Winds of Change:

Winds of Change: Cost Reductions and Shifting Demand Regimes in the European Wind Turbine Manufacturing Industry

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Doctoral Thesis

UCL

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Declaration

I, Keno Sun Montano Haverkamp, confirm that the work presented in my thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

This PhD analyses various aspects of the renewable energy transition and the industrial dynamics of the underlying sectors. On the basis of reduced costs of renewable energy technologies, the energy transition has become a huge opportunity for economic growth and job creation. Despite the overall expansion of wind energy projects in many countries, European wind turbine OEMs (Original Equipment Manufacturers) have struggled with increased cost competition and squeezed profit margins since the switch from feed-in tariffs to renewable energy auctions in the EU in 2017. The PhD researches the drivers of cost reductions of wind energy technologies and the determinants of industrial dynamics and market leadership. To do so, various aspects of cycles linked to demand, technological change and organisational reconfiguration will be analysed. Each empirical chapter will examine these elements from distinct theoretical perspectives, providing a comprehensive analysis of how they interact and influence one another. Given the multifaceted and multi-tiered nature of this research as well as limitations to quantitative data availability, a mixed-methods and case study research design that triangulates quantitative analyses with in-depth semi-structured interviews will be used. Overall, the thesis shows how changes in the European Demand Regime for wind turbines have on the one hand driven cost reductions and on the other hand affected industrial dynamics in the wind energy sector to which wind turbine OEMs had to adapt.

Impact Statement

This PhD thesis represents a theoretical and empirical contribution to our understanding of cost reductions, innovation, and industrial dynamics in renewable energy technologies. Positioned at the intersection of multiple economic frameworks, this research combines i) Schumpeterian and evolutionary economic approaches to economic change and development, ii) structural economic theories of demand, iii) and institutional political economy analyses of interests and power. Different lenses and methodological approaches of these economic schools of thought are integrated in a novel and original combination. By further developing the idea of Structural Cycles and their underlying technology, demand, and organisational transitions, this PhD provides an original contribution to the academic literature. By incorporating an institutional political analysis angle, the PhD further aims to uncover the drivers of these cycles. This holistic and novel approach not only enhances our theoretical understanding but also provides empirical insights into the industrial dynamics of renewable energy sectors. Furthermore, the findings of this research carry significant implications for policymakers navigating the renewable energy transition and designing green industrial policies. The research underscores the role of active government involvement in renewable energy sectors and the green transition at large. Additionally, it highlights the importance of designing policy interventions on the demand side that are aligned with evolving technological landscapes, market demands, and organisational structures.

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I would not have been able to complete this PhD journey without my friends and family. Too many friends in both my hometown in Germany, as well as in London, Copenhagen, and Vienna have supported me in ways they might not have even realised. In particular, I want to thank Jan Altaner, who always encourages me and whose intellectual curiosity and sense of social justice constantly inspire me.

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Abbreviations

AWP	Corporación Acciona Windpower
BDEW	German Association of Energy and Water Industries
BDI	Federation of German Industries
BEE	German Federal Association for Renewable Energy
BMWi	German Federal Ministry for Economic Affairs (Now BMWK)
BMWK	German Federal Ministry for Economic Affairs and Climate Action
BNE	German Federal Association for New Energy Economics
BNEF	Bloomberg New Energy Finance
BNetzA	German Federal Network Agency
BSH	German Federal Maritime and Hydrographic Agency
BSW Solar	German Federal Association Solar Energy
BWE	German Federal Association for Wind Energy
BWO	German Federal Association of Offshore Wind
CapEx	Capital Expenditure
CDU	German Christian Democratic Party
CfD	Contract-for-Difference
CPC	Cooperative Patent Classification
DENA	German Energy Agency
DIHK	German Chamber of Commerce
DLR	German Aerospace Centre
EBIT	Earnings before income and tax
EEG	Erneuerbare Energien Gesetz (German Renewable Energy Act)
EEX	European Energy Exchange
EFET	European Federation of Energy Traders
EPO	European Patent Office
EU	European Union
FDP	German Free Democratic Party
FID	Final investment decision
FiT	Feed-in Tariff
GE	General Electric
GW	Gigawatt
GWEC	Global Wind Energy Council
ICP	International Patent Classification
ICT	Information and Communication Technologies
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JPO	Japan Patent Office
KFT	Climate and Transition Fund
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelised cost of electricity
MHI	Mitsubishi Heavy Industries

MNE	Multinational corporation
MW	Megawatt
MWh	Megawatt-hour
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OLS	Ordinary least squares
PNKS	Climate-Neutral Electricity System Platform
PPA	Power Purchasing Agreements
R&D	Research and development
SGRE	Siemens Gamesa Renewable Energy
SPD	German Social Democratic Party
UK	United Kingdom
US	United States
USD	US Dollar
USTPO	US Patent Office
VDMA	German Association for Machinery and Equipment Manufacturers
VKU	German Association of Local Utilities of Municipalities
VZBV	Federation of German Consumer Organisations
WAB	German Network for Wind Energy
WindSeeG	German Offshore Wind Act
WWF	World Wildlife Fund

Chapter 1: Introduction

1. Introduction and Research Context

Energy and electricity have become a central feature of our daily lives and have been described as the ‘lifeblood’ of capital and the economy (Huber, 2013). However, unsustainable levels of energy use are responsible for the majority of greenhouse gas (GHG) emissions and have unequivocally caused global warming. In 2022, with 14.65 Gt CO2 emissions the energy sector was the largest contributor of CO2 emissions, followed by the industrial sector which was responsible for 9.15 Gt CO2 emissions (IEA, 2023). The current GHG trajectory under existing policies is expected to lead to an approximate 2.7°C increase in temperature above pre-industrial levels (Dhakal et al., 2022). Thus, decarbonising the energy sector, electricity supply, and industrial production is vital for staying within a 1.5 °C global warming as pledged under the Paris Agreement and thus avoiding an irreversible climate breakdown.

To address this climate issue, many countries around the world have embarked on ambitious transitions from coal-fired electricity generation to electricity generated from renewable energy sources such as wind and solar. The International Energy Agency estimates that by 2025, renewables-based electricity generation will surpass coal-fired electricity generation as more and more wind, solar PV, and other renewable energy technologies are deployed (IEA, 2024).

At the same time, this renewable energy transition has driven huge opportunities for economic growth and job creation in the global manufacturing sectors for renewable energy technologies. Fuso Nerini et al. (2018) find that 85% of the UN Sustainable Development Goals are mutually reinforcing with affordable and clean energy (SDG 7). Particularly, the evolution of the wind and solar PV energy sectors globally is a remarkable story of transformation and growth. In key markets such as Europe, the United States, and China, wind energy has transitioned from a niche power source to a formidable challenger of traditional energy sources, including coal, gas, and nuclear power. This shift has disrupted the conventional business models of the world's major power utilities. As a result, the sector has also become a significant field of global economic rivalry that has led to a proliferation of state interventions in the domestic development and manufacturing of green and renewable technologies.

The economic benefits of renewable power generation, particularly in solar and wind technologies, have become increasingly compelling after decades of cost reductions and performance improvements.[1] From 2010-2019, unit costs of solar energy and wind energy have decreased by 85 per cent and 55 per cent, respectively (IPCC, 2023). Even before the fossil fuel price crisis of 2022, renewables were considered to be outperforming fossil fuels in terms of cost efficiency (IRENA, 2023). In many regions, renewables were even more cost-effective than existing fossil fuel plants and the spike in fossil fuel prices in 2022 further enhanced the competitiveness of renewable power. For many years, the notion of renewable energy being economically viable was considered highly improbable. The cost of generating electricity from fossil fuels was significantly lower than that from renewable sources, creating a substantial economic barrier to the adoption of renewable energy. This economic disparity seemed insurmountable, hindering the progress of renewable technologies. However, from the mid to late 2000s, significant changes began to occur: Financial investments in renewable energy surged, and technological advancements drove down the costs dramatically. By the mid-2010s, the cost of renewable energy had nearly converged with that of fossil fuels.

However, the primary focus on cost competitiveness and the speed of this has also had significant implications for the original equipment manufacturers (OEM) of renewable energy technologies. In the wind sector, the main European wind turbine OEMs Siemens Gamesa, Vestas, Nordex, and Enercon are facing significant financial struggles (WindEurope, 2022). This is often attributed to a combination of factors including rising raw material and logistics costs, supply chain disruptions, and increased cost

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[1] The costs of renewable energy projects such as wind farms and solar PV parks are almost entirely upfront capital investments. The costs to manufacture and install wind turbines and solar PV panels are thus highly linked to the cost of renewable electricity generation.

competition with lower-cost producers in China (Steitz et al., 2024). These challenges have led to decreased profit margins, project delays, and in some cases, substantial financial losses. These financial difficulties are causing concerns about their ability to sustain innovation and production capacity, which are critical for supporting the ongoing energy transition.

Wind turbine OEMs need substantial investment to continue innovating and improving their technology. Financial difficulties can lead to cuts in research and development budgets, slowing down the pace of innovation. This can hinder the development of more efficient and cost-effective turbines, which are crucial for making wind energy more competitive and widespread. Equally, financial instability can lead to project delays or cancellations. OEMs facing financial challenges may not be able to meet production deadlines, leading to delays in the deployment of wind farms. Financial struggles can also lead to disruptions in the supply chain. If key OEMs face insolvency or severe financial constraints, it can affect the availability of critical components needed for turbine production and maintenance. Overall, this could lead to increased costs and project delays, thus undermining the energy transition.

Renewable energy cost reductions and industrial leadership

This success and cost competitiveness of renewable energy technologies have been significantly underpinned by public policy (Lauber and Jacobsson, 2016; Rogge and Reichardt, 2016). Market mechanisms alone are often insufficient to drive the widespread adoption of low-carbon technologies due to various market and systemic failures (Christophers, 2024). These challenges necessitate proactive governmental intervention to internalise negative externalities, for example through carbon pricing, and to actively engage in industrial policy to create new markets for low-carbon technologies (Mazzucato and Penna, 2016; Mazzucato and Semieniuk, 2018; Rodrik, 2014).

Governments can foster technological change and create a domestic market for renewable energy technologies by implementing technology-push and demand-pull policies, which can stimulate both the supply and demand for renewable energy innovations (Nemet, 2009). While renewable energy technologies have witnessed remarkable cost reductions in the last two decades, the drivers of those reductions remain largely elusive. We aim to fill this gap in this PhD by analysing the effects of technology-push and demand-pull dynamics on renewable energy cost reductions.

At the same time, the manufacturing industries behind renewable energy technologies have changed substantially as the technologies matured. The wind turbine manufacturing industry has developed into a USD 185 billion industry, with around 1.4 million jobs, globally (IEA, 2024; IRENA and ILO, 2023). Originally most wind farms consisting of individual or few wind turbines were developed and operated by farmers and cooperative-owned schemes, while the production of wind turbines was dominated by small Danish firms (Backwell, 2018). Today, the wind energy sector has become a major global industry with utility companies dominating the development and operation of wind farms. The growth of the wind industry has also involved significant industry consolidation and changes to the industrial landscape of the wind turbine sector in recent years. The development and manufacturing of increasingly bigger and more powerful wind turbines is done by a few OEMs which have turned into large multinational corporations. This has also coincided with other shifts in global production dynamics and the emergence of new industrial leaders in countries such as China, India, and South Korea (Lewis, 2011).

Changes to economic structure and the rise of new firm entrance or development of entire firm ecosystems in the renewable energy sectors have been explained through so-called ‘Green Windows of Opportunity’ (‘GWO’): favourable, time-limited conditions for technological advancement and changes to international market leadership in sustainable technologies (Lema et al., 2020). While the concept of GWO has been largely applied in the context of latecomer countries, there remains a lack of understanding of how incumbent leaders are affected by and react to these challenges from latecomer entrants in the sector. This gap in the literature is surprising as the GWO framework explicitly states that not every window of opportunity necessarily translates into a change of leadership (Lee and Malerba, 2017). This appears particularly relevant for the onshore and offshore wind turbine manufacturing industries where despite the rapid development of Chinese wind turbine OEMs, supply chains remain relatively concentrated regionally. Thus, we aim to contribute to the debate on Green Windows of Opportunity and general industrial dynamics in renewable energy sectors by analysing technological developments and changes in demand within Europe.

As recognised in the work of Joseph Schumpeter, changes in industrial leadership are often viewed as a common characteristic of industries where competition is primarily driven by innovation (Schumpeter, 1976). Building on the Schumpeterian understanding of patterns of innovation, the concept of 'Technological Regimes' (Dosi, 1982) is often used to explain trajectories of innovation within a particular sector (Breschi et al., 2000). Technological Regimes, implied by the nature of a specific technology, encompass key economic aspects of technologies and the learning processes involved in innovation (Malerba and Orsenigo, 1997). As such, Technological Regimes influence the dynamics of industries, including the entry and exit of firms, the competitive strategies they adopt, and the patterns of investment in research and development (R&D). Shifts from one regime to another may thus lead to periods of rapid economic expansion, productivity improvements, and changes in the competitive landscape. Different regimes may favour different industrial structures, such as monopolistic, oligopolistic, or competitive markets.

To date, the academic literature on industrial dynamics has largely neglected the role of demand, missing critical aspects of competition and industry evolution (Malerba et al., 2016). Traditionally, theories have focused on competition in markets for homogeneous products, overlooking the complexities introduced by changes in the structure and composition of demand for these products. Existing examples of studies on the role of demand include an analysis of the computer industry, where cost reductions and the invention of new technologies enabled the emergence of a new demand class, centred around smaller and individual customers compared to large firm consumers (Malerba et al., 1999). This new demand class changed the industrial dynamics in the computer industry and gave rise to a new set of dominant firms focused on the production of minicomputers and microprocessors.

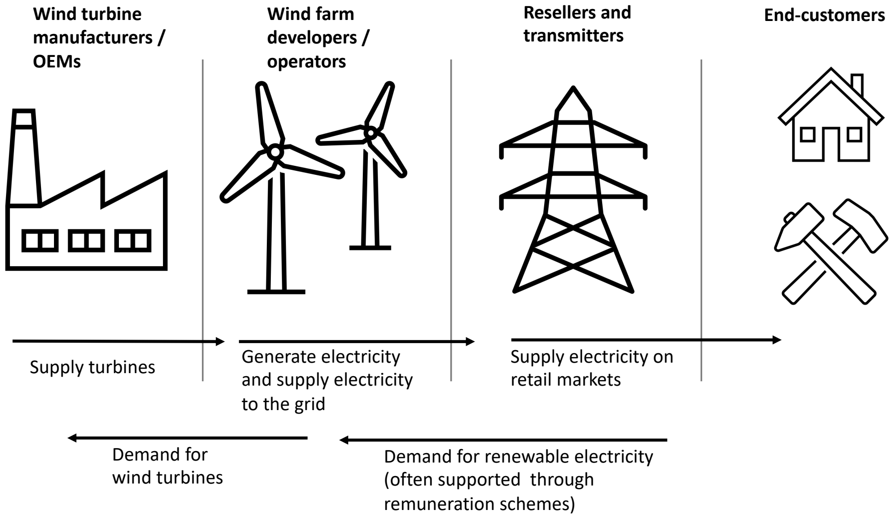
We will further investigate the role of ‘Demand Regimes’ as analogous to Technological Regimes in the wind energy sector. Technological innovations can create new types of demand by introducing products and services that were previously unavailable. Conversely, shifts in demand can drive technological innovation as firms seek to meet new consumer needs and preferences. A Demand Regime refers to a distinct pattern or structure and composition of demand that influences industrial dynamics, including the development and diffusion of technologies, the strategies of firms, and overall economic growth. Demand Regimes are characterised by specific consumer preferences and behaviours that shape the types of goods and services that are in demand. The structure and composition of demand within a given Demand Regime have been defined as either fragmented or homogenous with regard to a product’s specific features and prices (Capone et al., 2013).

In the case of renewable energy technologies, which have been supported through government policies such as feed-in tariffs, the Demand Regime is not an emerging property of the market but rather shaped by government preferences for the direction of change. Thus, Demand Regimes are different when they are shaped by governments through incentives or pricing structures. Changes in government policies, regulations, and institutional frameworks can influence and shift Demand Regimes. The nature of renewable energy technologies and the crucial role that government policies have played in establishing demand for these technologies make this a particular case where different types of policy interventions and ways of structuring demand can have varying effects on the supply chain of the industry in question.

However, a definition of demand for renewable energy technologies such as wind turbines might not be straightforward: In its most simple form, today’s electricity markets can be understood as a system where electricity is produced, sold, and consumed. Generators, such as fossil fuel power plants or renewable energy projects, create electricity and sell it to the market.

