and magazine search, e.g., scientific co-publications between one of the case-study firms and research institutions - Crunchbase: investment and funding information, e.g., outbound M&A and key corporate investments of the case-study firms - Platts World Electric Power Database: supplementary plant-level dataset provided by Li et al. (2020)
Archival records	350	Industry reports, company reports, technical papers, academic literature, company websites, internal presentations and bulletins, newspaper articles, social media

Note: (*) Interviewees were selected according to their affiliation (see group 1–4), position (targeting higher levels), and experience (in-depth industry and/or firm knowledge). To get a balanced view, interviews were conducted with both current and former employees, across different locations (including HQ, subsidiaries, and R&D hubs) and with multiple external R&D partners.

Despite categorizing external partners on an aggregated market- and science-based level, the specific sector of each partner was documented to allow inferences on the changing patterns of R&D foci over time. Market-based sectors displayed different levels of relatedness to the wind sector such as component suppliers, EPC, solar PV, power grid, battery, testing and certification, utilities and independent power producers, oil and gas, nuclear, water treatment, consulting, aviation and aerospace, logistics, industrial engineering, biotechnology, semiconductors, telecommunications, big data analytics, cloud computing, cyber security, nongovernmental organizations (NGOs), think tanks, and government agencies. Science-based partners include universities, research institutes, and other government-led or EU-funded research programs. In total, around 400 R&D partnerships were identified for the period between 1998 (when the first

[110] Previous studies have shown that higher levels of autonomy are positively correlated with engagement in local R&D networks (Gassmann and von Zedtwitz, 1998).

case-study firm, Goldwind, was founded) and the first half of 2020. The data collection process was continued until no new partnerships could be identified.

In the next step, all partnerships were assessed in terms of novelty and impact. To determine different levels, the typology of firm-level innovation capabilities drawn up by the OECD (2018a; see also Bell, 2009; Gault, 2018) proved to be useful. This framework differentiates between 'new-to-the-firm,' 'new-to-the-market,' 'new-to-the-industry,' and 'new-to-the-world' (with increasing novelty and impact). As the differentiation between 'new-to-the-market' and 'new-to-the-sector' turned out to be challenging in a number of cases, the four categories were converted into three ordinal values with 'high' corresponding to 'new-to-the-world,' 'low' corresponding to 'new-to-the-firm,' and 'medium' covering both intermediate categories. As interpretations of both dimensions, novelty and impact, are prone to subjectivity, the categorization was carried out in close cooperation with industry experts, especially technical ones such as engineers and R&D managers with long-term and in-depth industry experience, to ensure reliability. Technical comments by industry experts were also provided on earlier drafts of this paper.

Table A3. Exemplary documentation of R&D partnerships

R&D unit/partner	**Case-study firms**		
	Goldwind	**Envision**	**Ming Yang**
Name	Vensys	Frauenhofer IWES	Reliance Group
Country	Germany	Germany	India
Location (lat/long)	49.3481600, 7.2345600	51.3121605, 9.4777268	19.0759837, 72.8776559
Launch date	2003	2015	2012
End date (if applicable)	2008	2019	-
Sector	Licensing, engineering, design	Applied research institute	Conglomerate
Collaboration type (stated)	'License technology'	'EU-funded EcoSwing project'	'Strategic partnership'
Collaboration purpose (stated)	'PMDD R&D expertise'	'World's first superconducting low-cost and lightweight wind turbine drivetrain—on a large-scale commercial wind turbine'	'Development of up to 2,500 MW Clean Energy Projects in India and Expansion into South Asia Region'
Connected R&D partners	HTW Saarland, ReGEn Powertech, Enerwind/IMPSA, Eozen	Eco 5, Delta Energy, DNV GL, University Twente	Global Wind Power Limited (GWPL)
Organization type	External	External	External
Partner type	Market-based	Science-based	Market-based
Novelty and impact	Medium	High	Low
Additional comments	Established in 1990 as a working group/2000 university spin-off; Goldwind acquired 70% in 2008	Described as novel and high-impact technology by interview partner [xy]	Reliance Group is the largest shareholder of GWPL
References	Annual report (2004, 2008), Interview Nr. [12, 67], Lewis (2012)	Project website, Interview Nr. [55, 79]	Annual report (2018), Interview Nr. [36, 41], Backwell (2017)

