CATCHING UP IN ELECTROMOBILITY

WINDOWS OF OPPORTUNITY, INDUSTRIAL POLICIES, AND FORMATIVE SECTOR DEVELOPMENT IN THE ELECTRIC VEHICLE SECTOR IN CHINA

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PRIMOZ KONDA

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AALBORG UNIVERSITY
DENMARK

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Primoz Konda, (2022). *Domestic deployment in the formative phase of the Chinese Electric Vehicles Sector: evolution of the policy-regimes and windows of opportunity*, Innovation and Development, DOI: 10.1080/2157930X.2022.2053806

ENGLISH SUMMARY

The green transformation requires producing renewable energy in parallel with energy-efficient solutions. The existing literature mainly focuses on the former, e.g., wind and solar energy, while the latter is still understudied. The development of both types shares common motivation and goals. However, their idiosyncratic characteristics require different responses from the governments, and this observation motivated the analysis of the development of the electric vehicle sector in China.

Positioned between innovation studies and evolutionary economics, the thesis's main conceptual apparatus is focused on catching up, systems of innovation, and windows of opportunity. Despite extensive studies analyzing different sector development trajectories, the literature lacks an integrated perspective that analyzes performance trajectories using both market and technology indicators. Thus the first objective of this thesis is to fill this gap by introducing a market-technology framework for analyzing catch-up trajectories that uses market data and patents' novelty as market and technological indicators, respectively. While making a conceptual and methodological contribution, the application of this framework brings out new insights about the type and extent of catching up in the Chinese EV industry. The second objective moves from performance to its determinants in terms of policy and the influence of policy on creating an opportunity for the green shift. Precisely, to what extent and how does the government promote novel EV solutions that are still inferior to the commonly used vehicles on internal combustion? Third, without a dominant design and several alternative solutions, newly generated knowledge inside the EV sector could soon become obsolete. Hence the thesis seeks to explore how domestic OEM with limited technological capacities can acquire knowledge and use it in a fast-developing sector. Fourth, although latecomer countries share many aspects, their unique features require nationally tailored strategies and policy responses. Thus, the fourth and final objective is to analyze three latecomer countries with undeveloped electric vehicle sectors by exploring their strategies and unique potentials.

To achieve the research objectives and answer the overall research question "*What catch-up trajectory is observed in the EV sector in China and what are the key determinants, in terms of industrial policy and sector development, of this relative catching up success?*" the thesis applies a mixed-methods design under a pragmatic research philosophy. The combination of patent data, market indicators, policies, and interviews in different case studies makes it possible to analyze the phenomenon from various perspectives.

The thesis shows how the Chinese government played an essential role in endogenizing (creating) green windows of opportunities that were not yet present due to the early stage of technology at its inception. Using a green industrial policy strategy, China used a coordinated approach, stimulating production while extensively addressing demand. During the initial stages of development, there were only nascent EV solutions, and the knowledge acquired by Chinese firms soon became in danger of becoming obsolete. Thus, the traditional knowledge transfer methods needed to be accompanied by learning the process of producing novel technology. Finally, developing countries must adopt tailored development strategies that fit their unique characteristics, shortcomings, and opportunities.

The main contributions of the thesis are [1] an integrated market-technology framework to analyze catching-up trajectories that applied to the studied case shows [2] what development path the EV sector in China followed. The government endogenized GWO, and the analysis fills the gap on [3] how policy could initiate the development of the energy-efficiency sector.

DANSK RESUME

Den grønne omstilling kræver, at der produceres vedvarende energi sideløbende med energieffektive løsninger. Den eksisterende litteratur fokuserer hovedsageligt på førstnævnte, fx vind- og solenergi, mens sidstnævnte stadig er underrepræsenteret. Udviklingen indenfor begge områder er motiveret af de samme visioner og mål, men deres idiosynkratiske egenskaber kræver forskellige reaktioner og handlinger fra politiske beslutningstagere. Det er netop denne observation, som motiverede analysen af elbilsektorens udvikling i Kina.

Positioneret mellem innovationsstudier og evolutionær økonomi er afhandlingens vigtigste begrebsapparat fokuseret på innovationssystemer, "catching up" og "windows of opportunity". På trods af omfattende studier af forskellige sektorers udviklingsforløb mangler litteraturen et integreret perspektiv, der analyserer industrielle udviklingsforløb ved hjælp af både markeds- og teknologiindikatorer. Afhandlingens første mål er dermed at anvende et integreret perspektiv ved at introducere en markedsteknologisk ramme til analyse af "catch-up" forløb, der anvender markedsdata og patenters nyhedsværdi som henholdsvis markeds- og teknologiindikatorer. Samtidig med at yde et konceptuelt og metodisk bidrag, medfører anvendelsen af denne ramme ny indsigt i typen og omfanget af "catching up" i den kinesiske elbilindustri. Afhandlingens andet formål flytter fokus fra de observerbare udviklingsforløb til deres determinanter. Der ses især på transport-, innovations- og industripolitik og hvordan disse influerer mulighederne for at skabe grøn omstilling og økonomisk udvikling på samme tid. Nærmere bestemt undersøges det, i hvilket omfang og hvordan regeringen fremmer nye elbilløsninger ved hjælp af både udbuds- og efterspørgselspolitik. Det tredje mål vedrører, hvordan ny viden indenfor elbilsektoren (EV-sektoren) hurtigt kan blive forældet uden et dominerende design og flere alternative løsninger. Derfor søger afhandlingen at udforske, hvordan indenlandske OEM med begrænset teknologisk kapacitet kan tilegne sig viden og anvende den i en sektor i hurtig udvikling.

Endelig er afhandlingens fjerde for, at se på udviklingslande som - på trods af at de deler mange karakteristika og aspekter – hver især kræver skræddersyede strategier og politiske handlinger. Således er det fjerde og sidste formål at analysere tre udviklingslande med ikke-udviklede elbilsektorer ved at undersøge deres strategier og unikke potentialer.

For at opnå forskningsmålene og besvare det overordnede forskningsspørgsmål: "Hvilket udviklingsforløb kan observeres i elbilsektoren i Kina, og hvad er de vigtigste determinanter med henblik på industripolitik og sektorudvikling for denne relative *catch-up* succes?" anvender afhandlingen en pragmatisk forskningsfilosofi og kombinerer kvantitative og kvalitative metoder. Kombinationen af patentdata,

markedsindikatorer, politikker og interviews i forskellige casestudier gør det muligt at analysere *catch-up* fænomenet ud fra forskellige perspektiver.

Afhandlingen viser, hvordan den kinesiske regering spillede en væsentlig rolle i endogeniseringen (skabelsen af) grønne udviklingsmuligheder, der endnu ikke var til stede på grund af det tidlige teknologiske stadie ved udviklingens begyndelse. Ved at anvende en grøn industripolitisk strategi brugte Kina en koordineret tilgang, der stimulerede produktionen og i vid udstrækning imødekom efterspørgslen. I de indledende stadier af udviklingen var der kun tidlige EV-løsninger, og den viden, som kinesiske virksomheder erhvervede sig, kom hurtigt i fare for at blive forældet. Derfor måtte de traditionelle metoder til overførsel af viden ledsages af læringsprocessen i at producere ny teknologi. Endelig må udviklingslandene adoptere skræddersyede udviklingsstrategier, der passer til deres unikke karakteristika, mangler og muligheder.

Afhandlingens vigtigste bidrag er [1] en integreret markeds-/teknologiramme til at analysere "*catching-up trajectories*", og som i anvendelsen i den undersøgte case viser [2] hvilken udviklingsvej elbilsektoren i Kina fulgte. Identificering af det internaliserede "*green window of opportunity*" udgør et selvstændigt bidrag til den tilgængelige litteratur om [3], hvordan politik kan igangsætte udviklingen af grønne industrier.

ACKNOWLEDGEMENTS

It happens that I have a passion for climbing. I enjoy every aspect of the sport. The mental game of finding the best route, the clever moves that gets you to the top or makes you reach new heights, the pure physical work, the endurance you must build to overcome pain and fear. Perhaps it is a bit far fledged to use climbing as a metaphor for writing a dissertation, however, as I love this sport, I keep finding aspects of likeness. And to some degree, I feel that I have made it to the top of this wall that I set out to climb September 2017.

Like climbing, writing a dissertation can seem like a solitary endeavor. And it is at times. But behind every climber there is (at least) one partner (who holds the fate of your life in a rope between his hands). And (apologies for the perhaps dramatic comparison) likewise am I humbly aware that this work - this PhD project - would not have been realized without the guidance, support, conversations, and discussions that took me and the work that I undertook to the top of this wall. I am delighted to have made it to this point where finally I can thank and acknowledge all the people who contributed to the realization of this dissertation.

Foremost, thanks to my supervisor Rasmus Lema for commitment, sharp comments, wise guidance and for leading me all the way to the end. (Or top, if I may continue the metaphor, you were this climbing partner with the rope).

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As I feel that I have reached the top of this dissertation-wall I think that I will soon be ready to unwind and start the decent. As I land on my feet before the wall, I know that soon enough my eyes will look towards new climbs and new challenges.

TABLE OF CONTENTS

SYNOPSIS **1**
1. Introduction **1**
1.1. Motivation 1
1.2. Climate change 2
1.3. Types of Green energy industries 3
1.3.1. Green Transitions and industrial development 3
1.4. Key Theoretical concepts 6
1.5. Research gaps and objectives 6
1.6. Research focus 10
2. Empirical context **12**
2.1. Electric vehicles 12
2.2. The electric vehicle sector in China 16
2.3. Other Emerging economies 18
3. Theoretical Framework **21**
3.1. Systems of innovation 21
3.1.1. National Innovation System 21
3.1.2. Sectoral System of Innovation 22
3.1.3. Technological System of Innovation 22
3.2. The Catching-up concept 23
3.3. Leapfrogging and Windows of Opportunities 24
3.3.1. Green Windows of Opportunities 25
3.3.2. GWO in Renewable energy generation sectors 27
3.4. Government interventions 27
3.4.1. Interventions for Green transformation 28
3.5. Absorptive capacity and Forms of knowledge 29
4. Methodological considerations **31**
4.1. Research strategy and design 32
4.2. Case Study 33
4.3. Quantitative research 34

4.3.1. Data ... 34
4.3.2. Methods ... 35
4.4. Qualitative research ... 36
4.4.1. Data and analysis ... 36
4.5. Research Limitations ... 37
5. Summary of Articles ... 39
5.1. Article A ... 39
5.2. Article B ... 40
5.3. Article C ... 41
5.4. Article D ... 43
6. Conclusion ... 44
6.1. Articles' contribution ... 45
7. REFERENCES ... 48
II. ARTICLES ... 63
Article A ... 65
Article B ... 109
Article C ... 143
Article D ... 175

LIST OF FIGURES

Figure 1: Intertopic Distance Map (via multidimensional scaling) 14

LIST OF TABLES

Table 1: Research gaps and objectives 9
Table 2: Overview of articles 11
Table 3: Topics from LDA Model 15
Table 4: New Electric Vehicle sales by country 17
Table 5: Economy, demography, and automotive industry indicators 19
Table 6: Unpacking the dimensions of WOOs 26
Table 7: Overview of the research design 32
Table 8: Overview of the data and methods used in the analysis 37

SYNOPSIS

1. INTRODUCTION

The development of the EV sector is a part of an overall 'green push' in China. Prior research has shown how several green industries have witnessed rapid development, leading to combined environmental improvement and industrial development. An essential part of this process was the interplay between environmental and industrial policies. However, concerning the overall green push, most of our insights pertain to the supply side of green energy, i.e., the various green solutions for electricity generation—e.g., wind, solar, and hydro. Much less is known about the demand side of these energy systems, where the relevant sectors and technologies have markedly distinct characteristics. For example, in contrast to electricity-generating solutions, EVs have fragmented demand patterns, consisting of private end-users and public institutions. Seeking a deeper understanding of EV deployment in China, this thesis aims to contribute to the literature on green industrial development in developing countries.

Among emerging economies that introduced EV policies, China has been able to roll out EVs at an unprecedented speed and scale with established production that led to a significant share of vehicles on the road. At the time of market entrance, EVs were substantially inferior to 'dirtier' traditional solutions, i.e., internal combustion engine vehicles (ICE). Thus, supply and demand had to be stimulated and coordinated. Heavy subsidies to manufacturers and purchase incentives to consumers effectively created the domestic market. While the industry's international competitiveness is still uncertain, it is clear that there is now a solid domestic industry with both manufacturing and innovation capability. This thesis aims to analyze the Chinese forging ahead in the Electric vehicle (EV) sector in order to inform debates about greening and economic development in emerging economies.

1.1. MOTIVATION

By the time I started my Ph.D., most of the general public had realized that economic growth based on the overuse of natural resources had reached its limit. Many countries started to shift towards producing electricity from renewable sources decades ago, and some solutions steadily increased their share in the global energy mix, e.g., wind and solar (OECD, IEA, and IRENA 2017). However, with few exceptions, the electrification of road transport was still in the development stage. Although the first electric vehicles date back to the 19th century, it was only after 2010 that EVs started to take the first tenth of a percent of market share from gasoline and diesel vehicles. Transportation causes an essential share of air pollution, which harms human health and the environment. Thus, its electrification is crucial for a sustainable future.

In 2016, China transitioned into a market forerunner[1] with the highest number of electric vehicles on its road and almost one-third of the global EVs. Unlike some other green sectors, at the time of the Chinese entrance in 2009, the EV sector was at the start-up stage and without a dominant design (Howell, Lee, and Heal 2014; Quitzow, Huenteler, and Asmussen 2017). Furthermore, some countries in western markets have been reluctant regarding the electrification of transport. These features triggered my interest in this case, aiming to have an in-depth understanding of the process and perhaps form a model for other emerging and developing countries.

1.2. CLIMATE CHANGE

In the last few centuries, the World transitioned from an agrarian and a handicraft economy to a highly industrialized society that helped achieve many social objectives and improved living conditions. However, development has been achieved at the expense of damaging environmental conditions. The World thus now faces the challenge of restructuring the economy from the progress that harms the environment to one that protects the environment. Potentially, the transformation could create co-benefits between green and economic goals.

The international community started to debate climate change issues back in the 1990s and signed several agreements to reduce greenhouse gas emissions. The most important were the Montreal Protocol (1987), Kyoto Protocol (1997), and the Paris Agreement of 2015. The latter aims to limit global warming below 2, preferably 1.5 degrees Celsius, compared to pre-industrial times (Maizland 2021). The goal is achievable from the technical perspective, yet this will require further technological innovation, major policy reforms, and increased carbon pricing. The essential role of de-carbonization is on renewables and energy efficiency. Despite the high investments, the transition would generate USD trillions in economic growth until 2050. Apart from millions of newly generated jobs, the overall benefits—environmental, climate, and health—would exceed six times more than the costs of transforming energy sectors (Blyth et al. 2014; OECD et al. 2017). An effective human capital support system is critical. The analysis of existing green jobs shows that they differ from non-green mainly by requiring more non-routine cognitive skills and higher dependence on formal education, experience, and custom training (Consoli et al. 2016).

[1] As in Hain et al. (2020) a market forerunner leads in market share figures with lower technological development compared to competitors

1.3. TYPES OF GREEN ENERGY INDUSTRIES

The green transition is multifaceted and contains many different sectors and technologies, but strategies consisting of developing renewable energy sources and green technologies for efficient energy use are central in this wider process. Only the interaction and combination of green electricity generation on the supply side and in thoroughly electrified sectors on the demand side can lead to desired goals of the Paris agreement (Gielen et al. 2019). The difference between these two sides of the coin lies mainly in the type of actors and the decision-makers to use it. While state-owned or private corporations generate the vast majority of energy, the energy efficiency lies on individuals. Thus, governments have limited leverage to establish demand for the latter. To support the R&D and the start of the green industries, governments introduced supporting policies and financial mechanisms. For energy production, governments use mechanisms that allow providers of green energy to compete with fossil fuels, e.g., feed-in-tariff (FIT), a long-term contract for renewable energy producers that guarantee a specific buying price (Couture and Gagnon 2010). When it comes to renewable energy-efficient solutions[2], such as Electric vehicles (EV), governments can use purchase price incentives, motivating consumers to buy cleaner but still more expensive products (Kester et al. 2018). The collection of all policies and incentives represents the national strategy for the green transition, which also follows economic goals along with establishing environmental protection.

1.3.1. GREEN TRANSITIONS AND INDUSTRIAL DEVELOPMENT

The green shift will create diverse industrial outcomes for every country, primarily due to its starting point, national policy ambition, supply chain support, and fossil fuel dependency (IRENA 2020). For example, the lack of policy support and the continuation of supporting fossil fuels are fundamental causes of failed green transition projects in many countries (Mathews and Tan 2014). The support, such as subsidies, must be time-limited and avoid creating monopoly rents. Thus, according to Kemp & Never (2017), governments should have a proactive role with a long-term vision while including all stakeholders. Packing various policies (e.g., R&D, capability & capacity building, market development, stimulation of manufacturing) into a common big policy pack will clear the message and unify the shared purpose. Finally, the policy should have control mechanisms and be adapted to an ever-changing situation.

---

[2] In this thesis, Electric Vehicles are defined as renewable energy-efficient solution. This does not mean it uses only the electricity produced by renewable solutions, but it is characterized as renewable solution.

The green transition poses challenges to developed and developing countries, and the shift towards low-carbon development[3] gives them various roles. In many cases, the advanced economies invest in the R&D of new technologies and bring manufacturing to the stage where they are competitive with the traditional solutions. The emerging economies can already participate in some R&D activities. However, primarily, they use their lower-cost labor to increase solutions' competitiveness and consequently lower the prices. Finally, the poorest economies still need to develop innovation capacities, prepare the workforce for green jobs, and gradually implement new technologies. To optimize the transition, countries should be interconnected and support each other's development regardless of their input. Nevertheless, most pollution is caused by developed countries, and the poorest suffer more from its consequences (Lema et al. 2014).

Despite promising benefits from the shift in the future, the process requires high investments from governments and firms involved. Thus, there is a need to make green solutions economical as fast as possible (Geels 2014). In one way, stakeholders invest in R&D to increase the solution's efficiency or lower the production cost with economies of scale (Gross, Leach, and Bauen 2003). After decades of incremental improvement, solar PV and onshore wind energy generation plants are more efficient than new fossil fuel plants due to technological innovation, cost optimization, and efficient financial policies (IEA 2021). Similarly, EVs' efficiency is better than vehicles with internal combustion, however, the results vary due to the type of technology that produces the electricity (Albatayneh et al. 2020). Incremental innovation in electric motors, batteries and charging combined with exponential sales growth decreased the price and improved the EVs range. Both—price and range—are dominant factors in the buying process (Cecere, Corrocher, and Guerzoni 2018; Feng and Magee 2020).

Countries consider future benefits and present high investments to decide when is the optimal moment to start the green transformation and how progressive the actions should be (Geels 2014; Pegels and Altenburg 2020). Depending on their resources and capacities, they can establish the green industry[4] and manufacture the products—e.g., wind turbines, solar panels, EVs—, or only import the solution. In the latter, they have to support the implementation of the solutions—e.g., FIT, purchase subsidies—, and in the former, they also have to support the firms and enable an innovation

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[3] Concept that aims to mitigate emissions to avoid dangerous climate change, while at the same time achieving social and economic development in a carbon constrained world (Urban and Nordensvärd 2013:7, as cited in Lema et al., 2014)

[4] In this thesis, the terms sector and industry are used interchangeably to describe different actors that operate in the same segment of the economy.

system that connects stakeholders—e.g., manufacturing subsidies, tax incentives, R&D funds (Creutzig et al. 2014).

In recent decades, several emerging economies started green transition following environmental and economic goals. The most proactive was China, which in parallel, started a few green industries, yet used different paths (Binz et al. 2017; Capozza and Samson 2019; Quitzow et al. 2017). In many, they manage to gain the leading position—e.g., solar (Fu and Gong 2011), wind power (Lewis 2012), and EV (Li, Yang, and Sandu 2018)—, while using adapted industrial policies—Green Industrial policies (Rodrik 2014). The Chinese catching up in renewables was based on taking over the market and less technological leadership (D. S. Hain et al. 2020; Watson et al. 2015).

Renewable solutions are frequent objects in World Trade Organization's (WTO) disputes regardless of enabling a green transition. The support of nascent industries that are inferior to "dirtier" solutions requires subsidies, which give an advantage to domestic producers on the global market. Trading partners impose trade remedies to protect their producers, such as countervailing and anti-dumping duties, increased import tariffs, and specific domestic content requirements to favor domestic production (Wu, M. & Salzman 2014). As a result, trading berries may slow down the green transition and decrease its benefits. For instance, while China was gaining global market share in Solar PV by subsidizing domestic producers, the US imposed countervailing duties on importers from China. In response, China filed a complaint[5] on WTO (Hajdukiewicz and Pera 2020). Contrariwise, China's policy for developing the automobile sector—including EVs—led to several complaints[6] about importing automobiles and auto parts and exporting rare earth elements.

To sum up, in response to climate change and as an opportunity to strengthen their economic position, countries started to develop low-carbon solutions, which can generate renewable energy or increase the efficiency of its use. In the early stages of green industries, R&D and manufacturing were in the domain of developed countries, yet, China started various renewable sectors with strong policy support, high investments, and ambitious goals to become the global market leader. It is key to note that in the EV sector, China is the only emerging economy that has established the industry in a profound way (Article D). Yet little is known about this catch-up trajectory. The next section provides a very brief introduction to the conceptual foundations of this thesis while a later section (section 3) unfolds the analytical framework in detail.

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[5] Dispute number: DS437 https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds437_e.htm

[6] E.g.: Dispute numbers: DS339, DS340, DS342, DS431, DS440, DS450, DS508 at https://www.wto.org/

1.4. KEY THEORETICAL CONCEPTS

The main theoretical concepts of the thesis come from innovation economics, which originates from Schumpeter's understanding of economic development. The Schumpeterian approach to latecomer development relies on innovation promoted by knowledge and learning, where innovation goes beyond technology and includes institutions, marketing, and organizational innovation (Malerba and Lee 2021). Nevertheless, sustainable growth is possible in combination with generated demand by Keynesian fiscal policies (Dosi, Fagiolo, and Roventini 2010).

In this tradition, research on catch-up cycles and global changes in industrial leadership focused on how windows of opportunities and disruptions in technologies or markets created openings for newcomers and challenges for incumbents. This key theoretical framing for understanding the market development, which at a specific time in the sector's lifecycle, allows latecomers to reduce the gap between them and the forerunner or even take over leadership. Traditionally, latecomers would exploit such Windows of Opportunity (WOO), which could emerge from technological, demand, or institutional change (Lee and Malerba 2017). This body of research analyzed countries' or 'firms' advancement compared to leaders, but despite several studies, there is no recipe for success that would generally work, mainly because circumstances change, and successful and unsuccessful latecomer development cases are always context-specific. This goes in hand with Schumpeter's assertion that only the decomposition and new combination of processes can lead to development due to the ever-changing environment. In this fashion, the thesis aims not to provide new insights into latecomer development when the root cause of new opportunity windows is the green transformation. It will analyze the Chinese 'model' of EV deployment and contribute to the existing literature. As mentioned, the literature to which this thesis contributes is specified below.

1.5. RESEARCH GAPS AND OBJECTIVES

The thesis has both conceptual-methodological and empirical objectives (Table 1). The **first objective** is mainly conceptual and methodological. This is because most of the innovation literature still has shortcomings when it comes to 'measurement' of catching up. The catching-up studies looked at different sectors, e.g., steel, ICTs, pharmaceuticals, automobiles, agro-food (Malerba and Nelson 2011; Shin 2013), and vastly measured sectors' leadership with market parameters (Lee and Malerba 2017; Morrison and Rabellotti 2017; Mowery and Nelson 1999; Shin 2017). The studies that looked at catching up over technological performance (e.g., Awate, Larsen, and Mudambi 2012; Fu, Pietrobelli, and Soete 2011) measure technological innovativeness by quantifying patents, which can be inaccurate. Neglecting the patents' quality can diminish the importance of patents with a significant impact

(Torrisi et al. 2016). Similarly, patent citation analysis overlooks insights into technology development paths due to its shortcoming in presenting the overall relationship among patents (Yoon and Park 2004). Thus, the thesis's first objective is to propose an integrated market-technology framework for catch-up trajectories of latecomer countries. It will use technical indicators that measure patents' novelty and impact. The country's trajectory and development path's presentation by combining market and technological performance would help understand the catching-up process and give better insights into the relationship between market and R&D policies. In green sectors, economies of scale and performance efficiency improve competitiveness towards fossil fuels and decrease the need for governments' investments to deploy green solutions (Geels 2014). However, based on their characteristics, countries might start production with a different technological development level and compensate with market orientation.

The **second objective** is empirical and shifts the focus from outcomes (the degrees and types of catching up) to the underlying causes. Historically, governments have played an essential role in the catching-up process of developing countries. They protected the infant industries and provided capital to domestic firms to boost production while using an undervalued exchange rate to stimulate export. In other words, by mediating market forces, governments put domestic firms in a favorable position (Amsden 1992). The drivers that enabled catching-up in the first decades after World War II—capital accumulation and manufacturing base—changed towards technological capabilities in the 1980s-90s. Thus, the past's successful practices cannot be reused in the same manner but adapted to the time's context. Likewise, the emergence of international control and regulation over past tools—industrial policies—might have lowered the opportunity for other developing countries to catch up (Fagerberg and Godinho 2004). With the green transition, governments now use (green) industrial policies, such as localized and sector-targeted subsidies, policies favoring domestic over imported goods, and feed-in tariffs. Benefits for the environment and citizens rationalize these interventions, which at the same time provide a promising foundation for economic development (Wu, M. & Salzman 2014). Unlike latecomers' catching up in traditional sectors, renewables require institutional change, and therefore, the created opportunities are endogenized (Lema, Fu, and Rabellotti 2020). The so-called Green Windows of Opportunities (GWO) were studied in green energy generation industries (Binz et al. 2020; Dai, Haakonsson, and Oehler 2020; Hansen and Hansen 2020). Yet, there is a knowledge gap in opening GWO for renewable energy-efficiency sectors. The infrastructure—charging stations and a sufficient electrical grid—is an essential prerequisite for successful deployment in transport electrification. So, in parallel to developing the industry, the governments have to provide needed infrastructure. Against this background, the second objective of the thesis is to analyze how the government could create an opportunity for the green shift by simultaneously addressing production, demand, infrastructure, and innovation capabilities.

The **third objective** seeks deeper insights into a specific but central element of the dynamic interplay of causes in the latecomer development process. This is the element of technology transfer and collaboration, which has been shown to be very important across a range of green industries (Oehler 2022). The majority of the thesis focuses on China's EVs industry, particularly its development in the first six years after the start of production. The government played a proactive role with constant policy modification, designed for countries' unique characteristics (Howell et al. 2014). One of them is the ownership of the car manufacturers, which shapes their business model (Zhang, Liu, and Kokko 2019). The state-owned OEMs have strong support with an inflow of resources and thus use them less efficiently. By contrast, private firms need to acquire resources on their own. Consequently, private firms are more dependent on government support from the policies to build innovation capabilities. Nevertheless, the industry's progress and building capabilities heavily rely on government support (Wang et al. 2019). Several studies pointed out the importance of gaining innovation capabilities for catching up (Fu et al. 2011; Haakonsson, Kirkegaard, and Lema 2020; Hansen and Hansen 2020). Still, there is a lack of studies on implementing the acquired knowledge successfully. Since emerging country multinationals often fail to capture the knowledge (Amendolagine et al. 2018), filling the gap might also benefit the practitioners. Thus, the third objective is to analyze how a private automobile OEM built up innovation capabilities by acquiring a recognized western brand and successfully integrating the captured knowledge into new products.

The **fourth objective** is to expand the Chinese case study and discuss the relevance of Chinese experiences to other developing countries. As mentioned in the previous paragraphs, the regulated industrial policies made it more difficult for developing countries to catch up. Thus, its reincarnation as a green industrial policy should again enable faster development. Many of them achieved notable transformation by introducing green solutions, e.g., solar PV in India (Behuria 2020) and wind in Kenya (Gregersen 2020). However, not many manage to establish the industries. Apart from China, no other emerging countries could start the EVs sector, even though many have a functioning automobile industry and natural resources for the battery sector. The opening of GWOs in China raises the question of the possibility for other emerging countries to follow a similar path. Thus, the fourth objective is to analyze what hinders the development of the EV industry in emerging economies. The analysis of EV sector development in India, Brazil, and South Africa might show the shortcomings in each country. Nevertheless, all three countries have established the automobile industry and follow shared environmental goals. From the theoretical perspective, the analysis looks to what extent the GWO is a Chinese phenomenon and what countries' characteristics present the essential obstacles to its implementation.

Table 1: Research gaps and objectives

	Research gap	**Objective**
A	The catching-up trajectories and leadership changes are mainly measured with market indicators. A few studies measure technological catching up by counting patents or with patent citations. Both methods have critical shortcomings.	Develop an integrated market-technology framework for catch-up trajectories of latecomer countries. It will use technical indicators that measure patents' novelty and impact.
B	For emerging markets, China is the only country that managed to establish an EV sector. The government's support was critical for the development. The existing literature focused on specific policy segments. However, it is still missing an in-depth analysis of policy regimes and how they evolved.	To analyze how the government can create an opportunity for the green shift in energy-efficiency sectors by simultaneously addressing production, demand, infrastructure, and innovation capabilities.
C	When it comes to innovation capabilities for green sectors, the literature showed the importance of knowledge transfer and its absorption. There is a lack of positive case studies to show how to gain and efficiently implement the acquired knowledge.	To analyze how EMNE built up innovation capabilities with cross-border M&A and, together with the target firm, integrated the captured knowledge into new products.
D	The well-studied GWOs in China's sectors are tailored according to their unique characteristics. A research gap exists for other emerging markets, especially in the EV sector.	To explore if there are GWOs for transitioning to electric transportation in emerging economies.

1.6. RESEARCH FOCUS

This thesis investigates the development of the EV sector in China, mainly from a policy-maker perspective, and the role of knowledge and markets in this regard. The insights will be compared to the well-studied development of renewable energy sectors, which have many differences. Probably the most obvious is customer types. In electric generation sectors, projects are established by governments or big corporations, e.g., wind turbine farms, and the produced energy is used in national grids. In turn, the customers in energy efficiency sectors are typically private end-users, e.g., a buyer of electric vehicles. The green industrial policy gives more tools and freedom to governments to intervene in sectors' development. The analysis of several sectors in China revealed a strategy of simultaneously endogenizing different WOO. The so-called GWO is a series of government interventions that could, in parallel, endogenize various WOO (e.g., technology, institutions, demand, production) in combination with possible exogenous WOO.

Main RQ: What catch-up trajectory is observed in the EV sector in China, and what are the key determinants, in terms of industrial policy and sector development, of this relative catching-up success?

By addressing the main research question, the thesis seeks to understand the nature of the green opportunity window in energy efficiency sectors and examine which elements enable sectoral development and catching up. Answering this question thus requires that we expand our knowledge in several ways which connect, presented here in a summarized form, to the research gaps and objectives:

1. It is necessary to understand the specificity of the latecomer trajectory and catching up observed in the Chinese EV industry, including the extent to which (or not) and along which dimensions global leadership is changing and being disrupted in this sector
2. It is necessary to understand the specific characteristics of the GWO in this sector and whether it is driven mainly by technology, demand, institutional changes, or some combination of these aspects. This means that it is necessary to understand how policies affected technological and market development and whether there were feedback effects.
3. It is necessary to examine the critical underlying determinants in the process of latecomer development, including the role of the innovation system level and enterprises. Specifically, it is necessary to understand the process of technology acquisition, the capture of acquired knowledge, and its use in the operating processes.
4. It is necessary to explore how latecomer countries with different characteristics could set the strategy to endogenize GWO in an energy-efficiency sector such as the EV sector.

Table 2: Overview of articles

	Article A	Article B	Article C	Article D
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	Domestic deployment in the formative phase of the Chinese Electric Vehicles Sector: evolution of the policy regimes and windows of opportunity	From Transaction to Co-creation in Geely's Acquisition of Volvo Cars: Impact on Innovation Output and Market Performance	Transitioning to electric transportation in emerging economies: Are there green windows of opportunity?
Co-authors	Daniel S. Hain Roman Jurowetzki Lars Oehler		Dmitrij Slepniov Jun Jin	Rasmus Lema Tobias Wuttke
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 did the policy regime evolve in the initial stage of the EV sector in China? How did the policies affect technological and market development?	How can EMNEs transition from fragmented and transactional relationships with the acquired firm to integration and co-creation? How did the transaction influence the similarity between firms' patent portfolios and technological base? How did knowledge co-creation influence actors' market performance?	Are there green windows of opportunity for transitioning to electric transportation in Brazil, India and South Africa? What are the prospects for replicating the Chinese EV success story in these countries? How do the countries compare concerning green industrial policies as well as in their preconditions of the supply base and related industries?
Status	Published in Industrial and Corporate Change, Oxford University Press, doi: 10.1093/icc/dtaa021 (BFI: 2)	Published in Innovation and Development, doi: 10.1080/2157930X .2022.2053806 (BFI:1)	Paper submitted to Asian Journal of Technology Innovation, Revise & Resubmit (BFI:1)	Working paper. Article to be submitted to Technological Forecasting and Social Change, Elsevier (BFI: 2)

2. EMPIRICAL CONTEXT

2.1. ELECTRIC VEHICLES

Electric vehicles form a broad concept comprising several EV types and technologies. It can be distinguished between four classes: battery (BEVs), hybrid (PHEVs), range-extended (REEVs), and fuel-cell vehicles (FCEVs). This thesis defines EV in the narrow sense, including BEV and PHEV. The former is 100% electric vehicles powered only by batteries, and the latter are plug-in hybrid vehicles. "Plug-in" means a vehicle that needs to be plugged into a charging point to charge its battery and a hybrid that has a gasoline or diesel engine combined with an electric motor (Emadi 2014).