Sellers or retailers buy this electricity from the market and then sell it to customers, including households, businesses, and industries. Grid operators transmit the electricity and ensure that electricity flows from generators to consumers. Renewable energy producers have to compete with fossil-fuel power plants in selling their electricity. End-customers such as individual households usually have very limited power in choosing what kind of electricity they consume, i.e. whether it is produced using renewables or fossil fuels. The ‘demand’ for renewable energy technologies such as wind turbines is therefore primarily driven by the developers and operators of wind farms, which can be small-scale consumers such as local energy cooperatives, large utility companies, or even state-owned enterprises. Thus, an understanding of the types of commercial entities and their respective business models for developing and operating wind farms is crucial to understanding ‘demand’ in the wind sector.

Figure 1: Overview of electricity markets and the demand for wind turbines



Source: Own elaborations

Within the EU, the wind turbine Demand Regime has been shaped by increased cost pressure through the use of renewable energy auctions rather than feed-in tariffs since 2017. Renewable energy auctions are price-based and thus focus predominantly on the levelized cost of electricity of the renewable energy technology. As a result of this increased cost competition among wind park developers, the customers of wind turbines have been demanding larger and more cost-effective wind turbines, which can achieve a lower levelized cost of electricity. As a result, OEMs of wind turbines have had to adapt to this new set of customers and changes in the Demand Regime through firm-specific strategies including organisational restructuring. In order to analyse these dynamics, we explicitly link macro-structural analyses of technology and demand changes with a micro-founded view of firm capabilities and learning processes in this PhD.

Given the emerging importance of demand and the Demand Regime for both cost reductions in renewable energy technologies as well as the respective technology's manufacturing sector, an investigation into the political economy affecting demand-side policies appears crucial. Central to the shaping of the Demand Regime for wind turbines have been domestic government policies such as feed-in tariffs and market premiums. However, as these technologies have become more mature, governments are starting to scale back their support measures and increasingly rely only on the market to drive further expansions of the renewable energy sector. For example, recent changes to the offshore wind auctions in Germany have removed most subsidies for renewable electricity generators and instead rely on a bidding system whereby developers compete by offering to pay for access to future wind farm locations. This marks an important shift and will have significant implications for the profitability of offshore wind projects in Germany with effects on the entire wind turbine manufacturing supply chain.

2. Research Motivation and Research Questions:

My motivation for this PhD is twofold: First, to understand how wind energy projects have become cheaper and how this can serve as a case study for other renewable and green technologies. Second, to understand the industrial dynamics behind changes in the wind turbine manufacturing sector and how states can develop other green industries. This will provide important lessons for industrial policy both for advanced economies as well as latecomer countries seeking to emulate their success in renewable energy sectors.

Given the scale of change required to address climate change, a wide range of green technologies must be available, affordable, and produced on a large scale. There is no single solution and relying on just one or even a few technologies is insufficient. Successful adoption of a broad set of technologies is necessary to tackle climate change comprehensively. The wind energy sector has been chosen as an exemplary case study for the wider green transition. This is because the existence of both onshore and offshore wind technologies allows for a comparative analysis within the same industry.[2] Onshore and offshore wind represent fundamentally different technologies, each maturing through distinct cycles and having become established markets at different times. This analysis can provide valuable insights into other renewable and green technologies, illustrating how diverse technological approaches can collectively contribute to large-scale climate solutions. By examining the successes and challenges within the wind sector, we can identify strategies and frameworks applicable to other areas of renewable energy, ultimately supporting a more integrated and effective approach to combating climate change.

Overall, we seek to answer the overarching research question of how changes in the Demand Regime in the wind energy sector have in turn driven cost reductions and affected the overall industry as well as individual OEMs of wind turbines. To translate this research aim into a tangible research project, the following sub-research questions will be answered:

RQ1: *What role did technology-push and demand-pull dynamics play in driving cost reductions of onshore wind and solar PV energy projects?*

RQ2: *How has the structure and composition of demand for wind turbines changed following the adoption of renewable energy auctions in the EU and what impact has this had on European wind turbine OEMs?*

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[2] Due to the limited availability of cross-country longitudinal data for offshore wind energy projects, Chapter 4 uses solar PV as a comparative case study for onshore wind energy. This was justified given that the onshore wind energy technology primarily competes with solar PV technologies when it comes to the levelized cost of electricity.

RQ3: *How have European wind turbine OEMs restructured their internal organisation as well as external supply chain structure following changes to the structure and composition of demand for wind turbines?*

RQ4: *How can the profitability implications of different renewable energy pricing regimes explain the political economy behind changes to Germany's new offshore wind remuneration schemes and auction designs?*

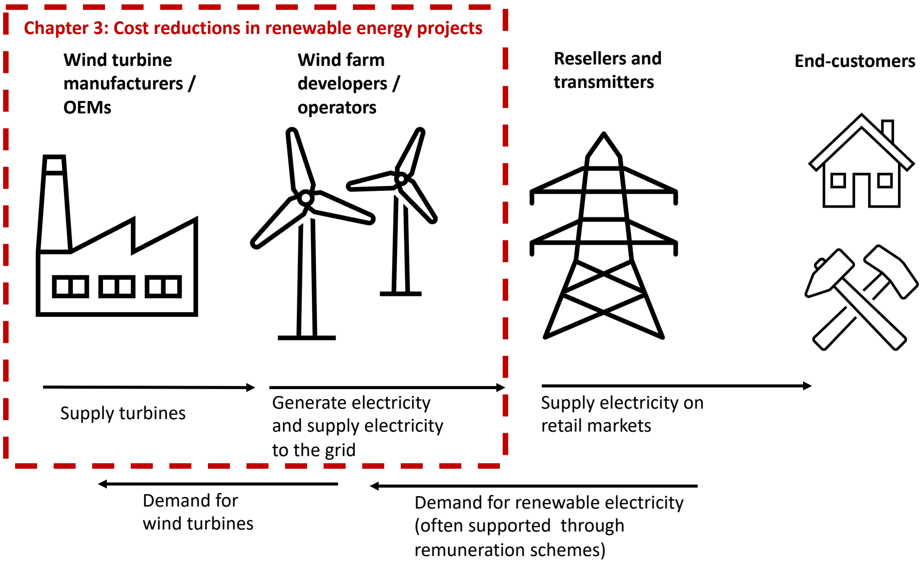
In short, this PhD examines various aspects of the energy transition, including i) cost reductions of renewable energy technologies, ii) changes to the structure and composition of demand for those technologies, and iii) the implications of these dynamics for OEMs. It does so to understand the multifaceted challenges of green industrial policy. Each empirical chapter 3-6 examines various aspects of cycles that are intrinsically linked to both technological change and demand. These cycles will be examined from distinct but interrelated perspectives, providing a comprehensive analysis of how they interact and influence one another. Therefore, while the chapters and their respective research questions speak to each other, they can also be viewed as independent research papers.

Given the multifaceted nature of this research and the limitations to quantitative data availability, we employ a mixed-methods research design that triangulates quantitative analyses with in-depth semi-structured interviews and case studies from the onshore and offshore wind energy sectors.

3. Structure of the PhD thesis

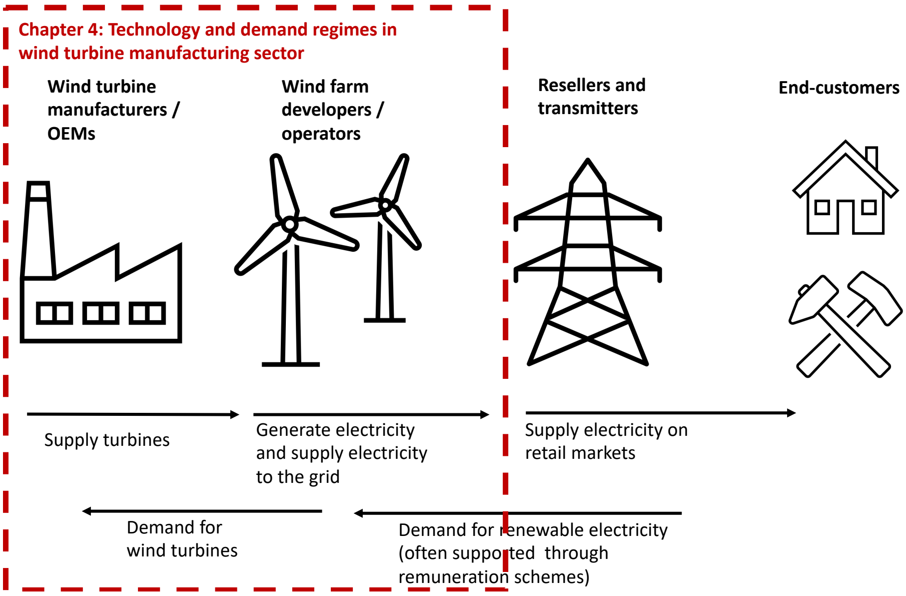
Chapter 2 critically engages with the existing academic literature on different macro-structural approaches to technological transitions and micro-founded theories of firm capabilities. Together, the reviewed approaches constitute different micro, meso, and macro analyses of Technological and Demand Regimes as well as underlying changes in organisational dynamics. Despite their respective insights, there has been a notable gap in efforts to integrate these different approaches. To bridge this gap, the PhD adopts and further develops the concept of Structural Cycle analysis by Andreoni et al. (2016) as a unifying framework. This framework helps to combine the different theoretical perspectives, emphasising that the transformation of industries depends on continuous and varied changes in the composition of manufacturing systems and technology platforms. Chapter 2 will also present methodological considerations of using this approach and the impact on the resulting choice of research methods in the subsequent empirical chapters.

Figure 2: Focus of Chapter 3



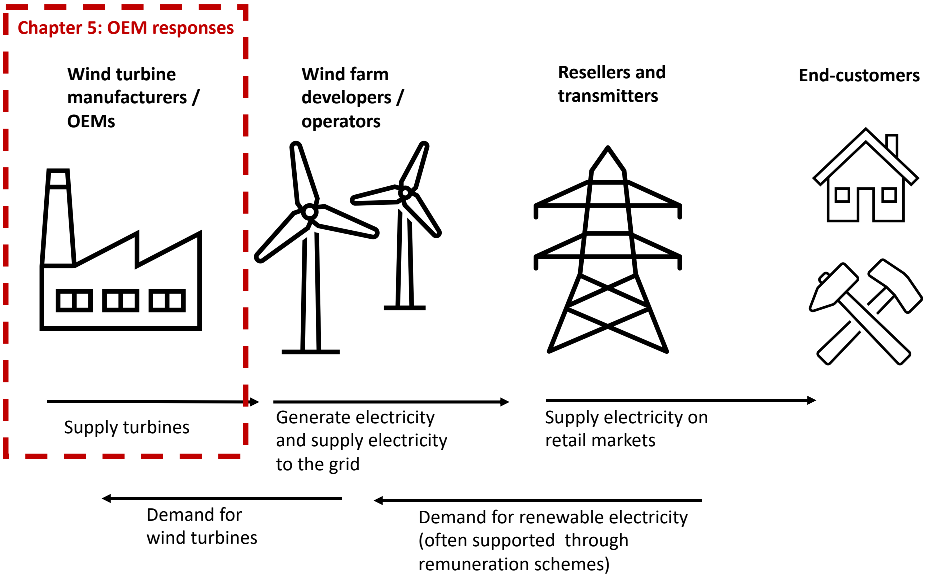
Central to the success of the renewable energy transition is the cost competitiveness of renewable energy technologies compared to fossil fuels. Chapter 3 examines the drivers of cost reductions in renewable energy technologies by conducting an econometric study of proxies for technology-push and demand-pull dynamics on the average installed costs of onshore wind and solar PV energy projects. Despite remarkable cost reductions globally, significant national differences remain in the average cost of constructing renewable energy projects, and the actual reason for cost reductions for the relevant technologies currently remains surprisingly elusive. By conducting a cross-country regression analysis of the period between 2004 and 2017 when onshore wind and solar PV were commercialised, this PhD goes beyond popular approaches of learning curves for renewable energy technologies to uncover the main drivers for such cost reductions. By using both public and private financial investments as our proxy for demand-pull dynamics, we are able to investigate different types of demand-pull.

Figure 3: Focus of Chapter 4



Despite the overall expansion of wind energy projects in many countries, European wind turbine OEMs have struggled with increased cost competition from Asian OEMs and squeezed profit margins since the EU instructed member states to switch from feed-in tariffs to renewable energy auctions by 2017. Chapter 4 further examines recent changes within the onshore and offshore wind energy sectors. To do so, structural dynamics on the macro-meso level are mapped through a so-called Structural Cycle analysis to understand technological and demand development in the onshore and offshore wind industries. As the quantitative data on European wind farm developers and operators is surprisingly scarce, it was decided to investigate these changes through a mixed-methods case study. It was further decided to treat Germany as a critical case study given the size of the German market and relative importance for European wind turbine OEMs.

Figure 4: Focus of Chapter 5

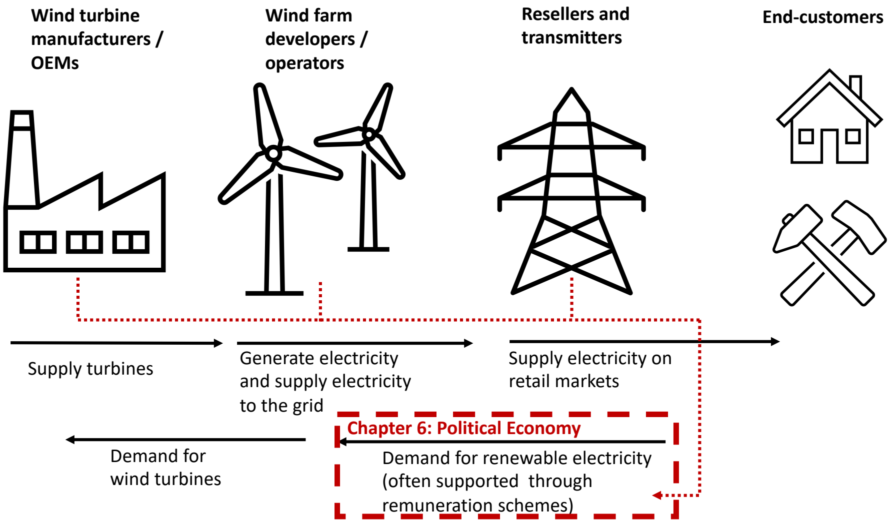


Findings from Chapter 4 point to fundamental changes in the European Demand Regime for wind turbines. Chapter 5 analyses the micro-meso dynamics of organisational restructuring by wind turbine OEMs in response to these changing dynamics. Firms' capabilities and abilities to react to the uncertain, collective, and cumulative dynamics in Technology and Demand Regimes depend on three key factors: i) strategic control, ii) organisational integration, and iii) financial commitment as spelt out in the Theory of Innovative Enterprise (Lazonick, 2022, 2019). This analytical approach reveals the key dynamics driving industrial transformations and underscores the importance of aligning industrial policy interventions to shifts in technologies, demand, and organisational structures.

Having established the importance of demand, the last empirical chapter will analyse how different interests try to influence government policies that can affect changes in the Demand Regime. As stated above, Demand Regimes in renewable energy sectors are often shaped through government policies such as feed-in tariffs, market premiums, or Contracts-for-Difference. The policy choice for different renewable remuneration schemes and their underlying pricing regimes depends on whether the public or private sector should bear the risks of the energy transition. Different remuneration schemes have underlying pricing regimes or price controls, which have implications for profitability for different actors involved. Chapter

6 examines the underlying political economy behind the policies shaping the Demand Regime on the example of two changes to Germany's new Offshore Wind Act in 2020 and 2022, comparatively.

Figure 5: Focus of Chapter 6



Chapter 7 elaborates on the overall findings of this PhD and discusses its policy implications. The findings from the different empirical chapters carry significant implications for policymakers navigating the renewable energy transition. The research underscores the importance of designing policy interventions that align with evolving technological landscapes, market demands, and organisational structures in order to utilise GWO in the energy transition. Furthermore, it highlights the need for proactive government involvement to ensure a smooth transition towards sustainable energy sources. By considering the insights from this PhD, policymakers can better formulate strategies that foster innovation, competitiveness, and sustainability in the renewable energy sector.