To identify different forms of upgrading mechanisms, the differentiation between conventional and unconventional technology transfer mechanisms provided by Lema and Lema (2012) was useful for this study as it classifies collaboration activities along varying degrees of cross-border interaction, on the one hand, and degrees of recipient effort (here understood as levels of co-creation), on the other. Conventional transfer mechanisms comprise international trade, FDI, technology licensing, and local joint ventures and are often not directly related to R&D. In turn, unconventional transfer mechanisms include overseas collaborative R&D, acquisition of foreign firms, and overseas R&D in the form of outward FDI. Unconventional collaboration types in this study included strategic R&D alliances (with varying degrees of formality),[111] joint R&D activities (e.g., co-patenting, co-publication of scientific articles, and the establishment of joint R&D facilities), and financial investments in external organizations (e.g., M&A and corporate venture capital). All collected information was documented in a spreadsheet, as Table A3 shows on an exemplary basis. Finally, it is worthwhile to mention that the data collection process was not linear but highly exploratory. While collecting data on recent R&D collaborations, it turned out that existing transfer mechanisms could not provide sufficient explanation for the changing properties of R&D networks. Finally, to apply a quality filter, all external R&D partnerships were reviewed and excluded from the list in case they did not meet the five criteria of R&D activities described above.

(3) Mapping and analyzing R&D partnerships over time

To visualize the identified R&D partnerships in a network diagram, the collected information had to be converted into two spreadsheets: (1) a node list (including ID number, label/name, and all other relevant node attributes) and (2) an edge list or adjacency matrix, which contained all central information about the relationship between two nodes. In the displayed network, all nodes and edges were checked multiple times and incorrect connections and/or attributes were corrected. The original purpose of specifying the location of each node was to create a world map showing the changing patterns of R&D collaborations of the three case-study firms as shown in Figure A1. However, given the long time frame and density of the network, a geographic map proved to be less informative than a case-study firm-centered map to highlight the changing structural compositions of the networks. Nevertheless, information about node locations was still relevant for the analysis as it provided insights into the changing geographies of the respective firms' R&D networks.

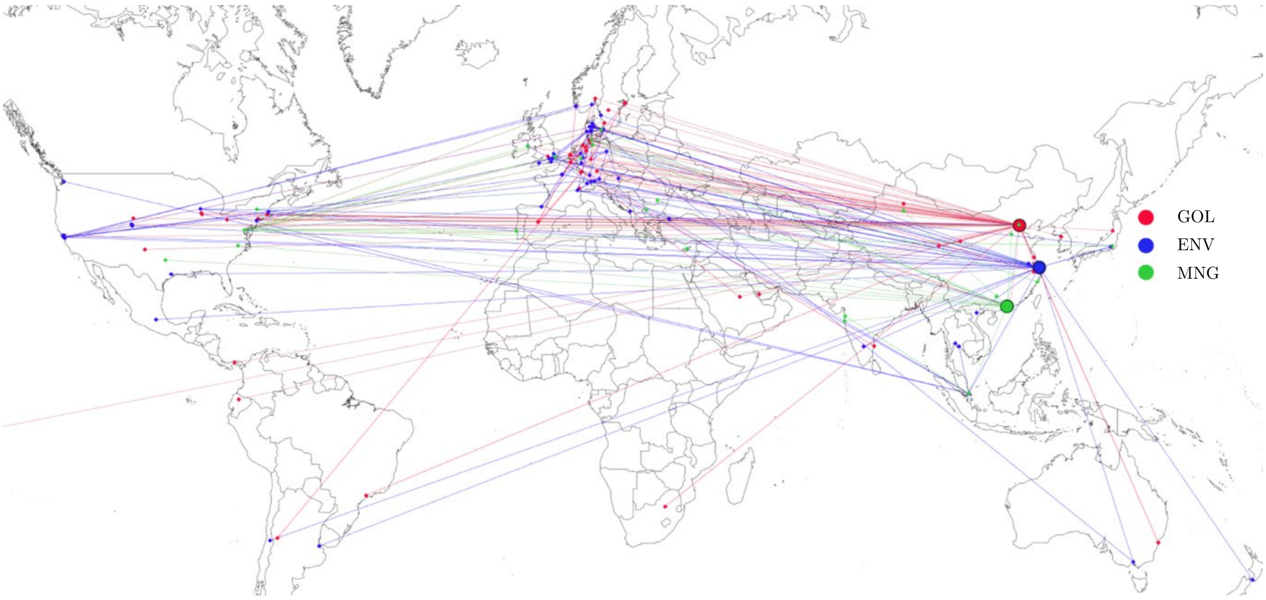
The firm-centered mapping of the networks showed that the network structures and properties had changed significantly over time. Not only have networks grown considerably over the last five years, but so too the case-study firms – especially Envision and Goldwind—have increasingly shifted their R&D activities to externalized and decentralized R&D projects. Upon closer examination, it turned out that these projects had three characteristics in common: first, they consisted of at least three actors; second, they comprised at least one science- and one market-based partner (including the respective case-study firm); and third, they had a very specific innovation purpose, which is why they were usually formed for a limited period of time. These three criteria were used to mark externalized R&D projects by dotted circles. Science-based partnerships with a more general innovation purpose were not marked as such. Based on