In 2008, when the first serial production of EVs started, there was no widespread interest among automakers (Masiero et al. 2016). In a few years, most leading automakers announced the start of development, yet with different timelines. The new powertrain type required new knowledge and expertise, which resulted in many newly established collaborations. The main problems were short-range, expensive batteries, uncompetitive prices, and lack of infrastructure. Disadvantages and slow deployment forced manufacturers to maintain production of ICE vehicles and, in parallel, work on electrification of their models. The emergence of EVs challenged the existing technology and forced automakers to adapt their business models and learning mechanisms (Aggeri, Elmquist, and Pohl 2009; Wolschendorf, Rzemien, and Gian 2010).

An essential factor in EV deployment is R&D inside the industry and scientific institutions. Apart from the policies, technological advancement decreased EV costs. Due to the battery improvement, the cost per kWh decreased from more than USD 900 in 2009 to below USD 300 in 2015. In the same period, battery energy density increased from 120 to 300 kw/L (OECD et al. 2017). Further market and technological development manage to lower the average lifetime ownership cost. As of 2020, the costs of EVs are lower than the costs of vehicles with internal combustion (Harto 2020). This is not only the case in developed (Lewis 2020) but also in emerging and developing countries (Ayetor et al. 2021; Hao et al. 2020).

Electric vehicles are studied in several scientific disciplines, ranging from technical, environmental, business, and social. In the last part of this section, this topic will be presented through business and economics' lenses, followed by a review of the development of EVs in China.

The bibliometric search on WOS (Clarivate 2021) for business and economics articles matching string ("electric vehicle*" OR "electric car*") gave 968 items. Although some date back to the 1970s, the publications started rapidly increasing after 2009. A similar production trend is observed for all scientific fields combined—28,214 published articles.

To review the main themes from the Business and Economics corpus, topic modeling was conducted using the Latent Dirichlet Allocation (LDA)[7] model. Following the method described by Syed & Spruit (2017), the topic coherence measurement calculated the optimal number of topics. As seen in table 6 and figure 1, each topic is associated with related terms that define it. The results show that articles in the Business and Economics fields are evenly distributed among five topics.

The first is related to the cost-effectiveness of different solutions, the second has to do with the environmental effect, the third centers on demand and adoption, the fourth is connected with infrastructure, and the fifth is about policies for market development. All five groups are of a relatively similar size (ranging between 17 and 21 percent), and some are closer to each other than others. Figure 1 shows distances between topics, and groups one (cost of solutions) and two (transport and pollution) are most isolated. The closest to each other are groups 4 (infrastructure) and 5 (government policies), while "consumers' adoption" stands between 1 and 4. This indicates that the technology adoption appeared together with the infrastructure and cost of the solutions. Table 6 contains the topics' most essential terms, the number of articles, and a sample title. The mapping of the literature used in the thesis shows that the majority of sources come from topics 3 & 5, nevertheless, each of the remaining consists of at least two cited sources.

[7] LDA is a three-level hierarchical Bayesian generative probabilistic model (Blei et al, 2003).

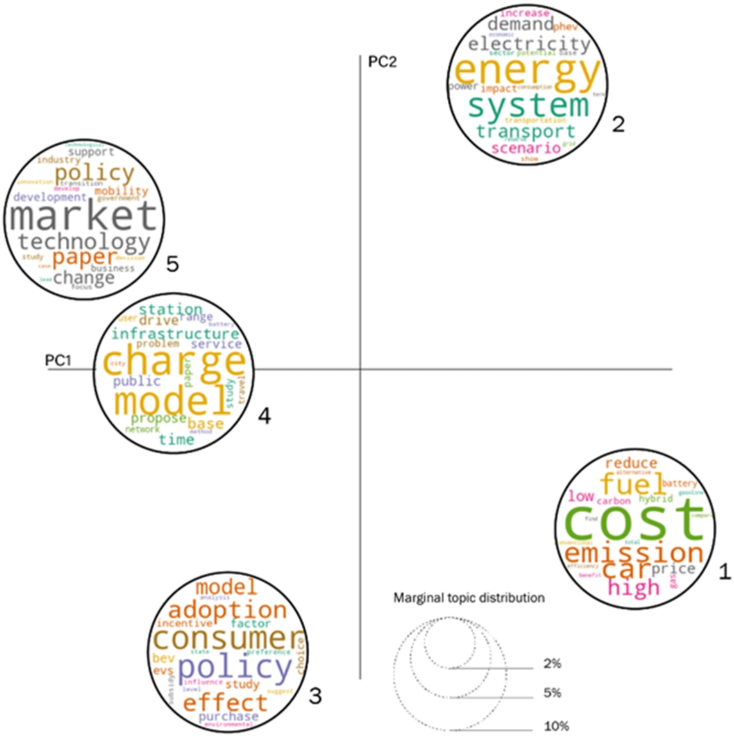

Figure 1: Intertopic Distance Map (via multidimensional scaling)

Table 3: Topics from LDA Model

Topic	Topic Terms	Number of articles	Sample Title
1	cost, battery, car, high, price, bev, reduce, hybrid, range, phev	166 (17%)	COMPARING RESALE PRICES AND TOTAL COST OF OWNERSHIP FOR GASOLINE, HYBRID AND DIESEL PASSENGER CARS AND TRUCKS
2	emission, energy, fuel, electricity, transport, scenario, demand, carbon, power, sector	204 (21%)	A COMPARISON OF ALTERNATIVE TECHNOLOGIES TO DE-CARBONIZE CANADA'S PASSENGER TRANSPORTATION SECTOR
3	consumer, adoption, model, purchase, effect, factor, evs, study, choice, preference	202 (21%)	PERSONAL VALUES, GREEN SELF-IDENTITY AND ELECTRIC CAR ADOPTION
4	charge, model, base, system, infrastructure, station, time, public, propose, service	189 (20%)	AN ELECTRIC-VEHICLE CORRIDOR MODEL IN A DENSE CITY WITH APPLICATIONS TO CHARGING LOCATION AND TRAFFIC MANAGEMENT
5	policy, market, technology, paper, government, development, analysis, support, measure, mobility	206 (21%)	INNOVATION FROM EMERGING MARKET FIRMS: WHAT HAPPENS WHEN MARKET AMBITIONS MEET TECHNOLOGY CHALLENGES?

2.2. THE ELECTRIC VEHICLE SECTOR IN CHINA

Three articles in the thesis are based on data from China. Therefore, this section briefly introduces its economy, automotive industry, and electric vehicle sector development. The fourth article looks at the possibility of opening GWO in other developing countries—namely Brazil, India, and South Africa. Hence, this section will end with a brief description of their common and unique characteristics and the state of the automotive industry.

As of 2020, China has the second-largest economy in the World. Despite the progress, China is still considered a developing country. Development status and 'Right to development' assigned lower targets in the Paris agreement to reduce emissions (Benoit and Tu 2020; Gupta 2016). However, the aggregate development figures should not be considered equally for each province. Comparison of urbanization & economic development (Chen et al. 2014), innovation in renewable energy technology (Bai et al. 2020), and EV adoption between provinces illustrate significant differences.

In the recent few decades, Chinese economic development was enabled by foreign capital, gradually opening the economy, a rapid increase in productivity, and reforms (Wu 2003). The State-Led institutional system, where government plays an active role with direct intervention in the economic ordering of society, makes it possible to stimulate the economy, and it enables the growth of state-owned firms (Fainshmidt et al. 2018). The rapid growth of the automobile industry in China is based on supplying increasing domestic demand. The large domestic market is one of the essential factors contributing to the economy's rapid growth, which accelerated after joining the World Trade Organization (Brandt and Thun 2010). The pattern is similar in many other industries.

The automobile industry started to develop with a reform program in 1978, based on the central state's pro-active industrial policy. The inadequate policies from the beginning were constantly modified, and after a few decades of local experimentation, they built up a vital industry (Chu 2011). Using the production data (OICA 2022), the compound annual growth rate (CAGR) between the years 1990 (509 thousand vehicles) and 2020 (25.2 million vehicles) was 13.89 %. The country's trade balance in 2020 was negative (US$6.9 billion), with 4.3 percent of produced vehicles exported (CAAM 2022).

The government planned to promote R&D and manufacturing and, with indigenous innovation, leapfrog towards leadership (State Council 2006). In 2006, the government carried out 'The National Medium and Long-Term Program for Science and Technology Development (2006–2020)'. The policy contained several priority areas—including Electric vehicles. Before this program, a few policies addressed the R&D for an alternative to fuel vehicles. The first policy to address manufacturing was introduced in 2009—'Plan on Shaping and Revitalizing the Auto Industry.' It had four general goals—technological upgrading, energy security, local pollution reduction, and lowering carbon emissions. More concrete production goals were 500 thousand EVs and a 5% EVs share of all vehicle sales by 2012 (Zheng et al. 2012).

In 2015, China overtook the USA in EV sales with a 37.9 percent global market share, which increased to 41.3 percent with the sale of 1.37 million EVs by 2020. The year 2020 seems to be the turning point for global EV sector development, with 43 percent of year-on-year (y/y) growth. Unlike the years before, China was not the main engine for the growth, but Europe with 138 percent y/y growth. Finally, the promising development in a few markets—Europe, China, USA—accounts for more than 94 percent of global EV sales (Table 4).

The thesis' primary focus is on the Chinese deployment of the EV sector, and this is from the start of production in 2009 until they became market leaders by the quantity of produced EVs in 2015/16. However, due to the article's research design, Article A covers the period from 2005 to 2017. Likewise, since Article D investigates the opportunity for other emerging countries to catch up in EVs, the time frame is ten years, ending with the beginning of the year 2021.

Table 4: New Electric Vehicle sales by country

	EV sales in thousands (Global market share)			
	2010	2015	2019	2020
China	1.43 (17.4%)	207.38 (37.9%)	1060.30 (50.5%)	1337.00 (41.3%)
USA	1.47 (17.9%)	113.87 (20.8%)	326.64 (15.5%)	328.00 (10.1%)
Europe	2.36 (28.7%)	189.16 (34.6%)	564.20 (26.8%)	1395.00 (43.1%)
India	0.45 (5.5%)	0.45 (0.1%)	2.09 (0.1%)	1.60 (0.05%)
South Africa	0	0.24 (0.0%)	0.23 (0.0%)	0.17 (0.0%)
Brazil	0	0.09 (0.0%)	1.91 (0.1%)	2.00 (0.07%)
Japan	2.44 (29.7%)	24.65 (4.5%)	38.90 (1.9%)	31.00 (1.0%)
South Korea	0.06 (0.7%)	3.30 (0.6%)	31.86 (1.5%)	45.62 (1.5%)
Others	0.03 (0.4%)	7.45 (1.4%)	75.54 (3.6%)	149.00 (4.6%)
Total	8.21	546.59	2101.68	3240.00

Source: IEA (2021); EV-Volumes (2019)

In 2009, China started mass production of EVs to reduce urban air pollution and upgrade the automobile industry. In the first few years, neither goal was achieved (Altenburg, Feng, and Shen 2017). Although the government actively supported the sector with supply policies, they neglected the demand side (Kennedy 2018). In addition, at a time when it was still a nascent solution, EV required high R&D investments and specific knowledge that China did not possess (D. S. Hain et al. 2020). Policies are introduced by central and local governments, which in some cases led to local protectionism. For example, Shenzhen was almost exclusively buying from BYD or Beijing from FOTON. In addition, protectionist policies at the national level—import tariffs—made it difficult for foreign companies to import, consequently limiting the import of advanced knowledge (Howell et al. 2014; Li et al. 2018). A high amount of given subsidies (RMB 66.8 billion) and low output (less than 300 thousand EVs on-road) at the end of 2015, mainly due to high prices compared to traditional vehicles, did not present a success (Kennedy 2018). Moreover, after a decade of high investments and various modes of support that were essential for the sector's growth, the sector cannot progress without them. Several studies indicated that their removal would critically impact further development (Kong et al. 2020; Wang et al. 2019).

Scholars gave a significant focus on studying the demand side, more precisely, what influences consumers' decision on whether to purchase EVs or not. Interestingly, purchase incentives have no significant effect on the decision, while general knowledge about EV's usefulness has positive, and knowledge related to potential risk has adverse effects. The latter also had the most substantial effect (Wang et al. 2018), however, the social-psychological factors in decision-making vary between the cities (Yang and Chen 2021). The government used various policies to stimulate citizens to buy EVs—convenience, financial, information provision—and the policies improving the convenience had the most potent effect. These include policies on improving charging infrastructure, which minimized one of the solution's most significant weaknesses—range (Wang, Li, and Zhao 2017).

Finally, China's path to developing the EV sector was adapted to its specific characteristics; therefore, it differs from the paths of developed countries. Due to lower technological capabilities, the first vehicles were low-tech solutions, leading to a niche product of cheap EVs with lead-acid batteries. On the demand side, people with lower purchasing power accepted the solution (Altenburg et al., 2016).

In respect of Chinese EV sector literature, the thesis's main contribution is to the understanding of the development trajectory from a market and technology perspective. The in-depth analysis of the policies and their evolution through the industrial policy lenses will supplement several existing papers which mainly focused on the long-term effects on development or cost-benefit analysis.

2.3. OTHER EMERGING ECONOMIES

Except for China, the electrification of transport is still not in the domain of emerging countries (Table 4). Poor charging infrastructure, relatively higher prices, and lack of government incentives are the most common obstacles to slower EV market development. On the other hand, dense cities and intensive industrialization caused high pollution levels in many developing countries. Thus, EVs could help to reduce the adverse effects (Rajper and Albrecht 2020).

The automotive industry in India is the 4th largest in the World. Passenger cars account for only 13% of all vehicles, and the vast majority are two and three-wheelers (more than 80%). The industry—including the auto parts sector—is one of the country's most significant industries and the main manufacturing export. Hence, it has strong government support and clear goals for the future. Part of the support covers EVs, which until 2019, still have not made significant progress (Table 4-5; DPIIT, 2020).

Brazil is among the World's top ten automobile manufacturers and has the sixth-largest automobile market. The latter attracts many foreign direct investments (FDI) and OEM firms. Like in India, the number of EVs is still considerably low—less than 0.1% in all vehicles—, and the government introduced policies for EV development. However, Brazil has strong support for producing biofuel for transportation, with the first policies dating back to the 1980s. So, a bit less progressive EV development actions could be explained with long-term support and high investments into the biofuel industry (Table 5; Consoni et al., 2019).

South Africa is the biggest automobile manufacturer in Africa, and the industry accounts for more than 25% of its manufacturing output and 15.5% of its export. Two-thirds of the export goes to Europe and the USA, making South Africa highly dependent on these markets' trends and dynamics. The government supports the industry, however, there are relatively fewer incentives for developing the EV sector (NAAMSA, 2022).

Table 5: Economy, demography, and automotive industry indicators

	China	India	Brazil	South Africa
Population (in thousands)	1 415 046	1 354 052	208 495	57 726
GDP/c in (2019, USD)	10 216	2 099	8 717	6 001
Vehicle production[8] (2019, in thousands)	25 721	2 945	4 516	632
Automotive sector import (2019, thousand USD)	47 057 996	221 712	3 320 226	3 939 385
Automotive sector export	8 637 814	7 003 036	3 781 712	6 713 124
Trade Balance	-38 420 182	6 781 324	461 486	2 773 739
Share in GDP	10%	7.1%	5.5%	6.4%

Sources: World Bank (2021), OECD (2022), OICA (2022), ITC Trademap (2021)

[8] Figures include passenger cars, light commercial vehicles, minibuses, trucks, buses, and coaches

3. THEORETICAL FRAMEWORK

This section elaborates on the broader theoretical and conceptual view of the thesis. The first part presents theoretical concepts—systems of innovation, catching up, leapfrogging, WOO, government interventions, and absorptive capacity—and the second is a brief overview of the literature on the EV sector.

The central position of this volume is based on innovation studies. Their foundations originate from Schumpeter, who objected to the neoclassical economic view in his understanding of the economy and studied the 'source of energy'—innovation—that continually disrupts the equilibrium. In his early work, the innovation happened on the individual level—entrepreneurs—and later, the focus shifted to larger firms. In the decades after the 2nd World War, scholars focused on determining R&D's success or failure and later systems that enable innovation (Fagerberg and Verspagen 2009). The development of EVs as a new technological solution presents a new cycle in the automotive industry. The solution's effects are not fixed but rather evolve with constant incremental innovations that influence the future of transportation. Therefore, the evolutionary perspective is critical in studying the dynamics of the phenomenon.

3.1. SYSTEMS OF INNOVATION

Economic and societal development is based on constantly implementing new ideas into reality, i.e., innovation. Rather than a linear process, the innovation process is characterized by the interaction between actors and share of information. The determinants that enable these processes are combined in Systems of innovation, "*all important economic, social, political, organizational, institutional, and other factors that influence the development, diffusion, and use of innovation*" (Edquist 2009:182). The system contains learning processes to accumulate knowledge and reuse it in an ongoing problem-solving environment. Finally, SIs can be applied on several levels, e.g., sector, technology, and national (OECD and Eurostat 2018). To adequately answer the thesis's research questions, all three mentioned concepts were used.

3.1.1. NATIONAL INNOVATION SYSTEM

In the late 1980s, a new conceptual framework, which put innovation as a primary sought outcome, emerged. It was produced by the interaction of various components in the system—firms, universities, government, and the environment—, i.e., National

Innovation System (NSI). The concept's initial scholars were Freeman, Lundvall, and Nelson, with slightly different views. Nevertheless, they all emphasized the national context in which the interactions between actors enable firms' innovation activities (Edquist 1997; Rakas 2020). In this thesis, NSI follows Lundvall's definition, a broader approach, where the system's setup affects the ongoing innovation processes—learning, searching, and exploring—, resulting in new products, techniques, types of organization, or markets (Lundvall 1992). To align the approach with the thesis's level of analysis, I also adopt the Sectoral Innovation System concept (SSI), which considers the unique characteristics of the sectors, and the Technological Innovation System (TSI), which considers the development and diffusion of a specific technology, in some cases over different sectors.

3.1.2. SECTORAL SYSTEM OF INNOVATION

Sectoral System of Innovation (SSI) emerged as a combination of Industrial economics and economics of innovation. However, concerning the first, it looks at the sector from a dynamic perspective and not as a static form with homogeneous knowledge and demand (Malerba and Mani 2009). The SSI approach is primarily based on evolutionary theory and puts innovation processes and dynamics at the center of the analysis (Malerba and Nelson 2011), defined as "*a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production, and sale of those products*" (Malerba 2002:250). In this view, a sector is a set of activities with a related group of products, demand, and basic knowledge. In the form of learning and capabilities, knowledge and technology play an essential role in the sector's dynamics and innovation building. The other two building blocks are actors and networks, and institutions.

3.1.3. TECHNOLOGICAL SYSTEM OF INNOVATION

From the technology perspective, SSI combines all the different technologies that are present in a specific sector. Contrary, the Technological system of innovation focuses on a specific technology that can be used in different sectors (Schrempf, Kaplan, and Schroeder 2013). The latter's origin goes back to 1991 when Carlsson and Stankiewicz elaborated on central features of TSI: economic competencies, clusters, and networks, institutions. In addition, instead of the flow of goods and services, the system is defined by technological knowledge and competencies (Carlsson and Stankiewicz 1991). At first, the TSI framework focused mainly on technology development, later scholars also focused on creating a market for specific technologies—namely, market-related substructures for different end-user markets (Dewald and Truffer 2011).

Although NSI, SSI, and TSI share the underlying understanding of innovation, their application gives a different understanding of the processes. The main difference is that while NSI focuses on innovation capabilities across national boundaries, SSI and TSI only consider innovation and technological change inside a sector or specific technology (Freeman 1987; Malerba 2005; Mu and Fan 2011; Nelson 1993). Therefore, when latecomer countries decide on strategies in a specific sector, they have to account for the sector and technology's unique characteristics and their innovation capabilities on the national level (Malerba and Nelson 2011). Explicitly, SSI acknowledges the boundaries of the sector and its unique characteristics, influencing the interaction between agents, learning processes, and technological regimes (Breschi, Malerba, and Orsenigo 2000; Pavitt 1984). In addition, SSI also identifies the factors that influence firms' diverse performance in the sector or sectors between different countries. In the latter, variations are also caused due to different institutional settings on the national levels (Cefis and Orsenigo 2001). Finally, the TSI framework follows specific technology development and how it can be diffused among different end-user segments. Despite a sound innovation system, the firms' limitation in developing and implementing technology depends on firms' competencies, which can broaden via different networks and clusters (Carlsson and Stankiewicz 1991; Dewald and Truffer 2011).

3.2. THE CATCHING-UP CONCEPT

In a nutshell, the catching-up hypothesis suggests that countries dealing with backwardness towards leading countries can have faster growth and, consequently, catch up with the frontier. By analyzing historical data, Abramovitz (1986) described four characteristics: (1) technological opportunity that allows growth also spurs capital, (2) productivity growth positively affects aggregate output, (3) catching-up brings modernization of both embodied and disembodied technology, and (4) a high number of redundant workers in agriculture can increase productivity by improving the allocation of labor. In neo-classical literature, the reducing productivity gap is also referred to as convergence, however, in that case, it deals with decreasing the productivity and income differences in the World as a whole. On the other hand, catching-up looks at single countries or firms' development and tries to explain why some tend to reduce the gap and some do not (Fagerberg and Godinho 2004). In the former, knowledge from technological change freely moves across borders and reaches countries with low technological knowledge, and it does not play an essential role in explaining the phenomenon. Contrary, in catching up from the Innovation Systems perspective, knowledge—learning, creation, transfer—is a central element of development (Lundvall 2010; Verspagen 1991). The application of the catching-up approach allows moving the analysis from macro to mezzo and micro levels of the analysis. In that case, the SSI is the main analytical framework, however, all (NSI, SSI, and TSI) provide complementary analytical insights.

The successful catching-up on the sectoral level results in market share changes or even leadership changes (Lee and Ki 2017; Shin 2013). In stable and established industries, leaders can control the market with incremental technology innovation and consequently leave less space for latecomers to catch up. However, due to the evolutionary nature of society, industries have beginnings and once evolve into a new form. In these so-called catching-up cycles, the change in the constellation of different factors allows latecomers to disrupt the market (Morrison and Rabellotti 2017). The unique sectors' characteristics and actors' strategies can produce different outcomes, i.e., a country that catches up in some sectors could fail in others (Lee and Lim 2001; Lee and Malerba 2017).

The sectoral catching-up studies industries with frequent technological changes, e.g., mobile phones (Giachetti and Marchi 2017; Malerba and Nelson 2011) and old or long-term evolution industry analyses, such as the wine industry (Morrison and Rabellotti 2017), steel and iron (Shin 2013). In some sectors, the catching-up is more manageable than in others, i.e., sectors with explicit and easily embodied knowledge regimes give better opportunities than sectors with a higher level of tacit knowledge, e.g., the automobile industry (Jung and Lee 2010).

In this thesis, catching up is understood as developing a specific sector to reduce the market and technological gap, where knowledge is one of the foundations for success.

3.3. LEAPFROGGING[9] AND WINDOWS OF OPPORTUNITIES

While those economies catching up need to follow the established path, but faster than forerunners, some create their development paths differently from latecomers. In that way, they can reduce the gap between them and the leaders or jump ahead in terms of significant technological changes or paradigm shifts (Perez and Soete 1988; Soete 1985). From a more dynamic perspective, Lee (2019) describes catching up by following the path of the forerunners as paradoxical. In an ever-changing society, the target is always moving. Thus, the latecomers have to make detours in the same way as the archer needs to adapt the angle when shooting at a moving target. This does not mean latecomers should not imitate and learn from others, but at a certain point, they

[9] Academics use the term leapfrogging with association to renewable sectors in two different ways. Some see it as skipping the stage of using traditional solutions (environmentally unfriendly) and start with green solutions, e.g., renewable energy in places without good electricity distribution (Levin and Thomas 2016; Schäfer, Hughes, and Richards 2014). On the contrary, some scholars use leapfrogging as skipping stages in the technological development of renewable solutions, e.g., catching up in the Chinese Wind turbine sector (Dai et al. 2020; Lewis 2007).

should change the strategy. Wang and Kimble (2012) distinguish three types of leapfrogging: *Stage-skipping*, where latecomers skip the stage taken by forerunners and go straight to the more advanced but existing stage. *Path-creating*, where latecomers take a different development path between the stages, and *Paradigm-changing leapfrog,* where latecomers take a big jump (disruptive innovation) into an unexisting stage.

In general, leapfrogging is possible when latecomers can use the favorable circumstances that emerge in the sector. Perez and Soete (1988) defined these as WOO—an opportunity for latecomers that emerge at a time of techno-economic paradigm shift. If latecomers react faster than the incumbent firms, they can reduce the gap. By analyzing catching up in different sectors, Lee and Malerba (2017) widened WOO from technological to building blocks in SSI, i.e., technology, demand, and institution. Scholars identified all three types of WOO in several case studies, and latecomers mainly used the exogenous windows (Table 6; Yap & Truffer 2018).

The emergence of WOO is not an opportunity limited to latecomers but requires a response from all actors. Suppose forerunners do not react to new technological WOO and stick with the technology they use. Consequently, they can fall into the "incumbents trap," e.g., the US did not adopt newer technology in the iron industry in the second part of the 20th century (Yonekura 1995). On the other side, missed WOO for latecomers may increase the gap (Shin 2017). Finally, in the dynamic perspective of SSI, the WOO has to be supported by other circumstances for successful catching-up. In Table 5, the examples are sorted by the initial WOO; however, it is hard to neglect other conditions that enabled catching up.

3.3.1. GREEN WINDOWS OF OPPORTUNITIES

The increasing effect of climate change and the pressure from various climate agreements forced governments to act towards green transformation. Latecomer countries, whose functions in the global value chain are predominantly exploiting natural resources and manufacturing, are more susceptible to pollution. This can be decreased with the improvement of the global value chain (GVC) position and especially the shift towards technology-intensive manufacturing (Sun et al. 2019; Ye et al. 2020). Commitments under environmental agreements give governments justifications to play a more active role in forming and promoting green industries. China, in particular, manages to establish firm conditions in many renewable sectors by stimulating manufacturing, creating demand, and favoring domestic manufacturers (Lema et al. 2020). Yap and Truffer (2019:1031) described endogenized opportunities in renewable sectors as: "*a process by which latecomers proactively translate globally foreseeable opportunities or threats into a specific selection environment that privileges certain technological trajectories.*" Compared

Table 6: Unpacking the dimensions of WOOs

	Technology	**Market (Demand)**	**Institution**
Definition[10]	"… an opportunity provided by a new technological development in an industry."	"… an opportunity emerged due to a new type of demand both in local and foreign markets."	"… an opportunity emerged from changes in public intervention in the industry or changes in broad institutional conditions (including certain macro-variables)."
Global	- Biotechnology and Nanotechnology in China, India, and Brazil (Niosi and Reid 2007)	- ICT in India due to the Y2K and dotcom boom (Lee, Park, and Krishnan 2014)	- new wine producers emerged after the institutional change in the EU (Morrison and Rabellotti 2017)
Domestic	- In the semiconductor industry, newly developed technology allowed the US to forge ahead in 1975 (Shin 2017)	- China managed to become the biggest producer of the Electric Two-Wheelers solely by meeting domestic demand (Humphrey et al. 2018)	- change in patent law enabled the development of the pharmaceutical industry in India (Guennif and Ramani 2012)

Source: own creation based on sources cited in the text

with the conventional catching-up where a latecomer has to respond when the WOO occurred, governments here play a more active role in creating time-bounded conditions that allow interaction between institutions, markets, and technology to take place (Lema et al. 2020).

Likewise, the conventional catching up, GWO also gives a combination of different windows, yet the endogenized windows are the dominant factor for the success in GWO. The sectors' unique characteristics play an essential role in how the government's policies endogenized GWO. Significantly, the formative sectors (e.g., concentrated solar power) pose higher uncertainties for their future, giving better opportunities for latecomer countries to catch up (Gosens, Gilmanova, and Lilliestam 2021).

[10] Definitions from Shin (2017:406) based on Lee and Malerba (Lee and Malerba 2017)

3.3.2. GWO IN RENEWABLE ENERGY GENERATION SECTORS

In the Special issue on GWO edited by Lema, Fu, and Rabellotti, scholars analyzed the development of renewable sectors in China, i.e., Dai et al., (2020) in Wind; Hansen & Hansen, (2020) in Biomass; Zhou et al., (2020) in Hydro; Binz et al., (2020) in Solar PV; Gosens et al., (2020) in CSP. Except for Solar PV, the development started by supplying to domestic and later tried to enter the global market actively. The government endogenized institutional WOO in all five cases to create a domestic market. Furthermore, in each case, a mix of different WOOs enabled sectors' development together. The government imposed the renewable energy law in 2006, including grid connection, purchase policy, and feed-in tariff system. In practice, the grid operators have to make an agreement with renewable electricity generators, connect them to the grid, and purchase all generated electricity. Accounting for an additional fixed amount for each kilowatt-hour of electricity produced, the law gave a firm condition for sectors to grow (Schuman and Lin 2012). In that way, both public and private projects had a low risk for selling potential products and did not compete with the existing non-renewable energy sources.

The determinant of success for a specific solution was not if they would be able to sell generated electricity but rather if the technological advancement was sufficient to cover the investment. Despite good institutional support, it was crucial that firms accumulated specialized know-how and created networks. Furthermore, compared to "world-class" technology, the state of technology is the main determinant in catching-up trajectories (Lema et al. 2020).

3.4. GOVERNMENT INTERVENTIONS

The historical reason for constituting a state was to provide the safety of people and property. However, the degree and justification of state interventions have been debated for centuries. While the utilitarians would approve the interventions only when the society or free-market—laissez-faire—would not be able to provide the optimal outcome, the Marxists defend the constant interventions by the state. In that way, regulations would minimize the differences between classes caused by capitalism or the free market (Biersteker 1990). In some latecomer countries, government interventions enabled economic and/or technological catching up, e.g., South Korea and Japan (Abramovitz 1986; Gerschenkron 1962). These industrial policies have firm theoretical support, however, the results in practice showed various outcomes. Industrial policies should address market failures by containing embeddedness and a carrots-and-sticks approach and ensuring accountability (Rodrik 2009).

In contrast, important international institutions (IMF, World Bank) and US Congress proposed a set of free-market policies in 1989. The so-called "Washington Consensus" was based on the neoclassical economic ideas about the "invisible hand," economic actors' rationality, and minimalistic governments' intervention. It aimed to help developing countries converge with the developed World (Lopes 2012). Since its beginning, the consensus was criticized by several economists, who warned that it leads to recession and that developing countries should mimic the successful Asian model instead of the USA (Krugman 1995; Naím 2000; Stiglitz and Schoenfelder 2003).

3.4.1. INTERVENTIONS FOR GREEN TRANSFORMATION

The debate on the appropriateness of governments' active interaction with the market intensified due to the financial crises in 2008 (Rodrik 2009; Stiglitz and Yifu 2013; Wade 2010) and climate change mitigation (Altenburg and Pegels 2012; Rodrik 2014). The latter, so-called Green industrial policies, mainly rely on different rents for favoring domestic firms (Schmitz, Johnson, and Altenburg 2015). Wu & Salzman (2014) divided elements of Green industrial policies into sector-targeted subsidies, conditional local-content subsidies, and export restrictions of critical materials. Strong theoretical justification and positive effect on the environment shifted the debate from whether governments should intervene to making intervention successful. Finally, it is better to have a subsidy war, promoting R&D development and production, than a tariff war, which tries to increase competitiveness by harming others (Rodrik 2014).

According to Erdmann et al. (2007), the optimal scenario for implementing sustainable innovation is when it solves the sustainability problem with lesser effort and costs. The political intervention at the wrong time increases the risk of failure, e.g., the outcome of the solution compared to the traditional is too low, or the implementation is too costly compared to the created benefits. The ‘time strategy’—evolutionary policy approach—deals with different responses to techno-economic WOO by looking at the status of the old technology compared to the new alternatives. Following this logic, Nill & Kemp (2009) developed a techno-economic dynamics and policy objectives taxonomy. When there are promising alternative solutions but not yet competitive, governments can start preparing for potential WOO. If pressure for the change still fails to result in a competitive solution, the government has to create (endogenous) WOO, and finally, when there is at least one competitive solution, the government could use (exogenous) WOO. The potential risk for WOO creation due to the pressure is that the introduction of non-competitive solutions could be costly compared to the benefits (Erdmann et al. 2007).

3.5. ABSORPTIVE CAPACITY AND FORMS OF KNOWLEDGE

The SI presents the environment in which firms can innovate and develop, yet not every firm equally uses the potential. The critical factor lies in firms' absorptive capacity (AC), defined by Cohen & Levinthal (1989) as a firm's capability to recognize, assimilate and commercialize the value of external knowledge, e.g., collaboration with other actors, exploitation of external R&D. Zahra & George (2002) further developed the AC concept into a process—dynamic capability—with four types of knowledge absorption: acquisition, assimilation, transformation, and exploitation. The quality of these processes determines how much of the potential AC a firm realizes.

The method of how firms absorb knowledge—learning—depends on its form. One—codified—is scientific and technological knowledge, e.g., patents, technical documentation, and recipes. Firms can learn it using Science, Technology, and Innovation mode (STI), which is easily transformable. The second form of knowledge—tacit—is know-how, and firms learn it with the Doing, Using, and Interacting mode (DUI), e.g., skills and collaborative practices. The tacit knowledge is often collective and kept between workers inside the firm. Thus, firms can learn it with external collaboration or M&A (Lundvall and Johnson 2016).

4. METHODOLOGICAL CONSIDERATIONS

This section discusses methodological considerations as to how the thesis was framed and carried out. It seeks to capture complex and dynamic phenomena with an established methodological approach that can be used to answer the overall research question. The thesis, therefore, breaks the overall research problem down into different elements which have been addressed with the use of different methods. Many aspects of the methodology are discussed further in the individual papers, but this section brings the elements together and provides an overview.