Chapter 2: Literature Review and Methodological Considerations

1. Introduction

This chapter provides a critical review of the theoretical literature that this PhD draws from and develops. The PhD can be positioned at the intersection of i) Schumpeterian and evolutionary economic approaches to economic change and development, ii) structural economic theories of demand, iii) and institutional political economy analyses of interests and power. It combines macro-structural elements with micro-founded theories around dynamic capabilities and the resource-based capability of the firm. This approach stems from the belief that macro paradigm approaches to structural dynamics of innovation and demand need to be combined with a microlevel perspective of the firm on co-evolving organisational reconfigurations. Understanding these dynamics from different perspectives and at different units of analysis can help us understand not only the drivers of cost reductions of renewable energy technologies but also the winners and losers of technological change. While the following empirical chapters will cover the empirical literature of each topic, this chapter aims to step back and cover the bigger picture of the theoretical building blocks and resulting methodological considerations of the PhD. A particular emphasis of this literature review will be the role of technological change and demand within different schools of economic thought and how this informs the research project.

The drivers of cost reductions analysed in Chapter 3 indicate there are structural elements of learning connected to “technology-push” and “demand-pull dynamics. These structural elements, particularly with regard to changes to the Technology and Demand Regimes also have broader implications for industrial dynamics and organisational configurations of firms on the micro-level (Guerrieri and Pietrobelli, 2004). These different elements have so far not been combined analytically and analysed together from a multi-tiered perspective. Thus, this PhD seeks to contribute theoretically to the notion of structural learning and industrial dynamics in renewable energy sectors and to advance analytically the framework of Structural Cycles for understanding these two phenomena.

The literature review in Section 2 is structured as follows: The first sub-section will briefly introduce neoclassical economics, evolutionary economics, and structural economics and their respective underlying assumptions. The second sub-section will elaborate on theories of technological change and technological paradigms as explanations for economic development over time. This will be juxtaposed with the notion of Demand Regimes and the role of the institutional political economy in shaping the structure and composition of demand in the third sub-section of the literature review. The fourth sub-section examines these insights through the framework of Windows of Opportunity and how this can help us understand changes in industrial leadership. The fifth sub-section of the literature review will shift away from these macrostructural approaches and instead focus on learning dynamics and firm capabilities at a micro level. This will include resource-based theories of the firm, dynamic capabilities, and the theory of innovative enterprise. Last, the concept of Structural Cycles will be introduced as a framework that allows us to combine and integrate the different macro and micro elements of the literature discussed.

Following the theoretical literature, methodological considerations of this PhD will be discussed in Section 3. This will include the underlying philosophy of science, the overall research strategy and research design, as well as the case study selection and data sources. The concluding section of this chapter elaborates on how the different theoretical building blocks and their underlying methodological implications relate to each other and are integrated with each other.

2. Theoretical Literature Review:

2.1. Neoclassical, evolutionary economic, and structuralist schools of thought and approaches to growth and technological change

Modern economics, whose beginning is often linked to the publication of Adam Smith's (1776) *The Wealth of Nations,* has been concerned with the coordination of economic activity, the constellation of prices, inputs, and outputs, as well as the question of economic growth and development. Initially, the question of economic growth was mostly centred around an understanding of dynamic and evolving market economies (Nelson and Winter, 2002). Contrary to the prevailing understanding of the economy as static, Smith was concerned with economic development as a result of economic restructuring and changes to production procedures. Similarly, the works of Karl Marx can be understood as having a dynamic approach to the economy and related class struggle and capital accumulation which changes over time. Thomas Veblen famously asked why economics was not an evolutionary science and called for research on cumulative change in methods of doing things (Veblen, 1898). Even the works of Alfred Marshall (1890), which is often viewed as the beginning of neoclassical economics and the idea of "market equilibrium", leaves room for dynamic changes in supply and demand as the economy is evolving toward long-term equilibrium (Nelson, 2020). In the first half of the 20th century, Joseph Schumpeter famously highlighted the dynamic and evolving properties of capitalism which stimulate innovation.

However, the paradigm of neoclassical economics that subsequently came to dominate the economic discipline after World War II has been heavily focused on researching existing equilibrium conditions and centred around the assumption of rational profit maximisation. Instead of seeing the economy as continuously evolving towards a long-run equilibrium, neoclassical economists increasingly viewed the economy as being in equilibrium, with disequilibrium treated only as a temporal deviation. Mathematically tested theories of such an equilibrium state and its conditions made any dynamic changes and economic progress difficult to analyse and questions of economic progress were thus pushed to the fringes of the discipline. Additionally, profit maximisation was no longer seen as a business motivation for innovation, but rather as true and correct optimisation by rational firms (Nelson and Winter, 2002).

Furthermore, classical economics and the seminal works of Adam Smith, David Ricardo and Thomas Malthus all considered technology as a critical aspect of economic growth. For example, the classical version of the economic theory of comparative advantage regarded differences in technologies as a key determinant for differences between countries' comparative advantages. Yet, in the neoclassical version of the theory (the Heckscher-Ohlin-Samuelson model) that came to dominate neoclassical economics in the 20th century, technology is assumed to be readily available with all countries having access to the same productive capabilities. As such, neoclassical approaches to technology and technological development do not consider the often costly and lengthy processes of learning (Pietrobelli, 1997).

Robert Solow was among the first scholars among neoclassical economists to suggest that 'technical change' should receive more attention as a driver of long-term economic growth, surpassing the significance of capital and labour in the production process (Perez, 2015; Solow, 1956). In his seminal work Technical Change and the Aggregate Production Function, Solow formalised how technical change could shift the aggregate production function (Solow, 1957). His research exerted a profound influence on subsequent economic analyses, which led economists to make substantial efforts in identifying this 'residual' element that positively influenced output per worker, now referred to as 'technological change' (Nelson and Winter, 1982). However, Solow's growth theory was still viewed through the lens of neoclassical models of economic growth, where the economy was considered to be in a state of equilibrium, rather than a continuous disequilibrium as argued by Schumpeter and others.

The 1980s saw a (re-)emergence of dynamic analyses of economic change through the works of evolutionary economists which will be briefly introduced below. Evolutionary economics put forth the importance of technological change in particular in explaining differences in innovation and growth across different geographies (Dosi, 1984, 1982; Freeman, 1987; Nelson and Winter, 1982). Building heavily on the works of Joseph Schumpeter, evolutionary economics focuses on firms that seek to gain a competitive edge against their competitors through innovation. Evolutionary economics differs from neoclassical economics in the sense that economic growth is seen as fundamentally dynamic. Contrary to the neoclassical equilibrium assumption, technology is no longer seen as a readily available blueprint but rather as something that requires complex learning processes by institutions and actors such as productive organisations. At the same time, it is acknowledged that coordination and market failures, path dependencies, or technological lock-ins can impact existing firms' ability to adapt to technological change. Their different responses can help explain cross-country differences (Nelson, 2020; Nelson and Winter, 2002). As such, technologies and technological change are seen as the primary drivers of economic growth and structural change in evolutionary economics (Nelson, 2005). Therefore, technological advancements and their origins have been the focus of a large body of empirical literature within evolutionary economics (Dosi and Nelson, 2018; Rosenberg, 1994).

Aside from the importance of technology and technological change, an important point of departure for evolutionary economics compared to its predecessors is the micro consideration of how firms behave and make decisions (Helfat, 2018). Evolutionary economics rejects the neoclassical assumption of rationality and rational and informed profit maximisation. Rather than assuming that individuals and organisations make decisions based on complete and accurate information, always maximising their utility, it instead assumes a bounded rationality as defined by Herbert Simon (1957). Such bounded rationality recognises the limitations of human cognitive abilities and information processing. As such, evolutionary economics recognises the existence of imperfect information and acknowledges that decision-making processes by firms often do not follow explicit profit maximisation (Cyert and March, 1963). As a result of this, there exists a diversity of behaviour among firms and organisations. This justifies the use of a "micro-founded" theory that involves an understanding of how agents such as productive firms behave (Dosi, 1997). A large part of evolutionary economic analyses thus focuses on firm competencies and capabilities as well as micro-level routines and learning processes (Morrison et al., 2008). Firm behaviour is shaped not only by established routines and capabilities but also by the ongoing evolution and innovation within firms themselves. By treating routines and learning processes of firms, evolutionary economics rejects neoclassical assumptions that all technologies within a production function are readily and effortlessly accessible at any time (Nelson and Winter, 2002). Instead, it is acknowledged that acquiring and adopting new technologies involves costly learning processes for firms and thus might prompt path dependency (Pietrobelli, 1997). Thereby, it constitutes an important contribution to the puzzle of the "black box" of innovation and technological change (Rosenberg, 1983).

At the same time, evolutionary economic approaches to economic change and industrial dynamics can be complemented with structuralist theories. According to the structuralist school of thought, structural change within the economy and between sectors is largely a result of changes in technologies and the size of the market (Pasinetti, 1993). This structuralist perspective allows for a greater emphasis on the role of demand. By building on Engel's law (Engel, 2021 [1857]) - which states as household income rises, the proportion of income spent on food decreases - structural economic theories emphasise that the economic structure, encompassing consumer demand and the sectoral composition of production is closely linked to the level of development (Kuznets, 1971; Pasinetti, 1981). Thus, according to a structuralist understanding à la Pasinetti differences in output growth of different sectors will not only depend on the overall growth of demand but also the "structure of demand" (Landesmann, 2022, p. 557). This conceptualisation of demand allows us to consider shifts in demand structures and their effect on the supply of a particular technology.

The following two sections will further consider the assumptions and implications of evolutionary economic approaches in greater detail: Firstly, with regard to an understanding of the economy as dynamic and the importance of technological change, the role of Technological Regimes and Windows of Opportunity for industrial leadership changes will be elaborated on. Here we will also introduce the notion of Demand Regimes and elaborate on the role of institutional political economy within a Demand Regime. Secondly, the role of technological learning, firm capabilities, and organisational structures will be unpacked in greater detail to justify the need for a micro-founded approach.

2.2. Technological Change and Technological Regimes

Despite the dominance of neoclassical economics, technological capability has been considered a key factor in understanding economic growth by important economists and linked to the comparative development of countries or regions. For example, in the 19th century, Friedrich List proposed industrial policy measures for Germany in order to catch up with England’s technological and economic leadership (List, 1841). Around 100 years later, Alexander Gerschenkorn linked the adoption of advanced technologies to the successful industrialisation of economically backward countries (Gerschenkorn, 1962). Similarly, Nathan Rosenberg famously “explored” and “opened” the black box of technological change and deepened our understanding of technological change as endogenous to economic growth (Rosenberg, 1994, 1983)

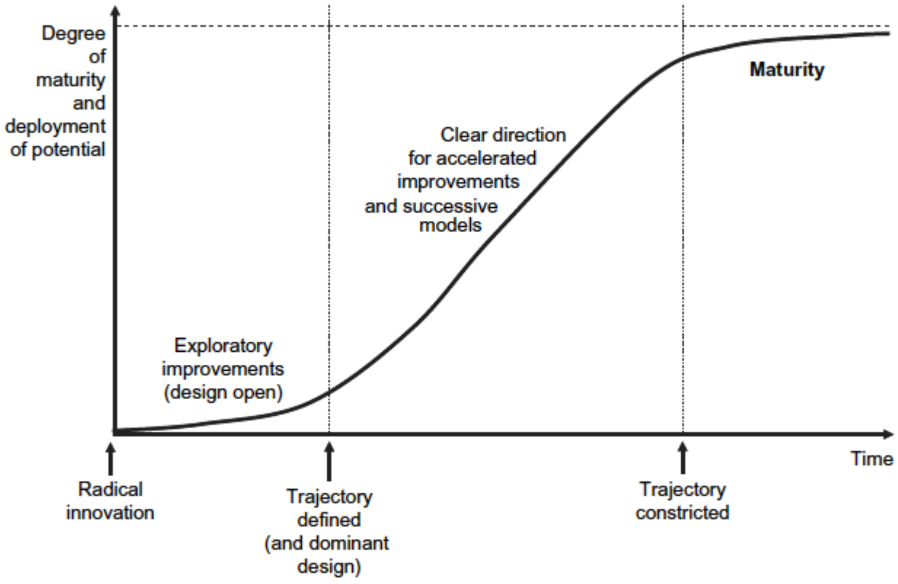
While it's widely acknowledged that technological change and inventive activity can vary in different sectoral and geographical contexts, the economic literature has made significant efforts to identify common elements (Dosi, 1982). These efforts often aim to identify a central driver of inventive activity and can be grouped into two primary approaches: 1) the first emphasises the influence of market forces as the primary drivers of technical change, known as "demand-pull" theories, 2) the second characterises technology as an autonomous or semi-autonomous factor, particularly in the short term, referred to as "technology-push" theories.

Although in practice, the distinction between these approaches can be somewhat blurred, it remains helpful for explanatory purposes (Dosi, 1982).

The fundamental distinction between these two approaches lies in the role assigned to market signals in guiding innovative activity and driving technical change and will be explored in greater detail in the first empirical chapter (Chapter 3).

From an evolutionary economics perspective, an important aspect of technological change is the idea of "techno-economic paradigms" or "Technological Regimes" (Nelson and Winter, 1977) that determine the factors influencing how a technology evolves. For a new technology to become dominant and shift the techno-economic paradigm, the deployment potential of the respective technology has to reach a certain level of maturity (Perez, 2010). Successful technologies of any kind tend to follow an "S-curve" for deployment, starting with a long phase of exponential growth in production and ending with eventual maturity and market saturation. These general patterns describe the trajectories by which technologies diffuse through competitive markets and are usually observable when plotting the deployment of a particular product or technology, such as different sources of electricity (Grübler et al., 1999).

Figure 6: Technological change and diffusion



Source: Perez (2010)

Starting with the initial invention of a technology, growth is usually slow before it accelerates as early investments lead to compounding cost reductions and a dominant design emerges. This gives the technology a clear direction for development and incremental innovations up until the market becomes saturated and the technology reaches maturity. As already outlined above, the adoption of a new technology is often contingent on the innovation becoming cheap enough to be commercially viable for customers. Indeed, it is with profit in mind that inventions are being turned into innovations and mere technical possibilities are turned into economic realities (Perez, 2010). Only once the costs of new technologies are low enough that they are able to compete with incumbent technologies, can diffusion become widespread (Wilson and Grubler, 2011). Cost reductions have therefore been described as the single most important feature determining preferences for certain technologies vis-à-vis others (Nemet, 2013). This is particularly the case for new (renewable) technologies in the context of energy transitions, where it is largely the end-use applications that drive supply-side transformations (Wilson and Grubler, 2011). As such, energy technologies are often viewed to be at the core of technological revolutions and subsequent paradigm shifts (Grubler and Wilson, 2013; Smil, 2018).

Carlota Perez identified five key technological "surges" from 1771 until the present: i) the Industrial Revolution, ii) the Age of Steam and Railways, iii) the Age of Steel, iv) the Age of Oil, and v) the Age of Information and Telecommunications (Perez, 2010). Each of these particular technological revolutions was noteworthy because they opened up broad new opportunities for innovation, introducing a range of new general-purpose technologies, infrastructures, and organisational methods that significantly enhance the efficiency and effectiveness of various industries and activities. These significant economic shifts often result in the obsolescence of existing technologies and incumbent firms, a phenomenon Joseph Schumpeter famously termed as "creative destruction". He described it as an ongoing " *process of industrial mutation [that] incessantly revolutionised the economic structure from within, incessantly destroying the old one, incessantly creating a new one*" (Schumpeter, 1976, p. 83).

The study of cycles in the economy and the analysis of underlying economic structures that influence these cycles has a long tradition in economics. This has resulted in the hypothesis that the economy is a dynamic, evolving system, characterised by periods of growth and resulting crises (Andersen, 1991; Dosi et al., 1988; Freeman, 1987; Freeman et al., 2001). Freeman and Perez (1988) introduced a taxonomy of innovation comprising: incremental innovations, radical innovations, changes in the technology system and organisational innovation, and lastly changes to the techno-economic paradigm. They further argue that each techno-economic paradigm is characterised by a key dominant technology with rapidly falling costs, unlimited supply, and clear potential for the technology to become dominant in the production system of the economy.

Perez (2002) further argues that the process in which a technological revolution develops can be broken into two distinct periods: 1) a period of installation, where new technologies and industries become established alongside a period of Schumpeterian 'creative destruction', and 2) a period of deployment where the installed technologies spread across the entire economy. While we are currently still in the process of deploying the ICT-driven paradigm, the installation period of a green transition has arguably already started (Mathews, 2018). A combination of these two periods under a 'smart green' paradigm "as a direction for innovation could be the most suitable way to bring about a successful deployment of the ICT age" (Perez and Murray Leach, 2018).