[111] Formal ones could be identified as memorandums of understanding, framework agreements, and joint initiatives. Less formalized ones were, for example, R&D collaborations in the course of industry association memberships.

the network visualizations and descriptive statistics on the structural centrality of the three case-study firms (i.e., degree, eigenvector, closeness, and betweenness), observations of changing network patterns were further documented.

When analyzing the changing networks over time, it was also interesting to see how indirect partnerships and extended networks (i.e., partners of partners) affected the case-study firms. For example, the fact that Vensys licensed not only to Goldwind but also to a range of globally dispersed market-based partners (e.g., the wind turbine manufacturers ReGen Powertech in India, IMPSA in Brazil, and Eozen in Spain; see Table A3) provided Goldwind with valuable insights into turbine design in different regions and under different environmental conditions. In addition, the close connection between Vensys and the science-based HTW Saar (*Hochschule für Technik und Wirtschaft des Saarlandes*), specifically 'INNOWIND'—a wind research group around Prof. Friedrich Klinger—served as a springboard to access cutting-edge scientific knowledge on novel concepts for wind turbines, which was further strengthened through an endowed professorship funded by Goldwind. Other indirect yet relevant secondary connections were created through industry association memberships, which in some cases resulted in joint R&D projects.

Figure A1. R&D networks on a world map



B: Empirical Appendix – Market Development of the Case-Study Firms

B.1 Domestic market

During the first phase (until 2009), two central policies paved the way for the rapid scaling up of China's domestic wind energy market, namely the Wind Concession Program in 2003 and the Renewable Energy Law in 2006.[112] Thereafter the number of Chinese market entrants grew from a few first movers to over 80 by 2008 (IRENA, 2013). While Goldwind (GOL), founded in 1998, was the first Chinese wind turbine manufacturer to produce a successful design, Envision (ENV) and Ming Yang (MNG) entered the industry relatively late and initiated commercial operations almost a decade after GOL. Today, the three firms make up two-thirds of China's wind capacity, with GOL accounting for triple the installed capacity of each of the other two firms (Table B1).

All three firms have diversified their installed capacity across more than 25 provinces. However, a relatively high market share is concentrated in a few provinces, with the top three provinces accounting for 35–40%. The firms' provincial focus, as shown in Table B1, is determined by various factors: availability of natural resources (areas with adequate wind speeds), regulations (wind farms are government-planned), and the respective firm's geographic origin. The latter played an important role in the firms' subsequent market and technology development. Concerning *market* development, local governments acted as market catalysts, either directly as customers or indirectly through support schemes (e.g., funding, industrial policies). As a manager from MNG put it: 'We have an internal joke, the most important capability of our company is to get financial support from the local government.' In terms of *technology* development, local conditions such as wind speed and land availability were central determinants. GOL was established in Northwest China (Xinjiang) near high-wind-speed onshore areas. In contrast, ENV and MNG were founded in coastal areas (Shanghai and Guangdong) with limited access to adequate onshore, yet technologically less developed offshore, territory. As a result, the relative offshore capacity of the two coastal firms is considerably higher than GOL's. Similarly, South Korean wind turbine manufacturers had to directly leapfrog to offshore wind turbine technology due to lack of land availability (Lewis, 2012). However, by contrast, Chinese firms were endowed with a significantly lower industrial base and technological capabilities, which required a market detour (Hain et al., 2020).[113] Due to its location, MNG was one of the first firms to equip its turbines with typhoon-resistant systems.