The section, therefore, begins with the overall positions adopted concerning key aspects of the philosophy of science—ontology, epistemology, axiology—followed by the thesis's research design and strategy, data collection, and data analysis. The thesis uses a pragmatic research philosophy, where methods are not unified and less critical than the questions asked. Instead of mixing different worldviews[11], pragmatism works like an 'umbrella' over the study (Creswell and Clark 2017), covering different realities. Remarkably, between mutually exclusive views—interpretivism and positivism—the researcher might recognize that no single point of view can sufficiently explain the studied phenomenon with different realities (Saunders, Lewis, and Thornhill 2019). Although the 'umbrella' allows covering a mix of elements that suits the research questions, they have to be adequately presented by the researcher.

The worldview consists of the view on reality (ontology), the relationship between the researcher and the studied phenomenon (epistemology), the role of values (axiology), and the methodology. In this thesis, the primary view on reality is objective, however, in several cases, data had to be interpreted by the author. Thus, the distance between the researcher and the study changed among articles.

The development of the EV sector in an emerging economy is a complex social phenomenon and is influenced by many factors. Thus, its in-depth understanding requires a more flexible research design. Mixed method research allows a researcher to mix or combine qualitative and quantitative techniques, methods, and concepts in the same study and be closer to what researchers actually use (Johnson and Onwuegbuzie 2004; Onwuegbuzie and Leech 2015). This thesis emphasizes the complementarity of mixed-methods research, primarily to gain completeness and

[11] A basic set of beliefs that guides the research (Guba 1990)

explanation. The first refers to the researcher's ambition to present the phenomenon comprehensively, and the explanation refers to using one method to clarify the results gained from the other method (Bryman 2006). For example, the findings from article A suggest that China entered the EV market with low technological capabilities, which did not change in the first years of deployment. To understand the reasons, article B looks at government policies and how they address knowledge development. Similarly, in article C, interviewees explained that EMNE successfully captured the knowledge from M&A and learned innovation processes. Their answers were later tested with a quantitative technique—cosine similarity and technological base of patent portfolios.

4.1. RESEARCH STRATEGY AND DESIGN

The thesis consists of inter-sector, cross-sector, and cross-national analyses to fully answer the proposed research questions and get a comprehensive overview of EV sector development in China. Although the main interest is to understand how developing countries can establish and promote the EV industry, each paper has a different case-study design (Table 7).

Table 7: Overview of the research design

	Ontology	**Epistemology**	**Axiology**	**Method**
Thesis	Multiple ontologies	The distance varies regarding the questions	Both biased and unbiased perspectives	Mixed-Methods
Article A	Objective	Objectively collected data	Unbiased perspective	Quantitative methods
Article B	Objective	Objectively collected data	Unbiased perspective	Quantitative methods
Article C	Multiple ontologies;	Objectively and subjectively collected data	Both biased and unbiased perspectives	Quantitative & Qualitative methods
Article D	Objective	Objectively collected data	Unbiased perspective	Quantitative methods

Source: Author following Creswell & Clark (2017, Table 2.5)

4.2. CASE STUDY

A case study research can explain the phenomenon in its real-life context, resulting in a detailed and empirical description (Eisenhardt 1989; Ridder, Hoon, and McCandless Baluch 2014), especially when there is an interaction between the studied phenomenon and its context (Dubois and Gadde 2002), or the boundaries between both are not entirely evident (Yin 2018). Case selection essentially influences the outcome of a study, thus, the reasoning for the selection needs to be considered in the result interpretation. Researchers construct a case study strategy based on the research questions, data availability, and a degree of focus on the case. It can follow exploratory, explanatory, descriptive, or comparative design (Bartlett and Vavrus 2017; Yin 2018).

Looking at the thesis's overall design, the selection of Chinese development of the EV sector is an extreme case, providing richer information as "*they activate more actors and more basic mechanisms in the situation studied*" (Flyvbjerg 2006:229). Their EV deployment was at unprecedented speed and scale, and the case may thus provide more substantial evidence.

The method used in article A allows the comparative design between two different renewable sectors—EV and Wind turbine—and three countries, i.e., China, Japan, and South Korea. The selection criteria for the type of technology were similarity (both being the prominent solution in green transformation (Altenburg, Schamp, and Chaudhary 2016; IEA 2021), and differences (one generates electricity and one uses it efficiently). The country selection was based on the proximity, market regimes, and stages of industrial development.

Article B has an in-depth single case study design, attempting to understand the government’s interventions in sector development. It follows the central thesis’s case study design and analyses the phenomenon on the macro level.

Similarly, article C has a single case study, yet the unit of analysis is the M&A of a Western car brand by a Chinese private firm. It is an extreme case selection, as Geely's acquisition of Volvo Cars was, along with Tata's acquisition of Rover, the most significant cross-border M&A by EMNE in the automobile industry.

Finally, the fourth paper follows a comparative research design and analyzes the development of the EV sector in three developing countries, i.e., Brazil, India, and South Africa. The selected developing countries have established the automobile industry and could have the opportunity to, in some way, follow the Chinese path. The aim is to review the existing situation in each case and explore the potential development.

4.3. QUANTITATIVE RESEARCH

In this pragmatic research design, the majority of the thesis is based on quantitative research. The following subsections provide information on the data and methods used in each article.

4.3.1. DATA

The main data used were patents, market figures, and policies. In article A, the patent data were retrieved from European Patent Office's (EPO) worldwide database PATSTAT[12]. It consists of bibliometric and legal event patent data from more than a hundred patent offices. The database had 48 million records where English language abstracts were available at the time of patent collection. After the filtering process, the final corpus had around 12 million patent documents. In addition, the analysis of article A also uses industry figures from different organizations[13].

Primary data for article B were retrieved from the China Association of Automobile Manufacturers (CAAM 2022) and consists of all policies and government interventions in the EV sector in China. All documents were in the Chinese language and were before the analysis translated into English by using an application programming interface for two online translation tools[14].

The quantitative part of article C uses patent data retrieved from Lens (2022), an aggregator of academic and patent metadata, which maps and analyzes global innovation knowledge. The main corpus consists of 790 and 710 patents entries by Geely and Volvo, respectively.

The data for article D consists of policies collected from governments' websites and reports, market data from industry reports (IEA 2021; ITC 2021), patent and academic data (LENS 2022), and different news articles.

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[12] PATSTAT is available at https://www.epo.org/patstat

[13] Different reports from International Energy Agency (IEA), and The International Renewable Energy Agency (IRENA)

[14] Google Translate at https://translate.google.com/ & Baidu Translate at https://fanyi.baidu.com/

4.3.2. METHODS

Natural language processing and vector space modeling

Broadly speaking, natural language processing (NLP) is a research field that tries to develop tools and techniques for computer systems, which mimic human understanding and use of language. The complexity of the goal requires interdisciplinary collaboration from various fields, e,g., computer and information science, linguistics, AI, and psychology (Chowdhury 2003). In the social science field, NLP can be used to process large volumes of text data and, with less effort, gain an in-depth understanding of qualitative analysis (e.g., Crowston, Allen, and Heckman 2012). Moreover, the extracted data can be further used as a new variable in quantitative analysis (D. Hain et al. 2020). In article A, NLP was used to analyze patents' abstracts with the Word2Vec method, which learns meaning from the context surrounding the term and forms a vector. After creating one vector for each patent, the Annoy method (Bernhardsson 2019) positioned vectors in vector space. This nuanced method allows identifying novelty levels for each patent by using interrelatedness and omitting the drawback of using explicit links, i.e., forward and backward citations.

Policy triangle analysis

With policy analysis, a researcher can understand how and why governments implement a specific policy, identify the strategy, or measure the effect. According to Browne et al. (2019), there are three main orientations; Traditional looks for the best policy solution for a specific problem, Mainstream focuses on the relationship between actors and policymaking; and Interpretive, which investigates how policy reflects a problem's social construct. The **policy triangle method**—the mainstream approach—uses triangulation between policy context, content, and actors addressed by the policy. Walt & Gilson (1994) used the policy triangle method to analyze health policies in different countries. The analysis showed that policy analysis should not focus only on the technical feature of policy but also on the system's context, i.e., the same policy gives various outcomes in different contexts. The policy triangle method was used in article B to analyze the government's policy interventions in establishing the EV sector in China. By combining policies, the sector's context over time, and desired goals, the results provide an integrated account of policy development.

Vector Similarity

Cosine similarity is a metric that calculates the similarity between two sets of data represented as a vector. Technically, it finds the angle between them by calculating the inner product of vectors divided by the product of vectors' lengths. In article C, firms' patent portfolios were divided into two periods. Looking at IPC classes, the similarity of portfolios in the second compared to the first period presented, to what extent firms learned from each other after the M&A. The analysis was supported by the Jaccard coefficient, which also calculates the similarity between two vectors. However, instead of using the frequency of each element, it uses the binary values, i.e., instead of counting how many times a specific IPC appeared, it looks at whether it was present in the portfolio. Although this method sufficiently illustrates the similarity between patent portfolios, it does not measure the quality of the portfolios and the size of technological capacities.

4.4. QUALITATIVE RESEARCH

The innovation study field has two dominant lines of research; systems and ethnographies of innovation. The system of innovation approach mainly looks for indicators of newness (e.g., patents, R&D) and ethnographic focus on analyzing the innovation process more directly, observing the prerequisite-ridden aspects of innovation (Engelhardt 2015). The dichotomy between approaches creates a lack of "*balance between adequate abstraction from and focus on uniqueness in processing newness*" (p.11). Innovation is an ongoing process integrated into all aspects of society, becoming a panacea for every socio-economic problem (Windeler 2017), and composed of institutions, regulations, and actors. The so-called reflexive innovation is the interplay of practices, orientations, and processes between them, going beyond traditional R&D and scientific centers (Hutter et al. 2015). In this thesis, innovation is understood beyond the traditional view of creating something new—e.g., electric vehicles—as a societal challenge of creating a new solution that would be enabled, provided, and adapted by actors inside the system. Therefore, part of the thesis consists of a qualitative approach to provide insights into how the development occurred inside firms. Interviews from managers who were present in the industry throughout the period give a perspective of actors who were addressed by the government's interventions.

4.4.1. DATA AND ANALYSIS

The primary data in article C consists of three in-depth semi-structured interviews conducted between 2014 and 2017 with two managers from Geely and one from Volvo Cars. This allowed gathering perspectives from both parties in M&A and how it changed over time. In addition, different interviews and statements from both firms' representatives in different media were included in the analysis. All interviews were recorded, transcribed, and later analyzed by following modified Burnard's (1991) 14-stage method of analyzing interview transcripts.

Table 8: Overview of the data and methods used in the analysis

Article	Primary data	Secondary data	Technique
A	Patent database (EPO-PATSTAT), Market indicators	Reports (IRENA, IEA) Documents	NLP and vector space modeling
B	Policies (CAAM)	Market indicators Documents	Policy triangle analysis
C	Interviews, Patent database (LENS)	Databases Documents	Vector similarity, Coding of text data
D	Market indicators	Databases Documents	Policy triangle analysis

4.5. RESEARCH LIMITATIONS

The first limitation of this study is its time frame. Both technological and market development of EVs is still in process. Thus, it is hard to clearly point at certain causes of the success or failure, e.g., slower market development in the first years could be the result of insufficient policies or simply the state of technology was not at a sufficient level.

The second limitation of this study comes from its scope. The researched phenomenon is a complex process that consists of cross-industry interactions. Although the results of the articles together form a view of the development of the EV sector, many important components remain unexplored. For example, the development of the energy storage sector or the interactions between actors in knowledge creation inside the SSI.

The third limitation stems from the changing unit of analysis. This ranges from the entire sector to a specific M&A case. Different units have various relations to the same concepts. For example, in articles A and C, knowledge was measured with patents, which neglects tacit knowledge. In article C, this was adjusted by using interviews, which to a large extent addressed learning by interacting. However, in article A, knowledge generation could be analyzed by looking at interactions between actors—e.g., universities and firms' collaborations.

Another important limitation relates to data collection. The plan for the qualitative part of article C was to conduct more interviews. Due to various circumstances, the second series of interviews were cancelled. At first, we tried to include another case of cross-border M&A in the automobile industry, but the uniqueness of the original case limited this option. In the end, we decided to implement the research with patent portfolio analysis and test what interviewees state about learning from each other. In summer 2022, we were finally able to conduct a new series of interviews, however, this is not included in the current Article C version.

Finally, there was a clear difference in view on China's EV sector development between the Western and the Chinese public (general and academic). One year of fieldwork in China enabled a more 'objective' understanding of a situation and the reasoning behind certain decisions. However, several stakeholders in the EV sector gave interviews but would not agree to use the data for the articles.

5. SUMMARY OF ARTICLES

5.1. ARTICLE A

The article entitled 'From catching up to industrial leadership: towards an integrated market-technology perspective,' compares the development trajectories in the EV and Wind energy sector for three different countries. Aside from China, the ‘extreme case’ (Flyvbjerg 2006) and the central empirical focus of the thesis, we also analyzed Japan and Korea. The selection was made according to several factors: geographical proximity, different stages of industrial development, and different market regimes. The criteria to pair the EV and Wind sectors were a combination of similarities—renewable sectors, China's market orientation—, and differences—the EV is energy-consuming, and Wind generates electricity and different speeds of technology cycles. Nevertheless, both sectors are among the leaders of the low-carbon transformation (Altenburg et al. 2016).

The starting premise of the article was that despite scholars measuring the development (and trajectories) in catching-up literature in several ways, the new methodological techniques could give us better results. In general, scholars measured with market indicators, e.g., market and production share (Lee and Malerba 2017; Morrison and Rabellotti 2017; Shin 2017), and technological indicators (Bell and Pavitt 1993). The existing approaches often measure technological development by using patents, but the results could be misleading. Every patent should, by its nature, bring some novelty, yet with different technological and economic significance (Basberg 1987). Consequently, the quantity of patents is not a good indicator of the aggregate level of technological capabilities. The majority of patents' quality measures used in the literature are by patent counting IPC assignments and citations—backward and forward (Harhoff, Scherer, and Vopel 2003; Lanjouw and Schankerman 2001; Lerner 1994). According to Yoon and Park (2004), the citation analysis neglects the overall relationship among the patents and thus left out technological development paths.

Against this background, the aim was to analyze countries' development trajectories using a framework that combines market and technology indicators and answer (1) What implications does sector specificity have for market, 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?

Instead of using existing methods for measuring technology development, we used micro-level identification of technological similarities between patents towards the past and the future. In that way, patent-to-patent similarity mapping allows us to measure patent novelty and impact, which can be aggregated on the level of technologies and geography. Using the Word2Vec embedding model, we transformed each patent's abstract into a vector and generated vector space (see Section 4.3.2. for a detailed description).

Findings:

The results show that countries' strategies are predefined by the state of technology, market, and institutional support. In both sectors, China created a domestic demand that supported the deployment, while Japan's lack of institutional support hindered the scaling up of the markets. We identified two trajectories, market-technology and technology-market. MT trajectory aims towards sectoral leadership by first taking over market leadership. On the contrary, TM trajectory aims first to advance technologically and wait with intense production incentives until the level of technology reaches a certain point. Regardless of the trajectory type, the development process could be hindered by the traps, emerging due to the imbalance of market and technological capabilities. Also, the results show that sectors require different entry and upgrading trajectories, mainly due to the different pace of technology cycles.

5.2. ARTICLE B

The article called 'Domestic deployment in the formative phase of the Chinese Electric Vehicles Sector: evolution of the policy regimes and windows of opportunity' explains the findings from article A—Chinese MT trajectory in the EV sector. China started with EV production in 2009, and in a period of six years, became a world leader from the market perspective, yet with low technological capabilities. In the past, China managed to catch up in several industries, e.g., the mobile phone sector (Capone, Li, and Malerba 2021), the telecommunication system industry (Lee, Gao, and Li 2016), and solar PV (Binz et al. 2017). The first view on China's EV sector development between 2009 and 2015 and its goals reveals that the policies could not start the development in the first three years. The situation changed after the policy regime was replaced in 2012, resulting in rapid growth. Thus, the paper looks at the institutional support in both periods.

With industrial policies, governments tried to stimulate the development of a specific sector by providing additional capital to domestic firms for boosting production and by mediating other market forces put domestic firms in a favorable position (Amsden 1992; Dahlman 2009). With the emergence of renewable industries with a connection to global goals for tackling climate change, governments started to adopt Green industrial policies. In fact, a common goal towards a sustainable economy gave justification for promoting green against "dirtier traditional industries." In addition to traditional industrial policies, here government also stimulated the demand side, e.g., purchase subsidies. Finally, some policies stimulate knowledge generation and collaboration between actors inside NSI.

The latecomers' catching up in traditional sectors were enabled by exogenous Windows of Opportunity—technological, demand, and institutional (Lee and Malerba 2017). In the era of green transition, China endogenized this opportunity by parallel addressing various SSI elements, consequently opening Green Windows of Opportunity (Lema et al. 2020).

The in-depth analysis of all policies and regulations in two different three-year policy regimes (before and after 2012) tried to answer (1) How did the policy regime evolve in the initial stage of the EV sector in China, and (2) how did the policies affect technological and market development?

Findings:

The analysis showed that the first regime mainly used traditional industrial policy's supply and demand mechanisms without resolving obstacles that emerged in the sector's development. The central government's role was focused on establishing the system and was less active on lower levels of development. The accumulation of obstacles, policy shortcomings, and practices that hindered progress turned the year 2012 into a real inflection point resulting in a major change in the policy regime and government's role.

In the second period, policy targets were expanded and paid particular attention to 'learning failures' by addressing knowledge creation within firms as well as collaboration between firms and scientific institutions. Moreover, by stimulating knowledge sharing and reforming subsidy programs, new linkages appeared between actors in different sectors—e.g., the battery sector, the automobile sector, and IT companies.

5.3. ARTICLE C

The article 'From Transaction to Co-creation in Geely's Acquisition of Volvo Cars: Impact for Innovation Output and Market Performance,' applies an in-depth case study of the cross-border acquisition of an established Western car manufacturer Volvo Cars, by EMNE (Geely). Seven years after the transaction, firms jointly established a new car brand Lynk&Co, which was the result of the common R&D center. The focus of the article was on how EMNE used the acquired knowledge and how it influenced both firms' innovation output and market performance.

In the last decades, Chinese firms used cross-border M&A as the primary internationalization mode (Alon and McIntyre 2008; Deng 2012), with substantial government support (Ström and Nakamura 2014). The transactions' success was in many cases defined by post-integration processes that influenced newly produced products (Chen and Lin 2011). Despite the desire to transfer missing knowledge, the process was often limited due to the neglected tacit knowledge and human capital (Ai and Tan 2018; Gugler and Vanoli 2015).

We used a mixed-methods strategy by first using the interview data to get managers' views on the transaction and the integration process. Interviewees from both firms described obstacles and their responses. We hypothesized that the successful knowledge transfer and its integration would be reflected in Geely's patent portfolio. Thus, we measured the portfolio similarities before and after the transaction. In addition, we also looked at the technological base for both periods.

The research tried to answer (1) How can EMNEs transition from fragmented and transactional relationships with the acquired firm to integration and co-creation? (2) How did the transaction influence the similarity between firms' patent portfolios and technological base? (3) How did knowledge co-creation influence actors' market performance?

Findings:

The results showed that the high level of freedom given to the acquired firm in the period after the transaction allowed them to stabilize from several years of increased uncertainty. Moreover, they preserved innovation capacity and successfully incorporated it with the acquirer through a shared learning process. Yet, to achieve the desired outcome, both firms had to deal with problems mainly associated with cross-border transactions, where cultural differences could be a deal-breaker.

The patent portfolio similarity analysis confirmed that the acquiring firm gained knowledge and used it in its further development. After the transaction, patent portfolios became more alike, and the acquirer was newly patenting in several patent classes that were previously used by the acquired firm. The analysis of patents' technological base showed that the acquirer overpassed the one from the acquired firm, indicating EMNE managed to capture the established knowledge, learn, and successfully integrate innovation processes.

Finally, the performance analysis demonstrated that firms benefited from the transaction in various ways, especially at different paces.

5.4. ARTICLE D

In article D, we analyzed to what extent GWO is unique to Chinese characteristics. Most scholars researching GWO focused solely on China, thus, its implacability in other emerging economies remains unknown. The selected countries are Brazil, India, and South Africa, emerging economies with the established automobile industry. All three aim to electrify transportation; however, individually, they have unique characteristics that hinder their development.

While traditional WOO primarily emerges from exogenous technological or demand change (Lee and Malerba 2017; Perez and Soete 1988), GWOs create favorable techno-economic conditions for green transformation by governments (Lema et al. 2020; Yap and Truffer 2019). GWOs are sector-specific, thus the analysis through the lens of the sectoral system of innovation helps to study technology, firms, and institutions coincidently. In such a manner, one should understand the sector's overall features, preconditions for new solutions, and green industrial policies that could enable the transition.

Each country was analyzed with an analytical framework, which looks at preconditions (automobile industry, supply chain, local content, natural resources), policy and enterprise responses, industrial development, i.e., how they altogether influenced the catching-up process. Accordingly, we collected policies, market figures, official publications, and reports from international organizations. The framework made it possible to answer the following research questions: *Are there green windows of opportunity for transitioning to electric transportation in Brazil, India and South Africa? What are the prospects for replicating the Chinese EV success story in these countries? How do the countries compare concerning green industrial policies as well as in their preconditions of the supply base and related industries?*

Findings:

The researched countries have established the automobile industry yet are second movers in the EV industry. Green opportunities and threats are unequally divided between the three countries. Their a bit passive approach is likely to be accelerated due to the pressure from international OEMs, which slowly abandon ICE development. Compared to China, they have better opportunities to source knowledge but face significant international competition. Their natural resources also allow them to play an important role in newly establishing global value chains for critical elements of EVs. Nevertheless, the upgrading in GVC would require major improvements to their NIS.

6. CONCLUSION

The thesis set out to investigate how China established and developed the EV sector and contributes to the literature on deploying and beneficiating green technologies. The focus was on the government's ability to start production, create demand, and finally enable technological innovation. More specifically, the main research question was: *What catch-up trajectory is observed in the EV sector in China, and what are the key determinants, in terms of industrial policy and sector development, of this relative catching-up success?* The results give insights into the nature of GWO in energy-efficiency sectors and what elements are essential for its development.

GWOs in industries that produce electricity are vastly analyzed while industries sectors for optimized use of energy remain under-researched. Looking at GWO in the former, institutional windows were the most essential in initializing the sectors, most often in interaction with technological WOO (Lema et al. 2020, Table 1). These sectors have large-scale projects, often owned by the governments, e.g., wind farms, and hydropower plants. Thus, less effort is needed to stimulate the demand.

In turn, the results from Article 2 show that for successful deployment of the EV sector, the government introduced several policies for creating demand, e.g., purchase subsidies, limiting the registration of vehicles on internal combustion, and tax incentives for EV buyers. In addition, despite providing purchase incentives to cover the difference in price to the alternative product, the decision for purchase is on the individual level. Therefore, the legitimacy and the performance of the technology are more critical. China developed the EV sector by following the MT trajectory, i.e., first developed market to become the market forerunner and later catch up in technology. However, the government had to update its starting policy mix emphasizing knowledge creation. Despite the low state of technology in the first years after deployment (Article 1), a certain level of knowledge was needed to trigger the purchase. To sum up, governments have to endogenize institutional and demand GWO simultaneously to deploy the energy-efficiency sector successfully. Nevertheless, in case of a higher discrepancy in performance between green and traditional solutions, governments should stimulate knowledge creation or its transfer.

Regardless of the introduced policies, the burden of development and manufacturing of the products lies on actors inside SSI. They have to accumulate knowledge, produce products, and finally, find customers. One way of capturing new knowledge is via cross-border M&A, however, the differences in culture, working processes, and markets can hinder the transaction. In industries, where technological progress is fast, it is more crucial to learn how to create knowledge (innovation process) than the technology itself (Article 3).

Finally, the thesis's case is unique and thus the results cannot be generalized over other cases. In other words, China's strategy to develop the EV sector was tailed to fit their characteristics (e.g., economy, technology, resources). As a second mover into the sector, other developing countries could rely on better knowledge sources but face higher international competition. The shift towards electrification of transport in the Western markets would pressure them to follow the transition, as opposed to losing important export markets and attraction from FDIs.

The dynamic perspective on the changing government policies showed that governments have to frequently react to the changes in the industry or shortcomings of the current policies in the nascent sectors. Moreover, adopting the strategy and policies is essential to avoid traps as the latecomer moves towards leadership.

6.1. ARTICLES' CONTRIBUTION

In Article A, the contributions can be divided into three groups. Theoretically, we developed an integrated market-technology framework to analyze catching-up trajectories. The second contribution is to the method for patent-quality analysis, as we used semantic patent-to-patent similarity to calculate patents' similarity to the future and past. This allows the detection of technological novelty and impact. Finally, the article contributes to understanding catching-up trajectories on the sector and country level from the empirical perspective. Several studies analyzed development trajectories in renewable sectors but had to neglect either market or technology parameters (Hochstetler and Kostka 2015; Zhang et al. 2013). Furthermore, some studies measured technological trajectory by analyzing patent portfolios but neglected the quality of the patents. For example, contrary to our results, Wu & Hu (2015) showed that China was a technological leader in three out of seven studied renewable sectors (including Wind). Accounting for the quality rather than the quantity of the patents, the country's trajectory changed, and consequently the understanding of the phenomenon.

In article B, the analysis of policy regimes' evolution contributes to understanding endogenized GWO by emerging economies in sectors dealing with energy efficiency. Despite MT trajectory, the technological and horizontally integrated sector needs incentives for knowledge creation and its flow inside SSI. Additionally, GWO evolved from green industrial policies and its predecessor industrial policy. For successful catching-up in renewable sectors, the policy regime should consist of incentives for production (industrial policy), incentives for favoring the green sector vis-a-vis traditional, and finally, incentives for knowledge inside the SSI. For each of the incentive types, there is no exogenous WOO, and the government has to open it by endogenizing GWO.

Muniz et al. (2019) analyzed the EV policies' trajectory (demand-pull, technology-push). Their results align with our findings regarding policy modifications, yet our contribution adds to the discussion on endogenizing GWO. Namely, how the role of knowledge generation in policies evolved over time. Additionally, several scholars researched EV policies in China by listing the policies and their main points. Without an in-depth analysis of each policy, its purpose and the reason for changing the previous policy could be lost. For example, Muinz et al. (2019) describe the first policy from 2009 as experimental, as in fact, it was placed for almost a decade-long period. Thus, the reason for renewed policy regimes in 2012 lies in the inadequacy of the first policy.

In article C, we use the case study to demonstrate how EMNEs transition from a fragmented and transactional relationship with the acquired firm to integration and co-creation. Firms within a sector have to compete with others, and one way to prosper is by gaining a technological advantage. Many scholars have identified external knowledge acquisition as an essential factor in developing the green sectors (Curran, Lv, and Spigarelli 2017; Haakonsson et al. 2020; Yoo, Lee, and Heo 2013). Hansen & Hansen (2020) analyzed a firm (Delta) in the Chinese biomass sector, which managed to catch up by using GWO. As a first mover in its domestic market, the company lacked the required technical knowledge and thus decided to acquire two firms from Denmark. In a period after the transactions, power plants' performance improved, and due to the transferred technology, secured the leading position in the market. The acquired knowledge later spilled over the sector and enabled other competitors to catch up as well. The authors demonstrated the importance of knowledge in nascent sectors in a specific country and how it can be transferred. Our work builds up and focuses on the process of capturing, integrating, and co-creating of the acquired knowledge. In highly technological sectors with faster technology cycles, knowledge gets soon obsolete. So, the crucial element for EMNE after the transaction is to keep the target's innovation processes going and, in the later stages, to learn from, and finally, implementing them into their processes. The case study of successful cross-border M&A from the innovation perspective adds additional view into a well-studied phenomenon.

In Article D, we explored if there are GWOs for transitioning to electric transportation among selected emerging economies. The paper adds to the literature on GWO in a few ways; first, most existing literature studied latecomer development potentials in producing renewable electricity (Dai et al. 2020; Hansen and Hansen 2020; Oehler 2022), while we expand this to the energy-efficiency sector. Second, most of the research regarding EV development is focused on China, and we address the understudied potentials of other latecomer countries. Third, while prior literature explored cases with a significant element of proactive-window creation and endogenous contribution to the relevant technology-economic paradigm shift (Yap and Truffer 2019), we explore how latecomers react to an exogenous paradigm shift from ICE to EVs. The fourth and final, this is the first study to systematically analyze latecomer reactions to the same GWO, with an in-depth focus on the supply-side elements of the response.

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II. ARTICLES

ARTICLE A

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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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.

JEL classification: O31, O32, O33, Q55, Q20, L10, L60, L62

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 opportunity

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; Dutre´nit, 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 catchup 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[1] lines, the NIS focuses on innovation capabilities across national boundaries (Freeman, 1987; Lundvall, 1992; Nelson, 1993; Malerba, 2005; Coenen and Lo´pez, 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

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

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. technologyoriented 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 shares 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 Toward 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).

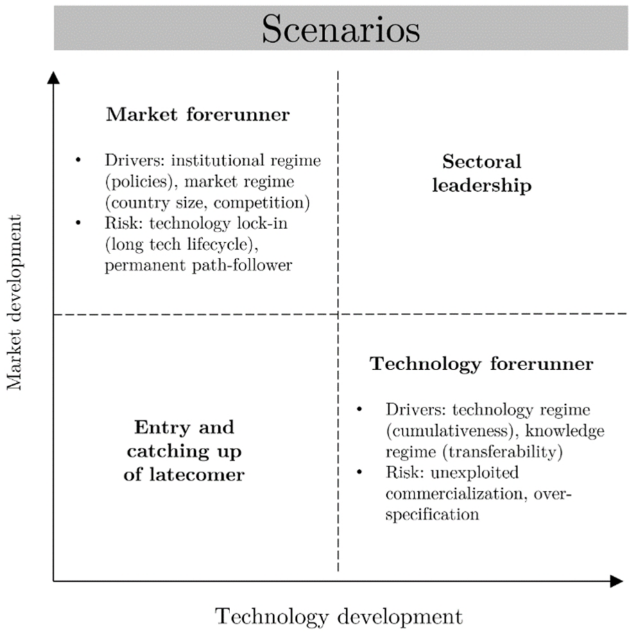

Figure 1: The MT matrix

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 shares, 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.

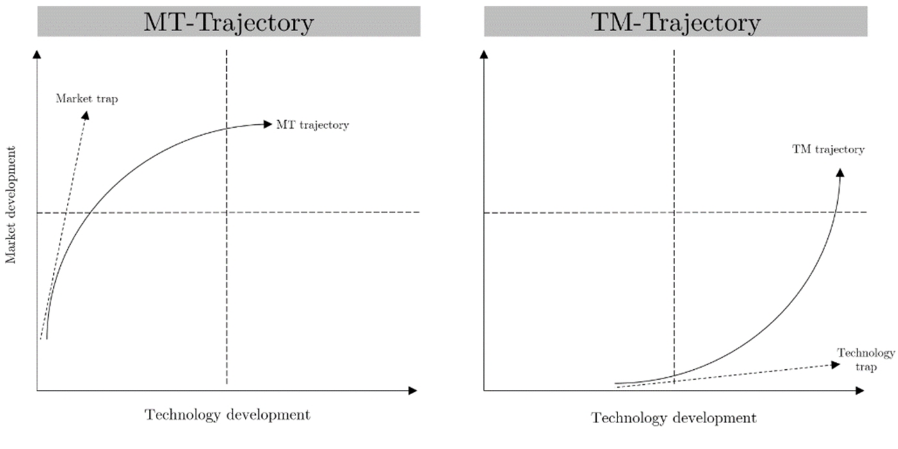

Figure 2: Trajectories and potential traps in the MT matrix

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 cross-cutting capabilities (Nahm and Steinfeld, 2014), the challenge here is scaling up the commercialization and gaining market shares. 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)

Sources: 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 (simpast) 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 (simfuture). 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.[2]

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 Englishlanguage 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 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

[2] 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.

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.[3]

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.[4]

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

[3] 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.

[4] 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).

(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 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.[5]

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.

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).

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

[5] 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 Migue´lez, 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.

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.

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).

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).

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.

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.

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

[6] The time lag can, to some extent, explain the following decline of patenting activity between the filed patent application and the appearance of the granted patent in PATSTAT.

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.

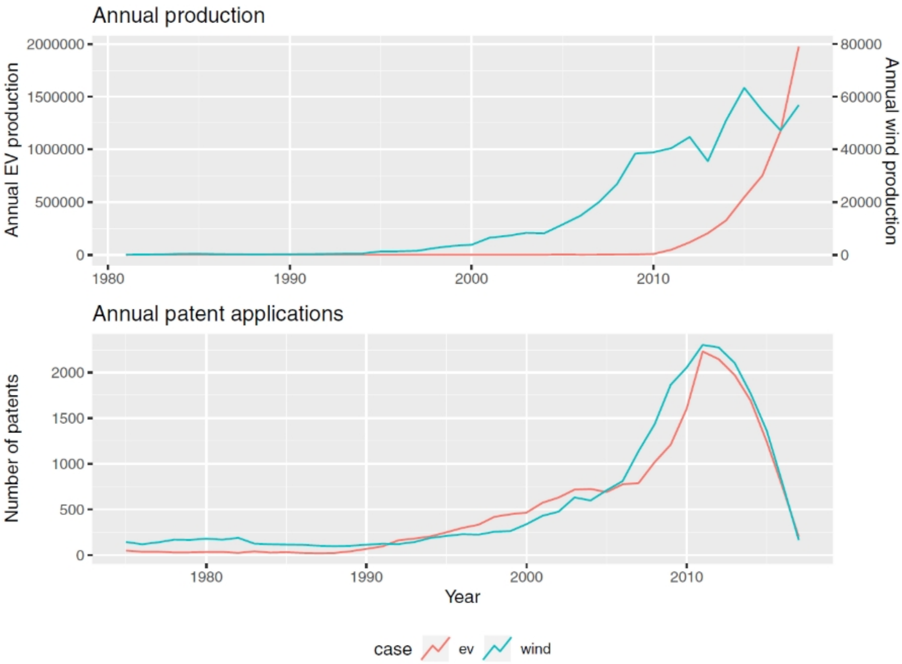

Figure 3: Production and technology development over time

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 591GW, 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.