As we know from Schumpeter, finance plays a key role in the process of 'creative destruction' that allows industry to produce technological advances and economic development (Burlamaqui and Kattel, 2016). Operating in an environment of competition, firms face inherent uncertainty that requires constant investments to improve production processes and process innovation. This makes finance a key driver of innovation. For Perez (2002, p. 74), incumbent technologies and what she describes as 'productive capital', require 'financial capital' which is willing to take on the risks of such innovation.

Financial capital encompasses those agents that possess wealth in the form of money (or other paper assets) and seek to grow their assets through investments and capital gains. Productive capital involves agents that seek new wealth through the production of goods or services. The distinction allows differentiating between the enabling mechanisms (such as finance) and the actual process of wealth creation through productive capital. At the start of any technological revolution, and during the exploratory stage, financial capital usually enables entrepreneurs to bring their inventions into commercial realities. As low-risk investment opportunities in the previous technologies, i.e. fossil fuels in the case of the energy transition, start to diminish, there is a growing amount of idle capital willing to take the risks of trial and error of new radical entrepreneurship. Once necessary breakthroughs in the respective technology are made, financial capital becomes even more available for the exploitation of the new paradigm. “Financial capital then acts as the agent of massive creative destruction” (Perez, 2002, p. 75).

The idea of a green techno-economic paradigm was first defined by Freeman as a shift towards greener technologies and modes of production (Freeman, 1996, 1992). It is centred around the idea of low-carbon innovation and renewable energy increasingly gaining attention (Mathews, 2019). John Mathews argues that an emerging paradigm shift towards renewable energies is evidently underway because we can observe the key factors of a techno-economic paradigm as identified by Freeman and Perez: i) rapidly declining costs of renewable energy, ii) unlimited supply of renewable energy sources such as wind or sunshine, and iii) a demonstrated potential for renewables to be incorporated in the energy mix and the production system (Mathews, 2019). While some argue that renewable energy technologies themselves do not qualify for a paradigm shift of the production system underpinning our economy, they stipulate a paradigm shift within the energy transition. Hence, Perez’s framework of technological revolutions is, therefore, a useful lens to understand the cyclical dimensions that enable and guide this renewable transition.

Innovation is regarded as one of the key issues in energy transitions and researchers generally agree on the importance of technological change for future energy transformations (Nakicenovic et al., 2000; Smil, 2003; Wilson and Grubler, 2011). The S-shaped curves therefore remain a useful framework as they can help analyse not only the diffusion of one technology but also the substitution of another previous technology. While not every new technology has the potential to trigger such profound economic transformation and creative destruction, there is widespread agreement that energy technologies have been at the core of most technological revolutions and subsequent societal and political change (Grubler and Wilson, 2013; Smil, 2016).

2.3. Demand Regimes and the structure and composition of demand

It has been shown elsewhere that innovation is not always triggered by new scientific knowledge but often comes as the result of demand-side variables (Cohen et al., 2002). Technological advancement might be induced by feedback from customers of a product, or simply the perception that there is a need and demand for a particular technological advancement (Dosi and Nelson, 2018). For example, Rosenberg (1963) shows how the technological development in the machine tool industry was shaped by feedback and learning processes prompted by the demands of the users of machine tools. Responding to the need for faster cut speeds, producers of machine tools adapted their designs accordingly. However, it turned out that higher cutting speeds were incompatible with carbon steel cutting blades as they could not withstand the additional stress and strain, resulting in the development of new blades. The higher temperatures of faster cutting speeds further spurred the invention and development of new cooling methods. Elsewhere, von Hippel (2017) has shown how often the users of products are important sources and drivers of innovation themselves. Von Hippel identifies a subset of users called "lead users." These individuals face needs that will be common in the marketplace but are ahead of the general market. Lead users innovate to solve their own problems, and these innovations often have significant commercial potential.

Thus, it is often consumer demand that determines changes in productive activities. Writing on ‘demand and the productive resources of the firm’ Penrose argued that “*other things being equal, it is usually cheaper and less risky to expand the production of existing products than to enter into new* *fields. When, therefore, the market demand for existing products is growing and entrepreneurs expect continued growth, 'demand' will appear as the most important influence on the expansion, and current investment plans may be closely tied to entrepreneurial estimates of the prospects for increasing sales in existing product lines. If expectations are disappointed, a sharp curtailment of investment plans may follow*" (Penrose, 1959, p. 82). At the same time, Penrose acknowledges that most of the older and larger firms in the economy have over time changed their product portfolio and expanded into other business segments as demand for their original products has fallen or disappeared. Thus, "*the growth of almost all large firms has been accompanied by far-reaching changes in the composition of 'demand' which the firm has considered relevant for its operations*" (Penrose, 1959, p. 83). This is similar to a structuralist economic understanding of the importance of demand and shifts in demand structures (Landesmann, 2022; Pasinetti, 1981).

Yet, the role of changing compositions of demand has rarely entered the analysis of supply-side industrial dynamics (for a few notable examples see Adner and Levinthal, 2001; Christensen, 1997; Malerba et al., 1999; Mathews, 2005). Malerba et al. (2016) state that demand should receive more attention in innovation studies. The authors state that they "*would put 'demand regimes' on a rough par with 'technological regimes' in the context of understanding industry evolution*" (Malerba et al., 2016, p. 227).

Capone et al. (2013) define customers within a given Demand Regimes as either fragmented or homogeneous (where there is no consumer heterogeneity). Horizontal fragmentation of demand concerns different consumers' opinions at the industry level about the features that are preferable in a product (Klepper and Malerba, 2010). Vertical fragmentation of demand at the firm level concerns the different minimum quality requirements that a product must satisfy in order to be taken into consideration for purchase (Adner and Levinthal, 2001; Malerba et al., 1999). In homogenous Demand Regimes, opportunities can arise from routinising processes and cumulative knowledge. In heterogenous Demand Regimes (both concerning horizontal and vertical fragmentation of consumers), firms can be entrepreneurial and benefit from opportunities by moving as first-movers.

In their 'history friendly' model of the computer industry, Malerba et al. (1999) analyse the effect of the emergence of a new 'demand class' around smaller and individual customers and how this explained the emergence of new dominant firms. They analyse two attributes of these subgroups: i) the 'performance' of the computer; and ii) its price, or 'cheapness'. The first group of 'large firms' analysed, valued performance and thus preferred to buy higher-value mainframe processors. The second group of 'individuals' or 'small users' analysed, had no need for high performance but valued the cheapness of the processor. The evolution from mainframe computers to minicomputers in the 1950s and the development of microprocessors in the 1960s enabled new firm entrants to serve a new set of smaller customers.

2.3.1. The political economy of Demand Regimes

The evolutionary economics approaches to the role of demand in innovation discussed above largely take the Demand Regime as an exogenous variable. While shifts in Demand Regimes are possible, the structure and composition of demand are viewed as a 'black box' without much attention given to the drivers of these shifts. As a result, the incentive structures that different players have to influence the emergence of a certain type of Demand Regime are largely ignored. This PhD will attempt to overcome this shortcoming by including an analysis of the institutional political economy of Demand Regimes.

The political economy has long been a central aspect of industrial policy analyses (Amsden, 1989; Chang, 1994; Johnson, 1982). These approaches largely showed the importance of institutions and state policies in industrialisation and economic development. The sectoral innovations systems literature has incorporated some aspects of these approaches to show how sector-specific institutions, policies, and interactions among various actors influence innovation processes and outcomes within particular sectors. The sectoral innovations systems literature often examines how institutions, such as standards, regulations, and labour markets shape the innovation landscape within specific sectors (Malerba, 2002). At the same time, government policies such as R&D subsidies, tax incentives, or intellectual property rights, are argued to play a crucial role in shaping national innovation systems (Lundvall, 2010, 1992).

Additionally, the French Regulation School has also written extensively about how institutional frameworks interact with Demand Regimes and shape economic dynamics (Boyer, 1990). Agiletta (2000) discusses the concept of regimes of accumulation and modes of regulation, highlighting how institutional arrangements influence consumption patterns and economic cycles. Demand Regimes in Boyer's understanding refer to the prevailing patterns of consumption and demand within an economy, influenced by institutional arrangements, social norms, and policies (Boyer, 2000).

Including an institutional political economy angle in the analysis of Demand Regimes is particularly important when the demand and its structure and composition is driven by government policies. In the case of the computer industry, as analysed by Malerba et al. (1999), the Demand Regime and shifts in the structure and composition of demand were largely market-driven. This is different in the wind turbine manufacturing industry where the demand for wind turbines is predominately shaped through government industrial and energy policies such as a feed-in tariff or renewable energy auctions. In such instances, the interests and abilities of different actors to influence industrial and energy policies become an important aspect to uncover and pose a crucial part of the wider political economy (Fudge et al., 2011).

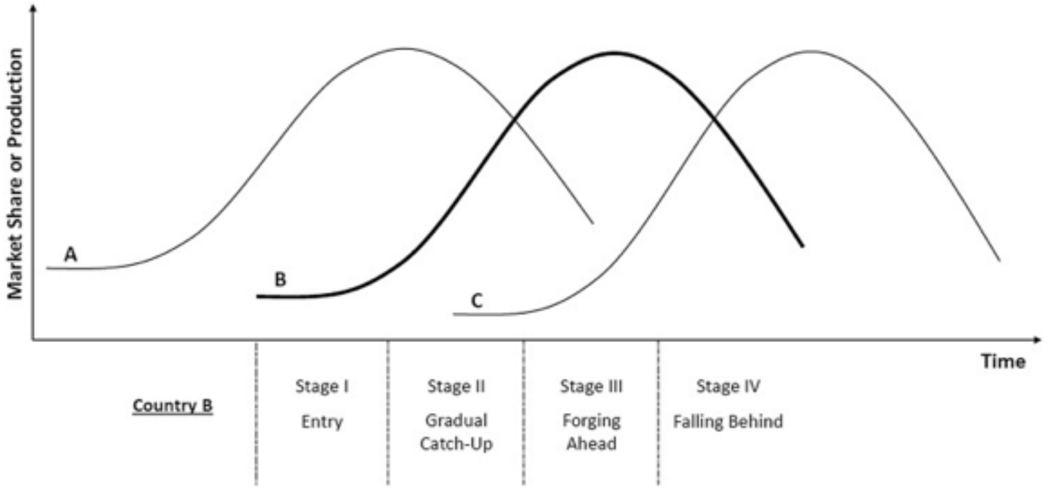
2.4. Windows of opportunity and changes in industrial leadership

Structural changes in technologies and demand can open entirely new opportunities for industry entrance and thus change industrial leadership dynamics. Christopher Freeman has argued that while 'technical change can indeed sometimes exacerbate problems of uneven development, some latecomers may actually have advantages over the established industrial powers' (Freeman, 1989, p. 85). Once a technology is commercially viable and challenges previous dominant designs, so-called Windows of Opportunity can emerge. Such Windows of Opportunity have far wider implications than just a shift in the dominant technology which is being deployed. Windows of opportunity affect the entire Socio-Technical Regime and socio-technical landscape. The notion of Windows of Opportunity was first described by Perez and Soete (1988) as a framework to explain the rise of new techno-economic paradigms which open opportunities for the economic leapfrogging of latecomers.

Lee and Malerba (2017) have expanded on the idea of Windows of Opportunity by using the building blocks from the sectoral innovation system literature. The sectoral system comprises knowledge and technologies, demand conditions, actors and networks, and institutions (Malerba, 2006, 2002). These building blocks of the sectoral system evolve over time through co-evolutionary processes and firms have to adapt to this in order to remain competitive (Nelson, 1993). These changes often involve the emergence of new modes of firm organisation and governance, designed to fit changes in the sectoral system. This also means that entire country sectors, rather than just individual firms, can evolve in a dynamic process of catching up or falling behind vis-à-vis other countries during long-term cycles. By and large, such structural changes are not predictable in any detail, but the way economic activities are organised and governed can be influenced and supported by government policies (Nelson, 2022). Consequentially, it is important to understand the macro-meso dynamics that trigger the organisational restructuring of firms at the micro-meso level.

Lee and Malerba have argued that three different Windows of Opportunity can be identified: 1) a technological window, 2) a demand window, and 3) an institutional window. However, the dynamics and structural changes following a window of opportunity are not predetermined but depend largely on the response and ability to adapt of firms and institutions in both incumbent and latecomer industries (Malerba and Nelson, 2011). Successful latecomer firms, properly supported by public policy and institutional actors, usually respond to Windows of Opportunity with high levels of learning and absorbing technological capabilities. However, firms and public institutions in incumbent countries also react to Windows of Opportunity and challenges from competitors, which can result in different outcomes.

Figure 7: Industrial leadership dynamics and catch-up cycles.



Source: Lee and Malerba (2017)

The standard cycle following a window of opportunity has four variations (Ibid): Firstly, an aborted catch-up where efforts by latecomer firms fail to generate sufficient learning and stagnate without challenging firms in leadership countries. Secondly, a case of persistent leadership where the incumbent invests to cope with new technologies and demand conditions to ensure it maintains leadership. Thirdly, a coexistence of old and new leaders. Lastly, a return to old leadership where the incumbent lost its leadership position but managed to return to a position of prominence during a new cycle.

Figure 7 shows the full catch-up cycle of a latecomer (country B) showing an initial catch-up, followed by forging ahead, and subsequently falling behind of the country compared to countries A and C. The forging ahead stage is characterised by country B seizing opportunities that emerge via Windows of Opportunity and responding effectively to these opportunities. During this stage, the latecomer country attains a leadership position and is therefore frequently linked to the decline of the incumbent entity A (Lee and Malerba, 2017).

Although the framework of Windows of Opportunity was initially developed for changes in leadership and opportunities for latecomer countries, it can just as well be applied to countries at the technological and industrial frontier. Indeed, applying the framework to countries with industrial leadership in certain sectors or technologies and their strategies for dealing with challenges from latecomer countries addresses an important gap in the literature on Windows of Opportunity. In doing so, the Windows of Opportunity framework follows a Hirschmanian understanding of development as an unbalanced growth process (Hirschman, 1958), where economic 'catch-up' is not an end state but rather a condition for the advancement of the frontier or falling behind (Burlamaqui and Kattel, 2016). At the same time, the Windows of Opportunity framework can help us to identify the macro-meso dynamics that incumbent firms have to adapt to and respond to in order to retain their industrial leadership position.

2.5. Micro-level technological learning, firm capabilities, and routines

Given the different variations of the standard 'catchup cycle' according to Lee and Malerba (2017), the question arises of how different outcomes following Windows of Opportunity can be explained. The second cluster of research on evolutionary economics that was highlighted in Section 2.1. focuses on firms' ability to maintain a competitive edge through micro-level technological learning, routines and capabilities as well as organisational reconfigurations.

As noted in Section 2.1., evolutionary economics recognises an explicit diversity of behaviours of firms operating in the same or similar industries, where firm behaviour can be explained by profit-seeking rather than rational profit maximisation. Joseph Schumpeter was among the earliest authors to attempt to define innovation as a process marked by sequential steps. As noted by Schumpeter (1934), firms must innovate or remain at the forefront of their competitors' capabilities and product offerings in order to survive.

Therefore, driven by their profit-seeking nature and assuming a competitive landscape, firms actively seek innovations to enhance their profitability.

According to Schumpeter, invention, innovation, and imitation are connected through a linear sequence. In his earlier works, such as *The Theory of Economic Development,* Schumpeter defined innovation as an exogenous process where new inventions by “heroic entrepreneurs”, disrupt existing markets, generate substantial profits during the transition, and eventually move back to a zero-profit equilibrium once the innovation becomes widespread (Schumpeter, 1934). This process has come to be known as ‘Schumpeter Mark I’. Recognising that innovation was not solely the result of individual entrepreneurs but also involved the activities of established firms, Schumpeter later shifted his focus to larger firms and their R&D processes (Schumpeter, 1976). This focus, which later came to be known as ‘Schumpeter Mark II’ hinted at the importance of cumulative effects and collective capabilities in driving firms’ innovation capacities and prosperity. Whereas ‘Schumpeter Mark I’ can be viewed as a widening process of innovation in which the concentration of innovative activities and barriers to entry are low, ‘Schumpeter Mark II’ represents a deepening process in which the concentration of innovative activities is higher and centred around larger incumbent firms (Malerba and Orsenigo, 1996).