Table B1. Domestic and global market distributions (2019)

Firm	Installed capacity (GW)	Top three provinces	Top three foreign markets	# provinces	# countries	Province		National	Global (export)
						Top one	Top three		
GOL	60.47	Xinjiang, Inner Mongolia, Shanxi	AU, AR, US	30	19	21.86%	40.14%	94.95%	5.05%
ENV	21.91	Jiangsu, Shandong, Hebei	IN, MX, KZ	27	8	15.11%	35.32%	96.97%	3.03%
MNG	20.88	Inner Mongolia, Guangdong, Hebei	PK, BG, IN	26	4	14.62%	36.12%	99.42%	0.58%

Source: Author's own compilation and calculation based on CWEA (2020).
Note: All figures based on accumulated installed capacity. The number of countries excludes China.

[112] The Wind Concession Program introduced local content requirements of 50% in 2003 and 70% after 2004, which reduced the domestic market share of foreign firms dramatically from 79% in 2004 to 12% in 2009 (Sun and Yang, 2013).
[113] Until today, none of the three firms has become a first mover in turbine size, which is one method to assess technological progress in the wind energy industry (Dai et al., 2021; Lewis, 2012).

B.2 Global markets

Despite various internationalization efforts, export shares of China's lead firms remain low, between 0.5% (MNG) and 5% (GOL). GOL has the strongest presence in foreign markets, with Australia being the core market, accounting for 40% of its exports.

Interview partners mentioned several reasons for their low level of overseas presence, including general and country-specific barriers. Managers from all three firms mentioned limited *technological credibility*, lower *financial profitability*, and different *market requirements*, particularly in advanced markets, as key factors: 'We are losing money in international markets'; 'the Chinese market has a different viewpoint on a product than the international markets.' Since advanced wind markets have been shifting from feed-in tariff to auction-based systems, differences in market requirements have become even more pronounced: '[T]he problem is that the headquarters expects the same margins internationally as in China, which is impossible' (Manager, ENV). Moreover, lack of certification by internationally recognized bodies long aggravated the lack of technological credibility and access to international financing. Given the high degree of technological customization of wind technology (Binz and Truffer, 2017), turbine configurations have to be designed for a specific market environment, which constitutes another barrier to rapid internationalization: '[E]ach region requires its own business model' (Manager, GOL).

As a result of the high entry barriers in advanced markets, the three lead firms have developed different market entry strategies. After 'aggressive' attempts to compete in international auctions, MNG has largely withdrawn from global sales: '[W]e had two subsidiaries in the US, but they became research offices instead of focusing on sales.' After going public on the New York Stock Exchange in 2010, the company was delisted six years later. Market entry into India turned out to be challenging as certifications did not comply with the country's standards. Attempts to enter the US market were suspended as MNG could not meet the production capacity as agreed with local partners.[114] In 2019, MNG did not export a single turbine to overseas markets.

In contrast, GOL has been gradually diversifying its markets, with exports to 19 countries across all continents. In 2019, it supplied its first turbines to Spain and South Africa. Rather than expanding aggressively, 'Goldwind has always been very conservative in all the markets,' as a manager explained. Similarly, an industry investor observed that GOL was 'playing the long game [...] they are very strategic.' To gain an international track record despite existing barriers, GOL developed wind projects either through Chinese customers overseas or on its own, that is, by acquiring land, supplying its own turbines, and self-managing the operations and maintenance process: 'What we are doing in Australia is project sales, we develop, we invest, and we sell the project.' This approach was imitated by other firms such as MNG: '[W]e also tried this in Eastern Europe and South America.' To overcome the lack of access to foreign financing and facilitate its expansion into international markets, GOL formed strategic partnerships with the Bank of China and China Development Bank.

[114] E.g., Texas-based GreenHunter Energy.

ENV long lagged behind GOL in terms of global exports. However, the firm caught up rapidly in the last five years and supplied its first turbines to Mexico and France after acquiring the local project developers Vive Energía and Velocita Energies in 2015 and 2016, respectively. As declared by a firm manager, 'we have a clear market roadmap for post-2020.' As the Chinese market is undergoing a shift to an auction-based system, Chinese firms had to redirect their focus from volume to profitability and market diversification. In this vein, ENV is putting a stronger focus on global sales, admitting that 'the Chinese market, it has been a paradise for Chinese companies.' While GOL faces various market restrictions due to its licensing agreement with Vensys, ENV is benefitting from larger market share in countries such as India.[115] In sum, all three firms still have considerable potential to upgrade to higher-added products through learning-by-exporting (Gereffi et al., 2005; Haakonsson, 2009).