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,[7] EV is still in the exploratory phase where multiple competing designs coexist, 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 mid2000s 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 simfuture 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

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

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.

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

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

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.

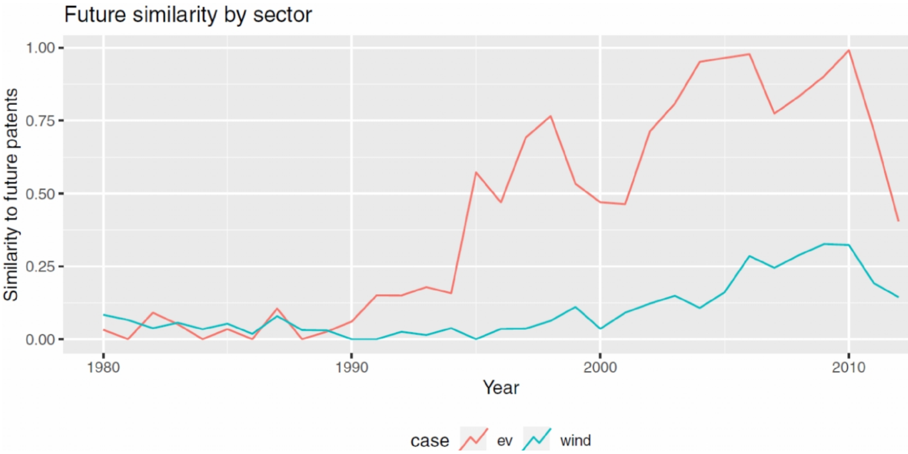

Figure 4: Development of temporal similarity

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.

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).

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.

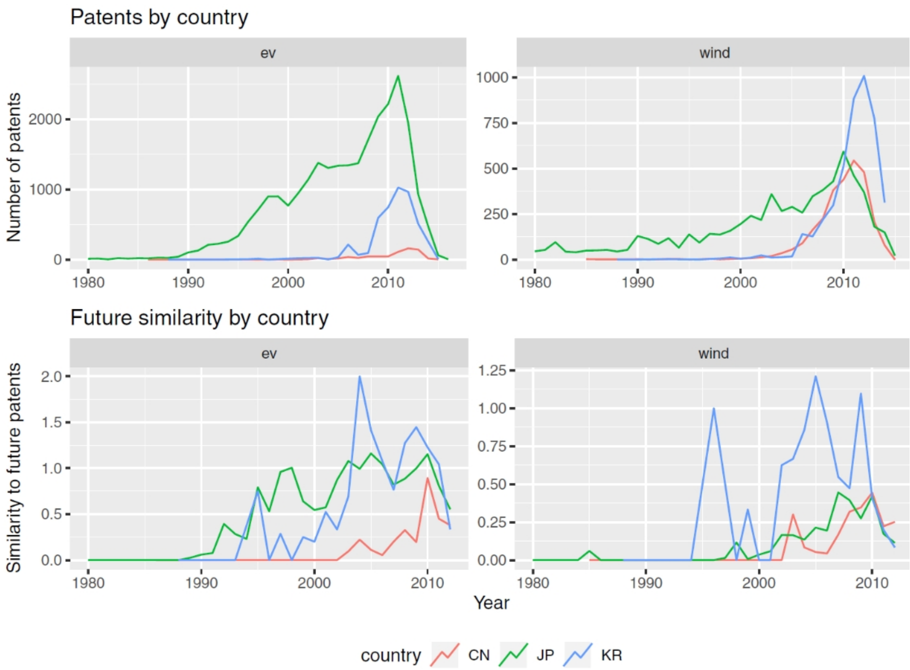

Figure 5: Number of patents and future similarity by country over time

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 1GW threshold 5 years later, South Korea still had minimal market traction (~100MW). By 2018, Japan had slowly grown to 3.6GW, while South Korea was still at 1.3GW. Thus, both countries belong to the group of slowest growing countries among the 30 countries in the world with more than 1GW 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 highimpact 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 211.3GW, 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 (47GW 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 pathcreating 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.

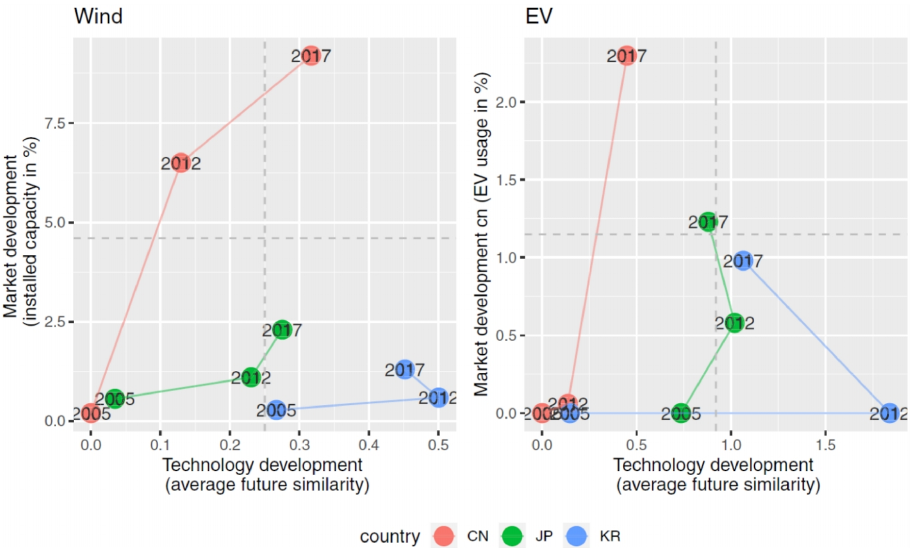

Figure 6: Market vs. technology development in China, Japan and South Korea.

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 simfuture 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.

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A Methodological appendix

This section provides a detailed technical description of the text vectorization, largescale semantic similarity- and indicator calculation. While the method is exhaustively described and verified in Hain et al. (2018)

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 ∈ Rn 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 vector $\vec{\imath}$ 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 Si,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 with 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). Already such a simple weighting scheme and the representation of patent abstracts as a sparse matrix can be rather 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 allows 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 and have been experimenting with more advanced approaches such as Sequence2Sequence models based on autoencoder 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, does carry less information in its syntax.[8]

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[9] 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 9471069 observations that explicitly mention one of the symbols as “first” and evaluated on 100000. 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 missclassified 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 everyone of those the patents which 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

[8] In machine learning and related domains, new methods that are meant to automatize some human tasks are usually evaluated in comparison with human performance. Computer vision methods are, for instance, evaluated on the basis of image datasets 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 benchmark dataset does not exist.

[9] Python’s Gensim library (Rehurek, 2010) is used for the training https://radimrehurek.com/gensim/

present case, such approach would be technically not feasible. 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))[10] implementation that constructs a forest of trees (100) using random projections. We in the next step calculate the cosine similarity between focal patent and all other patents to be found in neighbouring leaves of the search tree, where we discard patents-pairs with a cosine similarity beyond the threshold of 0.35.

$$sin^{cosine}(x, y) = \frac{x^T y}{||x|| \cdot ||y||} \tag{A.1}$$

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 which 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 continuous over time, making patents within the same IPC class published more than 7 years apart not significantly more similar than patents from different classes.

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[10] Extensive documentation of the annoy package can be found here: https://github.com/spotify/annoy

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 that 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 others. 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.[11] 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 to 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 on 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 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:

$$sim_i^{future} = \sum_{j=1}^{m} \frac{\{\Delta t_{j,i} > \tau\} s_{i,j}}{m} \tag{A.2}$$

[11] 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.

Consequently, sim_i^{future} prepresents patent i's share of similar patents with application date in the future, weighted by their similarity $s_{i,j}$. The parameter τ 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 $s_{i,j}$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 $s_{i,j}$.

$$sim_i^{past} = \sum_{j=1}^{m} \frac{\{\Delta t_{j,i} > \tau\} s_{i,j}}{m} \tag{A.3}$$

B Supplementary Tables

Table B.1: 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 B.2: IPC-classes Wind

IPC class	Level	Description
F03	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 B.3: Main policies by country

	CN	JP	KR
WIND	Plan for Science and Technology (1991)	Long-term purchase menus for renewable power by electric company (1997)	NRE Development, Utilization, and Deployment (1972)
	Plan for Renewable Energy Development (1996, 2001)	Kyoto Protocol (1997)	National energy plan (2006)
	National Renewable Energy Law (2005)	Voluntary "green power fund" (2000)	Green New Deal (2009)
	863 Wind Program (2006)	Renewable Portfolio Standard law (2002)	
	Plan for Wind Power Science and Technology (2011)		
	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)	Government-industry RD programme (1971)	Law for Eco Friendly Cars RD (2004)
	National Clean Vehicle Action program (1995)	Internal company RD (1978)	Eco-Friendly Car Master Plan (2005)
	EV Key Project - 863 (2001)	New Sunshine Programme (1992)	Law for Low Carbon Green Growth (2010)
	Alternative Fuel Vehicles Key Project-863 (2006)	Public procuremenet (1995)	Green car Industry Stimulating plan (2010)
	Plan on Shaping and Revitalizing the Auto Industry (2009)	Clean-Energy Vehicles Introduction Programme (1998)	Law for Sustainable Transport Development (2011)
	The Ten Cities, Thousand Vehicles Program (2009)		
	NEV Industry Development Plan (2012)		

Source: (Åhman, 2006; Chen et al., 2014; He et al., 2018; kyu HWANG et al., 2015; Lewis, 2011)

Table B.4: 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 B.6: 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%			

In thousand EVs. * In million USD Source: (Bunsen et al., 2019; Workman, 2019)

ARTICLE B

Domestic deployment in the formative phase of the Chinese Electric Vehicles Sector: evolution of the policy regimes and windows of opportunity

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Domestic deployment in the formative phase of the Chinese Electric Vehicles Sector: evolution of the policy-regimes and windows of opportunity

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Abstract:

China has been able to deploy electric vehicles at an unprecedented speed and scale. This paper explores the underlying policies during six years of sector formation, and it identifies a change in policy-regime after three years. The analysis of evolution of the policy-regimes indicates that creating, transferring, and sharing knowledge among the principal actors was key to catching up. The changing policy-regime enabled a minimum threshold of technology development required for deployment. Nevertheless, it was insufficient for pushing the sector to the global technology frontier. Key to the sector's relative success was the government's responsiveness to sectoral development and its ability to address production, demand, and knowledge issues simultaneously. In addition, it created synergies between policies designed to address environmental concerns and foster economic development concurrently. However, fast deployment required heavy subsidies and important policy initiatives came with potential pitfalls that may hamper international competitiveness of the sector.

Keywords: Green windows of opportunity; electric vehicles; catching-up; green industrial policy; government interventions

1. INTRODUCTION

The electric vehicle (EV) sector is currently among the most innovative and dynamic market segments in the global economy and has significant technological ramifications throughout many different branches of industry. It is advancing globally, with producers of vehicles, suppliers of components and services, and a wide range of potential entrants surveying opportunities in many disparate areas. China is promoting an ambitious electric mobility program with two primary objectives: to reduce urban air pollution and enhance the national automotive industry (State Council, 2009).

Given the nature of ambitions regarding EVs in China, this technology domain has received widespread attention from academics and decision-makers in industry, finance, and politics. Given the centrality of the EV sector in the green transformation, global stakeholders are concerned with the question of whether the Chinese mix of climate and economic policies creates conditions to become a global leader. These policies favor green technology, create demand for it, and stimulate production to satisfy demand. However, green industry development policy must adequately address the state of technology and the market situation and be modified according to the sector's development (Hain et al., 2020).

This paper analyses two distinct policy phases that have emerged before and after 2012. When the goals set in the first period had not been achieved by 2012, the government introduced a new plan for the next eight years (Howell, Lee, and Heal, 2014). By 2016, China had surpassed the United States (USA) in EV stock, with 32% of the global share and 44% of worldwide annual sales (IEA, 2019). Both phases were expressions of long-term government intervention, which influenced international and domestic markets alike. The key research questions addressed in this paper are: How did the policy regime evolve in the formative stage of the EV sector in China, and how did the policies affect technological and market development?

The two phases of EV policy are examined by analyzing all policies and regulations that included the term 'new electric vehicle,' both at national and provincial levels. Drawing on Binz et al. (2017), the policies were inspected along with four domains: knowledge, market access, financial investments, and technology legitimacy.

The paper is structured as follows. Section two reviews the relevant literature, focusing on green windows for latecomer development (Lema, Fu, and Rabellotti, 2020) and green industrial policies (Altenburg and Rodrik, 2017). After the data and methods are presented in the third section, the fourth introduces the EV sector, followed by an indepth analysis of Chinese domestic EV regulations and policies. Finally, the discussion and conclusion summarize the findings and reviews the contribution and limitations.

2. THEORETICAL FOUNDATIONS

2.1 GREEN WINDOWS OF OPPORTUNITY FOR LATECOMER DEVELOPMENT

In this new era ofgreen transformation, latecomer countries must decide between 'greening now' or 'growing first and cleaning up later' (Pegels and Altenburg, 2020). Despite promising market leadership, beginning a green transition early might lead to high investment and poor results. The characteristics of the sector and the unique position of each country urge individual governments to find their development paths.

Recent research has shown how latecomers have addressed windows of opportunity, which can be related to changes in technology, demand, or policies, in their efforts to catch up in a range of manufacturing and service industries (Lee and Malerba, 2017). To address climate change, governments promote green alternatives despite these still being economically inferior to dirtier industries. Thus, green sectors require simultaneous GWO policies, technologies, or market changes that create favorable conditions for their development (Lema, Fu, and Rabellotti, 2020). Compared with traditional opportunities, GWOs have a wider public good dimension, as it addresses climate goals and not solely economic targets. Moreover, the interventions must address 'dirtier' solutions (Droste et al., 2016). China has initiated institutional GWO in several green sectors, including wind (Dai, Haakonsson, and Oehler, 2020), biomass (Hansen and Hansen, 2020), and hydro (Zhou, Miao, and Urban, 2020), but their characteristics required different catching up trajectories (Lema, Fu, and Rabellotti, 2020).

The latecomers' goal is to lower the gap and eventually take over the leadership (Shin, 2013; Lee and Ki, 2017). According to Hain et al. (2020), latecomers can take market or technological trajectory; dominating in the market but lack technological development means market forerunner, and vice-versa for technology forerunner. Only the combination of both gives sectoral leadership. Scholars measure leadership with market (e.g. Mowery and Nelson, 1999; Lee and Malerba, 2017; Morrison and Rabellotti, 2017; Shin, 2017), and technological indicators (e.g. Fu, Pietrobelli, and Soete, 2011; Awate, Larsen, and Mudambi, 2012). In this study, the production and number of EV vehicles on roads are used to determine the market forerunner position.

In the time of regular development, sector leaders can protect their position with incremental changes. The significant changes in the sector – disruption – begins a new catching-up cycle that allows latecomers to leapfrog and consequently take over the leadership (Morrison and Rabellotti, 2011). However, to take advantage of technological paradigm changes, latecomers need policy support, access to knowledge, learning possibilities, and a skilled workforce (Mazzoleni and Nelson, 2009; Malerba and Nelson, 2011).

The governments play a significant role in sectoral catching up, promoting interactions between actors, stimulating production, and supporting internationalization (Quadros and Rasiah, 2003; Malerba and Nelson, 2011). Åhman (2006) suggests that instead of using a linear model – only supporting basic R&D – governments should actively intervene with financial and regulatory tools in different market segments. The support strategy cannot be universal but is defined by countries' unique characteristics (Niosi, Athreye, and Tschang, 2012; Binz et al., 2017) and is later frequently adapted to fit the new circumstances (Ernst, 1998).

In the previous century, a few countries have managed to catch up, Japan and Korea being two prime examples, mainly owing to their thriving industrial policies (Nolan, 2014). While these focused on productivity, they often neglected environmental goals, resulting in the severe exploitation of natural resources. However, more recently, some countries have proved that industrial policies, combined with environmental and energy policies, can create prosperity and be environmentally sustainable (Altenburg and Assmann, 2017).

2.2. GREEN INDUSTRIAL POLICY

Industrial policies – *any selective government intervention to promote the development of specific sectors* (Dahlman, 2009, p.5) – have played an important part in advancing older developed countries and latecomers that have used this tool to develop primary industries (Amsden, 1992). With the increasing development of emerging renewable energy sectors, governments began to implement specific green industrial policies. Significant investments were justified by benefits for their citizens and the environment and increased independence from fossil fuels and foreign energy sources. The main components of these policies were (1) sector-targeted subsidies – R&D, subsidies, feed-intariff programs; (2) conditional local-content subsidies and policies to encourage the use of domestic instead of imported goods; and (3) in some countries, export restrictions of crucial ingredients for the renewable industry – an example being 'rare earth' elements (Wu and Salzman, 2014). Strong theoretical justification and environmental pressure, some from international climate change agreements, shifted the debate from whether or not governments should intervene to how they should intervene successfully. Altenburg and Pegels (2012, p. 10) suggest a new concept of sustainability-oriented innovation systems for green transformation, consisting of '*institutions which create, import, modify and diffuse new technologies that help to reduce environmental impacts and resource intensity to a level commensurate with the earth's carrying capacity.*' However, proactive government interventions might collide with international trading agreements and consequently increase the tensions between the countries. After all, it is more desirable to have a subsidy war, promoting R&D development and production, than a tariff war, which tries to increase competitiveness by harming others (Rodrik, 2014). While developing countries used to be characterized as environmentally unfriendly in their production, the disputes in the World Trade Organization (WTO) over green industrial policies indicate a different situation. Many developed countries are now calling to terminate pro-environmental subsidy policies (Wu and Salzman, 2014).

2.3. POLICY MIX FOR CATCHING UP IN GREEN SECTORS

While green industrial policies focus on redesigning production-orientated industrial policy as environmentally sustainable, policies for catching-up also prioritize knowledge, linkages, and how they flow transnationally (Perez and Hansen, 2020). The framework proposed by Binz et al. (2017) contains a policy mix for catching up across three different industry types: design-intensive, complex product systems, and process-intensive. Industry categorization considers several features: design intensity, the scale of investments, the manufacturing process, learning mode, types of users and customers, products and markets, and the nature of necessary capabilities.

The automobile industry uses automated mass production with arm's-length market transactions to standardized customers and requires specialized R&D competencies. The emergence of EV solutions requires firms to use more advanced learning mechanisms and cross-industry partnerships, leading to more complex solutions (Aggeri, Elmquist, and Pohl, 2009; Wolschendorf, Rzemien, and Gian, 2010; Larminie and Lowry, 2012). The change in R&D did not change the manufacturing process and the relation to the customers, thus, the policies were investigated by using a mix for the process-intensive industry (Table 1).

The overview over proposed policy-mix through (green) industrial policy lenses shows that incentives cover a wider range of targets. Especially creation and deployment of new knowledge tend to have a significant part in the successful catching-up, and it is not limited only to favoring cleaner against traditional technology. As mentioned earlier, China managed to initiate GWO in many renewable sectors. However, in sectors with a big performance gap between nascent and traditional technology, governments might need to help the sector after the opportunities are created – e.g. EV in the early 2010s.

3. DATA AND METHODS

This paper's primary data consists of national and local policies regarding EVs in China between 2009 and the end of 2014. The policies were collected from the China Association of Automobile Manufacturers' website (Caam, 2020), and all policies, regulations, and news that include the term '新能源汽车' (new energy vehicles) were captured. The Chinese government uses this term to designate EVs in policies, and it consists of battery EVs and plug-in hybrid EVs. In total, 294 entries were found, with 113 dated between 2009 and the end of 2011, and the remaining 181 entries falling in the period 2012–2014. The data was translated from Chinese into English, coded, then reviewed. Additionally, statistical data was collected from different databases and market reports to evaluate the results of policies and measure industry development, production, and sales.

Table 8: Policy mix for catching up in process-intensive product industries

System resource	Policies for process-intensive products
Knowledge	Government-funded basic science and R&D programs Supporting the quick translation of new technologies to the manufacturing process Support for entrepreneurial experimentation in private start-ups Support for imports of capital equipment, turn-key plants, and/or knockdown kits
Market access	Promotion of domestic markets: • Policies aimed at creating domestic mass markets to facilitate economies of scale in production Promotion of export market: • Establishment of export processing zones with state-of-the-art trade infrastructure • Intervention to decrease factor costs (raw materials, capital costs, labor costs, energy costs)
Financial investments	Arrange low-cost loans for plant expansion, equipment purchase Creation of supportive private equity and venture capital system
Technology legitimacy	Adoption of international quality certification and standards systems Mobilization of policy/public support based on success stories in export markets

Source: (Binz et al., 2017)

4. THE EV SECTOR IN CHINA

The automobile industry is an essential component of many countries' economies, and owing to its scale and intensity, governments support its development (Quadros and Rasiah, 2003; Åhman, 2006). Mass production started in the USA and later spread across Western European countries, followed by Japan's triumphant entrance (Cusumano, 1988). Industry developed an oligopolistic structure, and a few latecomers managed to catch up, e.g. South Korea and some East-Central European countries (Malerba and Nelson, 2011; Pavlínek, 2017). In the automobile sector, old and new leaders coexist, with latecomers sharing leadership with traditional leaders. Recently, the automobile sector has begun a technological paradigm shift, as decarbonization of the world economy demands cleaner transportation methods (Altenburg, Schamp, and Chaudhary, 2016).

4.1. CHINESE CATCHING UP IN THE AUTOMOBILE SECTOR

The Chinese passenger cars sector began to develop after the economic reform program was launched in 1978, and since then, its production has gradually increased. China produced 42,000 cars in 1990, rising to 607,000 in 2000, and 3.8 million in 2006, with fewer than 100,000 being exported in that year (Chu, 2011). In 2017, China was the biggest car manufacturer globally, with a 34% market share, production of 24.8 million, and 891,000 cars sold abroad. However, China only took twentieth place in global export, with 1%, which indicates the Chinese automobile sector's complete reliance on the domestic market. In 2016, Iran (19.3%), India (9.5%), and Vietnam (6.8%) were leading destination countries for the country's vehicle exports (Caam, 2020). However, despite rapid growth, China did not take any market share from traditional leaders – the USA, Germany, Japan – but nevertheless managed to fill the demand from a growing domestic market. The government saw an opportunity to upgrade the automobile industry by being one of the first to move on a large scale into EVs and start mass production in 2009.

The basis for this optimism originated in a demonstration project that ran during the 2008 Beijing Olympic Games, in which spectators and athletes were transported by a fleet of fifty electric buses that used lithium-ion batteries and 500 electric cars from various producers (The Auto Channel, 2008). Although the goal for EV production in the 2009 plan was to reach 500,000 units by 2011, production only started to grow after 2013. The 2012 plan moved the 500,000 units goal to 2015, and in 2014, production growth reached the desired pace (Figure 1). These production numbers exclude low-speed EVs in the unregulated Micro EV (A0 or A00 class) sector. However, this area allowed Chinese manufacturers to create a path towards electrification, and in 2014, more than 2 million units were produced (Ou et al., 2017).

4.2. THE STATE OF TECHNOLOGY IN THE EV SECTOR

In 2009, China began mass production in the EV sector without any novel technical knowledge (Hain et al., 2020). Despite the subsidies that were made available, customers did not demand EVs in the following years, mainly owing to their shortcomings compared with internal combustion engine vehicles. In 2010, battery technology was not satisfactory. The manufacturing cost per kWh was between 3400

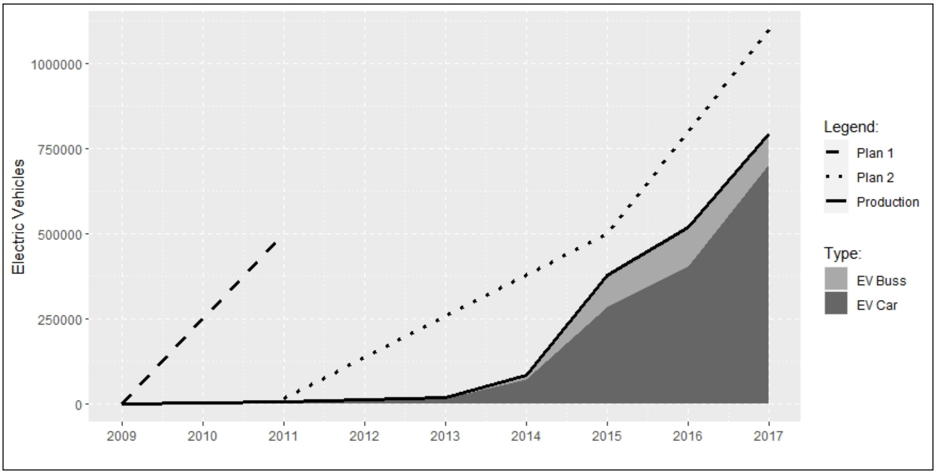

Figure 2: EV plans and realized production by vehicle type (Caam, 2020; State Council, 2012; IEA, 2019)

and 5000 yuan, and this presented a large proportion of EV costs. Battery life was between three and five years or circa 160,000 km, making EVs much less of an economic proposition than conventional vehicles (World Bank, 2011). By February 2014, battery production cost had decreased to around 3150 yuan per kWh, which was still much higher than the 2000 planned for 2015 (Howell, Lee, and Heal, 2014).

In 2011, the average Chinese EV had an average range ofaround 160 km (World Bank, 2011), and this did not improve much in the next two years. The best-selling EV in 2013 (JAC iEV) had a range of around 120 km, and the second highest-selling (BYD e6) around 160, with an option to use bigger batteries, 62 kWh, and thus reach 300 km (Shahan, 2014).

Supporting infrastructure presented a crucial obstacle in the sector's development. In 2010, pilot cities used different tactics to tackle this problem, but charging stations were mainly developed for electric buses. A slow charging speed lowered buses' potential operating time, and thus a battery swapping model emerged. Consequently, battery costs increased as 60% more batteries than buses were required (World Bank, 2011). Owing to high battery prices, investment was high. Slow charging also affected passenger EVs: this took up to eight hours, and many charging facilities could not charge batteries to capacity. Some pilot cities developed battery swapping systems, which decreased the EV purchase cost, yet customers had to pay monthly fees. Without subsidies, the price was relatively high for users (Howell, Lee, and Heal, 2014).

4.3. SUB-SECTOR ANALYSIS

Both policy regimes studied had the same regulations for EV passenger cars and buses. However, global market development was different. For the former, many countries started production, and for the latter, it was mainly pilot programs that began. The EV bus sub-sector was in a different cycle stage than EV passenger cars. China was not a latecomer, so it had to invest more in domestic R&D. Despite the problems mentioned with charging stations, the EV bus industry developed relatively faster than the internal combustion engine bus industry. In 2014, electric buses made up 2.55% of all Chinese EVs, which was more than twelve times higher than the proportion of buses with internal combustion engines as a percentage of all vehicles produced in China that year (CISION, 2015; ITDP, 2018). Regulations from 2013 forced big cities to replace existing buses with electric ones rapidly and consequently increased demand. As a result, by 2017, many cities had become highly electrified, e.g. Shenzhen reaching 100% (ITDP, 2018), and Chinese purchases of EV buses accounted for more than 99% of global sales (Reily, 2018).

Another view of industry development could be to look at manufacturing and the willingness of car manufacturers to produce EVs. Government policy addressed both public institutions and private purchases, first with direct orders and subsidies (State Council, 2013), and latterly mostly through subsidies. As seen in Figure 2, the number of projects involving electric or hybrid buses increased faster than those that focused on passenger EVs. The demand from pilot cities was mostly stimulated by the electrification of public transport and not as much by private citizens.

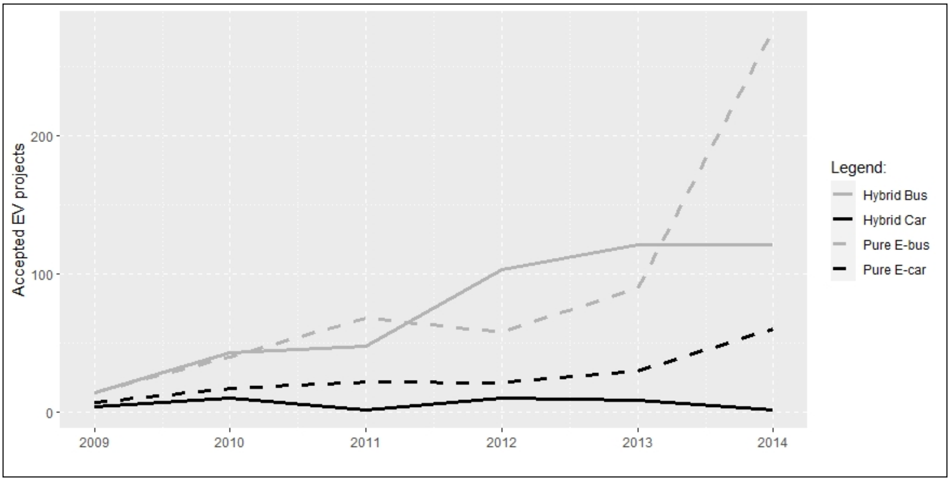

Figure 3: Accepted EV projects by type (Caam, 2020)

New manufacturing projects were the result of demand, and as there was no real demand for passenger vehicles, car manufacturers did not see any advantages to be gained by faster transitioning. The data here were obtained from the 'Catalogue of Recommended Models for Energy Saving and New Energy Vehicles, Demonstration, Extension and Application Projects,' which has been published monthly since June 2009 by the Ministry of Industry and Information Technology. This contains all products and projects approved by the central government, and that local governments are consequently allowed to support (Caam, 2020). The graph reproduced here shows the effect of the policy from 2013, which speeded up the electrification of public transport, primarily purely electric buses.

4.4. EV SECTOR AT THE END OF THE SECOND PERIOD (2015)

Slow market development during the first period was improved upon, and the overall results in 2015 looked promising. However, an in-depth study reveals many shortcomings. Around 70% of all EVs sold were in the Micro EV category: six of the ten bestselling models (Ou et al., 2017). The pilot city model resulted in local protectionist policies, which the government addressed in 2014 (State Council, 2014). Despite this, local brands were dominant in most pilot cities owing to the customized subsidy qualifications. Another aspect was the unbalanced distribution of EVs across the country. The area covering more than 80% of EVs presented only a quarter of the whole market for regular vehicles. Furthermore, great variety was present among pilot cities, with the share of EVs being between 1% and 10% overall (He et al., 2018).

Development also came with high costs, with total government spending being around 400 billion RMB, 42% of total sales (Kennedy, 2018). Part of the investment drained away through the small manufacturers owned by local governments, which never delivered vehicles to the market despite receiving subsidies and loans (Cai, 2017). There were more than a hundred registered EV manufacturers, but only twenty-three were in production in 2015, and the eight largest accounted for more than 90% of total sales (He et al., 2018). In 2018, the government announced an investigation into manufacturers that gained financial support but never reached mass production. The initial findings removed 1882 EV models from the tax exemption list, and consequently, firms could claim no further support for them (Hao, 2018).

5. DOMESTIC EV REGULATION IN CHINA

In this section, domestic regulations are analyzed in four ways: policy before and after 2012 at national level (Table 2), at local level (Table 3), and a comparison between regimes. The analysis follows a chronological order and is later grouped according to the categories laid out in the overall framework. The Chinese government introduced a series of different regulations to stimulate the EV sector. There were four primary goals: technological upgrading, energy security, local pollution reduction, and solving carbon emissions. The alternative fuel vehicle policy was first introduced in China in 1991. It has been updated in every five-year plan since, as transportation is recognized as a crucial factor in meeting the nation's energy and air quality goals. During the tenth five-year plan – starting in 2001 – an R&D strategy for EVs was introduced for fuel cells, hybrids, and pure EVs. High financial investment in R&D continued in the eleventh five-year plan, and this was supplemented with the first commercial market development (Zheng et al., 2012).

Table 2: EV policies in researched periods

Type of policies	Period	Description	Policy reference
Knowledge	prior 2012	Manufacturers must have patents for their products	State Council, 2009
	after 2012	Scientific planning of industrial layouts	State Council, 2012
		Twenty-five technology innovation projects launched	MIIT, 2012
		Companies should have 3% share of R&D in their income	MF, 2012
		Strengthening of technological innovation	State Council, 2014
		National grant for R&D and innovation	863 plan
Market access	prior 2012	EV solutions classified by technical stage	MIIT, 2009
		10/1,000 pilot cities program	MF and MST, 2009
		Improving competition and speeding up manufacturing	MST, et al., 2011a
		EV placed in FDI catalog in the' encouraged' group	NDRC, 2011
		Investigation into why pilot cities do not progress	MST et al., 2011b
		International demonstration zone	Marquis et al., 2013
	after 2012	New production plan	State Council, 2012
		Building charging facilities; improving standards	State Council, 2012
		Supporting internationalization (trademark registration and acquisitions)	State Council, 2012

		Encouragement for private purchase; granting car licenses	State Council, 2013
		Increase in the number of pilot cities	MF and MIIT, 2013
		30% of public vehicle purchase to be EV	MF and MIIT, 2013
		Elimination of local protectionism, improving quality, business model innovation	State Council, 2014
		New parking areas need to have EV charging	MF et al., 2014b
		The number of pilot projects increased to thirty-nine cities	MIIT, 2014
		New grant for cities with outstanding performance	MF and MIIT, 2014a
Financial investments	prior 2012	Subsidies for EV purchase and EV manufacturers	MF and MST, 2009
		Subsidies extension	MF and MIIT, 2010
	after 2012	Support for financial institutions for supporting EV projects	State Council, 2012
		Additional funds for tech. innovation and new EV models	MF and MIIT, 2012a
		Additional subsidies for pilot cities	MST et al., 2013
		Tax exemption for EV purchase	MF and MIIT, 2014
Technology legitimacy	prior 2012	Warranty for three years or 150,000 km	MF and MST, 2009
		Establishing an accident warning information system	MST et al., 2011b
	after 2012	Firms should have ISO 9001, ISO/TS 16949 quality certification	MF and MIIT, 2012b
		Public and educational activities for promotion EV	MF and MIIT, 2014b

In 2006, the State Council introduced 'The National Medium and Long-Term Program for Science and Technology Development (2006–2020)', and this included the EV sector. This fifteen-year plan relied on indigenous innovation, leapfrogging, promoting development, and leading into the future. Indigenous innovation was defined as *'enhancing original innovation, integrated innovation, and re-innovation based on assimilation and absorption of imported technology, in order to improve our national innovation capability'* (State Council, 2006, p. 9). This policy was supported by restricted EV imports and demand for better technology transfer from foreign firms, yet it resulted in lower technology imports (Howell, Lee, and Heal 2014).