A Schumpeterian perspective of economic change focused on innovating firms can provide some explanation of firm variety and dynamic leadership changes. However, as noted earlier, a central assumption of evolutionary economics is the concept of bounded rationality (Cyert and March, 1963; Simon, 1957). Thus, in order to explain firm behaviour in a continuously and unpredictably changing market, it is essential to recognise and highlight firm capabilities for adaptation and innovation (Nelson, 2020). Furthermore, building on a Schumpeterian understanding of innovation, evolutionary economics stresses the role of “routines” including sets of rules, procedures, techniques and modes of organisation once firms have acquired new modes of production (Nelson, 2020). Organisational routines of firms are treated as the collective equivalent of individual skills whereby high competence is achieved through learning by doing which often includes costly learning experiences. This is an important distinction from neoclassical economic assumptions in which all techniques along a production function are equally accessible to any firm at any time.

Organisational capabilities of firms, as aggregates of routines, cover broader aspects of organisational activities than individual routines (Dosi et al., 2000). Organisation capabilities of firms thus derive from a collection of routines and the ability to coordinate and operate them. Capabilities also involve the ability to execute activities crucial for a firm's survival and success (Winter, 2000). Generally, capabilities are more intentional than routines, often having a specific intended purpose, even if it's not explicitly stated. Routines and capabilities are often the result of the profit-seeking behaviour of firms as they seek to find new forms of production. This can be focused on traditional R&D activities but also on other parts of the firm such as marketing departments looking for new product segments or customers, as well as manufacturing departments seeking to enhance and optimise production processes.

As profit-seeking firms attempt to beat their competitors through deliberate efforts at innovation, routines often develop and change over time through a learning process. The continuous process of firm evolution can lead to commonalities in such routines as well as heterogeneity among firms operating within the same industries (Helfat, 2018). On the one hand, firms often imitate each other in order to keep at the technological frontier, which leads to similarities in routines and capabilities. On the other hand, heterogeneity can persist or develop as firms’ learning process takes place within the specific firm context and is shaped by the initial sets of competencies and assets of the respective firm. Differences in company actions, caused by variations in their foundational routines and capabilities, can result in diverse economic outcomes.

Within firms, these routines and capabilities often rely on unique ways of communication specific to the firm, facilitating information exchange and coordination among its employees. Since capabilities are founded on routines, they exhibit patterned behaviour, ensuring that the tasks they perform can be repeated by the firm with predictable and reliable outcomes

(Helfat et al., 2007). Routines are important as "*together with its implementing input flows, [they] confer upon an organisation's management a set of decision options for producing significant outputs of a particular type*" (Winter, 2000, p. 983).

Building on the Schumpeterian notion that firms must innovate or at least stay close to the technological frontier of their competitors in order to survive, evolutionary economics assumes that firms are constantly evolving and innovating (Winter, 2006). These processes involve the strategic adaptation and change of existing routines and capabilities. The term "dynamic capabilities" is used in this context to refer to the strategic responses of firms to the changing nature of the business environment (Teece et al., 1997). Dynamic capabilities become especially important when factors like time-to-market, the pace of innovation, and the uncertain nature of future competition and markets come into play (Ibid). The dynamic capabilities literature recognises the "*importance of the choices managers make to render resources more productive and to meet customer demand*" *and that "technology and know-how do not fall like manna from heaven but rather result from search, R&D, and investment*" (Teece, 2019, p. 7).

'Dynamic capabilities' can be distinguished from 'organisational capabilities' in the sense that they are explicitly concerned with active change rather than maintaining existing practices (Winter, 2003). Such change can include internal firm-level changes to "*the product, the production process, the scale, or the customers serves*" (Winter, 2003, p. 992) as well as changes to the external environment of firms (Teece, 2007; Teece et al., 1997).

Dynamic capabilities are seen as a key factor for the long-term success of a firm. At the same time, the concept of dynamic capabilities of firms has been of interest not only to those researchers seeking to understand changes to the technological frontier but also to those studying the process of economic catch-up of latecomers as they seek to emulate the success of the incumbent. As such, they can provide an important lens to analyse industrial leadership changes and different outcomes of Windows of Opportunity.

2.5.1. Resource-based view of the firm

Parallel to the above development of concepts of routines and capabilities, a stream of research in strategic management emerged, which took a resource-based view of the firm. The resource-based view of the firm explains value creation dynamics through learning processes whereby firms accumulate their internal pool of resources in response to new business opportunities (Penrose, 1959; Teece, 2007). Penrose elaborates that "*a firm is more than an administrative unit, it is also a collection of productive resources the disposal of which between different uses and over time is determined by administrative decision*" (Penrose, 1959, p. 24). Resources are defined as "t*he physical things a firm buys, leases, or produces for its own use, and the people hired on terms that make them effectively part of the firm*" whereas services are "*the contributions these resources can make to the productive operations of the firm*" (Penrose, 1959, p. 67).

In "The Theory of the Growth of the Firm", Edith Penrose presents the concept that large industrial firms expand by fostering organisational learning, which equips them with distinctive productive skills. Restructuring the internal pools of resources of a firm and the way they are deployed can create structural learning through a "*continuous process of structural adjustment and transformation of production 'triggered' and 'orientated by' existing and evolving production structures*" (Andreoni, 2014, p. 65). Understanding the technological and market characteristics of a particular industry is crucial for this structural learning as "*a firm that can grow successfully is one that engages in organisational learning specific to that industry*" (Lazonick, 2022, p. 3)

On the one hand, the Penrosian resource-based view of the firm can help us understand *internal* organisational structures as well as firm reconfigurations through either the expansion of productive capacities or mergers, acquisitions, and joint ventures. On the other hand, learning dynamics can also occur *external* to the specific firm and shape the overall industry organisation as well as the structure of supply chains (Richardson, 1972).

2.5.2. Theory of the Innovative Enterprise

Having discussed 1) macro-structural dynamics of technology and Demand Regimes, and 2) micro-level insights on the firm including dynamic capabilities and the resource-based view of the firm, the question becomes how best to integrate these perspectives. The Theory of Innovative Enterprise put forward by William Lazonick (2019, 2015) integrates insights from business history and economic theory, to shed light on the organisational and financial aspects of innovation. Lazonick's work pays particular attention to how firms invest in and organise around new technologies, and how these investments contribute to broader industrial dynamics. His theory underscores the role of firms as the primary agents of economic change and development, challenging conventional neoclassical views that downplay or overlook the significance of firm-level innovation in economic analysis. The theory highlights the importance of strategic decisions *within* firms to develop and utilise new technologies and processes, leading to sustained economic growth and competitive advantage. It further argues that the key to understanding broader economic development and growth lies in the innovative activities and learning of enterprises, which transform scarce resources into valuable products and services.

The risk associated with a firm’s innovation strategy lies primarily in the upfront fixed-cost investments needed to develop new productive capabilities and the uncertainty connected to this. These capabilities, if successfully acquired, could lead to the production of a higher-quality product than what is currently available. If the firm can sustain high quality while scaling up production for a broader market, it will be able to lower the unit cost by distributing its fixed costs over a greater output volume. This is in contrast to the neoclassical assumptions outlined in Section 2.1, by which firms are viewed as profit-maximising through cost optimisation.

Lazonick (2019, 2015) treats the innovation process as uncertain, collective, and cumulative. He therefore outlines three critical conditions for innovative enterprises that facilitate essential aspects of learning and innovation: 1) strategic control, which involves a set of relationships that empower decision-makers to allocate the firm's resources to address technological, market, and competitive uncertainties inherent in the innovation process. 2) organisational integration, which pertains to the structure of relationships *within* the organisation that creates incentives for individuals to apply their skills and efforts toward strategic objectives. 3) financial commitment, which encompasses a set of relationships that ensure the allocation of funds to sustain the ongoing innovation process until it generates financial returns.

Lazonick argues that through a combination of these three critical aspects, innovating firms can stand out from their competitors and secure a lasting competitive edge by delivering products of superior quality at lower costs (Lazonick, 2022). Thus, in the long run, innovative firms are likely to be more successful at bringing down the unit costs of a technology. However, it is important to recognise that pursuing an innovation-led strategy, aimed at producing more superior and cost-effective products, might initially place the firm at a disadvantage when production volumes are low. This disadvantage stems from the inherently higher fixed costs associated with innovation strategies, compared to those costs associated with strategies focused on optimisation within existing technological and market limitations.

Innovative firms are characterised by their ability to capture a significant market share through the introduction of new products that are of superior quality and lower cost. Furthermore, the innovative firm can reach industrial market leadership through larger output at a lower unit cost than if a large number of firms dominate the industry. This contrasts with the neoclassical economics theory, which views perfect competition as the ideal of economic efficiency. Within the context of 'Schumpeterian competition', *innovative firms* outperform traditional *optimising firms,* which are the cornerstone of neoclassical economic theory (Lazonick, 2022, p. 24).

Neoclassical economics, with its focus on constrained optimisation, suggests that firms should not invest in the development or acquisition of new productive capabilities. This lack of investment leaves firms following this neoclassical logic unable to adapt and transform in response to the macro-structural dynamics discussed in Section 2.2. and 2.3. Contrary to this, innovative firms as understood in the approaches of Penrose and

Lazonick are better suited to restructure their internal and external organisation and utilise emerging Windows of Opportunity.

Changes to the macro-structural dynamics and shifts in the demand or technology regime require substantial industrial restructuring, both at the organisational level as well as the industry level (Guerrieri and Pietrobelli, 2004). Organisational reconfiguration, both internal to the individual firm as well with regard to their supply chains can have different drivers. In the case of the aerospace industry, Lazonick and Prencipe (2005) have analysed how the engine manufacturer Rolls-Royce adapted their strategic control and financial commitment at different stages. In the context of the wind turbine manufacturing industry, a key question is to what extent corporate strategies around cost reductions in response to the shift in the Demand Regime shaped the type of organisational restructuring or to what extent a need for external finance drove the organisational restructuring of wind turbine OEMs.

2.6. Integrating the macro-structural and micro-capability building blocks of the PhD through a Structural Cycle Analysis

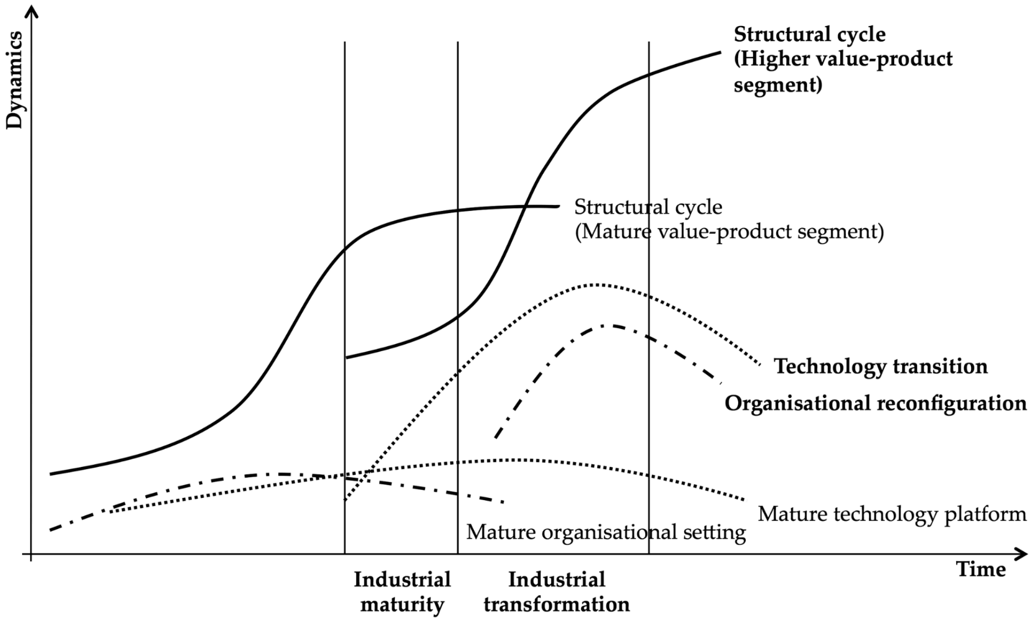
The (re-)emergence of dynamic approaches in economics marks a significant shift away from the neoclassical emphasis on static analyses. Schumpeterian and evolutionary economic approaches as well as the micro-level theories of the firm discussed in the section above challenge the traditional neoclassical framework by emphasising complexity, historical context, and the evolving nature of economic systems. The respective theories which were described in Sections 2.2 to 2.5. constitute different tiers of analysis focusing on different micro, meso, and macro elements. However, there remains a surprising lack of attempts to integrate these with each other. This is particularly surprising as the process of economic development has been described as the integration of "*micro-learning dynamics, economy-wide accumulation of technological capabilities and industrial development*" (Cimoli et al., 2009, p. 543).

From the above literature review, it emerges that there are different theoretical approaches to elements of structural learning, industrial dynamics, and organisational configuration. Combining and integrating macro-structural and micro-capability approaches is a promising endeavour given their respective emphasis on supply-side technological change, demand-side structural change, and organisational change and adoption (Andreoni, 2014). Such integration is essential for capturing the multifaceted nature of economic development, which necessarily involves both large-scale structural shifts and firm-level adaptive capabilities.

The PhD relies on the concept of Structural Cycle analysis by Andreoni et al. (2016). to combine the different theoretical approaches in one conceptual framework. The economic transformation of industries relies on ongoing and multitiered changes in the composition of manufacturing systems and technology platforms. As outlined in Sections 2.1 to 2.5., these changes encompass a wide array of technological, organisational, and institutional aspects that generally respond to the dynamics of "technology-push" and "demand-pull" (Dosi, 1982).

Andreoni et al. (2016) employ the concept of "Structural Cycles" to analyse these interconnected processes of i) technological transitions and ii) subsequent changes in organisational structures as firms shift into higher value-product segments. Their framework bridges some of the above-outlined macro-level economic theories of industry structure with micro-founded theories of firms, resource-capability literature, and evolutionary perspectives on technological change. By integrating these tiered approaches, a better understanding of how technological advancements and new production opportunities can stimulate learning processes and reshape internal firm organisations (Penrose, 1959; Teece, 2007) as well as the overall structure of the relevant industry and organisation of supply chains (Richardson, 1972) can be gained.

Figure 8: Stylisation of Structural Cycles



Source: Andreoni et al. (2016)

As stated above, Andreoni et al. (2016) examine two dimensions underlying each Structural Cycle: i) a technology transition, and ii) an organisational reconfiguration. This PhD will add a third dimension centred around a demand transition in order to further advance the concept of Structural Cycles.

As we have seen from the Windows of Opportunity literature in Section 2.4., changes in demand can open up important opportunities for industrial leadership changes. Similarly, in both Product Life Cycle (PLC) and Industry Life Cycle (ILC) theories, demand is not just a passive backdrop but an active force that shapes and is shaped by the product and industry dynamics. Understanding demand patterns is crucial for firms to strategise and navigate through the different stages of the product or industry life cycle, adapting their approaches to marketing, innovation, and competition accordingly. In PLC theory, demand initiates and fuels the growth of a product from introduction through maturity, then diminishes during the decline phase, guiding marketing and innovation strategies (Levitt, 1965). In the ILC theory, demand can influence the evolution of an entire industry from its emergence, through rapid growth, into maturity, and eventually to decline. It thus significantly influences competitive dynamics and market structure (Klepper, 1997).

Thus, the enhanced concept of Structural Cycles is used in this PhD as an attempt to combine the different elements discussed so far in this literature review: Firstly, the technology-push and demand-pull dynamics that affect not only cost reductions in renewable energy projects but also determine industrial leadership. The integration of Demand Regimes and the related structure and composition of demand into the Structural Cycles framework constitutes the first original contribution of this PhD. Crucially, it treats the economy as a cumulative, dynamic, and evolving system, characterised by changing dynamics of supply and demand. Secondly, the framework is to analyse the organisational restructuring by firms in response to these dynamics and whether they are successful at this. A particular emphasis of this second contribution of the PhD will lie in integrating the role of different types of corporate finance in organisational restructuring in response to changes in the Demand Regime as part of the Structural Cycle. As argued by the Theory of the Innovative Enterprise, firms have to adapt their strategic control, organisational integration, and financial commitment (Lazonick, 2019, 2015). Lastly, this PhD will further develop the concept of Structural Cycles by integrating an institutional political economy analysis into the framework. The idea of Structural Cycles is not just an analytical method for understanding transformation processes through technological revolutions, but can also assist governments in selecting the right choice of policies to intervene and support these processes (Andreoni et al., 2016). Analysing the political economy of industrial policies in relation to Structural Cycles will further uncover the drivers of policy alignment or misalignment.