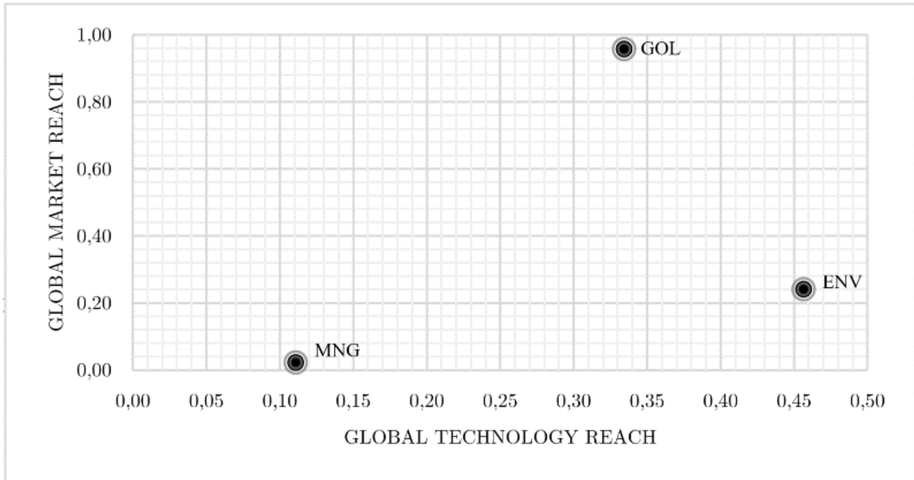
Table B2 and Figure B1 provide a quantified overview of the market versus technology reach of the three firms. It shows that GOL leads in terms of market and ENV in terms of technology reach, whereas MNG lags behind in both dimensions.

Table B2. Overview of global market and technology reach [values]

Firm	Market reach			Tech reach		
	% exports	# foreign markets	Total	% global partnerships	Betweenness	Total
GOL	5.05	19	0.96	0.62	0.54	0.33
ENV	3.03	8	0.24	0.93	0.49	0.46
MNG	0.58	4	0.02	0.56	0.20	0.11

Note: The totals are calculated by multiplying the market and tech reach sub-values.

Figure B1. Overview of global market and technology reach [matrix]



Note: The market and technology values are the totals as presented in Table B2.

[115] In 2019, ENV accounted for 10% of India's market share, ranking after Siemens Gamesa, Suzlon, Vestas, Inox Wind, and GE (BNEF, 2020b).

C: Supplementary Tables and Figures

Table C1. Existing perspectives on latecomer learning and upgrading

Concept	Description	Examples of knowledge sources	References
Technology transfer	Learning through knowledge flows between OECD and emerging countries	- Conventional (trade, FDI, licensing, joint venture) - Unconventional (R&D partnerships, R&D hubs, M&A of foreign firms) - Knowledge-intensive business services (KIBS)	Lema and Lema (2012), Haakonsson et al. (2020)
Learning linkages	Learning through linkages across the value chain between stakeholders within and across natural-resource-related industries	- Backward linkages (upstream) - Forward linkages (downstream)	Hirschman (1981), Figueiredo and Piana (2018)
Knowledge/learning networks & innovation systems	Learning within innovation systems/spaces comprised of building blocks, i.e., actors, networks, technologies, and institutions	- Actors: firms, universities, scientific and technological institutes - Learning network types: passive, active, innovation, strategic innovation - System boundaries: geographies, sectors, technologies	Malerba (2002, 2004, 2005), Dantas and Bell (2009), Slepniov et al. (2015), Lewis (2012)
Linkage, leverage, learning	Learning understood as overseas capability seeking through asset augmentation (rather than asset exploitation)	- Joint ventures, supply chain contracts, technology licensing, market-entry partnerships	Mathews (2006, 2017)
Learning mechanisms	Learning through the purposive accumulation of external and internal knowledge to create innovation capabilities	- Hiring expertise, training/R&D with suppliers, training/R&D with local institutions, learning from users, codified knowledge acquisition, internal knowledge sharing	Dutrénit (2000, 2004, 2007), Figueiredo (2003), Hansen and Lema (2019)
Knowledge spillovers	Learning understood as domestic industry development through inward FDI to broader domestic industry development	- Labor mobility, supplier relationships, demonstration effects, university–industry collaboration	Hansen and Hansen (2020), Fu et al. (2011)
Global production networks	Learning through global outsourcing networks, i.e., in lower-cost locations	- Dispersed supply and customer bases, e.g., from multinational enterprises to lower-tier network suppliers	Ernst and Kim (2002), Yang (2013), Horner (2017)