Table 9: Five pilot cities' strategies

Pilot	Model		Plan/Realization 2012
Beijing	State Leadership	Creation of a strong EV industrial base Public and private collaboration EV exemption from car license plate lottery system	5,000 / 1,700
Shanghai	Platform-Led Business Innovation	International demonstration zone EV rental business	1,700 / 1,150
Shenzhen	Cooperative Commercialization	Financial leasing model for purchasing cost reduction Substantial private firms support EV. Promotion of its own plug standard	4,000 / 2,400
Hangzhou	Flexible Rental	EV battery rental to reduce purchase cost Battery switching	4,100 / 1,500
Chongqing	Fast Charging	Fast-charging batteries	2,200 / 1,000

Source: (Marquis et al., 2013)

5.1. PRIOR 2012

In the years of the Great Recession (2007–2009), the Chinese government introduced a policy package to spur the economy. Its primary element was the 'Plan for Shaping and Revitalizing the Auto Industry.' In addition to its environmental goals, the government saw an opportunity to leapfrog and consequently catch up in the automobile sector by taking a leading position in EVs. Policymakers acknowledged three main bottlenecks – market, technology, and supporting facilities. This policy from 2009 aimed at a production of 500,000 EVs, and an increase in the share of 'non-fuel' vehicles to 5% of total passenger cars sold before the end of 2011. This stimulation was directed at the whole automobile sector. It planned to expand own-brand vehicles in the domestic market to 30%, and exports to 10% of production (State Council, 2009).

The supporting policy by the Ministry of Finance and the Ministry of Science and Technology proposed the 'Ten Cities, Thousand Vehicles' program, with fiscal instruments to encourage the development of the EV sector; this started with thirteen pilot cities. Central government provided these cities with a one-off subsidy that was to be used to stimulate the purchase of EVs. Local governments had to issue grants towards providing support facilities and their maintenance. EV producers had to give a warranty for three years and 150,000 km. Additionally, car parts producers had to provide a specific scale for their production capacity (MF and MST, 2009). In July 2009, the Ministry of Industry and Information Technology announced regulations for EV manufacturers, and placed their products (MIIT, 2009)indifferent technical stages:

initial, development, and mature. According to the stage, different management methods were adopted. The classification that was announced was greeted with skepticism, as lithium-ion batteries were placed only in the development stage and nickel-metal hydride batteries were favored (China Business News, 2009). Manufacturers had to provide necessary production capacities and consistency in their output. Additionally, products had to meet safety standards, environmental protection criteria, and theft prevention regulations, and they were not allowed to infringe intellectual property rights (MIIT, 2009). In 2010, four ministries introduced an extension to subsidy regulations (MF and MIIT, 2010), which covered the private purchase ofEVs and battery leasing. Subsidies could go up to 50,000 yuan for a hybrid EV and 60,000 yuan for a pure EV. This was limited to the first 50,000 EVs to be sold.

In 2011, regulations for strengthening EV pilot projects were launched to understandwhy the EV sector was still in the initial stage of large-scale production. Pilot cities had to conduct comprehensive and systematic investigations into all aspects of uptake and establish an accident warning information system to increase EV legitimacy (MST et al., 2011b). As a result, improvements launched at the end of 2011 were intended to establish fair competition in the market and clean up existing local policies that discriminated against foreign products. Furthermore, EV manufacturers had to speed up development and production, and improve sales and after-sales services, while a battery recycling scheme with tracking systems had to be established by both EV and battery manufacturers (MST et al., 2011a). In December 2011, the National Development and Reform Commission revised a 'Foreign Investment Catalog' that divides FDI into three groups: encouraged, permitted, and restricted. Conventional automobile investments were removed from the catalog, and EV investment was placed in the 'encouraged group' (NDRC, 2011).

According to Howell, Lee, and Heal (2014), the results were far short of the goals, with fewer than 12,000 EVs reaching the roads – 6% global share – by the end of 2012 and approximately 40,000 (including 8000 privately owned vehicles) by the end of 2013. Besides global problems, such as battery costs and low mileage range, China had four additional issues that slowed down progress. There was a lack of capacity to create or transfer state-of-the-art EV technology, and trade barriers hindered foreign companies from entering the market efficiently. Moreover, China's trade barriers between provinces blocked the creation of sufficient supply value chains, and the government's focus towards high-end EVs resulted in overlooking the fast-developing low-speed EVs. Contrary to the government's plan to leapfrog and take a leading position, China had fallen behind in EV readiness. Krieger et al. (2012) measured this by considering 'countries' supply and demand sides. According to this analysis, Japan and Germany overtook China in 2010, which had only been behind the USA and France two years earlier.

The 5 billion yuan subsidy fund was enough to cover more than 83,000 vehicles, but the results were disappointing. By estimates, only 500 vehicles were privately owned, in Shanghai only ten, for example. The main reasons were a higher price than conventional vehicles and inconvenience in daily use (China Auto Web, 2011). In addition to state policies, municipal governments introduced their own stimuli. In Beijing, electric car buyers were excluded from the license plate lottery, the goal ofwhich was to cut new car sales in congested cities (China Daily, 2013).

Unrelated to the policies that the government introduced in this period, yet connected to the sector, was a dispute in the WTO over Chinese export restrictions of 'rare earth' elements. These are crucial in EV and other renewable sectors. The USA, formerly one of the biggest producers, stopped mining activities in 1998, which gave China a monopoly – with over 90% of world production. Export restrictions were advocated as pro-environmental, but also to be considered was that these only harmed foreign countries. An additional argument that restrictions were used as political and industrial tools was indicated by the ban of 'rare earth' exports to Japan during the territorial dispute of2010 (Wu and Salzman, 2014).

5.2. AFTER 2012

The weaknesses in the policy from 2009 were addressed in the 'Energy Saving and New Energy Auto Industry Development Plan 2012–2020' (Table 4). The premises ofthis were that technological and transformational upgrading in the automobile sector was an important task in terms of economic growth and international competitive advantage (Howell, Lee, and Heal, 2014). The goal was production of 500,000 EVs in 2015 and 2 million in 2020. The policy also addressed the pollution created by vehicles with internal combustion engines, and it was advocated that the fuel used per 100 km should decrease to the proposed international level in 2020 (State Council, 2012). The policy suggested five groups of tasks. The Ministry of Finance and Ministry of Industry and Information Technology introduced this supporting policy with additional funds (MF and MIIT, 2012). The first supported technological innovation in the sector and the second newly designed and developed vehicles. Funds could be assigned to different technical teams that combined industry, academia, and research institutions. To ensure projects' continuity, funds were disbursed in batches: 40% after the plan's implementation, 50% after mid-evaluation of the project had passed, and the last 10% at the end. The same ministries supplemented this policy with additional application conditions (MF, 2012; MIIT, 2012). Companies should have strong R&D capabilities, which in the last two years had accounted for at least 3% of the primary business income. They should also have key-parts supply systems and after-sale service systems, and their production should pass ISO 9001 and ISO/TS 16949 quality system certification. In the frame of these policies, additional subsidies for pilot cities to accelerate sectoral development were proposed in 2013 (MST et al., 2013). To be subsidized, pilot cities had to have a cumulative number of at least 10,000 vehicles in mega-cities and 5000 in other cities in the period between 2013 and 2015. The number of foreign brands – that is, nonlocal – should not be less than 30%, and obstacles placed in their way should be removed. The purchase of new vehicles by public institutions was not to contain less than 30% of EVs, and manufacturers could also gain subsidies for each unit sold.

In September 2013, the State Council issued the 'Air Pollution Prevention Action Plan,' which included promoting EVs in the public sector and encouraging private purchase with financial subsidies and through the granting of car licenses. Additionally, more than 60% of all public buses in Beijing, Shanghai, and Guangzhou had to be electric or 'clean fuel' (State Council, 2013). At the end of 2013, the government decided to increase the number of pilot cities (MF and MIIT, 2013), and new policies for public purchase were introduced six months later (MF and MIIT, 2014b). The share ofnew vehicles purchased gradually increased from the 30% that had been set in 2013. The charging facility ratio for EVs had to come closer to 1:1, and every new parking area had to offer charging services. Finally, both public and educational activities had to increase awareness of EVs' importance for the environment. Five years after the first significant plan and two years after the second, the State Council announced the third plan (State Council, 2014). This consisted of twenty-five specific points in six chapters: construction of charging facilities; guiding manufacturers towards innovation in their business models; public services promotion; policy improvement; elimination of local protection; strengthening of technological innovation and product quality. The proposed innovation was tax exemption for EVs (MF and MIIT, 2014), introduced at the end of the year, covering the period 2014–2017. The plan was joined by two additional policies at the end of 2014. The first of these announced the second batch of pilot groups (MIIT, 2014), increasing their number to thirty-nine. The second related to the construction of extra charging facilities (MF and MIIT, 2014a), working as a reward for pilot cities with outstanding results and no local protectionism.

5.3. LOCAL POLICIES

In China, EV policy followed its development formula with an experimental strategy for localized pilots to initiate systematic reforms. Based on Chinese gradualism's central metaphor, '*crossing the river by feeling for the stones,*' this approach allowed the testing of different development models, of which the most successful were later reflected in national policy (Goldstein, 1995; Marquis, Zhang, and Zhou, 2013). Thus, the policy came from central government 'top-down' or from local government 'bottom-up', and each pilot city could choose its strategy, as illustrated in Table 3.

Table 4: Energy Saving and New Energy Auto Industry Development Plan 2012–2020

Policy targets:	Description:
Energy-saving and EV technology innovation project	– Link national science and technology programs with the technological innovation system. – Public and private collaboration (especially on batteries). – Provide shared test platforms, development databases, and the standard collection of relevant patents for firms so they can invest more in R&D and promote cross-industry collaboration.
Scientific planning of industrial layouts	– Establish conditions to implement R&D in production. – Develop new EV production capacities according to actual needs. – Establish a battery cluster with large-scale production companies that have continuous innovation capabilities.
Improvement of pilot cities program	– Widen pilot cities' scope to large and medium-sized cities, supported by a new subsidy policy. – Search for a dominant model for battery handling and promote business model innovation for battery leasing, charging, and replacement services. – Promote research for EV alternatives (e.g. fuel cell).
Charging facilities construction	– Create a new development plan. Every new urban planning must include charging facilities. – Encourage pilot cities to use the government's offers and actively use other funds.
Improvement of standards and support policies	– Build a technological innovation system by funding technological development, standard-setting, and market application. The goal is to integrate production, research, and supporting institutions to accelerate advancement. – Improve 'punishment' policies for vehicles powered by fuel. – Support for financial institutions that participate in EV projects, e.g. risk compensation. – Establish a cross-disciplinary multi-level talent training system (e.g.,product development, business management, intellectual property rights, electrochemistry, vehicle engineering), and encourage companies, universities, and scientific research institutions to recruit talents from abroad. – Stimulate international collaboration between manufacturers, universities, and research centers, so the inflow of missing knowledge can be generated. – Provide support for firms in internationalization processes, e.g., trademark registrations and acquisitions.

The pilot cities used their individual characteristics as a starting point and designed specific models based on different business models. Beijing used strong public and private collaboration experiences to build an industrial base (Marquis, Zhang, and Zhou, 2013). Shanghai created an EV rental business and an international demonstration zone to attract private investment. The latter was the only internationally orientated program and included testing zones, data collection, and a network of science scientists, manufacturers, and energy suppliers (Marquis, Zhang, and Zhou, 2013). In Shenzhen, the local government actively promoted industry development and introduced a financial leasing model to reduce purchase costs. Hangzhou decided to start renting both vehicles and batteries or just batteries.

Additionally, battery switching was implemented. Chongqing invested in fast-charging batteries (Marquis, Zhang, and Zhou, 2013).

In August 2011, two years after the project started, all pilot cities were far from fulfilling their plans, with average progress of 26% (Gong, Wang, and Wang, 2013), and the national government intervened with a policy to strengthen these projects (MST et al., 2011b). The city with the greatest progress (55% of its plan) was Hefei, whose local policy gave an additional 10,000 yuan per vehicle on top of the national subsidy from 2010. The strategic alliance for technological innovation was formed with twenty-four manufacturers, key universities, research institutes, and financial institutions. The aim was to increase collaboration and to build brands (Anhui Province 2010). In 2012, the '*Ten Cities, Thousand Vehicles'* program came to an end, and the national government transferred it into national policy. Owing to the diversity of the pilot projects, standardization was hindered. The city pilot strategy therefore did not manage to jump-start a national EV industry, and consequently leapfrog (Marquis, Zhang, and Zhou 2013).

5.4. REGIMES ANALYSIS

A thorough analysis of both periods' policies allows a comparison between policy mix suggestions. Figure 3 displays the number of policies targeted in each category, and this indicates the government gave more attention to knowledge and financial investments in the second period than in the first one. For a more precise picture, policy descriptions from Table 2 should be compared with the recommendations presented in Table 1. Relevant to the knowledge category, Binz et al. (2017) suggest that governments should fund R&D programs, help integrate innovative solutions into products, and create an ecosystem that supports private start-ups. In the period prior to 2012, the government did not address knowledge creation, only encouraging firms to patent their inventions. In the post-2012 period, knowledge was addressed on different levels; promoting scientific planning, supporting innovation projects, increasing R&D expenses, and establishing national grants. In this latter period, the government clearly targeted manufacturers and a wider range of actors involved in innovation. Similarly, in the financial investment category, policies continued to support purchase and manufacturing as in the first period. The government tried to motivate other actors in the financial system to participate in the sector's development. These approaches fit with the framework's recommendations.

Regarding technology legitimacy, the proposal in the second period was to implement international quality certificates and standards, together with promotional activities aimed at customers. The market access category received most interventions and covered most of the recommendations in the framework. It is worth noticing that in the post-2012 period, the government addressed negative practices and shortcomings. Notably, the elimination of local protectionism hindered sales across provinces and created local monopolies.

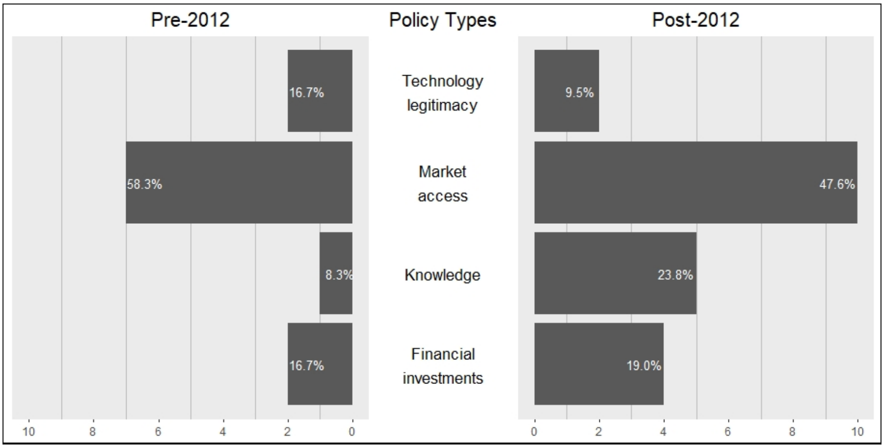

Figure 4: Policy regimes comparison

5.5. EVALUATION OF POLICIES' IMPACT

As presented in the previous sub-chapters, the policies were very fragmented, coming from different institutional stakeholders and different levels – e.g. Ministry of Finance, Ministry of Industry and Information Technology, local & national level. Thus, it is hard to draw causal effects of a particular policy on either market or technological development. Yet, by combining the findings from other scholars and chapter 4, it is possible to get insights into the sector situation and its development. Although China introduced R&D incentives for EVs back in 1991 and continued to do so in each five-year plan, manufacturers came in the production phase with a lack of required knowledge (Howell, Lee, and Heal, 2014). In fact, in the early stages, technological readiness was more critical than market development (Zhou, Zhang, and Ding, 2015), opposite to the primary targets ofthe 1st period – production & demand. Several scholars identified problems with R&D subsidies that were mainly given to state-owned firms (Zheng et al., 2012), which were not as innovative as private firms (Howell, Lee, and Heal, 2014). However, the correction in the 2nd period increased the number of patents, and more than 3000 invention patents were granted in 2015. According to Kennedy (2018), most ofthem were not significant innovations or only locally registered patents developed elsewhere. This goes in hand with Hain et al.'s (2020) findings that showed only minor technological improvement in the studied period. On the other hand, in the second period, the firms reached a sufficient level of technological readiness and consequently started to produce EVs. Similarly, there was a slight improvement in battery costs and range (Chapter 4.2). The main incentive for technology development in the first period – a requirement to patent – was supplemented with a minimal share of R&D in income, scientific planning, and innovation projects (Table 2). A proactive market and demand incentives from the first period did not generate the desired results (Zhou, Zhang, and Ding, 2015; Figure 1). Some pilot city projects were more successful than others. Still, by pursuing local goals, many ofthem introduced regulation for local patriotism (Li, Yang, and Sandu, 2018), which the central government later addressed in the second period (State Council, 2014; Chapter 4.4). Subsidy programs had a few critical problems in the first period, e.g. only in 2010 first subsidies were offered to private customers, and many customers were not eligible to use them. Despite the improvement in the second period, at the end of 2015, only one-third of the buyers were private customers (Howell, Lee, and Heal, 2014). In addition, the policies and incentives were forcing the production and demand with an inadequate level of technology, resulting in high expenditure with the relatively low outcome and unbalanced development (Chapter 4.4). Finally, the incentives for production and consumption were not balanced with incentives for infrastructure, causing an insufficient number of charging stations. Policies in the second period enforced faster deployment of charging stations, which resulted in faster growth after 2015 (Cheng and Tong, 2017).

6. DISCUSSION

In China, the leapfrog strategy towards e-mobility and its goals were promising, but an in-depth analysis of policies raises many doubts. In the first period, policymakers neglected creation and knowledge sharing, focusing mainly on starting production and creating demand (Figure 3). In the second period, the government stimulated scientific planning, strengthening innovation and R&D (Table 2), which covered most of their framework's recommendations (Table 1). In both regimes, policies addressed domestic demand and production, but there was a lack of export support. Nevertheless, the government encouraged trademark registrations and cross-border acquisitions during the later period.

According to Hain et al. (2020), China started production with low technological knowledge and took a market development path. Although they became the market forerunner, they were not sector leaders, mainly owing to technological inferiority. Import restrictions (State Council, 2006) meant that knowledge transfer from abroad was insufficient, which hindered R&D capabilities. The government addressed this in the 2012 plan, which supported internationalization processes through trademark registrations overseas and international acquisitions (State Council, 2012). Additionally, focusing exclusively on the domestic market meant that manufacturers were far behind the international market leaders, who were responding to the demand for more efficient EV vehicles. The government created demand, but customers lost the ability to choose the best products because of import restrictions and local patriotism. Filling the local – less demanding – market did not compel manufacturers to innovate. This was unlike the mobile phone sector, in which Chinese consumers were always free to buy top foreign brands: domestic manufacturers were therefore forced to innovate (Liaogang, Chongyan, and Zi'an, 2007).

The government created indigenous GWOs by promoting technology that began a new catching-up cycle in the automobile industry, but a dominant design failed to emerge. Like in other green sectors, the goal was to create synergies between economic opportunities and climate policy demands. The EV solution presents a disruption to the automobile industry, and according to theory, a new catching-up cycle allows taking over a leadership position (Morrison and Rabellotti, 2017). Similarly, the government's response to negative policies' outcomes and its frequent interventions goes along with theoretical recommendations (Ernst, 1998; Åhman, 2006). Compared with Binz et al. (2017) policy recommendation, especially in the second period, there are no significant policy inconsistencies. Yet, the sector's development is more a successful domestic deployment story than a successful technological catching-up story in the global economy. Significant institutional support was needed to stimulate production and demand. If the sector mainly consists of private customers and not big public projects, performance and price factors are more important in the purchase decision process. This could explain the slower development of electric passenger vehicles compared to the faster development of the e-bus subsector.

7. CONCLUSION

This paper examined the evolution of the policy regime for EVs in China during the formative years of the sector's development (2009–2015). This was done to bring out insights regarding the relationship between policies and sectoral trajectories in the context of newly established green industries in latecomer countries. In particular, the question ofhow the EV policy regimes evolved during the initial stage ofthe sector development was analyzed by focusing on differences between two phases in China's policy before and after 2012. The key conclusions are threefold.

First, 2012 was a real inflection point with a major step-change in terms of policy. The first period was characterized by traditional supply and demand mechanisms from the industrial policy toolbox and less by the government's active and dynamic role in resolving obstacles that hindered the sector's development (cf. Rodrik, 2004). In the second period, policy targets were expanded and paid particular attention to 'learning failures' by addressing knowledge-creation within firms as well as collaboration between firms and scientific institutions. Moreover, by stimulating knowledge sharing and reforming subsidy programs, new linkages appeared between actors in different sectors – e.g. the battery sector, the automobile sector, and IT companies.

Second, apart from this key change in policy regimes, there was a significant adaptation to sectoral developments within the two periods, not least in the second period. It is noticeable that the government frequently addressed shortcomings immediately when they emerged as opposed to waiting until the policy period would end. Due to the significant technological uncertainties during the 'era of ferment,' the government had to constantly adapt the policies throughout the whole period to ensure the sector's development. This adaptive intervention approach continued during the entire period (see also Jin et al., 2021).

Third, the changing policy regimes had a profound influence on the sectoral trajectory as well as on the relative degree of industrial leadership in the global sector. To bring this out, we distinguished between market leadership and technology leadership. Policies in the deployment stage provided a foundation for the attainment of significant market share. By 2015, China surpassed the USA in EV stock, with 32% of the global share. However, the policies in the first period did not create technology leadership, and while policies in the second period made advanced, they did not bring the country to the forefront. China entered the production stage with a low degree of novel knowledge, and despite becoming market forerunner, the level of novel knowledge did not improve to reach global frontier levels. However, this does not imply that no knowledge is needed for market development. In fact, the analysis showed that insufficient technological readiness hindered market development. After the government's requirements for R&D investments, scientific planning, and collaborations, firms built up innovation capabilities and, consequently, start production. On the other hand, pilot city projects and limited foreign supply resulted in local protectionism with limited competition. In an environment without proper competition and where both supply and demand receive subsidies, firms had insufficient incentives to channel green rents into innovations.

These conclusions make several contributions to the literature on green windows of opportunity. Unlike prior studies of green opportunity windows, such as of the solar PV sector (Binz et al., 2020) and wind industry (Dai, Haakonsson, and Oehler, 2020), the EV sector did not have a dominant design during market formation in the first phase, and therefore the higher uncertainty and changes had to be frequently addressed. The chronological policy review reveals the constant proactivity from the government, which addressed the changing environment was critical in this context.

Furthermore, the EV sector has different demand characteristics. Compared to other sectors where the decision for purchase lies only with professional users at the institutional level, in the EV sector, it is also at the level of household consumers. The key point is that policies were able to sequence between different types of demand. The main engine of purchase of EVs in 2015 was still public institutions, which implies that for the successful deployment of EVs, the performance gap between EVs and traditional solutions should be significantly smaller. The analysis showed that deployment did not start regardless of stimulating purchase subsidies but only after manufacturers improved their technological readiness.

Chinese intervention in the EV sector can be seen as creating a GWO for domestic take-off. However, the core technology was not yet mature enough at this stage, and hence the government had to address all aspects of the ecosystem. The policies evolved from traditional green industrial towards broader policies that enable catching up by combining climate and economic goals. The first creates a demand for a technological solution that is still economically less efficient than dirtier solutions. The second enables knowledge transfer and creation, and the third boosts production to fulfil the demand. The case shows that strategies and initiatives related to responding to initial green window opportunities based on building basic production capacity were insufficient for technological capabilities upgrading and deepening. This required a gear change of policies that regulated several components in the sectoral environment (cf. Lema, Fu, and Rabellotti, 2020).

This paper studied the period from market formation until leadership in deployment, but it does not cover the most recent period. After 2015, the government continued to support the sector, which rapidly advanced, particularly in the domain of technological development. In the same period as EV technology reached competitiveness with traditional internal combustion engine technology, Western manufacturers – especially those from the EU and the US – increased their engagement in the electric mobility space. Despite the fact that deployment of EVs in China was costly and took lots of policy experimentation, they may now be better positioned than other emerging economies. However, although there are indications of technological upgrading (Jin et al., 2021), this study has not endeavoured to assess the latest development in catching up. Furthermore, China is an 'extreme case' whose model is hard to replicate in other latecomer countries. Although it is not the only emerging economy that introduced EV policies, it seems to be the only one that fully developed the market deployment system to a global leadership level. Future research needs to understand better the prospects for catching up in other emerging markets and how lessons about government interventions and institutional support in China can be adopted and adapted elsewhere.

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ARTICLE C

From Transaction to Co-creation in Geely's Acquisition of Volvo Cars: Impact on Innovation Output and Market Performance

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The paper is currently under review.

From Transaction to Co-creation in Geely's Acquisition of Volvo Cars: Impact for Innovation Output and Market Performance

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Abstract
The recent decade has witnessed numerous cross-border mergers and acquisitions (M&As) undertaken by emerging market multinational enterprises (EMNEs). Only a few EMNEs manage to co-create with the acquired partner by mobilising and enhancing their knowledge resources. This paper centres on how post-M&A co-creation is achieved and what its impacts are for the innovation output and market performance of firms. We employ an in-depth longitudinal case study of the acquisition of Volvo Cars by Geely supplementing the case study with patent portfolio analysis and business analysis. We link innovation and cross-border M&A literature to address the co-creation phenomenon of post-M&A. Findings show how the high level of freedom given to the acquired firm allowed it to preserve innovation capacity and, later, successfully integrate it with the acquirer. The patent portfolio analysis demonstrates that the firms' innovation outputs overtime became more similar, proving a successful knowledge integration achieved in the case.

Keywords: cross-border M&A, co-creation, Geely, Volvo, innovation output, market performance

1. INTRODUCTION

Emerging challengers are developing fast and gaining resources they are eager to put to use. As a result, the popularity of cross-border mergers and acquisitions (M&As) has been steadily growing among emerging market multinational enterprises (EMNEs). In addition to providing access to Western markets, M&As may also become a source of technical manufacturing capabilities and advanced knowledge for EMNEs, particularly when these assets are scarce or difficult to develop in the domestic market. Although the M&A transaction often generates positive effects on the stock values, multiple challenges exist that pose a risk for creating added value and sufficiently integrating the acquired assets (Deng, 2009; Li et al., 2016). One of the ultimate sought-after outcomes can be co-creation, where both parties dedicate resources to create new knowledge leading to new value creation, delivery and capture. Numerous studies rely largely on quantitative methods to identify different elements affecting cross-border M&A performance and focus on financial indicators, stock market reaction, patents and acquisition data (e.g. Hain et al., 2016; Wang et al., 2020; Song et al., 2021). However, this approach lacks a deeper understanding of the processes and relations between the actors.

Thus, in our investigation, in addition to quantitative methods (used in later parts related to the patent portfolio and technological base analysis of firms), we employ a qualitative approach based on an in-depth longitudinal case study of the cross-border acquisition of Volvo Cars by Geely to delve deeper into the emerging developments and their trajectories over time. M&A is a complex process that creates uncertainty for both firms, and in the case of EMNEs acquiring Western firms, various types of not only geographic but also cognitive distances may make the transaction convoluted. Geely, however, managed to integrate acquired assets and change a poorly perceived image at the beginning into a positive story. Our research investigates the process that led to this outcome and seeks to answer the question: *How can EMNEs transition from a fragmented and transactional relationship with the acquired firm to integration and co-creation?*

This main research question is further supplemented by two sub-questions seeking to uncover and better understand the post-M&A changes in the firms’ 1) patent portfolios and technological base and 2) market performance.

With regards to the first one, the co-creation by both actors requires more than the capture of successful assets and involves integration across multiple dimensions, including innovation processes. The uncertainty present in the acquired firm after the transaction has to be addressed correctly to prevent a brain drain and other possible negative outcomes that may manifest post M&A. If these issues are successfully overcome, then one of the desired outcomes of innovation activities post M&A can be reflected in the number of newly filed patents. Another, and perhaps even more important, indication of successful integration will be seen in how the patent portfolio and technological base of both firms will become more alike. We look at this aspect of convergence in relation to knowledge co-creation in the innovation processes post M&A and seek to answer: *How does M&A influence the similarity between the patent portfolios and technological base of firms?*

With regards to the second one, from the extant literature (e.g. Boateng et al., 2008), we know that in cross-border M&As, although actors enter the deal with different technological bases and positions on the markets, both can often can gain access to the new markets. However, due to their different starting points, actors cannot transfer knowledge in the same way, and consequently, their market performance will differ. Over time, this situation may change and co-creation may have an influence on the market performance of firms. We therefore seek to answer another sub-question related to this aspect: *How does knowledge co-creation influence the market performance of actors?*

The remainder of this paper is organised as follows. In Section 2, we review existing literature on cross-border M&A, with a focus on organisational integration. In Section 3, we present the methodology consisting of the qualitative and quantitative parts. Following this, in Section 4, we describe the case, followed by Section 5 analysing the processes that led to the co-creation and its effects. In Section 6, we conclude the paper with a summary of our key findings and their relevance for companies and scholars conducting research in the cross-border M&A context.

2. THEORETICAL AND CONCEPTUAL CONSIDERATIONS

2.1 CROSS-BORDER M&AS AND EMNES

The M&A literature appears to be vast and overlaps with diverse literature streams. According to Dezi et al. (2018), there are two main study streams focused on M&As: economic and corporate. The economic approach explores the overall impact of M&As on the economy and the economic system, ranging from purely financial-based studies on M&A transactions and shareholders to ‘industrial organisation’ studies exploring firms’ structure and how it affects performance (e.g. Coeurdacier et al., 2009; Kiymaz & Baker, 2008’ Guo & Clougherty, 2020). Meanwhile, the corporate approach investigates firms involved in M&A, focused especially on their strategy and behaviour (Guo, 2013; Chen et al., 2015; Alvstam et al., 2019). In the scope of this study, we undertake a more corporate management approach to the literature and focus on corporate strategies that may impact the performance of an acquisition in a specific case. To do so, we consider the literature on cross-border M&As from emerging markets and their cultural impacts as well as on post-merger integration and restructuring.

Cross-border M&As have interested scholars and practitioners for many decades. However, it was only relatively recently that this practice gained popularity among emerging market firms who, through M&As abroad, seek to avoid institutional constraints, gain access to new markets and upgrade their existing technological base—also called knowledge base (Luo & Tung, 2007; Mathews, 2006). Some studies (e.g. Liu & Deng, 2014; Alon & McIntyre, 2008; Deng, 2012) found that cross-border M&A was the primary internationalisation mode for Chinese firms who, among other reasons, were motivated to choose it because of the government policy 'Go Global', which promoted outward foreign direct investment (FDI) (Ström & Nakamura, 2014; Wang et al., 2012). Despite outward FDI targeting both developed and developing countries, there are differences between the types of businesses targeted in different localities. In developed countries, the main focus is advanced technology and high-end brands, whereas in developing countries, firms look for infrastructure projects (Liu & Deng, 2014; Kaplinsky & Morris, 2009). Guo and Clougherty (2020) tested the effect of cross-border M&A on Chinese domestic productivity, and their results showed a positive effect. Note that high-tech and business-related targets have more decisive influence than do low-tech and unrelated targets.

The reasons for the new wave of cross-border M&As can also be linked to an increased competition at the local level and the rise of the information and communication technology industry. Hence, maintaining a competitive edge (Hitt et al., 1998; Hitt, 2000; Useem, 2009) and responding quickly to the fast-paced global economic environment (Andersen, 1997; Kogut & Singh, 1988) have become crucial. However, cross-border deals are not a guarantee for success. Many barriers are in the way of EMNEs seeking to benefit from their cross-border acquisitions. Several studies have identified a lack of familiarity with economically developed markets, which increases uncertainty among prospective advanced markets targeting stakeholders (Rui & Yip, 2008; Tingley et al., 2015). As a result, this uncertainty lowers the performance of the deals (Aybar & Ficici, 2009) or the integration levels that prevent knowledge transfer (Rao-Nicholson et al., 2016; de Beule et al., 2014; Rao-Nicholson et al., 2016b), with deal abandonment occurring in more extreme cases (Zhang et al., 2011).

Caiazza and Volpe (2015) identified three main research areas common among prominent studies on cross-border M&As: 1) Factors affecting M&A decision, 2) Organisational and cultural integration and 3) Assessment and performance indicators. Recent research argues for a closer look into the M&As of EMNEs in advanced markets because of the presence of information asymmetries that affect cross-border M&A success (Heinrichs & Dikova, 2019). In response to this and similar calls, this paper looks into the process of integration and performance indicators post M&A between a Chinese EMNE and an acquired firm from the western market.

2.2 POST-M&A INTEGRATION AND CO-CREATION

Among the factors that may affect the process of integration in cross-border M&As, cultural factors are extremely important. According to numerous studies (e.g. Datta & Puia, 1995; Bauer et al., 2016), cultural differences highly determine the success of cross-border M&As. In nomothetic research with multiple cases, cultural differences are measured using Hofstede's cultural distance (Chakrabarti et al., 2009; Erramilli, 1991; Kogut & Singh, 1988), which was later expanded by House et al. (2004) to the Globe model. Both models have inconsistencies (McCrae et al., 2008; Venaik & Brewer, 2008), and generalising the culture of millions of individuals to the country's score is not always useful in decision making at a firm level. The majority of articles studying the effect of cultural factors on M&As are based on nomothetic research; however, 'case study contributions can be relatively greater by exploiting underutilized idiographic research benefits' (Bengtsson & Larsson, 2012, p. 150).