In summary, Structural Cycles provide a conceptual bridge that links technological transitions, demand shifts, and organisational restructuring. In each of the following empirical chapters, different elements of cycles that are structurally connected to innovation and demand will be analysed from different levels. While these chapters can be seen as individual contributions, together they form a holistic analysis of Structural Cycles in the wind energy sector. This approach captures the dynamic interplay between broad technological shifts and firm-level adaptive capabilities, offering valuable insights into the drivers of economic growth, industrial leadership, and technological innovation. Through this integrated perspective, we can better understand the complex processes that underpin structural learning in renewable energy industries. This in turn can guide both theoretical advancements and practical policy interventions.

3. Methodological considerations

While each of the following empirical chapters discusses respective methodological issues and data sources in a stand-alone methods section, this section concerns the broader methodological considerations and research design of this PhD.

3.1. Philosophy of science

As outlined in the theoretical literature review in Section 2, this PhD departs from many of the assumptions of neoclassical economics and instead adopts an evolutionary economics approach. This has important ontological and epistemological implications for the research project itself. Neoclassical economics focuses on coordination and largely assumes away any dynamics within the economy. Evolutionary economics views the economy as a complex, evolving system characterised by dynamic interactions among heterogeneous agents. This stems from the understanding of the economy as a "*complex evolving system*" (Dosi, 2023, p. 5). Socio-technical transitions, such as the energy transition, are multi-faceted phenomena that can be explored from multiple perspectives (Geels, 2010). This includes technological, demand, organisational, and institutional changes. Each perspective is shaped by its own set of ontologies—often implicit foundational beliefs about the nature of the social world and how it operates causally.

Neoclassical economics, with its focus on rational choice decisions under scarcity, views causal agents as self-interested individuals who maximise their utility and where the accumulation of individual choices creates the macro-order. Ontologically this approach is relatively static, with its emphasis primarily on equilibrium and efficiency under given constraints and preferences. From an epistemological point of view, neoclassical economics thus often relies on deductive reasoning from axiomatic principles, such as rationality and utility maximisation, and frequently uses deductive mathematical models to predict outcomes based on these assumptions.

Contrary to this, evolutionary economics is inherently dynamic, focusing on economic processes over time and evolving structures. From a macro perspective, shifts in the Technology or Demand Regime can cause broader socio-institutional changes (Freeman and Perez, 1988). However, on the micro-level, routines, heuristics, and capabilities can also shape the trajectories of these socio-institutional transitions. Heterogeneous firms, innovation, and market competition are thus viewed as key determinants for change (Nelson and Winter, 1982). As a result, its reasoning is often done inductively and by using ‘appreciative theorising’, where causal links and stylised facts are drawn from observed patterns (Ibid). Appreciative theorising is usually expressed verbally, rather than in symbols and formals (Pyka and Nelson, 2018). Using the building blocks of Giovanni Dosi’s (2023) manual, the approach of this PhD can be summarised as i) emphasising dynamics and change, ii) being micro-founded through its focus on firms, and iii) assuming heterogeneity to represent aggregate and cumulative dynamics.

Overall, the resurgence of evolutionary economic approaches reflects a growing recognition that to address contemporary economic challenges effectively, we must account for the complex and evolving dynamics that shape our world. Evolutionary economics offers a nuanced and empirically grounded approach to understanding economic dynamics, emphasising the importance of heterogeneity, learning, and adaptation in shaping the evolution of industries and economies (Dosi, 2023).

3.2. Research strategy and choice of methods

The divergence in ontology and epistemology between neoclassical and evolutionary economic schools of thought outlined in Section 3.1. also leads to different methodologies, analyses, and interpretations of economic dynamics and outcomes. Neoclassical economics provides a framework for deductive reasoning and understanding how economies should function under ideal conditions. Contrary to this, evolutionary economics offers tools to inductively study how economies change and develop in complex scenarios. Qualitative methods aimed at uncovering complex dynamics are often disregarded entirely by mainstream economic journals on the basis of methodological hierarchies, by which quantitative methods are viewed as superior and for providing more generalisable results. However, as will become clear in the following empirical chapters, data availability and data quality often pose significant limitations on research. For example, regression analyses require appropriate longitudinal cross-country data that is often unavailable. At the same time, purely quantitative analyses are often very reductionist in their approach, in other words, it can be oversimplistic. The existing learning curve literature on renewable energy cost reductions that will be criticised in Chapter 3 generally assumes a continuous and predictable relationship between installed capacity production and cost reductions in renewable energy technologies. In reality, learning and cost reductions are often non-linear and can be subject to periods of rapid advancement followed by plateaus or even temporary setbacks. Thus, structural and their effect on cost reductions and industrial dynamics cannot be properly understood using quantitative methods such as regression analyses alone.

The literature review in Section 2 has also shown how structural elements of i) learning and ii) broader elements of industrial dynamics and organisational should theoretically be combined. Technological innovation, demand shifts, or policy changes can all lead to cost reductions as well as changes to industry structures and organisational configurations. Quantitative methods alone might overlook these nuanced, context-specific aspects; qualitative methods can assist in uncovering them. Therefore, this PhD adopts a mixed-method approach, which can provide a more holistic and nuanced understanding of the research at different macro and micro units of analysis. Using mixed methods not only means different methods and different units of analysis, but also that quantitative and qualitative data can be triangulated with each other. Mixed-methods triangulation involves using multiple methods to study the same phenomenon, thereby providing a deeper and more comprehensive understanding (Downward and Mearman, 2007). This approach helps validate findings through cross-verification from different methods and perspectives (Tashakkori and Creswell, 2007).

This PhD therefore adopts the following methods: In Chapter 3, we use quantitative methods using Ordinary Least Squares (OLS) regression to analyse and generate generalisable results on the drivers of cost reductions in a cross-country longitudinal study. We then rely on mixed methods case studies including qualitative in-depth interviews for the analysis of different elements of Structural Cycles in the onshore and offshore sectors in Chapters 4 and 5. To further understand the interests and powers affecting policy decisions and changes to the renewable energy remuneration schemes, Chapter 6 analyses two recent changes to the German Offshore Wind Act in a comparative political economy case study.

3.3. Case study selection

To gain an in-depth and nuanced understanding of the issues discussed above, this research relies on the onshore and offshore wind sectors as critical case studies (Flyvbjerg, 2006). Qualitative case studies on technological capabilities and industrial production dynamics have a long history in the academic literature (Early examples include Bell, 1984; Dahlman et al., 1987; Figueiredo, 2003; Lall, 1992). A case study approach is particularly relevant here as it allows us to answer questions of *how* and *why* wind turbine manufacturers were affected by and have adapted to Structural Cycles by identifying and establishing causal links. Comparatively analysing the onshore and offshore wind energy sectors allows cross-case comparisons (George and Bennett, 2005). The following empirical chapters therefore constitute a ‘multiple case-study research design’ (Yin, 2017), which allows for a more nuanced understanding of complex issues like technological change, demand, and production

Wind energy technologies represent a critical case study of renewable energy given their importance in the transition to sustainable energy systems. For example, wind energy technologies have undergone significant advancements and cost reductions, making them a mature and efficient source of renewable energy. The distinction between onshore and offshore technologies allows for a further comparative element. On the one hand, the onshore segment has experienced significant technological maturity and the expansion of wind energy onshore is largely driven by large numbers of turbine installations. On the other hand, the technology of offshore wind turbines is still developing rapidly and the growth of the segment has so far been driven predominantly by the increasing size of individual turbines rather than the total number of installed turbines. Furthermore, the markets for the two technologies diverge significantly and the expansion and deployment of onshore and offshore wind turbines differ not only geographically but also in terms of their order lead times. While onshore wind has a cycle of 12 to 18 months, in the offshore sector it currently takes between four and five years between the initial order and delivery and instalment of the turbine.

When analysing the drivers of cost reductions in onshore wind energy projects, solar PV energy projects were chosen as the comparator for the following reasons: 1) The dataset we use for the costs and investors of utility-scale renewable energy projects covers the period from 2004 to 2017. While this period includes the timeframe when the onshore wind technology experienced its major cost reduction, it does not cover the commercialisation of offshore wind. 2) In terms of cost competition, solar PV is the main competitor for onshore wind making it a suitable comparator case in Chapter 3.

To conduct the Structural Cycle analysis in the onshore and offshore wind turbine manufacturing sectors, we examine how the Technology and Demand Regime for wind turbines have changed following a specific policy change (namely the switch from feed-in tariffs to renewable energy auctions) since 2017 using the critical case study of Germany. Unfortunately, disaggregated project-level data on wind farm developers and operators in Europe is surprisingly sparse. To overcome this limitation, we use the switch in the German wind energy remuneration scheme from feed-in-tariffs to renewable energy auctions as a breaking point and critical case study of the changes in the institutional setup for wind energy in Europe. Given the importance of the domestic market for manufacturers of wind turbines and the relative importance of the German market in Europe in terms of demand, the developments in Germany can be viewed as a key determinant for the structure of European demand and the overall effect on the supply chain.

Organisational reconfiguration in the wind turbine manufacturing industry is examined on the level of European Original Equipment Manufacturers (OEMs) of wind turbines. Wind turbine OEMs are similar to those in other industries, such as the aerospace industry, where OEMs operate along the entire value chain from initial R&D, to the manufacturing of components and final products, as well as the service segment and post-sales activities (Caliari et al., 2023). Wind turbine OEMs were often described by our interviewees and industry experts as dictating the dynamics in the industry with wider implications for the European supply chain. European OEMs were chosen given their continuous dominance in the European market. Although Chinese suppliers have achieved remarkable technological upgrading in recent years (Dai et al., 2020; Haakonsson et al., 2020; Hain et al., 2020), the wind turbine manufacturing sector today remains a tale of two almost entirely separate markets between China vs. 'the West' (including the US) (Backwell, 2018, p. 185).

As mentioned before in Section 3.1., data availability is often a problem for longitudinal analyses and the fact that offshore wind technologies matured only relatively recently makes a comparison between the onshore and offshore segments unfeasible with the available data. As a result of this data, the first empirical chapter (Chapter 3) therefore analyses the drivers of cost reductions in onshore wind and solar PV energy projects through a comparative econometric analysis of the two technologies. Solar PV was chosen as the alternative comparison to onshore wind given the technologies are both mature technologies with significant cost reductions over the past decades and similar deployment scales worldwide. For onshore sufficient cross-country longitudinal data exists. The time period between 2004 and 2017 for the econometric analysis was primarily dictated by the available data on disaggregated financial investments in solar PV and onshore wind energy projects. However, as 2004 to 2017 coincided with the period when onshore wind and solar PV recorded significant cost reductions and steepening of learning curves, this was deemed acceptable for the purpose of this research.

With regard to the political economy analysis in Chapter 6, the German offshore wind sector with its changing renewable energy remuneration scheme over time was chosen for the following reason: Germany recently removed most subsidies for developers of offshore wind farms and instead relies on a bidding system where developers compete by offering to pay for access to future wind farm locations. The German government has stated that subsidies for other renewable energy sectors shall also be discontinued once the phase-out of coal energy is complete. This is similar to other European governments which are starting to scale back their support measures and are increasingly relying only on the market for future expansions of renewable energy. Thus, understanding the political economy of the offshore wind sector as the first renewable energy sector without a renewable energy remuneration scheme and the implications for the offshore wind Demand Regime can serve as an important case study for other renewable energy technologies.

3.4. Data sources and data collection

The analyses in the following empirical chapters (Chapters 3 to 6) draw on several data sources and data collection techniques. Secondary data was collected through databases, annual reports, and archival data. Quantitative data was obtained from the Bloomberg New Energy Finance dataset (for data on financial investments in renewable energy projects data), the

PATSTAT database (for detailed patent data broken down by technology, country of the applicant, and firm), and the WindPower database (for detailed data on wind farm size, number of turbines, and manufacturer). Qualitative data was primarily gathered through official documents and archival records as well as semi-structured interviews. Official documents predominantly included the annual reports of the main European wind turbine OEMs (Siemens Gamesa, Vestas, Nordex-Acciona, and Enercon) as well as reports from various industry associations (WindEurope, Global Wind Energy Council, IRENA, IEA, and several German industry associations). For Chapter 6, the analysis further relied on further official data including official minutes from the German Parliament and Parliamentary Committees, and related press releases of relevant stakeholders (all in German). These official documents were used to understand the assessment and position of key actors, as well as their interests and power in the industry.

To gain a more nuanced understanding and ensure the validity of findings, this was triangulated against primary data from semi-structured interviews. In qualitative research, semi-structured interviews are frequently used as they allow a more inductive approach than structured interviews (Clark et al., 2021). Participants are given the space and flexibility to drive the discussion and elaborate on their own ideas and concepts, thus allowing for appreciative theorising. Overall, 32 semi-structured interviews were conducted between March 2023 - April 2024 in order to triangulate the secondary data outlined above. Predominantly, interviewees were chosen based on their past and current experience, roles, knowledge, and direct or indirect involvement in the European wind manufacturing sector as well as involvement in the formulation of the German's Offshore Wind Act. Participants were identified both through generic sampling methods based on the main industry actors as well as by snowballing method. Prior to each interview, participants were sent a detailed information sheet as well as a consent form (UCL Ethical Clearance Number IIPP0010). Interview participants were contacted through common channels: e-mail, social media (LinkedIn), or at conferences and industry fairs.

Table 1: Overview of Semi-Structured Interviews

Group	Number of Interviews	Chapters
Wind Turbine OEM	6	4,5
Wind Energy Industry Association	11	4,5,6
Public Research Institute	2	4,5,6
Industry Expert	7	4,5,6
Utility Company	4	6
Political Party	2	6

The semi-structured interview guides (see Annex 4.2, Annex 5.2 and Annex 6.2) were developed following initial scoping interviews with industry experts as well as informal discussions at the WindEurope industry conference in Copenhagen in April 2023. Interviews usually lasted for around 60 minutes and were conducted in either English or German as appropriate. Interviews were recorded through detailed notes during each interview. As such, transcription was not necessary as certain keywords and interview codes could be searched directly through the digital notes. The collection of personal data was limited to names, work roles, positions, and affiliations, which were pseudonymised through coding and kept separately from the interview notes. The research processes for Chapters 4 and 5, and Chapter 6 were deemed complete respectively once additional interviews were adding diminishing returns and it was concluded that a saturation point was reached.

4. Conclusion

The theoretical framework of this PhD research outlined in Section 2.6. diverges significantly from neoclassical economics by prioritising a dynamic, evolutionary perspective on economic change and development in the renewable energy sectors. Where neoclassical economics emphasises equilibrium, rationality, and static analysis, this research integrates Schumpeterian and other evolutionary economic theories at the macro-level with a detailed examination of micro-level dynamics, including firm capabilities and the strategic alignment of government policies. By doing so, it acknowledges the complexity of economic systems, the centrality of technological change, and the co-evolution of organisational structures within the broader framework of green Windows of Opportunity.

The original contribution of this research lies in its comprehensive and multi-tiered approach to understanding the cyclical dynamics of innovation and demand from both macro and micro perspectives. It further contributes to the concept of Green Windows of Opportunity by analysing the alignment of firm strategies and government policies towards capturing emerging opportunities in renewable energy technologies. The methods chosen for this PhD emphasise the heterogeneity of firm behaviours and the endogenous nature of technological change. This is an important distinction from neoclassical economics, which tends to view technology as *exogenously* given and firms as homogeneously rational actors.

Furthermore, by utilising the concept of Structural Cycles but with an enhanced focus on the changing structure and composition of *demand*, the research demonstrates how technological and organisational transitions are influenced by shifts in Demand Regimes. This approach provides a richer understanding of how innovations in renewable energy are not just technologically driven but also deeply intertwined with market forces, consumer preferences, and policy interventions. In essence, this research transcends the limitations of neoclassical economics by offering a more nuanced, multi-tiered and interconnected view of economic phenomena that captures the complexities of innovation, demand, and the transition to sustainable energy systems. Through this lens, it contributes to a deeper understanding of the factors that enable or constrain the shift towards a greener economy and the roles that various economic actors play in this transformative process.

Based on the methodological considerations arising from this theoretical approach, the PhD employs a mixed-methods triangulation strategy to analyse the complex and evolving dynamics of technological change and economic development. By integrating quantitative and qualitative methods, the research provides a more comprehensive understanding of the drivers of cost reductions, Structural Cycles, and policy changes in the wind energy sector, offering valuable insights for both theoretical advancements and practical policy interventions in other renewable energy sectors.

Chapter 3: Opening the Black Box of Learning Curves: The Role of Technology-Push and Demand-Pull Dynamics on Cost Reductions in Onshore Wind and Solar PV Energy Projects.