Table C2. Top five patenting country codes and respective patent numbers

Firm	1	2	3	4	5	% global patenting
GOL	CN	TW	DE	JP	DK	
	3564	18	6	4	3	1%
ENV	CN	DK	US	DE	JP	
	324	228	18	7	4	44%
MNG	CN	TW	VN	KR	HK	
	2679	75	8	2	1	3%

Source: PATSTAT (autumn 2018 edition). Note: 'Global patenting' excludes all patents registered under China's CNIPA (formerly SIPO).

Table C3. Detailed overview of growing innovation space across the three phases

Innovation space	GOL			ENV[(a)]			MNG		
	1	2	3	1	2	3	1	2	3
INTERNAL R&D ORGANIZATION									
R&D hubs, subsidiaries and centers of excellence									
# units									
# countries									
EXTERNAL R&D PARTNERSHIPS									
Science-based partners									
# partners									
# countries									
Market-based partners									
# partners									
# countries									
# sectors									
Externalized R&D projects									
# networks									

Declaration of co-authorship

Article I: Co-authored with Stine Haakonsson and Yixin Dai

CO-AUTHOR STATEMENT

Title of paper	Catching up through green windows of opportunity in an era of technological transformation: empirical evidence from the Chinese wind energy sector.
Journal and date (if published)	Industrial and Corporate Change, doi: 10.1093/icc/dtaa034

1. Formulation/identification of the scientific problem to be investigated and its operationalization into an appropriate set of research questions to be answered through empirical research and/or conceptual development
Description of contribution: Has contributed substantially (34-66%): Formulation of introduction, research questions, theory, and analytical framework. The investigation of the scientific problem was part of a broader framework of the PhD fellow's doctoral thesis.
2. Planning of the research, including selection of methods and method development
Description of contribution: Has contributed substantially (34-66%): Formulation of data collection and research methods; the planning of the research incl. participation in various workshops in Copenhagen and Beijing.
3. Involvement in data collection and data analysis
Description of contribution: Has contributed substantially (34-66%): Collection and analysis of qualitative data (semi-structured interviews, key policies, product partnerships). Collection and analysis of quantitative data (e.g. patents, mergers and acquisitions, turbine sizes, onshore/offshore statistics); definition of patent search codes for T3.
4. Presentation, interpretation and discussion of the analysis in the form of an article or manuscript
Description of contribution: Has contributed substantially (34-66%): Analysis, presentation and discussion of firm cases; formulation of key findings, contributions and limitations.

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Page 2 of 2

Article II: Co-authored with Primoz Konda, Roman Jurowetzki and Daniel Hain

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2. Planning of the research, including selection of methods and method development
Description of contribution: Has contributed substantially (34-66%): Planning of the research incl. participation in various workshops in Copenhagen and Beijing; adaption and formulation of methods to measure market and technology development (e.g. key market indicators and IPC classes for wind); selection and formulation of geographical and sectoral cases.
3. Involvement in data collection and data analysis
Description of contribution: Has contributed substantially (34-66%): Collection of wind energy data to complement patent-level indicators; prioritization and formulation of data analysis.
4. Presentation, interpretation and discussion of the analysis in the form of an article or manuscript
Description of contribution: Has contributed substantially (34-66%): Evaluation, interpretation and analysis of country wind cases and discussion of cross-sectoral specificities; formulation of key findings, contributions and limitations.

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Other publications by the author

The following publications by the author do not form part of the dissertation but are the result of SDC research collaborations during the PhD fellowship. Thematically, they are closely related to the dissertation.

Oehler, L., Lund Larsen, M. & W. Yao (2020), 'Financing the global low-carbon energy transition: China's dual role domestically and overseas', Chapter 14, p. 110-118, In: *SDC International Report 2020, Cooperating for Energy Transition*, Copenhagen, Denmark. DOI: 10.7146/aul.395.156

Oehler, L. & P. Konda (2019), 'Sino-German Innovation Networks in the Wind Power and Electric Vehicle Sector', p.3-5, In: *Green Market and Climate Change - Econet Monitor*, September Edition.

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Creativity as Balancing 'Constrainedness'

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