At the organisational level, resource-based view and institutional theory (Barney, 1991; DiMaggio & Powell, 1983) combined with the literature on organisational learning (Cohen & Levinthal, 1989) offer important insights into critical aspects of post-M&A integration. As mentioned above, the positive outcome of an M&A is not a result of acquired knowledge but rather the ability to absorb and integrate it into new products. Cohen and Levinthal (1989) defined absorptive capacity (AC) as the capability of a firm to recognise, assimilate and commercialise the value of external knowledge (i.e. exploiting external R&D).

In an attempt to strengthen the conceptual underpinnings of AC, Lane et al. (2001) further developed the three basic dimensions of the concept. In the perspective of joint ventures, cultural aspects and understanding the other party's knowledge were added to the first dimension of recognition. Assimilation was further expanded to the firm's flexibility, adaptability and management skills to enable it. Finally, the success of commercialisation relies on the management capability of both firms to strategically work together. Zahra and George (2002) further reconceptualised AC with the notion that it is kept in the processes—dynamic capability—rather than seen in financial statements. Consequently, the authors' four dimensions—acquisition, assimilation, transformation, exploitation—focus more on the quality of processes inside the firm to transform potential AC into realised AC.

With the increasing number of M&A, scholars started to analyse the role of AC in the success or failure of the transaction, focusing on M&As with technical objectives (Deng, 2010; Liu & Woywode, 2013; Jo et al., 2016). Deng (2010) analysed cross-border M&A and identified the ability to handle the acquired knowledge as a critical determinant in the deal's outcome. Furthermore, M&A success does not rely solely on administrative procedures but more on the post-M&A integration of processes that influence new products (Chen & Lin, 2011).

Taking the perspective of Chinese EMNEs, some studies show a limited knowledge transfer effect for Chinese firms' cross-border M&A (Gugler & Vanoli, 2015). In many cases, they neglect tacit knowledge, mostly due to the cultural differences and deficiency of talented staff (Ai & Tan, 2018). An essential factor for successful knowledge transfer is routine compatibility, which makes organisational unlearning a vital task (Wang et al., 2017). These processes tend to become even more complicated when Chinese EMNEs target firms from advanced economies (Zahra et al., 2011; Zhang & Stenning, 2014).

Another literature branch regards organisational behaviour, an individual-level perspective that mainly focuses on human resource management (HRM) and leadership. In the context of Chinese cross-border M&A, HRM constitutes one of the most understudied topics within M&A literature. Nevertheless, existing literature finds Chinese HRM practices unique and in line with their cultural norms, often used in their operation outside China to facilitate reverse knowledge transfer (Liu & Deng, 2014; Liu & Meyer, 2020). Similarly, leadership style is a key factor in the post-integration process, especially for talent retention (Zhang et al., 2015).

Many firms use M&A to acquire new knowledge and consequently increase their innovation output. Output quality depends on the sectors—better in technological—and knowledge base of both firms (Ahuja & Katila, 2001). Years after the integration, the positive effect on innovation output fades as the value of knowledge depreciates (Cloodt et al., 2006). Thus, the sought outcome should be the integration of acquired knowledge and the processes that generate it. We presume that joint development (co-creation) of new products out of the partners' regular processes can generate new knowledge and minimise the fading effect on innovation output. This outcome also enables learning from each other, especially the innovation processes.

Knowledge flow is crucial for better performance, and naturally, due to tangibility, it varies between service and manufacturing sectors (Heim et al., 2018). Finally, we define post-M&A co-creation as creating new products through knowledge and resource sharing by acquired and acquiring firms, not as a co-creation between a firm and its customers (Prahalad & Ramaswamy, 2004; Frow et al., 2015). However, collaboration and joint new product development do not necessarily increase market performance. Different post-M&A challenges, such as organisational culture, different approaches to innovate and different communication styles, could harm the process and result in the weak market performance of the new product (Chen et al., 2010).

Figure 1 presents the analytical framework of our study. The framework builds on the theoretical lenses of organisational learning and organisational behaviour (organisational-level explanations) as well as the role of employees and culture (employee-level explanations).

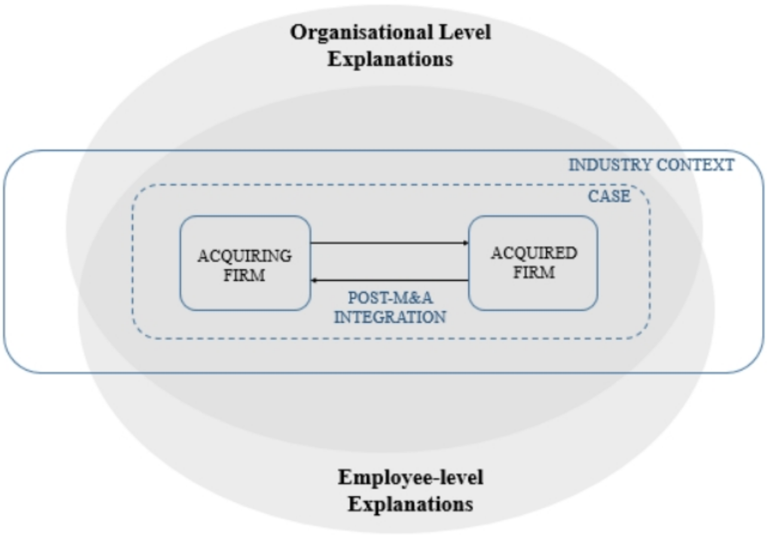

Figure 5. Analytical Framework of the Study

3. METHODOLOGY

3.1 RESEARCH DESIGN

Our research is designed as a longitudinal single-case study of Geely's acquisition of Volvo Cars with the post-acquisition process as the unit of the analysis. Following Pettigrew's (1990) contextualism, we studied the target of change at the firm level of Volvo and Geely and at the higher level of the automobile industry. The latter is important to take into account because the differences between Chinese and Western markets influence the decision-making process in the case. Newly established automobile brand Lynk&Co—the outcome of the co-creation process between Geely and Volvo Cars—was not planned at the outset of the transaction phase but rather emerged as a result of 'organic' development. Therefore, each interview was analysed as 'temporal interconnectedness', that is, not how well it explains the outcome but each separately as its own reality. The authors regarded the process that led to co-creation as a combination of the organisational processes that Geely and Volvo developed over time. Thus, Van De Ven and Poole's (2005) 'Process Study of Organizing' approach was adopted, and chronology was used as a way to organise the data with focus in the interviews on the past, current and future events within one of the entities as well as how these events were interconnected with the operations of the other entity.

In addition to a qualitative approach relying on interview data, we supported our investigation with a patent analysis to measure the similarity between the firms' portfolios in 2000–12 and 2013–20. The division point in the period marks two years after the acquisition to account for the time that may be required to establish innovation processes. We assumed that collaboration between both firms would increase their patent portfolio similarity, which is the similarity of the patents' international patent classification (IPC) codes. IPCs are unique features that sort patents in a hierarchical system of categories and sub-categories to determine patent technology. However, the IPC class of a patent does not entirely present the knowledge involved to produce the patent. Thus, we also calculated the firms' technological base, which could be used to evaluate the sector (Rosiello & Maleki, 2021) or knowledge (Han et al., 2018) of the firms. The success of M&As between similar technological firms depends on the technological base overlaps (i.e. target and acquirer overlaps). The firm's technological base is the knowledge that a firm is familiar with and uses to create new knowledge. It consists of a firm's patent and the patents cited by its patents (Sears & Hoetker, 2014). Given that knowledge relevancy decreases over time, we used only cited patents that were no older than six years from the first filing date of the patents. Hence, we compared both overlaps in the period prior to and after the transaction.

Finally, as the innovation output on its own may not be enough to judge whether the M&A is a success or failure, we also analysed the business performance of the firms after the transaction. For this purpose, revenue, number of employees and sales numbers were taken into consideration when performing the market performance analysis.

3.2 DATA COLLECTION

To develop the case narrative, three in-depth semi-structured interviews were conducted between 2014 and 2017. The first interview, which was also complemented with observations at the site visit, took place at Geely Group HQ in Hangzhou, China, with the Vice President of Zhejiang Geely Holding Group and the Senior Manager. The first part of the interview focused retrospectively on the transformation of Geely from a family business to a modern corporation, followed by the acquisition process and the relationship between both entities after. The second part of the interview targeted the processes within each firm and how they interconnect.

The second interview was conducted in 2016 with Senior Director from Geely Group. It also took place at Geely Group HQ in Hangzhou, China. The narratives were concentrated on the interconnected processes, culture and market differences that influence the processes and capture knowledge, learning and market values. The third interview was held in Shanghai, China, with Volvo's Design Operation Director in 2017. The questions in this interview focused on Volvo's view on the ownership transition from Ford to Geely, with a focus on the period after the transaction. Furthermore, the emphasis was on the differences in how Volvo is operating in Western markets compared to Chinese markets, what the role of Geely is in the daily processes and how new trends in the automobile market would change their business.

The secondary data used in the quantitative part of the study consisted of granted patents from 2000 to 2020. Data were collected from the Lens patent corpus (Lens, n.d.). For Geely, we searched for all patents, where the applicant was one of Geely Group's firms. In 2010, Geely acquired only one part of the Volvo Group (i.e. Volvo Car Corporation). Thus, we selected only patents that have Volvo Car as an applicant.

Aside from collected patents, different secondary data were used for the pre-interview preparation and chronological summary of the critical events.

3.3 DATA ANALYSIS

Primary data were analysed inductively using Burnard's (1991) 14-stage method[16] of analysing interview transcripts. The use of data analysis software allowed us to modify some of the steps. Firstly, we went through the interview notes and conducted open coding (stages 1–3). Next, the categories from the previous step were collapsed to higher-order headings, and sub-headings were rearranged to create the final version used for coding in the eighth stage. The sixth and seventh steps were integrated into the previous steps because the software allowed us to work together. Similarly, the software simplified stages 9–12. Produced visualisations were analysed in the same way.

The similarity between patent portfolios was measured using cosine similarity and Jaccard's coefficient. Each patent application contains at least one IPC class, which classify patents according to the technology areas they relate to. Each IPC is up to eight symbols long and comprises the combined symbols representing the section, class, subclass and main group or subgroup (WIPO, n.d.). If compared firms operate in a random industry, the first four digits of the IPC class would adequately demonstrate their similarity; however, for firms in the same sector—like our case study—the code would require the whole IPC class. Besides analysing the patent portfolios, we analysed the technological bases of the firms and their overlaps.

Cosine similarity is a metric that finds the angle between two vectors by calculating the inner product of the vectors divided by the product of their lengths. Its advantage is that the compared objects do not need to be the same size, and contrary to Euclidean distance, it is not based on counting the number of shared values. In our case, a vector with frequencies of unique IPC classes was generated for each firm separated into two periods from the collected patent data (Appendix A).

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[16] The original steps are 1. Taking notes, 2. Immersion in data, 3. Open coding, 4. Reduction, 5. Refinement of categories, 6. Collaborative checking, 7. Re-reading, 8. Re-coding with new categories, 9. Re-arrangement of text according to categories, 10. Re-arrangement according to sub-headings, 11. Informant checking, 12–14. Writing preparations and linking to existing literature.

$$\cos(\theta) = \frac{\vec{a}\vec{b}}{||\vec{a}|| \quad ||\vec{b}||} = \frac{\sum_1^n a_i \, b_i}{\sqrt{\sum_1^n a_i^2}\sqrt{\sum_1^n b_i^2}}$$

Jaccard similarity index (coefficient) compares the similarity of two vectors by looking at their shared and distinct values. Specifically, it is the division between the number of common elements and the number of all distinct elements. Contrary to cosine similarity, it disregards the frequencies but looks at the binary option; in our case, if a specific IPC subclass was used or not.

Jaccard's coefficient is

$$J(a,b) = \frac{|A \cap B|}{|A \cup B|} = \frac{\sum_1^n a_i b_i}{\sum_1^n a_i + \sum_1^n b_i - \sum_1^n a_i b_i}$$

The vectors used in similarity coefficients were transformed into binary values, in particular, whether the firm patented in a specific IPC subclass (1) or not (0) (Appendix A).

4. CASE DESCRIPTION

The studied acquisition of the Western automotive brand (Volvo Cars) by an emerging country multinational (Geely) was not a traditional financial or basic synergy-looking transaction (economies of scale and market price-earnings ratio) but rather a strategic M&A (Zhou & Zhang, 2011). The firms produced the same type of products but for different customer segments and had a technological overlap with minimal benefit on innovation capabilities (Ibrahim & El Katsha, 2017). Prior to the transaction in 2009, the companies had different development paths. Geely was founded in 1986 as a refrigerator manufacturer. While slowly expanding its production to inexpensive products and high-grade decorative materials, it entered the motorcycle industry in 1994. By the year 2000, it had reached a production of 600,000 units and was exporting to several countries, including the USA and European markets (Wang, 2008). Geely entered the automotive industry in 1997, and in the first decade, almost all its models were a result of reverse engineering. After 2006, Geely acquired a few foreign companies, including London Taxi, DSI and Volvo, and started its catching-up process in the Chinese automotive industry (Balcet et al., 2012). In the years preceding the acquisition of Volvo, Geely operated in several industries besides the automotive industry. These included tourism, trading, decoration materials and educational training facilities. With more than 30,000 students, the purpose of the latter was to produce human resources for different operations (Wang, 2008).

In contrast to Geely, Volvo had a long tradition in the automotive industry dating back to 1927 and played an essential role in the development of the industry. Its main activity was the production of cars, trucks, buses and construction equipment. In 1999, Ford acquired a part of Volvo that produced cars (Volvo Car Corporation) and formed Premier Automobile Group, which includes Aston Martin, Jaguar and Land Rover. The goal was to rationalise costs via modularisation but keep the brand from overlapping through separate promotions (Donnelly & Morris, 2003). The integration of Volvo and Ford's R&D had problems due to the differences in their decision-making process (Lundbäck & Hörte, 2005). Owing to the world financial crisis in 2008, Ford had to sell Volvo, and in 2010, the transaction with Geely was completed.

The acquisition gave Geely seven assets from Volvo (Intv. SVP&SM, 2014):

- Brand ownership and the right to use it on a global scale;
- 10 sustainable production platforms and upgrade strategies, including all the cars, commercial vehicles and SUVs;
- A brand-new scalable product architecture platform for mass production;
- Four factories producing complete vehicles;
- Manufacturing plants for engine, parts and transmissions;
- R&D system with 83 years of tradition (3800 engineers at the time of transaction);
- 10,933 IPRs involving engines, vehicle platform, safety and electronic technology (worth USD 1.6 billion as intangible assets on the balance sheet of Ford).
-

Although the synergies of the two automotive producers seem apparent at first glance, their obvious differences made the cross-border M&A a big challenge. For example, it took three years after the transaction for the negative coverage in Swedish media to switch to positive. The turning point was the increase in local jobs, boost in sales and the ability to retain the 'spirit of innovation' (Ward & Waldmeir, 2011; Fang & Chimenson, 2017). Notwithstanding the challenges, in February 2013, Geely announced the establishment of the China Euro Vehicle Technology (CEVT) R&D centre in Gothenburg, integrating Volvo's and Geely's resources. The aim was to create a new state-of-the-art modular vehicle platform called Compact Modular Architecture (CMA) (Yakob et al., 2018).

Table 1 shows the distribution of patents and unique IPC classes for both firms. The collected patent data were divided into two periods: before and after 2013 (i.e., before and after the establishment of CEVT).

4 Table: Distribution of patents and unique IPC classes

	Geely		Volvo	
	Period 1	Period 2	Period 1	Period 2
Number of patents	155	635	165	545
Unique IPC classes	218 (70)	910 (157)	385 (66)	956 (121)

(Numbers in brackets indicate unique four-digit IPC classes.)

Similar to the general public, the markets also did not perceive Geely's move positively at the beginning. In the first months after the announcement, Geely's stock prices decreased while Volvo's increased (Chandera & Widjojo, 2012). Over the next six years, the stock price ranged from HKD 1,5 and 4, with an exponential increase after 2016 (Figure 2). In that year, the new brand Lynk&Co was announced, and a year later, the first car model was offered across China (Lynk&Co, n.d.). In 2019, Lynk&Co became the fastest-growing automotive brand in the world.

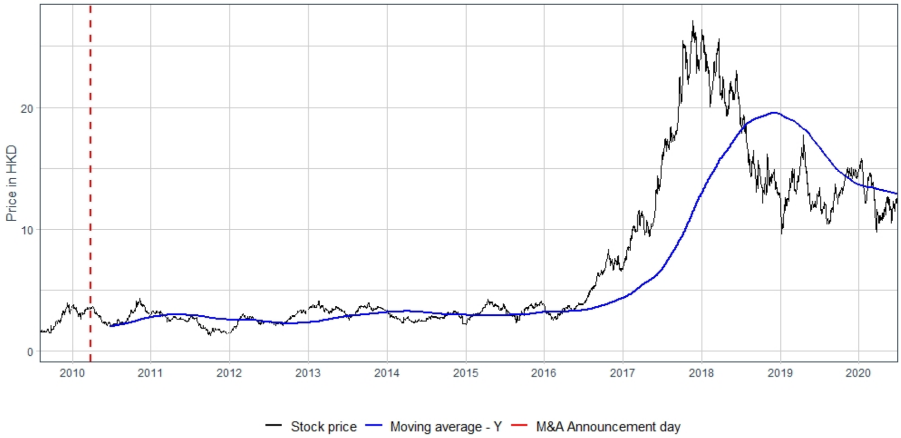

Figure 6. Geely's Stock Market Performance

5. ANALYSIS

The post-M&A period analysis, based on collected interviews and statements obtained from publicly available sources, is structured following the analytical framework of our study (Figure 1). It divides the post-M&A integration into organisational- and employee-level explanations of drivers and inhibitors of integration. In the second part of the analysis, we use secondary data to find traces of their actions and potentially evaluate the results.

5.1 ORGANISATIONAL-LEVEL EXPLANATIONS

In the decade before the transaction, Volvo had a turbulent time with increasing uncertainty. The financial crisis hit its owner Ford, who was required to sell it. The lack of investments over the years resulted in lower sales numbers and harmed innovation processes. Thus, on the one hand, Volvo needed a change, and on the other, there were significant concerns about its future and new ownership. Despite the fear over the new owner (i.e. Geely), Volvo's manager described the post-acquisition development as follows:

> *It was completely the opposite, and it still is. I mean, they came in, and we gave them a strategy and goals for the next 10 to 20 years. Basically, Geely said, 'OK, we will support you financially. We will make it easy for you to come into the Chinese market; the rest is up to you'. For the first time in many years, the Volvo management went, 'Hey, what do we do? We are free! We can do our own thing!' Of course, it took a little bit of adjustment*. (Intv. DOD, 2017)

However, there were still dilemmas that needed to be resolved at the organisational level. Firstly, it was a dilemma how to maintain Volvo as a western brand and to establish its position in the Chinese market. Soon after the transaction, they started planning new production plants in China, which allowed the export of China-made Volvo cars into the US market. The concern was that Volvo would lose its Scandinavian identity (Norihiko, 2011).

The second dilemma was caused by a different view on the future of the brand in Gothenburg and Hangzhou. Geely's owner intended to make Volvo compete with the high-level models of Mercedes and BMW with stronger engines (Yang, 2011). Volvo's CEO disagreed, pointing that this would be too early and would result in losing '*distinguishing points in its products*' and thus they should '*stop copying the Germans*' (Autocar, 2010).

Despite operating in the same industry, at the time of the transaction, the firms had a very different approach to developing cars. Geely managers were aware of Volvo's advanced technology, but they struggled with introducing it to their brand. The first big issue was customers' perception of the brand, as Geely started as a low-end brand, and in the eyes of many, it was a car for low-income populations. The manager described the hassle as follows: '*With that, we should be very careful. Volvo is a luxury brand, and in Geely, we want to go up, but at the same time, we are not Volvo…; currently, we have different customers'* (Intv. SD, 2016). The second issue was how to capture the value of the added technology and the increasing costs of R&D. The transaction happened in a long period of transformation from using reverse engineering to relying on in-house innovation. The value captured on the market could not cover the costs. As the manager put it: '*Incremental innovation in brand pricing power is not an easy question for us. It is hard to communicate to customers that I did something new and consequently increased the price and assume that the customer will accept it'* (Intv. SD, 2016).

According to the interviews, Geely was aware of Volvo's development capabilities and adaption to the changing circumstances. Thus, the primary strategy in the first period after the transaction was to give Volvo time and space to develop and provide financial capital to make this possible. The sales number started to increase in all markets and slowly grew over Volvo's production capacities. To be able to cover the demands from the US market, Volvo started to export China-made cars. Instead of a strategic decision at the transaction, the organic growth cause this to go largely unnoticed and did not harm the brand.

Similarly, the decision to change the model for the Chinese market was not imposed on Volvo. After a few media statements between both parties, Geely's owner took another approach. Geely's manager described it as follows:

> '*For instance, Chinese customers prefer larger and luxurious cars. So we suggested enlarging the Volvo cars by lengthening it by 10–20 cm in the China market, but Volvo engineers refused… Hence, Mr. Li (the owner) invited these engineers to come to China and experience the market'* (Intv. SVP&SM, 2014)

As a result, they developed model S60L, which was in short supply. The manager ended: '*The conflict in culture is solved by having respect and enforcing understanding'*.

If Volvo's transformation was mostly related to the transition to different environment settings, then the brand improving path of Geely was more complex and required more time. Manufacturers cannot improve the brand's position on current products but can on future vehicle models. In addition, if the change is too radical, then current targeted customers would not be able to afford the new model, and at the same time, the manufacturer cannot instantly reach the higher-level customers. Hence, Geely gradually improved their cars by introducing more innovative technologies and better design, both based on its collaboration with Volvo. Aside from many joint activities, in 2013, they announced a new R&D centre (i.e. the CEVT) in Gothenburg to build the CMA that will be used by both firms. Consequently, the new brand Lynk&Co was established, and the first cars came on roads in 2017.

5.2 EMPLOYEE-LEVEL EXPLANATIONS

Similarly, in terms of organisational-level tensions, the uncertainty of Volvo's employees evolved from their fear of bankruptcy due to Ford's poor financial condition into a fear of a new owner from a different cultural environment. Blue-collar jobs and engineers in the R&D department could be moved to China. This scenario would have had damaging consequences for them and for the local community at large. These concerns came from various directions, including media, politicians and labour unions (Billing, 2010; Radio Sweden, 2010).

The tension of Geely's employees emerged due to high expectations regarding how much they can gain from the acquisition. The aim was not solely to capture Volvo's technology but more to learn how to organise the processes that provide innovative technology. Therefore, the tension was not only on engineers but also on the management. As the interviewee puts it:

> '*I think that our leadership, the management, is aware of learning possibilities from our partners, Volvo, for example. I think some challenges are organising this learning and [knowing] how to implement the new processes into our system'*.

> He added:
> *'Geely is currently in the process of learning from other partners, especially in-house partners, about the organisation and developing processes. So in the new product development system, we are trying to implement things we are learning. For example, the stage-gate process…'* (Intv. SD, 2016).

According to interviewees from both firms, the main actions that helped reduce the concerns and fear among the employees were avoiding radical changes for Volvo after the transaction, ample time and independence at the management level and positive sales trends. One of the new owners' main goals was to maintain the innovative processes and not lose tacit knowledge; thus, a lot of the focus was on engineers. Looking outside the firm, it took three years for the sentiment of media coverage to change from negative to positive, and the turning point was the increasing head count at Volvo's plants in Sweden.

The tension on people in Geely mainly concerned engineers and management. Engineers had to absorb technological knowledge from Volvo and transform it into their product, and management had to learn, organise and integrate innovation processes. These complex operations involving various stakeholders are spread among different hierarchical levels and are difficult to copy, as it goes for dynamic and ever-changing tasks. Thus, firms decided to develop a new automobile brand—Lynk&Co—based on the commonly developed technological platform. By working together on most tasks, people could learn from one another and use accumulated knowledge and experiences in their primary brands.

Figure 3 summarises the results of the qualitative analysis connecting the dilemmas faced in the post-M&A period and their responses to the co-creation of Lynk&Co.

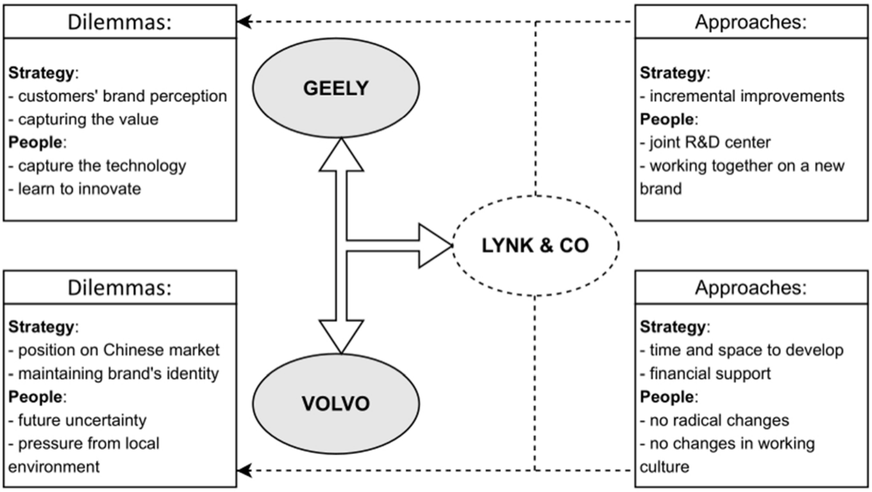

Figure 7. Dilemmas and Approaches in the Geely–Volvo case

5.3 PATENT PORTFOLIO SIMILARITY

To analyse the similarity between patent portfolios, we used cosine similarity and Jaccard's coefficient. The firms' portfolios, divided into two periods, enabled the comparison and showed if they became more similar after the transaction.

5 Table: Similarity between patent portfolios

	Cosine Similarity	Jaccard Coefficient
Period 1	0.178 (0.675)	0.081 (0.346)
Period 2	0.286 (0.778)	0.150 (0.463)

(Numbers in brackets are the results for the four-digit IPC class.)

Both coefficients show an increase in the second period. Cosine similarity increased by 61% and Jaccard coefficient by 85%. Looking at the four-digit level (subclass), the increases were 15% and 34%, respectively. The results show that after the acquisition, the patenting activity of both companies became more alike. This outcome could indicate that the collaboration in innovation processes widened the research focus to areas where either firm were not present before the transaction.

The similarity coefficients show a relatively high increase in the second period, but the measured effect is bidirectional. Thus, in the next step, we look at which firm 'entered' newer technological areas (IPC) in the second period, in which the opposite firm was already present in the first period. The results show that in the second period, Geely patented in 62 new IPC classes where Volvo was already patented in the first period. The same measurement for Volvo is 21.

5.4 TECHNOLOGICAL OVERLAP

The difference in innovation capabilities of the firms can be seen in the asymmetries in the acquirer and target technological overlap. The intercept of unique IPC classes between firms' technological base shows the common technological knowledge. Its share in each firm's base demonstrates the overlap. Geely's and Volvo's base consisted respectively of 781 and 1584 unique IPC classes in the first period, with 324 IPC classes in joint. At the transaction, Volvo had 41.48/% of Geely's technological base, and on the other side, Geely only had 20.45% of Volvo's.

The same comparison for the second period shows that Volvo decreased the overlap to 32.27% and, more interestingly, Geely managed to overpass the target firm with an overlap of 42.73%. Geely's base consisted of 2451, Volvo's 1851, with 791 unique IPC classes in common.

The similarity comparison of the firm's technological base shows a similar trend as the comparison of patent portfolios. Both coefficients—cosine and Jaccard—show the increase of similarity in the second period at 63% and 41%, respectively.

6 Table: Similarity of firms' technological base

	Cosine Similarity	Jaccard Coefficient
Period 1	0.346	0.159
Period 2	0.564	0.225

5.5 TRENDS AFTER THE TRANSACTION

The qualitative part of the analysis showed that the acquisition was successful for both firms. Geely managed to learn and adopt innovation processes from Volvo. On the other side, Volvo received necessary guidance and information about the Chinese market to improve its sales. With financial support and operating freedom, Volvo managed to re-set its business. The patent portfolio analysis confirmed that joint R&D activities might influence the patenting activities of the firms.

In the third step of the study, data from the annual reports and financial statements of both firms were analysed to test claims about the firms' operating performance after the acquisition. The data consisted of the number of employees, revenue and total sales for both firms. We added sales in China for Volvo and export for Geely. Sales number, including export, is the number of vehicles sold and not the sales in money value. All values were indexed to the year of the transaction (2010). Figure 4 accordingly shows the variables' dynamic.

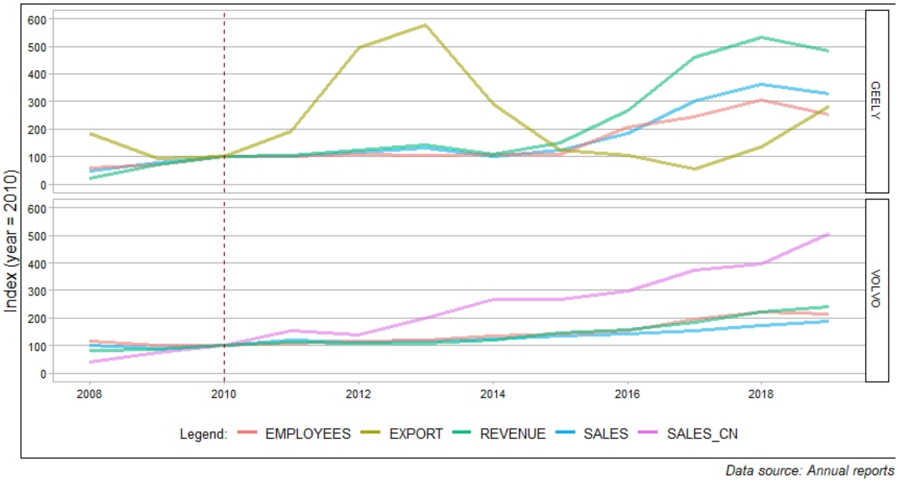

Figure 4. Business Performance of Volvo and Geely

Except for export, Geely's performance was relatively steady until 2014, and later all three variables started to increase with a similar path. In 2019, the number of employees increased by 150, sales by 220 and revenue by 400% from 2010. The export presents a minor part of Geely's sales (4.2% in 2019). Thus its fluctuation over the years is not that relevant. The sales numbers for the Lynk&Co brand are included in Geely's numbers, and they present 0.5%, 8% and 9.4% of Geely's total sales from 2017 to 2019, respectively.

Volvo's development path, except for sales in China, started to increase continuously after 2012, and in a decade, sales increased by 95, number of employees by 105 and revenue by 150%. The sale in China continued its trend from the year prior to acquisition and, in 10 years increased by 400%, reaching a 22% share in total sales in 2019.

6. CONCLUSION

A few studies have analysed Geely's acquisition of Volvo (Chandera & Widjojo, 2012; Guo, 2013; Alvstam et al., 2019; Yakob et al., 2018; Zhou & Zhang, 2011) but mostly analysed it from a single methodological perspective. Thus, we tried to build on these studies, and with the use of methodological techniques triangulation—in-depth interviews, patent portfolio analysis and business analysis—answer the question '*How can EMNEs transition from a fragmented and transactional relationship with the acquired firm to integration and co-creation?'*
While the studied M&A is often used as a positive example of an EMNE's acquisition of a western brand, our interview data revealed many problems and obstacles that managers from both firms had to overcome. Most of these issues were associated with cross-border transactions, where cultural differences could be a deal-breaker. Thus, besides identifying the problems, we also focused on how they proceed to solve them. The paper identified the most critical issues at the organisational and employee levels, together with approaches to deal with them (Figure 3).

In the first (the transition group), the acquirer must deal with uncertainty and fear derived from prejudices. The uncertainty could be solved with actions that do not change the target's business but still normalises its operation, that is, revitalises the innovation processes. In the studied case, Geely asked Volvo's managers to prepare a short- and long-term plan, provided the finances and kept Volvo going with minimal interventions. The acquirer should not take prejudices 'personally' as they are not based on their actions but from cultural differences. Therefore, this situation could be slowly changed over time, with cautious actions and being aware that any negative action can break down the process. In Geely's case, it took almost three years to change the negative perception of the general public at the transaction to positive one.

In the second (the operation group), both firms have to enable learning from each other and integrate acquired knowledge within their operation. Firms most likely have a different technological base, so it is essential to understand the gap. Filling the gap too fast might increase the costs that cannot be directly put on the price of the products due to specific demand. The innovation process is complex, involving engineers and management, and thus hard to replicate. While it is not difficult to transfer codified knowledge, tacit knowledge must be transferred through the interaction between the employees of both firms. In the studied case, both firms opened a new joint R&D centre in Sweden to develop a new platform for their future models. Later in 2016, the project resulted in a new car brand Lynk&Co.

Although both groups are essential, the operational group dictates the long-term dynamic between both firms. The approach to learning from each other and co-creation should leave traces on the knowledge output. Therefore, we tried to answer *how the transaction influenced the similarity between the patent portfolios and technological base of firms.* The patent portfolio similarity analysis showed that after the transaction, firms' portfolios became more alike. The same trend was observed in the technological base, which is required to produce knowledge. Interestingly, if Volvo's base was bigger in the period before the transaction, then Geely managed to increase its base in the second period. They likewise managed to overtake Volvo in the variety of knowledge they used to create patents. It is worth mentioning that in our analysis, we did not measure the quality of the output but only the quantity. We can conclude that Geely managed to capture the established knowledge and learn and integrate innovation processes. Aside from technological knowledge, it is crucial in cross-border M&A to share information and experiences about markets not known to partners. Volvo's managers emphasised vital information about the Chinese market gained from Geely. These include knowledge about customers, car parts distributors, marketing and human resources.