Abstract

A successful energy transition depends on the large upscaling and widespread deployment of renewable technologies. In the case of renewable energy, it is the upfront costs and cost-efficiency of technologies used to generate electricity that determine competition. To understand the key drivers of recent cost reductions in renewable energy technologies, specifically solar PV and onshore wind, this chapter is adopting alternative methods of analysis beyond the current preferred use of so-called learning curves (Grubb et al., 2021). By borrowing insights from evolutionary economics and innovation studies (Freeman, 1987), the chapter conducts a cross-country panel data analysis of the effects of technology-push (proxied by patent registrations) and demand-pull dynamics (proxied by financial investments) on average total installed costs of utility-scale wind and solar PV energy projects. By using financial investments as our proxy for demand-pull dynamics, we are able to further investigate the differences between public and private financial investments. The results of the econometric model show that demand-pull dynamics through higher financial investments are correlated with lower costs in both technologies. The technology-push effect was significant only for solar PV, particularly in the early years of our period between 2004 and 2017 investigated. This indicates a shift from technology-push to demand-pull as these technologies matured. The effect of public financial investments was stronger and more significant for solar PV. Private financial investments were found to be more relevant in onshore wind energy projects, again hinting at differences in the temporal relevance of the type of demand-pull effects.

1. Introduction

Although global electricity production is still dominated by fossil fuel sources such as coal and natural gas, the share of renewables is increasing at a fast pace. Clean energy is seen as the main solution to the early 2020s' energy crisis (IEA, 2022). The International Energy Agency (IEA) now sees each fossil fuel as either peaked or plateaued. While this is good news for the climate emergency, replacements in the form of renewable energy sources have to ensure energy security and affordability vis-à-vis fossil fuel based technologies. Thanks to policy support measures aimed at creating economies of scale such as feed-in-tariffs and declining costs in many countries, the installed capacity for wind and solar is growing at a much faster rate than expected and fast becoming the dominant technologies that drive the energy transition (Ibid). The levelized cost of electricity of newly installed utility-scale solar PV and onshore wind projects now often undercuts incumbent equivalent fossil-fuel or nuclear power plants in Europe, the US, China, and India (IRENA, 2022).

As a result, solar PV and wind are no longer niche markets but provide productive opportunities in the face of growing demand and expanding markets. Despite this overall trend, there remain country differences in the costs of solar PV and onshore wind projects and the actual source of cost reductions in these renewable energy technologies remains surprisingly elusive. To ensure an even greater and faster rollout of these technologies it is important to understand what drives changes in their respective costs. In the case of renewable energy technologies such as onshore wind or solar PV, it is the upfront cost of energy projects and cost-efficiency of technologies used to generate electricity that determines competition with other non-renewable technologies.

Most energy analysts and policymakers focus on learning curves for renewable energy technologies, which model costs or prices of a specific technology or levelized costs of electricity as a function of cumulative manufacturing experience or capacity installations. Learning curves are often aggregated across entire technologies or industries. However, in the case of onshore wind and solar PV energy projects, the average installed costs and resulting electricity prices still differ greatly between countries. Variations in the cost of these two technologies can be due to material, energy, manufacturing labour, or investment costs. In reviewing the methods used to calculate so-called learning curves it will be argued that they do not assist in our understanding of the actual source of cost reductions of these technologies. While learning curves can be a useful tool to visualise cost trends, they assume more installed capacity will always lead to cheaper prices and thus hold little analytical value on the drivers of cost reductions. This chapter tries to explore alternative explanations for the striking cost reductions and differences between countries and technologies beyond the simple assessment of individual technical factors.

Apart from being criticised for assuming causal relationships and being too reductionist, learning curves have further been opposed for being apolitical and not acknowledging underlying policy drivers and political dimensions (Breetz et al., 2018). Borrowing insights from evolutionary economics and innovation studies this chapter will aim to contribute to a greater understanding of the ‘black box’ of drivers of cost reductions in renewable energy technologies. Using the proxies of financial investment and patent registrations, the technology-push and demand-pull effects on the reductions of total installed costs of solar PV and onshore wind energy projects will be analysed.

Additionally, this chapter will distinguish between the role of public and private financial investments as different types of demand-pull - a perspective that so far has not been considered. Mazzucato and Semienuk (2018) and Semieniuk et al. (2021) have shown that heterogeneity in the sources of finance matters for innovation outcomes. Building on the importance of credit to innovation (Schumpeter, 1939), they show that public investments in renewable energy projects lead to larger private investments by banks and institutional investors. For this, we aggregate the database on project-level financial investments in renewable energy projects from Semieniuk et al. (2021) on a country level and extend this with renewable energy patent registrations. In doing so, this chapter seeks to apply the public versus private distinction to the econometric model to analyse how different types of finance matter for learning. This is intended to explain how solar PV and wind-generated electricity both have become cheaper over the past few decades and how this trend can be sustained into the future.

Most of the innovation studies literature has focused on technology-push or demand-pull *policies* such as R&D support to increase the supply of innovation or feed-in tariffs aimed at creating a market for innovations in individual countries (Nemet, 2009; Peters et al., 2012). These studies have shown how governments can use policies to enhance the supply of technologies for example through subsidies for research and development (technology-push policies) or by creating market demand for example through regulations or financial incentives such as feed-in-tariffs (demand-pull policies). However, as the market for solar PV and wind technologies becomes firmly established and technologies start to mature, many of these policies are beginning to be phased out.

To go beyond the impact of individual *policies*, this chapter will focus on technology-push and demand-pull *dynamics* in the renewable energy transition. So far, most of the literature links various drivers such as feed-in-tariffs or regulatory standards to R&D spending or cumulative installed capacity, which are in turn assumed to lead to cost reductions in renewable energy technologies. Instead, the econometric model of this chapter proposes to measure the effect of country aggregate patent registrations and financial investments on renewable energy cost reductions. This will be done using a comparative study of onshore wind and solar PV energy projects.

The aim for this selection is twofold: 1) onshore wind and solar PV are fundamentally different technologies with very different value chains. By comparing the results between the two technologies this chapter is specifically analysing this heterogeneity. 2) Demand-pull and technology-push dynamics can have varying importance over time. This goes back to the idea of innovation cycles in a system of interacting actors, technologies and institutions where a new technology undergoes a process of maturation from initial invention to diffusion (Freeman, 1987). Hoppmann (2015) showed that with regard to government policies, the balance between demand-pull and technology-push shifted towards demand-pull in recent years. By splitting the sample into two periods and rerunning the regression for each timeframe, these potential dynamic effects connected to the two phases and their changing importance over time can be analysed.

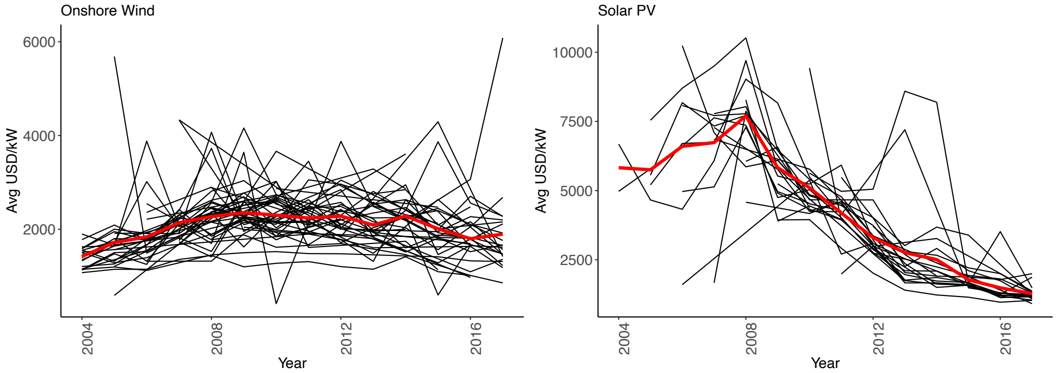
Additionally, while most learning curve based studies use cumulative installed capacity as the demand-pull effect and ultimately their main variable of interest, this chapter considers demand in the energy sector to be particularly unique. While demand ultimately stems from individuals and firms using the electricity as end-customers, they receive the electricity from various energy suppliers which buy electricity on the wholesale market. Depending on the country, these suppliers can be a mixture of public or private entities. In most countries, the suppliers of energy are vertically integrated and own various power plants of different fossil fuel or renewable energy technologies to supply electricity to their customers leaving the end-users of electricity with limited power to choose the source of their electricity consumed. This also makes capturing the demand-pull on particular renewable energy technologies difficult to quantify. Therefore, this Chapter proposes to use financial investments by public or private investors in such energy projects as a proxy for demand-pull.

While financial investments are a valuable proxy for demand-pull dynamics, it is essential to acknowledge their limitations and potential biases. Investments can be influenced by broader economic conditions, market sentiment, or specific policy interventions which might not always reflect pure market demand. To address these issues, we will incorporate certain control variables in our econometric model as discussed in Section 3.

In doing so this chapter seeks to answer the following research question: *What role did technology-push and demand-pull dynamics play in driving cost reductions of onshore wind and solar PV energy projects?* By analysing the effect of technology-push and demand-pull dynamics on cost reductions, the chapter also aims to contribute to a growing trend in the academic literature on renewable energy that tries to go beyond so-called learning curves which try to extrapolate future cost developments. The research question will be answered by investigating the following hypotheses: 1) demand-pull factors proxied by public and private investments in solar PV and onshore wind energy projects drive the continuous cost reductions of these projects. 2) technology-push dynamics proxied by cumulative patents drive these cost reductions. 3) the timing of demand-pull and technology-push factors matters and their relative importance changes over time. 4) the role of public investments was incremental in driving down these costs.

So far, most of these learning curves treat the installed capacity of renewable energy as the main explanatory variable for falling costs. Instead, this chapter proposes to look at financial investments. This allows us to further distinguish the source of financial investments (public vs. private) as well as different scale effects (cumulate investments vs. average investment size). Changes in average total installed costs for utility-scale onshore wind and solar PV projects are analysed between 2004 and 2017. The period covered includes significant cost reductions for both technologies, particularly from 2009 onwards when their learning curves became significantly steeper. Figure 9 shows the changes in average total installed costs for the two technologies during the period analysed by country (in black) as well as a global average (in red).

Figure 9: Average total installed costs for onshore wind and solar PV



Source: Own elaborations based on BNEF data

The remainder of this chapter is structured as follows: Section 2 will introduce the learning curve literature and identify its gaps. This section will also position the chapter with regards to the literature on technology-push and demand-pull innovation which this chapter seeks to integrate into the analysis of cost reductions. The section further outlines how technology-push and demand-pull will be defined in the context of renewable energy technologies. Section 3 will introduce the research design and the two econometric models for average cost reductions in onshore wind and solar PV energy projects. Section 4 will briefly summarise the data and data sources. Section 5 presents the main results. Section 6 discusses these results in the wider context of renewable energy technologies and cost reduction while Section 7 concludes.

2. Literature Review: Analysing changes in costs of renewable energy technologies

2.1. Review of the learning curve literature

As mentioned above, most of the academic literature relies on so-called learning curves for the explanation of cost reductions in renewable energy technologies. Learning curves have proven incredibly popular for visually showing the cost declines of a particular technology over time and for estimating future cost trends. However, while some of their usefulness stems from their simplicity, learning curves suffer from a number of methodological shortcomings. Most importantly this concerns problems of reverse causality where increased deployment could equally be caused by lower prices rather than vice versa. Additionally, while simplifying complex relationships through econometric models can help sometimes, there is a risk that important aspects such as the type of scale effects or sources of learning are overlooked and excluded from such a reductive representation. As a result, the sources of cost reductions in renewable energy technologies remain largely unexplained and future price predictions for these sectors have often been wrong. For example, the projected costs for solar PV calculated by the IEA using Integrated Assessment Models (IAMs) have consistently been much higher than historical trends (Way et al., 2021). In order to contribute to a better understanding of the source of renewables cost reductions, this chapter will assess the effects of technology-push and demand-pull dynamics on the costs of onshore wind and solar PV energy projects.

One-factor learning curves

Learning curves can be expressed in various forms to describe the relationship between cumulative capacity and cost but are often formulated as a log-linear function. A simple and often used specification of cost of technology as a function of cumulative capacity can be expressed as

$$C_Q = C_1 \times Q^{-\beta}$$

Where $C_Q$is the marginal cost of producing the Q-th unit, C_1 is the cost of producing the first unit Q is the cumulative quantity produced β is the learning coefficient (Elshurafa et al., 2018). In the case of energy technologies, learning curves can be described as the relationship between installed capacity (kW) or cumulative production (kWh) of a particular technology and total installed costs per unit (USD/kW) or unit cost per power production (USD/kWh):

$$C_t = a \times CC_t^{-b}$$

Where Ct is the unit cost per power production (USD/kWh) or total installed costs (USD/kW) in time period t, CCt is the cumulative production (kWh) or capacity (kW= in timer period t which is used as a proxy for learning, and the time interval is usually one year with Ct and CCt being varied every year (Yao et al., 2021). a is the normalisation index and the learning-by-doing coefficient b can be used to calculate the learning rate LR:

$$LR = 1 - 2^{-b}$$

The normalization factor a and experience rate b are obtained with a regression analysis of the logarithms of the given price or cost and capacity data (Schmidt et al., 2017).

One-factor learning curves have been criticised for oversimplifying complex processes to a single number and that important other drivers such as technological process, material prices, economies of scale or government policies are missing from the analysis (Elia et al., 2021, 2020; Kavlak et al., 2018;

Lindman and Söderholm, 2012; Nordhaus, 2014). This simplicity has also been criticised for suffering from omitted variable bias as other important factors impact learning rates and affect price reductions over time (Lewis and Nemet, 2021; Samadi, 2018). Specifically, as one factor learning curves only assess correlation and not causation, most studies simply assume that cost reductions are driven by deployment rather than the other way around. This is particularly problematic as learning curves could be subject to reverse causality. Increased cumulative capacity may equally be a result of reduced installed costs of a particular technology. Hence, one-factor learning curves have been described as a limited metric for quantitatively assessing the drivers of cost reductions (Samadi, 2018).

Two-factor or multi-factor learning curves

Two-factor learning curves – which often account for R&D spending as a driver of cost reductions – or multi-factor learning curves have been introduced to account for technical change and innovation (Jamasb and Kohler, 2007; Junginger et al., 2020; Kouvaritakis et al., 2000). These approaches usually examine the effect of R&D expenditure as further determinants of cost reductions. The two-factor learning curve can be expressed as the following extension to the one-factor model:

$$C_t = a \times CC_t^{-b} \times KS_t^{-R}$$

$$LBR = 1 - 2^{-R}$$

Where KSt is the knowledge stock (i.e. R&D expenditure) in time t and the learning by researching coefficient R can be used to calculate the learning by researching rate LBR. Methodologically, both one-factor and two-factor learning curves have been criticised as they cannot prove causal relationships between costs and various parameters. Additionally, by adding more drivers to the learning curve equation, correlations between variables can create further uncertainties which is why some scholars have resorted back to one-factor learning curves (Lin and He, 2016; Qiu and Anadon, 2012).

Different studies have focused on different levels of analysis. Some studies focus on average global prices whereas others take a regional or national perspective. These differences in measurement make it difficult to clearly compare learning rates of different decades against each other. Few studies have attempted to differentiate between local and global learning dynamics (Huenteler et al., 2014; Staffhorst, 2006; Steffen et al., 2018).

The methodological limitations of learning curves mean there exists a wide range of estimated learning rates in the academic literature (Grafström and Pudineh, 2021). The inaccuracy of learning rates has led to estimations of future cost changes consistently too low, i.e. observed costs changes even more than past models predicted (Way et al., 2021).

Cost models and engineering-based decompositions

Because of the methodological limitations of learning curves, recent studies have turned to the use of advanced bottom up cost models to assess the relationship between costs and various parameters (Candelise et al., 2013; Elia et al., 2020; Kavlak et al., 2018; Nemet, 2006). The cost model approach takes the most important cost components for a technology and used a bottom-up engineering model to quantify each effect on the overall technology cost. A cost equation is used to link all cost components and techno-economic variables (Elia et al., 2020).

The total change of costs of PV modules or wind turbines is expressed as the following function:

$$\Delta C_t = \sum \Delta C_{F,t}$$

Where C_F includes the different factors assumed to be influencing the price. Such an approach requires very granular cost and engineering data for each component, which can be difficult to obtain. For example, Nemet (2006) includes module efficiency, plant size, yield, poly-crystalline share, silicon cost, silicon consumption and wafer size as factors for the cost of solar PV. Using an engineering-based model, Nemet assesses the drivers behind technical change in solar PV by disaggregating cost reductions into technical factors. The study identified two main factors: plant size, which accounted for 43% of the change in solar PV costs, and efficiency improvements, which accounted for 30% of the change.