Finally, knowledge output does not determine the success of a business. In the last stage, we analysed the firms' performance between the 2008 and 2019 (Figure 4) to answer *how knowledge co-creation influenced the market performance of actors.* The results show that Volvo's performance was steady until 2013 and later started to increase at the same pace. The only variable that grew faster was the number of vehicles sold in China, which proves that Geely's information helped set a successful strategy. In turn, it took Geely five years for figures to start showing a positive trend. In the automobile industry, new solutions can only be introduced in the next generation of vehicles. Consequently, it takes some time for new knowledge to affect business performance. Figure 4 shows that the trend increased after the new brand was introduced in 2016. The only variation was the number of vehicles sold abroad, which presents a small margin in total sales and is, therefore, more sensitive to yearly changes.

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Appendix A: Details of the vector construction

A vector with frequencies of unique IPC classes was generated for each firm separated into two periods from the collected patent data. E.g., the number of appearances of IPC subclasses in patents by Geely and Volvo for period 1 (presented as 4-digit IPC class):

Cosine similarity

IPC	B01D	B23Q	B23K	B24B	…
Geely p1	1	0	4	4	…
Volvo p1	12	3	5	0	…

$$cos(\theta) = \frac{\vec{a}\vec{b}}{||\vec{a}|| \quad ||\vec{b}||} = \frac{\sum_1^n a_i\, b_i}{\sqrt{\sum_1^n a_i^2}\,\sqrt{\sum_1^n b_i^2}}$$

$$cos(\theta) = \frac{1*12 + 0*3 + 4*5 + 4*0+\ldots}{\sqrt{1^2 + 0^2 + 4^2 + 4^2+\ldots} * \sqrt{12^2 + 3^2 + 5^2 + 0^2\ldots}}$$

Jaccard Coefficient

IPC	B01D	B23Q	B23K	B24B	…
Geely p1	1 (1)	0 (0)	4 (1)	4 (1)	…
Volvo p1	12 (1)	3 (1)	5 (1)	0 (0)	…

$$J(a,b) = \frac{|A \cap B|}{|A \cup B|} = \frac{\sum_1^n a_i b_i}{\sum_1^n a_i + \sum_1^n b_i - \sum_1^n a_i b_i}$$

$$J(a,b) = \frac{1*1 + 0*1 + 1*1+\ldots}{(1 + 0 + 1 + \cdots) + (1 + 1 + 1 + \cdots) - (1*1 + 0*1 + 1*1+\ldots)}$$

ARTICLE D

The electric vehicle sector in Brazil, India, and South Africa: are there green windows of opportunity?

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Working paper.

The electric vehicle sector in Brazil, India and South Africa: are there green windows of opportunity?

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Abstract: The shift to electric mobility is driving disruptive transformation in the automotive sector worldwide. It poses significant but differentiated opportunities and challenges to incumbents and latecomers, both at the firm and the country level. In China, the use of green industrial policy has facilitated rapid catching up and even leapfrogging in some domains of electromobility. Can the exploitation of this green window of opportunity be replicated in other latecomer countries? This paper provides a comparative analysis of catch-up performance and underlying industrial policy in Brazil, India and South Africa. While all face constraints in replicating China's relative success, there are bounded but uneven opportunities for reaping the potential economic development effects of the paradigm shift currently occurring in the sector. The article shows how green opportunities and threats are unequally divided between the three countries.

Keywords: green windows of opportunity, electric vehicle sector, latecomer countries,

1. INTRODUCTION

The worldwide green transformation constitutes a techno-economic paradigm shift that creates windows of opportunity for latecomer development and leapfrogging. However, these green windows of opportunity, and the responses to them, vary significantly between sectors and countries (Lema et al., 2020; UNCTAD, 2022). The energy supply side is rapidly transforming, with several latecomer countries investing heavily in renewable energy sources, related infrastructure and associated industrial capacity, not least in the electric power sector where several technologies are now mature and new business models have become proven and viable (Mathews, 2020). The energy demand side is still in the stage of the open-ended search for effective green solutions in many areas, such as in the production of cement and steel (Nurdiawati and Urban, 2021) and it is only at the beginning of the learning curve in the construction of energy-efficient buildings (Gan et al., 2020). In the transportation sector, there are clearer paths forward: with the increasing technological maturity and price reduction of battery-electric vehicles, electromobility is now the main viable option, at least for the foreseeable future (IEA, 2021). The use of alternative fuels, such as biofuels, hydrogen, and natural gas, helps reduce the emission of air pollutants. Indeed, the transformation towards electromobility is surging ahead. In the first half of 2021, EVs made up more than 7% of global car sales, up from 4.3% in 2020 and 2.6% in 2019 (EVWSD, 2022).

It is not yet clear how this transition from combustion engines to electric vehicles will affect the position of emerging markets in the global automotive sector. It could increase entry barriers and make competitive barriers more demanding, or it could decrease them and provide new competitive advantages. Evolutionary economics suggests that the former scenario may prevail as technological transition often favours late entrants because incumbents will be locked into assets, routines, relationships and institutions established before the paradigm shift, whereas newcomers can embark on new trajectories more swiftly (Perez and Soete, 1988). Much will depend on the speed of the transition from conventional cars to EVs, its global geography and the knock-on effects on global value chains. Traditionally, the automotive sector has been dominated by relatively small numbers of global lead firms that have developed region-specific car models and supply chains (Humphrey, 2003; Sturgeon et al., 2008). In this respect, the automotive industries in Brazil, India and South Africa share salient features such as global lead firm dominance and significant use of follow sourcing, with foreign firms dominating vehicle assembly and tier-1 supply. There is a relative absence of locally owned lead firms and most locally owned supplier firms are locked into non-innovative activities. However, there are exceptions such as Indian-owned OEMs and Brazilian suppliers with significant R&D activity and insertion into global innovation networks (Lema et al., 2015). Due to such variations, each has widely different prerequisites for gaining or losing from the green transformation of the automotive sector.

In China, the use of green industrial policy has facilitated rapid catching up and even leapfrogging in some domains of electromobility (Altenburg et al., 2022; Yeung, 2018). Can the exploitation of this green window of opportunity be replicated in other latecomer countries? In this paper, we seek to take stock of the opportunities and discuss the prospects for reaping economic development gains arising from the transition.

The paper is structured as follows: The next section seeks insights from the literature on the exploitation of green windows of opportunity in emerging economies and develops a conceptual framework to compare and assess the potential for reaping economic development gains across countries. It also sets out the context and describes the current EV transformation in the automotive industry globally and in emerging economies. On this basis, it specifies the research questions. In section 4, we provide an analysis of the sectoral production-cum-innovation systems in Brazil, India and South Africa respectively. Section 5 concludes and brings out the policy implications.

2. LATECOMER DEVELOPMENT IN THE GREEN ECONOMY

2.1 WINDOWS OF OPPORTUNITY

Green windows of opportunity (GWOs) are favourable but time-bound conditions for economic development arising from changes in institutions, markets, or technologies associated with the transformation towards sustainability. They are different from traditional windows of opportunity for catching up that typically arise from exogenous technological change or major changes in consumer demand (Lee and Malerba, 2017; Perez and Soete, 1988). In the green economy, deliberate institutional changes lie at the heart of the climate agenda, and they are fundamental in causing persistent changes to the prevailing techno-economic paradigm. Governments actively seek to anticipate emerging opportunities or threats and they react by establishing selection environments that favour specific techno-economic pathways in given sectors (Yap and Truffer, 2019). This involves greening initiatives, such as demand-side policies, technical standards, subsidies, etc., to privilege certain trajectories. Opportunities can, therefore, emerge as the result of major modifications to government regulation or policy interventions, associated changes in market demand or induced technological change. The sequencing and interaction of institutional, market and technology changes are key to how specific opportunities unfold in different countries and sectors (Lema et al., 2020).

Whereas the nature and dynamics of new opportunities are one side of the coin, the conditions and the responses to them in latecomer countries constitute the other side. To address the nature of such responses to changes in specific techno-economic domains in the green economy, a lens focused on sectoral systems of innovation and production is highly useful. Rather than viewing them separately, this approach brings together technologies, firms and institutions (Malerba, 2002). Given the interlocking nature of these dimensions in the green economy mentioned above, a system-inspired approach can, therefore, provide a unified lens for addressing preconditions such as sectoral features, capabilities and strategies concerning national responses to GWOs. These preconditions may be divided into three types.

First, overall sectoral features matter greatly for the ability to respond. For example, the degree of technological maturity and tradability of different green technologies varies significantly and affects the processes of building and applying the relevant capabilities. Precommercial technologies such as concentrated solar power are still in the era of ferment and responses require investments in public R&D and experimentation on the supply side while on the demand side, they may require the introduction of market stimulus mechanisms for dynamic user-producer interaction effects to arise. Highly mature sectors, for example, wind energy or solar P.V., may be fully or partly cost-competitive and they tend to have much more codified knowledge bases and developed global technology markets, allowing for catch-up strategies based on fast technology acquisition and imitation. Sectors with high maturity combined with high tradability may allow for classic latecomer advantages, i.e., export competitiveness based on factor cost differentials as in the case of the Chinese Solar P.V. sector (Binz et al., 2020; Iizuka, 2015). Export competitiveness in other settings requires different preconditions, as illustrated by the case of wind energy where overseas assets are key as are investments in knowledge in the context of changes in the dominant design, from onshore to offshore (Dai et al., 2020a).

Second, the preconditions of the supply base and related industries are key. Existing capabilities may be inadequate vis-a-vis the capabilities of incumbents or otherwise misaligned with the requirements of the window of opportunity. For example, there is a significant green window of opportunity in the solar P.V. space across several low- and middle-income countries, but the required manufacturing capabilities are not in place, which means that the localisation of the associated economic benefits is highly constrained (Lema et al., 2018). Certain locations may have advantages in terms of natural resources or supply chains. In this respect, firms may be able to 'repurpose' existing capabilities to address the new green windows. For example, in Norway, existing oil and gas firms have been able to stretch their capabilities to become leaders in the global offshore wind industry (Andersen and Gulbrandsen, 2020).

Third, green industrial policies are needed to turn economic development opportunities into reality. A passive approach, a non-response, may turn opportunity into a threat and may lead to eventual loss of both competitiveness and ability to deploy new green solutions. This can happen if there are dramatic shifts in technologies or consumer preferences. In any case, mission-driven industrial policies are key. These include demand-creation and the safeguarding of public green investments through protectionist measures (Landini et al., 2020). It also includes the stimulation of requisite supply-side capabilities. Investment in R&D, both public and private, support for vocational training, export credits and finance are all possible elements of the green industrial policy mix (Altenburg and Rodrik, 2017; Anzolin and Lebdioui, 2021). Many dimensions of this mix are in the domain of environmental or energy policies, while others belong to more classic economic policy domains such as competition regulation, taxation and research funding. In other words, the coordinating and co-design of policies to promote environmental and economic objectives are needed.

While the factors above have been discussed in turn, the key is about the conjunction of these factors in the sectoral system: interactions among lead firms, suppliers, technology providers, and financial institutions in the context of active and technology-specific supporting policies.

2.2 GREEN WINDOWS IN THE EV SECTOR?

The automotive sector is facing a major disruption with the shift in dominant design (Utterback and Abernathy, 1975) from combustion engines to electric drivetrains (Brem and Nylund, 2021). While electromobility is not yet the dominant form of road transportation, the transition to EVs now has the commitment of the most powerful enterprises in the marketplace and is becoming the locus of competition among innovators. After an era of ferment in which several solutions were contending such as battery swapping and hybrid electrics (Magnusson and Berggren, 2011) a de-facto standard is emerging around battery electric vehicles with rapid charging.

Global sales of electric vehicles have skyrocketed and are expected to overtake sales of combusting cars by 2040. The global sales increased from 3.2 in 2020 to 6.7 million EVs in 2021, reaching 8.3 per cent market share. However, there are considerable differences between markets. In the same period, market share in Europe increased from 10 to 17, in Northern America from 2.3 to 4.4, and in China from 5.5 to 13.3 per cent. The combined value for the remaining markets is 1.5 per cent of EVs in automobile sales (IEA, 2021; Irle, 2022).

The new window of opportunity is significant, as the transition to electromobility is lowering barriers to entry and opening the door for newcomers through radical shifts in competitive dynamics (Altenburg et al., 2022; Brem and Nylund, 2021; Perkins and Murmann, 2018). These shifts include that (a) the incumbent carmakers' proprietary capabilities around internal combustion engine (ICE) powertrain design and development are becoming less of a competitive advantage given that batteries will become the most critical component and the main source of competitive advantage going forward (b) electric vehicles are easier to design and to build than combustion engine cars because electric powertrains are simpler and have fewer components; (c) EVs require entirely new supply chains for novel critical parts such as electric motors, lightweight materials, charging devices, etc. and they render specialised suppliers focused on combustion engine architectures obsolete, (d) the shift requires new infrastructure and creates new roles and systemic interactions between vehicle producers, utilities and other newcomers and (e) electromobility is immersed in wider trends in consumption and digitalisation focused on autonomous, connected and shared driving with new business models, ownership patterns and critical spaces for entirely new players, including software firms (Hoeft, 2021).

Concerning OECD countries, such as the USA, Germany, Japan and South Korea, the disruptive effects of the policies regimes, the emergence of newcomer firms and the reactions by incumbents auto firms are quite well illustrated (Aaldering et al., 2019; Dijk et al., 2016; Meckling and Nahm, 2018; Teece, 2018). The case of China has also received considerable attention and there is now a substantial body of academic literature, including comparisons of the EV sector in China with other countries and sectors (Altenburg et al., 2016; Hain et al., 2020; Lema and Lema, 2012). It confirms that the paradigm change in EVs has indeed been exploited through a particular strong policy push and creates a potential for competitive advantage which may in the long run be greater in China than anywhere else.

Xiong et al (2022) show how windows of opportunity emerge and influence the catching-up process laying out its technological, institutional and market demand elements. They focus on policy evolution - evolving over different phases from imitation to innovation – and its role in opening the different kinds of windows, i.e., how government policy influences market demand and induced technological change. In this respect, they confirm how the story of EVs in China is rather like those of renewable energy industries in which green windows have emerged. However, as shown by Konda (2022a) the industrial and innovative dynamics emerging in that window have been sufficient for domestic adoption of EVs while the jury is still out on Chinese export competitiveness. Hain et al (2021), drawing on a semantic patent-to-patent similarity method, find that EV production in China started with low technological capabilities and focused on scaling up the market. The identified trajectory contrasts with Korea and Japan, which first developed strong industrial knowledge bases, and later scaled up their production capacity. Altenburg and colleagues (Altenburg et al., 2022), while also questioning the export competitiveness of China in electric vehicles, go further and suggest that China is not only catching up in passenger vehicles but also leapfrogging domains such as battery production and electric buses. They argue that newfound competitive advantages were propelled by green transformation policies.

China seems to have particularly strong possibilities to combine capabilities in the EV sector and elements of IT capabilities, as exemplified by the disruptive start-up NIO and its promotion of innovations pertaining to connectedness and cameras and sensors on the vehicle (Lüthje, 2019). The ecosystem of firms around EVs in China includes internet giants (Baidu, Tencent), Incumbent automotive firms (SAIC, Geely), disruptive start-ups (NIO) and battery suppliers (BYD, CATL). The system creates new 'species' that successfully integrate new services and EVs leading to innovative solutions which may become a source of global leadership in the sector (Jiang and Lu, 2018; Teece, 2018). It remains to be seen whether indigenous Chinese lead firms have the capabilities to challenge established global flagships such as VW, Toyota and Hyundai in the passenger vehicle space not only at home but also abroad.

While the transformation of the automotive industry is significant and windows of opportunity abound, it is also important to not underestimate the power of current global lead firms and the likelihood that they will continue to dominate. Recent research on the production and sourcing activities of the majority of global electric vehicle makers, including both incumbents like Volkswagen, BMW and GM, as well as newcomers like Tesla and NIO, shows that carmakers continue to rely on proprietary product architectures and are in the process of insourcing and developing the capabilities around the production of the entire electric drivetrain, including batteries, the electric motor, the transmission, inverters, converters and related software (Alochet et al., 2022). While the manufacture of EVs is arguably simpler than that of combustion engine vehicles, the system integration capabilities of incumbent lead firms continue to provide a significant competitive advantage and barrier to entry against newcomers (Alochet et al., 2022).

2.3 THE PURPOSE, APPROACH AND SCOPE OF THIS ARTICLE

The starting point for this paper is that the green transformation may open new opportunities for economic development in latecomer countries (Lema et al., 2020; Pegels and Altenburg, 2020). This transformation is represented differently in distinct sectors, not least those sectors dealing with products that are producing and consuming energy. In the automotive industry, the shift from internal combustion to electric vehicles is a major disruption. How does this disruption affect opportunities for latecomer development in the automotive industry? While the case of China is well documented (see above) there is very little literature on other middle-income countries that have a significant stake in the industry such as Brazil, India and South Africa. A search for relevant literature in Scopus produces only four results, two on the battery subsegment globally and in India respectively (Gerybadze and Mengis, 2021; Retna Kumar and Shrimali, 2020) and two on EV catching up in China (Hain et al., 2021; Rong et al., 2017)[1]. In other words, there is a dearth of studies and this paper seeks to fill this research gap by addressing the following overall questions: Are there green windows of opportunity for transitioning to electric transportation in Brazil, India and South Africa? What are the prospects for replicating the Chinese EV success story in these countries? How do the countries compare concerning green industrial policies as well as in their preconditions of the supply base and related industries?

In answering these questions, the paper uses the GWO analytical framework tailored for this study by drawing on the literature discussed in sections 2.1 and 2.2. We structure the analysis according to this framework, which includes the operational indicators shown in Table 1. Using this as an analytical guide, the analysis allows for identifying, describing, and interpreting themes and patterns for each country and later enables cross-country comparison. Accordingly, we proceed with our comparative analysis in three steps:

1. We start by examining the domestic preconditions. This includes the (a) nature and the size of the existing automotive industry producing ICE vehicles, (b) relevant firms and supply chains for EV production, including local EV battery production and the upstream availability of key natural resources for EV production and (c) the potential size of the local target market for EVs. Strong preconditions enable countries to effectively respond to emerging windows. In general, the ability to exploit windows of opportunity in specific industries depends on the firm's existing, accumulated capabilities in the same or closely related sectors and on the development of the sectoral innovation systems in which they are embedded and formulate their strategies (Lee & Malerba, 2017). We consider both the supply-side of the sectoral, in terms of size and the capabilities of automotive companies, especially of locally owned firms as well as the demand side in terms of economies of scale and potential target markets for EVs. Beyond the automotive industry itself, preconditions, such as the size and range of proximate industrial activities and the upstream availability of key natural resources, are included in the analysis.

2. We then provide an analysis of policy and enterprise responses. This is divided into (a) policy responses, (b) responses in the science system and (c) enterprise responses associated with the GWO. Responses, in contrast to preconditions, are active measures by the public sector and private firms in relation to the GWO, of the transition to electromobility. There is also a temporal dimension to the distinction

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[1] The search string used in December 2021 was the following: TITLE-ABS-KEY ("electric vehicle*" OR "electric car*" OR "electromobility") AND TITLE-ABS-KEY ("emerging econom*" OR "latecomer econ*" OR "latecomer coun*" OR "Africa" OR "Asia" OR "Latin" OR "Brazil" OR "Brasil" OR "South Africa" OR "India") AND TITLE-ABS-KEY ("catching-up" OR "catch-up" OR "industrial development") AND LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE, "k")

between preconditions and responses because our analysis of responses focuses on recent and current initiatives as opposed to earlier (but relevant) actions taken before the GWO emerged.[2] Policy responses are examined in terms of public incentives for domestic production of EVs, for R&D for charging infrastructure and for stimulating local demand. Responses in the science system are assessed by examining the domestic publication of patents as well as the publication of scientific articles by universities and research institutes. Enterprise responses include responses such as development of EV models by OEMs and investment in supply chain activities at the component level, such as EV battery production.

3. This is followed by an analysis of the industrial development of the EV segment in the three cases. We focus on (a) EV domestic market development and (b) EV exports. Earlier research has sought to assess this dimension in relative terms, as 'catching up', by considering changes in the domestic capture (or loss) of global market shares in each sector (Lee & Malerba, 2017) or market shares combined with measures of domestic technological strength (Lema et al., 2020). However, given the emergent nature of the shift to electric mobility and second-mover position of Brazil, India and South Africa, only preliminary observable developments around electric vehicles are included in the analysis. This includes data related to the domestic market, current production of EVs and the share of EVs in total vehicle sales, as well as to the global market, exports and the trade balance. In section 3.3, we draw on this data and our wider evidence to assess scenarios of overall upgrading in industrial development (catching up) or downgrading (falling behind) in face of the mounting shift to electromobility in the sector. In this respect, we consider national-level trajectories and the potential for higher local content, development of local lead firms and localisation of technological solutions.

Table 1 contains a wealth of factors, and it is important to recognise that not all of the factors are equally important and that their importance may change over the course of sectoral development. For example, while preconditions such as the availability of EV-relevant raw materials can be leveraged to attract carmakers in the EV space[3], given the importance of economies of scale in the automotive industry, the potential size of the domestic market, as well as access to export markets, are much more important for the creation of a competitive automotive industry with potentially high local content and ideally the localization of design and technology development.

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[2] Such as, in this case, more general automotive policies that influence the ability to seize the new opportunity effectively after the window has emerged, although they were not designed and implemented with the GWO in mind

[3] A noteworthy example is Indonesia's current attempt to use nickel resources to pursue local beneficiation objectives and to create a local EV battery supply chain (Trivedi, 2022).

Table 1: Analytical framework and main Indicators

Dimension	**EV dimensions**	**Indicators**
Domestic Preconditions	▪ Size and structure of the existing automotive industry ▪ Relevant firms and supply chains for EV production ▪ Potential local EV market	▪ ICE domestic market size ▪ ICE exports ▪ ICE production volumes ▪ ICE local content ▪ EV potential market size ▪ EV-relevant capabilities in the local supply-base ▪ Availability of natural resources for the EV supply chain
Policy and enterprise responses	▪ Policy responses ▪ Responses in the science system ▪ Enterprise responses	▪ Policy incentives for domestic EV production ▪ Policy incentives for local demand for EVs ▪ Policy incentives for EV-specific R&D ▪ Policy Incentives for charging infrastructure ▪ Investment in EV infrastructure ▪ EV-specific patents published ▪ EV-specific publications published ▪ Enterprise responses by OEMs such as the development of EV models
Industrial development	▪ EV domestic market development ▪ EV exports	▪ EV stocks ▪ EV sale ▪ Share of EVs in total sales ▪ EV Trade balance

The paper adds to the literature on green windows of opportunity in important ways. First, much of the literature has focused on latecomer development potentials in green electricity production such as biomass, solar and wind, not on other types of green technologies such as EVs (Dai et al., 2020b; Hansen and Hansen, 2020; Oehler, 2022; Zhou et al., 2021). Second, it has tended to focus on the case of China, which has special characteristics, not on other emerging economies such as Brazil, India and South Africa. This is especially true in the case of the very small body of literature on electric vehicles in emerging economies which is exclusively focused on China (Altenburg et al., 2022; Konda, 2022; Xiong et al., 2022).[4] Third, most prior literature has focused on cases in which there is a large element of proactive-window creation and endogenous contribution to the relevant technology-economic paradigm change (Yap and Truffer, 2019). This paper seeks to understand how latecomers can react to

[4] There are very few exceptions, such as work on Togg in Turkey (Mordue and Sener, 2022).

an exogenous paradigm change in the automotive sector from ICE to EVs. Fourth, it is the first paper to examine different latecomer reactions to the same GWO in a systematic comparative way and fifth and relatedly, it explores more in-depth the supply-side elements of reacting to this GWO.

3. ARE ELECTRIC VEHICLES AN OPPORTUNITY FOR BRAZIL, INDIA AND SOUTH AFRICA?

This chapter presents an analysis of opportunities, preconditions and responses in Brazil, India and South Africa concerning the technological discontinuity in the automotive sector presented by the shift to EVs. Having already described the techno-economic paradigm change and the overall sectoral opportunities and threats, we concentrate on the country-specific elements of the framework. The purpose is to expand prior research on GWOs by seeking insights from a deeper analysis of preconditions and responses in the same sector in three different countries. This chapter analyses each country's potential, the actions that have been taken for developing the EV sector and the outcomes in terms of upgrading and catching up.

3.1 PRECONDITIONS

There is only a limited understanding of the required preconditions to exploit the window of opportunity emerging in the electric vehicle space, in part because of the still emergent nature of the technology and its associated industrial systems. It is possible, however, to draw insights from the global leader in deployment, i.e., China, and consider some of the key characteristics such as the size of the domestic market and the presence of a global supply chain. The development of electric vehicles relies on the opening of the traditional automotive industry to collaborate with other industries, e.g., the chemical industry and ICT industry (Delft, 2013; Enkel and Heil, 2014). The state of relevant input sectors relevant to EV development and deployment is thus an important factor for emerging economies as is the availability of key natural resources for EV production, not least lithium for battery production. Key data points are drawn from the information provided in the appendices.

In **Brazil**, the automotive industry has been a sector of the economy for more than 100 years, and the country has long been an automotive manufacturing hub for South America. As of 2019, the country was the world's eighth-biggest car manufacturer, and the sixth-largest automobile market, considering the new car registrations (Statista, 2021a). As a manufacturing hub, the country is host to many global OEMs such as Volkswagen and General Motors. More recently, dedicated EV manufacturers have located themselves in the country, such as Chinese BYD. Brazil held the same ranking in FDI inflows (72 billion US$), among which 10% goes into motor vehicles (Brazil Central Bank, 2021). However, while there are large multinational OEM suppliers present, significant parts of the supply chain are locally owned by large auto parts suppliers (Lema et al., 2015) which also play an important part in the country's export (Marx et al., 2020). Some of these locally owned suppliers possess significant design capabilities (Lema et al., 2015). The Brazilian automobile industry has a positive trade balance with the rest of the world. Since 2016, Brazil has had a positive trade balance in the passenger bus and motorcycle sectors which indicates the industry's robustness in the sector overall. In 2019 it had a trade surplus of 461 million US$ despite a negative 26% annual growth rate the same year. In terms of EV-specific preconditions, Brazil is rich in natural resources needed for EV batteries' production—it has the third-biggest reserves of graphite and nickel, and the seventh largest of lithium (Statista, 2021b). Despite having 8% of global lithium reserves, Brazil only accounts for 0.7% of world production, thus lithium must be imported (Zaparolli, 2019). The country also has existing low-voltage battery production of industrial and stationary batteries, based on local knowledge. However, scientific research and production lack connection, mainly as importing presents a barrier to scientific-technological knowledge collaboration. An essential part of the Brazilian automobile industry is biofuel (ethanol and biodiesel), which historically had firm policy support.

The automobile industry in **India** started developing at the time of independence and today is the world's fourth largest and had a 2.36% compound annual growth rate (CAGR) of domestic production in 2016-20. The growing population and social-economic changes allow market development by filling the rising local demand. In the last two decades, the industry attracted $24 billion in FDI, mainly due to its cost advantage of 10 to 25% compared to Europe or Latin America (IBEF, 2021). More than 80% of all vehicles are two-wheelers, followed by passenger vehicles with 13%. This decade, economic and demographic changes will allow the industry to grow from 7.1 to 12% of GDP until 2026 (DPIIT, 2020). Because of its large domestic market and associated economies of scale as well as bargaining power for localisation, India has a strong automotive component sector, which contributes 2.3% of GDP and 4% of total exports. India's auto component sector is growing faster than vehicle assembly and exports a quarter of its production. Several locally owned component firms like Motherson Sumi Systems have upgraded over the last two decades and have acquired design capabilities, as well as a global footprint (Saranga et al., 2019). Even in vehicle assembly, India has seen the growth of locally owned companies like Tata Motors, Mahindra and Ashok Leyland. This development is confined mainly to heavy and commercial vehicles, while in the most technologically advanced area of passenger vehicles, foreign firms including the joint venture Maruti-Suzuki, Hyundai, Honda, and GM continue to dominate. Nevertheless, it is a key difference between Brazil and South Africa where all vehicle assemblers are foreign-owned.

Despite being one of the leading automobile manufacturers, India ranked as the 22nd largest exporter in 2019 (Statista, 2021a). In recent years, India has had a strong positive trade balance in the passenger bus, and motorcycle sectors. More than half of its export goes to Europe (33%) and North America (29%) (IBEF, 2021b). The whole development is strongly supported by the government, which introduced several incentives to address the industry's changing paradigm. Concerning EV-specific preconditions, India is dependent on the import of lithium, which is currently a bottleneck, but the newly discovered lithium resources in 2020 could enable faster development of the sector (Sasi, 2021). In electric two and three-wheelers, the battery cost presents up to half of the vehicle's price. Thus, the government allowed manufacturers to sell vehicles without batteries, and in parallel, encourage the development of different battery swapping services (Chaliawala, 2020). In the last three years, it attracted high investments from domestic and foreign entities, e.g., Japan Bank for International Cooperation (US$ 1 billion), and Toyota Kirloskar Motors (US$ 272.81 million) for EV components. The electrification of the automobile sector allows establishing a new battery sector—or interconnecting with the existing I.T. sector. According to Indian Energy Storage Alliance, the battery market potential was $580 million in 2019 and is forecasted to grow to $14.9 billion by 2027 (ManufacturingToday, 2021).

As of 2021, **South Africa** was the 20th biggest vehicle manufacturer globally, and the automotive industry in 2019 contributed 4.9% to GDP. It is the biggest vehicle producer on the African continent, followed by Morocco (NAAMSA, 2022a; OICA, 2022). In contrast to Brazil and especially India, the domestic market is small, and the South African auto industry is much more export-dependent. In 2019, 64% of all vehicles produced were exported, the majority of which went to Europe (74%) (Automotive Industry Export Council, 2020). While vehicle production and exports are larger than component production and exports, component exports still make up 27% of total automotive exports (ibid). The country's leading export markets for vehicles (74% to Europe) and components (EU & USA, 60%) have high goals regarding electrification, thus South Africa might lose the markets if it does not follow the shift (NAAMSA, 2022b). The looming end to sales of ICE vehicles in Europe means SA has to switch to EVs if it wants to continue its current model of automotive global value chain participation (Planting, 22AD). Too slow adoption of EV production could mean losing the GVC position altogether. Unlike in Brazil and India, no locally owned automotive component firm in South Africa has managed to achieve a global supply footprint or acquired design capabilities through automotive GVC participation so far (Wuttke, 2022). This means that it is unlikely that South African firms will suddenly upgrade and throw off the shackles of foreign technology dependence even if local EV production is successfully introduced. Currently, while there is a significant number of firms in South Africa that assemble batteries based on imported cells, there is no local battery cells manufacture. AutoX manufactures lead-acid batteries which is a totally different product than lithium-ion batteries. Metair, South Africa's largest automotive component manufacturing holding, has battery manufacturing subsidiaries internationally, including in Turkey and Romania. It is, however, still far away from supplying batteries for EVs. South Africa possesses notable deposits of several materials that are relevant in battery manufacture, such as manganese, cobalt, iron ore, nickel, and titanium. But only manganese and aluminium are refined to battery grade locally (Montmasson-Clair et al., 2021).

3.2 POLICY AND ENTERPRISE RESPONSES

The three countries have widely differing platforms for embracing the turn to EVs in the automotive sector and they also differ significantly in terms of how the local sectoral system has responded to the opportunities and challenges. To bring this out, this section will conduct a comparative analysis of responses to the GWO in the automotive industry, covering both responses by different elements of the sectoral innovation systems, chiefly responses in terms of introduction of new policies and terms of enterprises, supporting institutions and infrastructure. The policies are divided into incentives for domestic production, local R&D, infrastructure, and demand-side support (Table 2).

To address the rising pollution in the urban and industrial areas, **Brazil** introduced the first policy for cleaner transportation in 1986—PROCONVE.[5] In early 2000, the government introduced several incentives for R&D and added biofuels derived from oils and fats for the energy matrix. Looking at the policies supporting domestic production, the government introduced four incentives in the last decade. Starting in 2011 with the BNDES Fundo project, two years later with "Inovar Auto" covering the period (2013-17), which was later replaced with the current "Rota 2030 program" (ICCT, 2019; Pousa et al., 2007).

Despite Brazil hosting many automotive OEMs, EV sales consist of imported vehicles (Consoni et al., 2019). In terms of supply chain responses, existing lead-acid batteries manufacturers—e.g., Moura Group—are starting with R&D for lithium batteries. Company Pxis (a collaboration between CODEMGE and Oxis Energy) is planning to establish the first mass-production plan of lithium-sulphur batteries which, in the laboratory, outperformed the current lithium batteries (Zaparolli, 2019). Regarding investments in infrastructure, there are a few private sector initiatives. Volvo Cars started to install charging stations at shopping centres in 2020, aiming to install between 500 and 700 stations in the first year. BMW is collaborating with gas stations and planned to install 180 charging stations in 2020. Zletric is installing charging stations at the parking facilities and aimed to build 400 stations in 2020.

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[5] Already in 1975, the Brazilian government started the PROALCOOL program to produce ethanol as a response to increasing petroleum prices. Six years later, the program was abandoned as international petroleum prices stabilized, however, the biofuels sector was established and remained present in country’s energy-mix.

Table 2: Key policies by country

	Incentives for domestic production	Incentives for R&D (scientific)	Incentives for charging infrastructure	Incentives for demand
Brazil	(2011–): BNDES Fundo Climate Program (2013–2017): Innovate Auto (2016): CAMEX (2018) Law No. 13,755	(2003–2016): CNPq (2008–2018): ANEEL (2010–2016): FINEP (2011–2013): BNDES (2011 –2015): Sibratec (2012–): ABNT (2018) Law No. 13,755	(2013–): Inova Energia (2016, 2018): ANEEL (2018) Law No. 13,755	(2015, 2016): CAMEX (2018) Law No. 13,755
India	(2015-) MAKE IN INDIA - STATE LEVEL - PMP	(2015-) MAKE IN INDIA	(2015 - 2022) FAME (I & II) - CENTRAL GOVERNMENT - LOCAL POLICIES	(2015 - 2022) FAME (I & II) - CENTRAL GOVERNMENT - LOCAL POLICIES
South Africa	(2013 – 2020): APDP (2018 – 2050): GTS (2021 - 2035): SAAM	(2018 – 2050): GTS	(2013 -): EMTIP	(2018 – 2050): GTS

Source: Appendices 7-9 (with description)

Aside from the planned private projects, there are more than 30 projects supported with $118 million by Brazil's electric energy regulator Aneel, and together, the charging infrastructure should significantly improve in 2020-21 (Bland, 2020). Apart from infrastructure, there is also evidence of development in the science system, promoted by the R&D policies mentioned above. Scholars affiliated with Brazilian institutions published 152 academic articles about EVs, with forty per cent being funded by domestic public institutions (Appendix 6; Figure 2). Looking at patenting activity, ninety-two patents were filled, having at least one applicant from Brazil. The most frequent applicants are BOSCH, CSEM Brasil, and Electric Dreams. Among applicants, three Brazilian universities patented their inventions in the EV field (Appendices 4,5; Figure 1). Despite several policies to stimulate R&D, the current innovation network favours the incremental development of vehicles on internal combustion and ethanol (Wolffenbüttel, 2020). Moreover, the solid and long-term biofuel policies rationalize the government's less progressive EV policies. However, the RenovaBio program incentivizes combining hybrid EVs with biofuel (Consoni et al., 2019; Wolffenbüttel, 2020).

Figure 1: Patent publication per country (Cumulative)

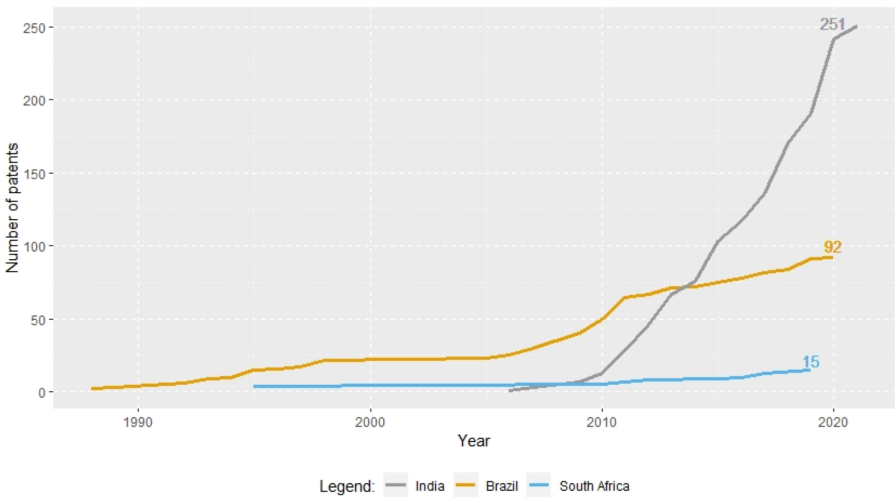
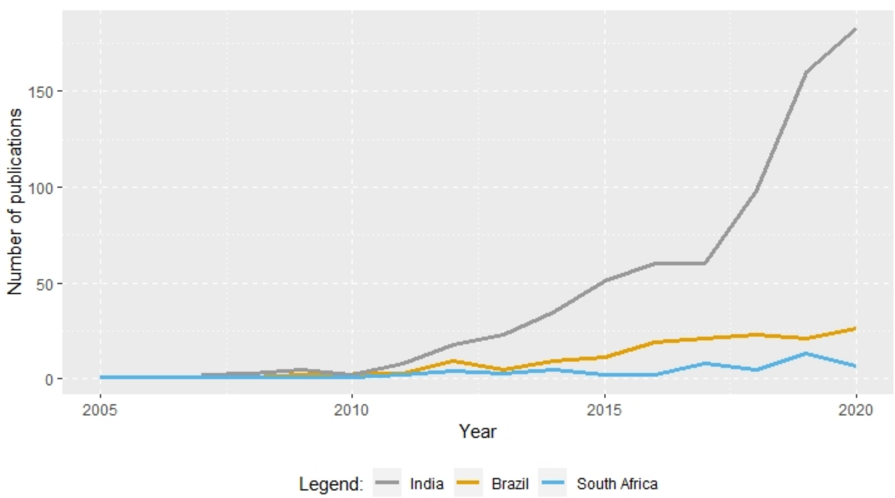


Figure 2: Academic publications per year



The **Indian** government started the path towards electromobility with the "National Electric Mobility Mission Plan 2020" (NEMMP2020) in 2013, a continuation of NMEM from 2011. The plan provided a roadmap to achieve sales of 6-7 million xEVs[6] in 2020, among which 400,000 units of e-passenger cars. In 2015, the government supported the plan with the "Faster Adoption and Manufacturing of Electric Vehicles" scheme (FAME), which transitioned into its second phase (FAME-II) two years later. FAME-II ends in 2022 and includes stimulation for purchase and the deployment of charging infrastructure. Also, it encourages manufacturers to use batteries with advanced chemistry—lithium—, instead of environmentally less-friendly lead-acid variants. The EV policy in India is spread among three levels of authority—national, state, and city—and the majority are placed on the state or city level. Aside from the FAME scheme, India supports the automobile industry with the "Make in India" program—stimulates FDI, TAX incentives for R&D—, and the "Phased Manufacturing program" (PMP). PMP first reduced a "basic custom duty" (BCD) in 2017 (between 0 and 25%) for electric vehicles, assemblies, and EV parts to support electromobility development. In 2020, BCD started gradually increasing (10 – 50%) to stimulate domestic manufacturing (DPIIT, 2020).

In the private sector, India started experimenting with locally developed EVs in the early 2000s, the REVA (Lema and Lema, 2012). However, it was not until 2019 that Tata Motors started the production of models Tigor EV and Nexon EV. As of 2021, there were 370 EV manufacturers in India, however, only three of them with electric 4-wheelers, i.e., Tata Motors, Mahindra, and Altigreen (e-AMRIT, 2022). Concerning the supply chain, India has a few lead-acid battery manufacturers, e.g., Exide Industries and Amara Raja Batteries, which are stepping into lithium production by establishing linkages with foreign manufacturers to acquire knowledge. Tata Motors, India's largest EV car manufacturer, signed an agreement with ISRO (Indian Space Research Organisation) to gain knowledge for setting up lithium battery production (Okcredit, 2022). The science system is also involved in other capacities. Academic output was 721 academic articles, where at least one author's affiliation is from Indian institutions. Among articles, 116 received funds, and 73 were funded by Indian public institutions (Appendix 6; Figure 2). Indian companies with the highest number of patent publications are TVS Motor LTD, Tata Motors LTD, Ather Energy PVT, and Bajaj Auto LTD. Besides, three Indian universities patented their inventions in the EV field (Appendices 4,5; Figure 1). Currently, the infrastructure projects are supported by national (FAME), local policies, and many private initiatives, e.g., YoCharge, Tata Power, Jio-Bp. The proposed plans should continue the growth dynamics in the next few years (Prakati, 2022; Roy, 2020; Shukla, 2021)

In 2013, the **South African** government introduced the 'Automotive Production and Development Programme' (APDP, 2013-2020), which did not specifically address the EV sector but the whole automobile industry. The policy's four pillars—import duty,

[6] xEVs are HEV & BEV 4 wheelers, e-3 Wheeler, e-2 wheelers, e-buses and LCA

production incentives, assembly allowance, and investment scheme—managed to keep the industry stable but had not improved its global position. In the middle of the previous decade, the policy targeting increasing pollution by road transportation (GTS 2018 – 50) was implemented. It stimulates domestic production, R&D, and consumption of alternatives to vehicles on internal combustion. At the end of the APDP period, the government updated it with the South African Automotive Masterplan (SAAM 2021-2035), with the primary goal to address the decreasing local content in the automobile industry (from 46.6% in 2012 to 38.7% in 2016). Despite the policy stressing the importance of EVs in the future, it does not make special provisions (Barnes et al., 2017). Overall, the EV development has explicit support in the policies related to cleaner transportation, mainly by penalizing dirtier solutions—Environmental CO2 levy— but not yet related to manufacturing (SEI, 2020). The Department of Trade, Industry and Competition (DTIC) is currently negotiating a policy plan regarding the production of electric vehicles, but publication is delayed.

None of the automotive OEMs in South Africa is producing full battery EV models, thus, the sale relies on imported vehicles (NAAMSA, 2022a). The situation is, however, slowly changing with Toyota and Mercedes-Benz already producing plug-in-hybrid models in small numbers. The most active company in EV infrastructure is GridCars, with more than 200 charging stations. The charging infrastructure is developing based on investments from the private sector, however, some local governments —e.g., Cape Town—have their frameworks to become electric vehicle-friendly cities (Zyl, 2020). Several emerging start-up firms are trying to find a niche inside electromobility. Some of them are Mellowcabs (Electric three-wheelers), Electric Boy (electric scooters), Electric Safari and Mazibuko which aim to produce electric pick-up vehicles suitable for the South African environment (Jacobs, 2022; Tracxn, 2022). Between 2005 and 2012, the company Optimal Energy developed a prototype electric passenger vehicle called 'Joule' and patented some of its battery technology. It went bankrupt in 2012 because the government did not extend its funding (Swart, 2015). The government plans that an existing industry will also cover electric vehicles' batteries and supports it under the THRIP program. It includes the University of the Western Cape, the uYilo e-mobility program, the Council for Scientific and Industrial Research, and Zellow Technology (Raw and Radmore, 2020). The first lithium-ion mega-factory—The MegaMillion Energy Company—plans to start a manufacturing plant in 2022 (TMEC, 2020). Scholars from South African institutions published 50 academic articles in the EV field. One-third of them were publicly funded (Appendix 6; Figure 2).

3.3 CATCHING UP IN ELECTRIC VEHICLES?

To what extent and how do the industry trajectories related to EVs differ in Brazil, India and South Africa? This section reviews trajectories in each country, focusing on comparative data about performance along the market dimensions. Table 3 shows that the year 2021 had an important relative increase in EV sales, despite the worldwide pandemic. In the observed year, the share of EV vehicles in all vehicles was the highest in Brazil, followed by India and South Africa. The promising sale numbers vastly increased EV stock in India and Brazil. Table 4 presents the trade balance of different EV vehicle types, and in most cases, countries have a minor part of export. To unfold these overall patterns, we now describe in more detail the key features of the trajectory in each country.

The first 90 EVs in **Brazil** were sold in 2012, and in the following years, the sales grew with a 48.9% CAGR, reaching 1910 EVs sold in 2019 (IEA, 2021). The steady growth gained momentum in 2020 and 2021, with record sales of 2.480 and 7.200, respectively (Table 3). Unlike the positive trade balance in the whole automobile industry, there is a negative trade balance with almost no export in the EV segment (Appendices 1-3). This indicates that EV manufacturing was not developing along world trends and relied on import despite the developed automobile sector.

The EV market in **India** started to develop in 2007 with the first 370 passenger cars. It grew with a 31.37% CAGR and reached 23,091 electric passenger cars in 2021 (IEA, 2021). The first commercial electric bus line was established in 2017, and the number of operating e-buses reached 400 in 2019 and an estimated 2,250 e-buses in 2020 (Srinivas, 2020). In 2021, 311 thousand EVs were newly registered; however, the vast majority were 2 and 3-wheelers, while electric 4-wheelers only account for 4 per cent. The growth trend continues in 2022, due to the government incentives and especially, increasing oil prices. On the contrary, the trade balance is negative in all three EV segments, which can allow an opportunity to develop the EV sector by using established trade channels (Appendices 1-3).

Table 3: Key market indicators[7]

2020 (2021)		**EV passenger car**	
	Stock in units	Sales in units	Sale share[8]
India	12050 (23091)	3131 (12041)	0.1% (0.4%)
Brazil	5400 (12700)	2480 (7200)	0.2% (0.5%)
South Africa	1470 (1740)	242 (271)	0.1% (0.1%)

Source: (IEA, 2022)

[7] Countries use different methodologies in reporting their figures, thus we use data from International Energy Agency to allow comparability.

[8] Sale share is a share of EV passenger car sale in sale of all types of passenger cars

Table 4: International trade indicators

2019 (2020)	EV passenger car		EV bus		EV motorcycle	
(Thousand USD)	Import	Export	Import	Export	Import	Export
India	5,133	3,027	607	0	2,951	1,417
Brazil	20,647 (26,106)	0	0	20,647 (26,106)	29,689 (13,052)	6 (49)
South Africa	6,616 (3,893)	238 (179)	49 (0)	1,375 (0)	7,048 (9,051)	60 (262)

Source: (ITC, 2021)

The first EVs in **South Africa** were sold in 2013 (30 units). The sales grew with a 50.1% CAGR in the following years, reaching a stock of 1.740 EV in 2021 (IEA, 2021). The comparison of the trade balance between automotive products and their components (car, bus, motorcycle) on internal combustion and electric versions shows a positive balance in cars but negative e-cars, a negative balance in buses but a positive balance in e-bus, and a negative in both motorcycles and e-motorcycles (Appendices 1-3). The trade values are low but there are export channels for EVs and their components.

3.4 SUMMARY

Table 5 provides a summary of the empirical evidence described in this section, structured by the analytical framework comprising (a) preconditions, (b) policy and enterprise responses and (c) latecomer development trajectories in the EV sector. The three countries differ markedly in these respects with different advantages and disadvantages, and each country's specific features translate into differentiated opportunities and threats. In India, the shift to electric vehicles may hold a certain degree of potential since the domestic market provides critical mass in terms of size, but the key bottleneck is that most batteries are imported, given the lack of key natural resources in the country. This also means that the battery components domain is the weakest link in the Indian EV sectoral system, as also indicated by the patent data. So, India has key manufacturing and innovation capacities, and it may also be able to further carve out the three-wheeler niche but lacks battery-related knowledge. However, this key component represents up to 40% of the EV cost. This puts significant pressure on the EV trade balance, and it severely affects competitiveness with Chinese EVs (The Financial Express, 2022). Compared to Brazil and South Africa, the lack of requisite natural resources is a key impediment and compared to China, the government and key enterprises have done less to cultivate and secure natural resource supply chains in Sub-Saharan Africa and Latin America.

In Brazil, there is also a sizeable domestic market and an established automotive industry. However, there is rather weak connection between universities and manufacturers in this space which results in diminished innovative capacity. In part, this can be explained by path dependencies stemming from the government's priority in supporting biofuel in a strong way. That being said, and in contrast to India, there is a knowledge base as well as natural resources related to battery production. For this reason, foreign manufacturers might push the EV space as Brazil has these very good conditions for battery production.

In South Africa, the transition to the emerging EV paradigm in the global auto sector is slow and constrained. While rich in critical natural resources, the knowledge base for EVs is weak compared to Brazil and India. While there is a base of chemical battery producers, there are few opportunities to develop this stronghold into a niche in the EV sector. Furthermore, India and Brazil have managed to become producers of technological solutions for digitalized manufacturing (not only EV), while SA is only a user of such solutions in the manufacturing process. Hence, international knowledge transfer may be the most prevalent route for capacity expansion in the foreseeable future.

4. CONCLUSION

The starting point for this article was that changes in technologies, markets and institutions associated with the green transformation may create new windows for latecomer development (Lema et al., 2020; UNCTAD, 2022). China's experience in electromobility is a case in point: the green transformation has driven important competitive advantages for China's automotive industry. In fact, the technological discontinuity represented by the shift to electric vehicles enabled China to move ahead of the established lead firms which had so far been technologically superior (Altenburg et al., 2022).

Is this opportunity exclusive to China or are there openings for other emerging economies with a foothold in the auto industry as well? To examine this question, we brought together a range of market indicators with policy assessment and analysis of enterprise sector dynamics, related to national preconditions and responses in Brazil, India and South Africa. In section 3, we showed that all three economies have started experimentation in the EV domain, but the sectoral systems of production and innovation are still in their formative stages. There are major differences between the three countries in terms of their automotive sector starting points and approaches to EV policy.

Table 5: Summary table

	Indicator	Brazil	India	South Africa
DOMESTIC PRECONDITIONS	**Size of the industry**	Strong automobile industry Big domestic market	Strong automobile industry Big domestic market	Important automobile industry
	Unique characteristic	Strong commitment to biofuel Many FDIs	The high share of 2 & 3-wheelers Important Auto component sector	An important position in GVC The main hub for Africa
	Trade balance (ICE)	Positive trade balance	Positive trade balance	Positive for vehicles
	Supply chain	Many foreign OEMs High export of vehicles and components	National and foreign OEMs High export of components	Foreign OEMs High import of components
	Natural resources	Rich in graphite, lithium and nickel. Low lithium production.	Dependant on the lithium import.	Rich in Manganese, Nickel, Calcium fluoride, Titanium, Aluminium, Copper, Iron.
POLICY AND ENTERPRISE RESPONSES	**Policy incentives**	Policy support is accorded lower priority than biofuel	Good and detailed support on the national and local level	Poor generic government support
	Firms' response	Upgrading of battery production	Domestic OEMs start EV production	Start-up firms try to find niche segments for local specific conditions
	Infrastructure projects	Mostly private initiatives and some publicly supported projects.	Strong government support for public charging network	Heavily rely on private initiatives.
	Knowledge base	Relatively low but increasing patent activity. Academic research receives good funding support.	Relatively low but rapidly increasing patent activity. Increasing academic output but receives less funding support.	Relatively low but increasing patent activity. Academic research receives good funding support.
INDUSTRIAL DEVELOPMENT	**EV sales & stock**	The turning point in 2020-21.	The turning point in 2020-21.	Stagnation
	EV Trade balance	Negative in EV cars and EV motorcycles but positive in EV buses.	Negative in all three sub-segments.	Negative in EV cars and EV motorcycles but positive in EV buses.

All three countries are second movers in the space, but further traction is likely to increase as foreign partners from Western countries are obliged to slowly abandon ICE and turn attention to EVs as lead markets intensify transformation regulation and incentives. Second mover status also means that there are fewer risks involved in the EV technology space as dominant designs become further entrenched. China started its EV sector development more than a decade ago with much higher uncertainties regarding technology and the future of electromobility. While this situation is now with less uncertainty, the second movers face more fierce competition than incumbents that seek to protect their competitive advantages. So, China was engaged in the race to experiment with alternative technologies, but this is not the case for India. In this sense, China was able to experiment with new solutions but did so without significant external competition. Second mover emerging economies have better opportunities to source knowledge but face significant international competition. They may speed up transport electrification by opening up for increased importation while at the same time, developing niche products such as EV 2-wheelers & EV rickshaws (in India) and biofuel & EV hybrid cars (in Brazil).

While electromobility, on the one hand, allows countries to upgrade the automobile industry, it also presents a threat of losing their current positions in the global automotive sector. All three countries rely heavily on FDIs from the Western automakers, which are rapidly introducing more EV models. The increasing demand for batteries on a global scale might incentivize new FDIs for battery production. Consequently, the GVCs are changing due to the need for different critical elements, i.e., batteries. Brazil and South Africa have considerable reserves of natural resources, but competitive advantage based on natural resource exploitation alone would amount to functional downgrading in the global automotive chain. On the other hand, upgrading depends on a strong and responsive system of production and innovation.

Future research should examine this 'resource curse hypothesis' in the context of EVs. For example, South Africa has tried beneficiation of steel, aluminium and polymers for the automotive sector for decades with meagre results. On the one hand, there is no reason to expect anything to be different in EVs in this respect. On the other hand, minerals are such a bottleneck for EVs (availability and exploding prices), so the playing field could be slightly different in the sense that local materials provide more bargaining power. Indonesia using its nickel might be a case in point; however, the jury is still out on whether that actually proves to be a successful strategy (Trivedi, 2022). Furthermore, new research should also examine how this shift to electromobility interacts with wider changes in automotive GVCs. In the shift to electromobility, current lead firms will be able to protect their powerful position, or in the worst case – from their perspective – will have to share it with battery makers. However, with fewer proprietary and more modular technologies and standards, it raises the prospect that the current lead could result in market power and dominance (Lüthje, 2022) and make space for more dynamic automotive sectors in emerging economies in the long run.

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6. APPENDICES

A.1 EV IMPORT

Import in thousand U.S. Dollars					
Country	**2016**	**2017**	**2018**	**2019**	**2020**
Passenger car					
Brazil	2,849,355	2,956,681	4,190,544	3,320,226	1,761,573
India	209,968	232,370	264,962	221,712	NA
South Africa	3,432,254	4,041,879	3,966,266	3,939,385	2,130,108
World	708,005,733	757,198,728	783,169,632	779,950,592	NA
E-Passenger car					
Brazil	-	1,486	3,845	20,647	26,106
India	NA	1,486	17,244	5,133	NA
South Africa	-	1,824	1,821	6,616	3,893
World	48	7,649,576	10,384,857	23,136,247	NA
Bus					
Brazil	47,081	92,139	124,316	166,352	94,237
India	3,885	12,602	4,047	5,888	NA
South Africa	96,277	107,853	92,685	96,445	58,508
World	15,686,825	16,448,347	17,567,102	18,941,768	NA
E-Bus					
Brazil	-	-	-	-	-
India	NA	NA	203	607	NA
South Africa	-	-	42	49	-
World	NA	153,047	260,523	799,713	NA
Motorcycle					
Brazil	9,912	10,248	20,794	51,955	29,734
India	45,507	46,988	46,937	42,151	NA
South Africa	92,623	100,330	79,928	94,807	66,729
World	19,066,892	21,826,601	25,123,828	26,669,823	NA
E-Motorcycle					
Brazil	-	2,044	6,244	29,689	13,052
India	NA	3,764	1,910	2,951	NA
South Africa	-	2,602	4,884	7,048	9,051
World	2	2,764,532	4,625,806	6,109,280	NA

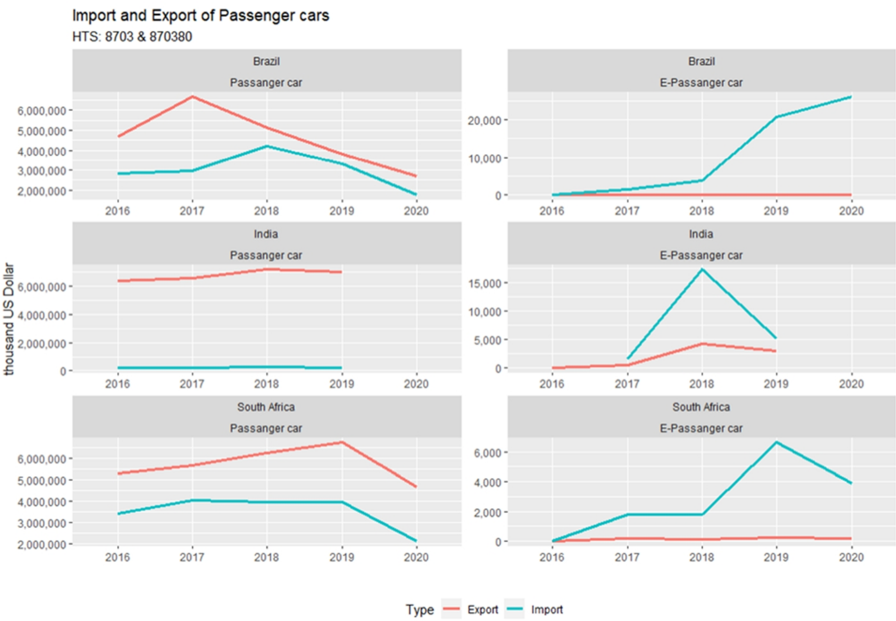
Source: (ITC, 2021)

A.2 EV EXPORT

Export in thousand U.S. Dollars					
Country	**2016**	**2017**	**2018**	**2019**	**2020**
Passenger car					
Brazil	4,671,383	6,669,807	5,141,234	3,781,712	2,713,522
India	6,367,514	6,591,608	7,191,708	7,003,036	NA
South Africa	5,289,459	5,669,262	6,228,532	6,713,124	4,659,112
World	708,005,733	757,198,728	783,169,632	779,950,592	NA
E-Passenger car					
Brazil	-	-	-	-	-
India	-	479	4,170	3,027	NA
South Africa	-	199	104	238	179
World	NA	8,301,055	11,274,682	25,307,122	NA
Bus					
Brazil	232,747	282,474	329,515	234,535	132,637
India	210,345	276,522	172,320	200,971	NA
South Africa	59,828	52,197	56,138	61,855	30,965
World	15,686,825	16,448,347	17,567,102	18,941,768	NA
E-Bus					
Brazil	-	-	-	21	345
India	-	2,899	916	-	N.A.
South Africa	-	737	354	1,375	-
World	138	190,480	450,693	838,551	NA
Motorcycle					
Brazil	111,353	156,736	141,821	88,164	78,686
India	1,606,257	1,902,960	2,146,757	2,092,550	NA
South Africa	24,617	17,944	20,144	17,740	18,757
World	19,066,892	21,826,601	25,123,828	26,669,823	NA
E-Motorcycle					
Brazil	-	10	-	6	49
India	-	191	566	1,417	NA
South Africa	-	56	38	60	262
World	NA	3,702,868	6,058,093	7,831,811	NA

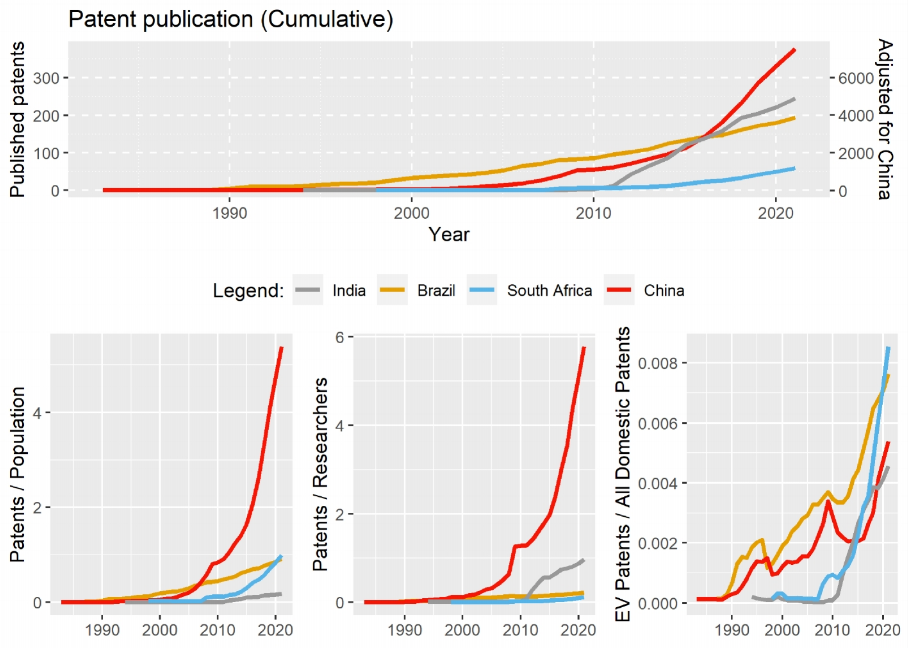
Source: (ITC, 2021)

A.3 IMPORT AND EXPORT OF PASSANGER CARS



A.4 PATENTS

The patent analysis consists of all published patents related to Electric vehicles, using technological classes (CPC) classes as in Altenburg et al. (2022). In total, Brazil, India, and South Africa have 194, 245, and 59 published patents, respectively. In comparison to China which has 7549, the numbers are low. To minimize countries' characteristics, patents were adjusted for Population, the number of researchers per million, and all domestic patents.



Source: World Bank (2021), BigQuery (2021)

A.5 PATENT APPLICATIONS

Patent applications – EspaceNet patent data base			
	Brazil	India	South Africa
Patents:	194	245	59
Main Applicants:	BOSCH, CSEM Brasil, Electric Dreams	TVS Motor, TATA Motors, Ather Energy, Bajaj Auto	South African Inventions, Optimal Energy
Nb of Universities:	3	3	4

A.6 ACADEMIC ARTICLES

Academic Articles – Lens database			
	Brazil	India	South Africa
Nb of Articles:	152	731	50
Articles with funding:	60 (39%)	116 (16%)	17 (34%)
Countries Public institutions as a funder:	60	73	12
Cited by patents:	3	17	1

A.7 BRAZIL – DETAILED POLICY DESCRIPTION

Incentives for domestic production	**(2011–):** BNDES Fundo Climate Program - Support the implementation of projects, the acquisition of machinery and equipment, and technological development related to the reduction of greenhouse gas emissions **(2013–2017):** Innovate Auto - increases a tax on industrialized products (IPI) by 30% for all light-duty vehicles (LDVs) and light commercial vehicles but gives a discount for manufacturers that meet a corporate average vehicle efficiency target (**2016):** CAMEX Resolution nº 34, of April 2016 (**2018**) Law No. 13,755, of December 10, 2018 - institutes the Rota 2030 Program - Mobility and Logistics - automakers must meet new energy efficiency and safety standards, otherwise, they must pay fines
Incentives for R&D (scientific)	**(2003–2016):** Research Projects (CNPq) related to EVs **(2008–2018):** R&D projects related to EVs (ANEEL) **(2010–2016):** Financing under the C.T. – Energia Sector Fund (FINEP) **(2011 –2015):** Call from Sibratec **(2011–2013):** BNDES Investment Support Program (2011–): Technological Fund (FUNTEC) **(2012–):** ABNT standards related to EVs **(2018)** Law No. 13,755, of December 10, 2018 - institutes the Rota 2030 Program - Mobility and Logistics - 398 million US$ in tax credit for investments in R&D
Incentives for charging infrastructure	**(2013–):** Inova Energia - Financing line included pilot projects for EV charging systems **(2016):** ANEEL Public Consultation on the need to regulate aspects related to the supply of electricity to EVs **(2018):** ANEEL regulation for the provision of electric energy recharge service for EVs **(2018)** Law No. 13,755, of December 10, 2018 - institutes the Rota 2030 Program - Mobility and Logistics **(2018)** Launch of public consultation No. 19/2018 for contributions to the call for Strategic R&D Project No. 22/2018: "Development of Efficient Electric Mobility Solutions".
Incentive for consumption	**(2015):** CAMEX Resolution nº 97 - reduction of VE import tax **(2016):** CAMEX resolution of import tax reduction for EV for goods transportation **(2018)** Law No. 13,755, of December 10, 2018 - institutes the Rota 2030 Program - State / Municipal Mobility and Logistics - EV owners are exempt from State Tax on Automotive Ownership (2014–): State IPVA exemptions from EVs (R.S., MA, P.I., C.E., R.N., PE, S.E.) and differentiated rates (M.S., S.P., R.J.) (2015): Exemption from rotation in São Paulo

Source: Consoni et al. (2019)

A.8 INDIA – DETAILED POLICY DESCRIPTION

Incentives for domestic production	**(2014 -)** MAKE IN INDIA - 100% Foreign Direct Investment (FDI) is permitted along with full delicensing STATE-LEVEL - manufacturers can get rebates in land cost, relaxation in stamp duty exemption on sale or lease of land, power tariff incentives, a concessional rate of interest on loans, investment subsidies/tax incentives, backward areas subsidies, and special packages for mega projects. PMP - adjusting BCD to support EV manufacturing according to the status of the ecosystem
Incentives for R&D (scientific)	**(2014 -)** MAKE IN INDIA - TAX Weighted deduction of 200% is granted to assess any sums paid to a national laboratory, university, or technological institute. The said sum is used for scientific research within a program approved by the prescribed authority. - TAX Weighted deduction of 150% of the expenditure incurred by a specified company on scientific research in the in-house R&D recentres as approved by the prescribed authority.
Incentives for charging infrastructure	**(2015 - 2022)** FAME (I & II) - 173 stations to 8 different cities (India Scheme Phase II) CENTRAL GOVERNMENT - the government is mulling issuing an order that 69 thousand petrol stations must provide charging facilities LOCAL POLICIES State and City authorities have different incentives for charging infrastructure, e.g., Delhi: - aim to create 200 charging stations in 2021, so charging stations every 3 km
Incentive for demand	**(2015 - 2022)** FAME (I & II) - USD 1.39 Bn for years 2020-22 (support for 7000 e-buses, 500.000 e-3 wheelers, 55.000 e-4 wheelers, and 1 million e-2 wheelers). Only advanced batteries and registered vehicles will be incentivized under the scheme. - 1 & 2 tranche of the incentive for electric busses (90 & 50 busses) LOCAL POLICIES Different demand stimulations come from state and city authority levels, e.g., Delhi: - Waiving off-road tax and registration fees for electric vehicles - Purchase subsidy up to 150.000 Rupee (2.000 USD) for e-passenger car and 30.00 Rupee (400 USD) for e-two-wheeler

Sources: Roy (2020), FAME-II (2020), DPIIT (2020)

A.9 SOUTH AFRICA – DETAILED POLICY DESCRIPTION

Incentives for domestic production	**(2013 – 2020):** Automotive Production and Development Programme (APDP) - import duties to protect domestic production - vehicle assembly allowance (VAA) - investment scheme (cash grant) for manufacturing capacity upgrading **(2018 – 2050):** Green Transport Strategy (GTS) for South Africa - Incentives to both produce and sell affordable EVs **(2021 - 2035)** The South African Automotive Masterplan (SAAM) - changing VAA to Volume Assembly Localisation Allowance (VALA); Strengthening the role of localized value-added - investment scheme from APDP modified; 5% decrease if not domestic tooling/machinery
Incentives for R&D (scientific)	**(2018 – 2050):** Green Transport Strategy (GTS) for South Africa - stimulate research on EV batteries
Incentives for charging infrastructure	**(2013 -)** uYilo eMobility Technology Innovation Programme (EMTIP)
Incentive for consumption	**(2018 – 2050):** Green Transport Strategy (GTS) for South Africa - stimulate national, provincial, and local government departments and authorities to upgrade the fleet with EVs

Sources: (Raw and Radmore, 2020)

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