Elia et al. (Elia et al., 2020) analyse the cost of wind turbines as a function of the cost of materials, energy consumption and labour plus the material quantity per kW produced, the price of materials, the energy consumption per kW produced, the price of energy, the employs' productivity per kW produced, and the average annual manufacture salary. A residual part is decomposed of i) the value of property, plant and equipment; ii) distribution (transport costs of turbines to site) and installation (turbine installation costs); iii) legal and financial costs. A decomposition analysis is then carried out to assess the relative importance of various cost components and their respective drivers (learning by deployment, learning by researching, supply chain dynamics and market dynamics).

To assess the drivers of learning, Kavlak et al (2018) distinguish between low-level mechanisms (efficiency, silicon price, silicon usage, non-silicon materials cost, wafer area, plant size, and yield) and high-level mechanisms (R&D, learning by doing, economies of scale, and other). The introduction of high-level mechanisms such as policy drivers is a step in the right direction for understanding how various cost drivers can be affected and changed. However, these high-level mechanisms are only somewhat arbitrarily estimated based on their respective low-level mechanisms responsible for it. Similarly, Elia et al. (2020) only assign different cost components to four main drivers: learning by researching, learning by deployment, supply-chain dynamics, and market dynamics based on assumed contributions to each cost components (Elia et al., 2020, Table 4).

These approaches can address some of the limitations of learning curves by establishing causal links between various variables and technology costs and quantifying their respective magnitude. However, similar to learning curve approaches, a main limitation of bottom-up cost models is the issue of data availability. Many studies rely on different sources for time series of varying quality (Grafström and Pudineh, 2021). At times these data sources include other academic sources estimating costs (Kavlak et al., 2018) or individual company reports as a proxy for entire industries (Elia et al., 2020).

Additionally, technological change together with the issues of measurement make it difficult to directly compare characteristics of onshore wind and solar PV technologies today to those from a few decades ago as well as between countries. These temporal and regional differences however are interesting discrepancies to analyse in order to uncover what unlocked steepening trends at various points in time or in certain countries.

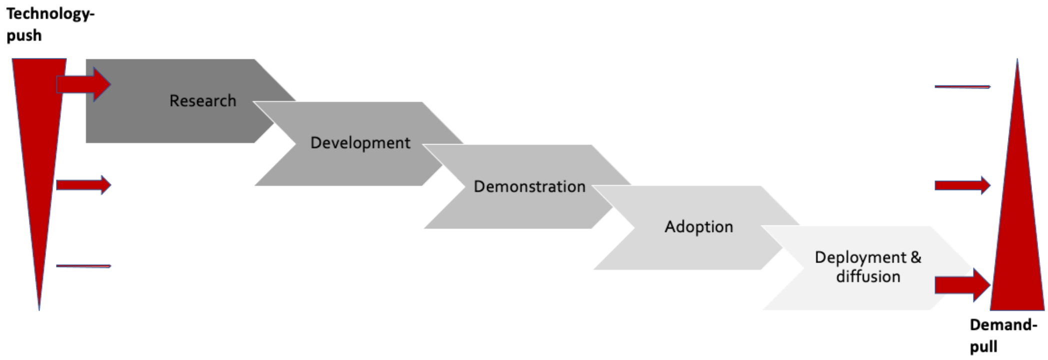
2.2. Technology-push and demand-pull dynamics as drivers of innovation and cost reductions

In order to understand the sources of cost reductions across time and between countries, we can turn to insights from the innovation- and evolutionary economics literature. Broadly speaking, innovation is the outcome of interacting actors, technologies, demand, and institutions (Freeman, 1987). As technologies mature and become commercially viable, they undergo a process from initial invention and development, to demonstration and commercialisation, and finally (mass-) deployment (Grubb et al., 2021; Grubler and Wilson, 2013). Innovation studies generally distinguish between “technology-push”, aimed at the supply of innovation or a particular technology and “demand-pull” factors, aimed at the creation of a market for innovation or a particular product. Other technological areas have seen a discussion of technology-push and demand-pull effects and the dichotomy between the two effects has led to fruitful debates, particularly in the 1960s and 1970s. The environmental innovation literature has subsequently adopted this lens to energy- and low carbon transitions (Jaffe et al., 2005; Norberg-Bohm, 2000; Taylor et al., 2005). Since then, many studies have been written on the effect of technology-push vs demand-pull factors and policies in the energy transition including several critical reviews and systemic literature reviews (Grubb et al., 2021). However, combining these insights with cost reductions and integrating technology-push and demand-pull dynamics into learning curves has not yet happened.

Just like any technology, new energy technologies have to go through several stages including a period of experimentation, scaling up at the unit level and subsequently scaling up at the industry level. This also includes a process of globalisation of the technology where the technology spreads from the innovation core to periphery markets (Sovacool, 2016). As such, an energy transition follows the classic Schumpeterian steps of technological development, invention, innovation, and diffusion.

The central argument of the technology-push perspective is that the rate and direction of innovation is determined by advances in scientific understanding and hence this is the crucial aspect of the innovation process. Generally, there has been a greater confirmation of the role of science and technology in innovation. Technology-push factors are argued to be particularly important during the early stages of the innovation chain (see Figure 10). Early R&D support by the US government in the 1970s and 1980s is often said to have started the innovation in solar PV technologies. Similar dynamics can be found with regard to wind energy technologies where early technology-push policies included research programs in the US, Germany and Denmark as early as the 1950s and particularly during the 1970s. Measuring technology-push effects in the context of renewable energy technologies is often done using policies that support a technology-push in a particular country rather than quantifying the global effects of these dynamics.

Figure 10: Innovation Chain



Source: Own elaboration, based on Grubb et al. (2021)

Within the innovation literature, many studies have focused on the effect of certain policies on innovation activities. Much of this literature aims to perform an empirical test of the Porter hypothesis which argues that environmental policies spur innovation (Böhringer et al., 2017; Jaffe and Palmer, 1997; Lanoie et al., 2011). This is often being done with patents as a proxy for innovation (Bäckström et al., 2014; Böhringer et al., 2017). Johnstone et al. (2010), for example, evaluate the effect of public R&D funding on innovation activities in renewable energy technologies, using patent counts as the outcome variable. Thus, patents as a proxy for innovation are being treated as the dependent variable, while policies such as feed-in tariffs, R&D support or environmental certificates are being used as explanatory variables. Similarly, Grubb et al. (2021) define demand-pull factors as policies such as technology standards, renewable certificates and feed-in-tariffs and review their effect on energy technology innovation.

At the same time, researchers increasingly acknowledge that energy technology innovation occurs across national borders and even through a global division of labour (Nahm, 2021). Analysing the effect of aggregated technology-push *policies* on a global level would be difficult given the large number of policies and initiatives internationally. In the context of continuous observed cost reductions, it becomes increasingly more relevant to assess the effect of technology-push *effects* on costs. Building on the research by Johnstone et al. (2010) and others, who use patents as a measurement for innovation, we can use patents as a proxy to measure the overall technology-push effect in renewable energy cost reductions.

More difficult to operationalise is the demand-pull effect. This effect is understood to drive the continuous improvement and cost reduction of a technology as it matures and usually becomes more relevant in the commercialisation, and deployment and diffusion stages of the innovation chain (Figure 10). Similarly, as with technology-push policies, measuring the global effect of all demand-pull policies is beyond the scope of this. This is particularly the case as certain popular demand-pull policies such as the feed-in tariff in Germany for example are starting to be phased out as markets are established.

So far, a large focus of the academic literature lies on how governments can create markets and thereby encourage private-sector investments. Romano et al. (2017) focus on countries with green policies for renewable sources of electricity and attempt to explain the motivation for driving investments. Similarly, Ritzenhofen et al. (2016) assess the effect of renewable portfolio standards, feed-in tariffs, and market premia on renewable energy investment. Wall et al. (2019) review the effect of policy instruments in attracting foreign direct investments in renewable energy. They find feed-in tariffs to be the most effective policy instrument to encourage investments in the renewable energy sector globally.

Rather than trying to gauge the effectiveness of individual policies in creating markets or fostering innovation, this chapter will use financial investments in onshore wind or solar PV energy projects as a proxy for the overall demand-pull effect. This allows us to further analyse the size and type of demand directly. Thus, instead of using investments in renewable technologies as an end in itself, it is proposed that investments should be used as a means to achieve greater innovation and reduced costs of renewable energy technologies.

As mentioned above, the energy sector is unique when it comes to the types of demand for renewable energy technologies. While the final customers are individuals, firms, or institutions, they have little say in what kind of electricity (i.e. renewable versus fossil fuel based electricity or even from a specific source such as solar PV or wind) they can buy but have to rely on the kind of electricity that utility companies supply. As a result, demand for renewable energy technologies can also be understood as the financial investment in certain types of energy projects, such as solar PV farms or wind parks by the suppliers of electricity, i.e. the owners and operators or power plants such as utility companies, independent power producers, or governments. Financial investments in renewable energy projects can therefore function as a proxy for demand-pull dynamics and as an explanatory variable for cost reductions.

This is an important difference to most learning curves which rely on installed capacity as their main variable of interest. Using financial investments, i.e. the total upfront costs of a renewable energy power plant, has several advantages: Firstly, whereas fossil fuel powered energy plants rely on not only the initial financial investment and operating costs but also the price of the fuel they burn (i.e. coal or natural gas), the input for renewable energy plants rely on essentially free inputs: Wind or sunshine function as the source of energy and do not need to be extracted from the ground. This means that once a wind turbine or solar PV panel is built and installed, the price of generated electricity is not impacted by changes in the price of inputs. Therefore, the final price of electricity depends to a large extent on the fixed costs and the initial investment in the project with its related financing- and capital costs, whereas variable costs play a lesser role.

Secondly, using financial investments in renewable energy project allows us to further analyse the size and type of investments. For instance, larger investments, measured as the average investment size per country and year, can enable potential economies of scale for the producers or solar panels and wind turbines. More importantly, we can distinguish the types of investors to account for differences between them. Public-sector investments, for example, could serve as a catalyst for further private-sector investments and important source for cost reductions during the early stages of a given technology. Mulugetta et al. (2022) find that the LCOE of solar PV energy projects in African countries is lowered by US$0.005 kWh when using public sector finance sources.

3. Research design and econometric model

In critiquing the learning curve approach, the aim of the research is twofold: 1) the chapter tries to address some of the shortcomings of the learning curve literature by analysing the effect of aggregated cyclical demand-pull and technology-push dynamics on overall cost dynamics. 2) in going beyond the assumption that costs will decrease linearly with growing deployment, the chapter seeks to assess the changing importance of technology-push and demand-pull dynamics over time. Generally, we would expect a technology-push effect to occur during the early stages of a technology and prior to the demand-pull effect becoming more important (see elaboration Figure 10). Assessing the correlation between technology-push and demand-pull effects vis-à-vis the average installation costs of onshore wind and solar PV energy projects and their relative importance over time can show some stylized facts about when and how learning occurred. Comparing the results across onshore wind and solar PV can further help us to understand the cyclical dynamics of technology-push and demand-pull. Rather than trying to calculate a learning rate for predicted wind and solar PV costs on a global level, this chapter aims to analyse the effect of aggregated technology-push and demand-pull dynamics on previous changes in onshore wind and solar PV energy project costs in a cross-country study.

Schauf and Schwenen (2021) have conducted an econometric study, which analyses cost reductions in wind energy by taking the levelized cost of electricity (LCOE) as the dependent variable. They use a range of cost drivers that affect learning in the wind sector and decompose the levelized cost of electricity in seven European countries. Their model can be regarded as an extension of the original one- or two-factor learning curves and assesses the effect of cumulative installed capacity, knowledge stock proxied by patents or R&D spending. The empirical approach of this chapter builds upon the methodological approach of Schauf and Schwenen (2021) but adopts the model in three important ways: 1) Rather than using the LCOE for onshore wind and solar PV for each country, we use the average total installed cost. 2) Patent registrations concern the onshore wind and solar PV energy sectors specifically, using the CPC Y02E patent classification. 3) Instead of cumulative installed capacity we use financial investments to proxy the demand pull. The reasons for these choices will be elaborated on in greater detail in Section 4 below.

To analyse the effect of technology-push and demand-pull effects on the costs of energy technologies, this chapter relies on two econometric models. Costs are estimated using average total installed costs (USD/kW) using the following multi-factor experience curves for solar PV and onshore wind respectively:

$$
\begin{aligned}
\log \mathrm{TC}_{it} solar = \beta + \beta_1\, log\ \mathrm{CumulativePATENTS}_{\mathrm{i,t-3}} &+ \\
\beta_2\, log\ \mathrm{CumulativeINVESTMENT}_{\mathrm{i,t}} &+ \\
\beta_3\, log\ \mathrm{Average\ Investment\ Size}_{\mathrm{t-1}} &+ \\
\beta_4\, log\ \mathrm{Average\ Project\ Capacity} + \beta_5\, log\ \mathrm{Exchange\ Rate} &+ FE_i + \varepsilon_{i,t}
\end{aligned}
$$

$$
\begin{aligned}
\log TC_{it} wind = = \beta + \beta_1\, log\ \mathrm{CumulativePATENTS}_{\mathrm{i,t-3}} &+ \\
\beta_2\, log\ \mathrm{CumulativeINVESTMENT}_{\mathrm{i,t}} &+ \\
\beta_3\, log\ \mathrm{Average\ Investment\ Size}_{\mathrm{t-1}} &+ \\
\beta_4\, log\ \mathrm{Average\ Project\ Capacity} + \beta_5\, log\ \mathrm{Exchange\ Rate} &+ FE_i + \varepsilon_{i,t}
\end{aligned}
$$

Where TC is the benchmark measure for renewable energy project costs, measured as the weighted average total installed cost (USD/kW) for utility-scale energy projects in solar PV and onshore wind per country. The subscripts i and t indicate country and year, respectively.

CumulativePATENTS and CumulativeINVESTMENT are the two main variables of interest. CumulativePATENTS is a proxy for technology-push effects and is measured as cumulative patent registrations per country in solar and wind energy technologies respectively. Assuming that patents take a few years to be fully commercialised, a time lag of t-3 is used, which is the same time lag for patents used in previous studies (Schauf and Schwenen, 2021). Secondly, CumulativeINVESTMENT measures the amount of cumulative financial investments in energy projects per country and functions as the proxy for demand-pull dynamics.

As mentioned earlier, using cumulative financial investments as a proxy for the demand-pull effect does not come without limitations and potential biases. Financial investments are made well before the actual capacity is installed and operational. There can be a significant time lag between when an investment is made and when the renewable energy project becomes operational. This time lag can create discrepancies between financial investment data and actual installed capacity, potentially misrepresenting the timing and impact of demand-pull dynamics on cost reductions. To account for this, all model specifications were also rerun using either no lags, a one-year, or a two-year time lag for the financial investment as well as patent variable. The results were largely similar across different time lags. Therefore, we decided to use no lags for cumulative financial investment and a 3-year lag for patents, which is in line with previous studies (Schauf and Schwenen, 2021). We acknowledge that financial investments might not be as accurate as installed capacity with regard to their timing but accept this limitation on the basis that it allows us to distinguish better between the types of finance.

Financial investments might overestimate the demand-pull effect compared to using installed capacity as the cost per unit of capacity can vary significantly between projects due to differences in technology, scale, location, and other factors. Projects with higher financial investments might be using more advanced or experimental technologies, leading to variations in cost-effectiveness and potentially skewing the analysis. We therefore included the following control variables: average investments and average project size (measured as average installed project capacity) per country and year, which capture two different economies of scale effects in solar or wind energy technologies: Whereas average capacity can be interpreted as a proxy for the scale of project size, average investment captures the economies of scale on the demand side. Assuming that producers of wind and solar PV technologies will reinvest their earnings only during the following year, a time lag of t-1 for average investments is used. We believe this to be a more accurate proxy for economies of scale than the manufacturing economies of scale variable based on the average firm size used by Schauf and Schwenen (2021). Furthermore, exchange rates are included given the ability to source input materials or even entire products such as solar PV panels or wind turbines from abroad. Lastly, an auto-regressive term of weighted average total installed costs in t-1 is included. By including past values of cost reductions, the auto-regressive term can indirectly account for the delayed effects of investments. This helps bridge the gap between when investments are made and when they impact costs. All variables have been log-transformed.[3] Country- as well as time-fixed

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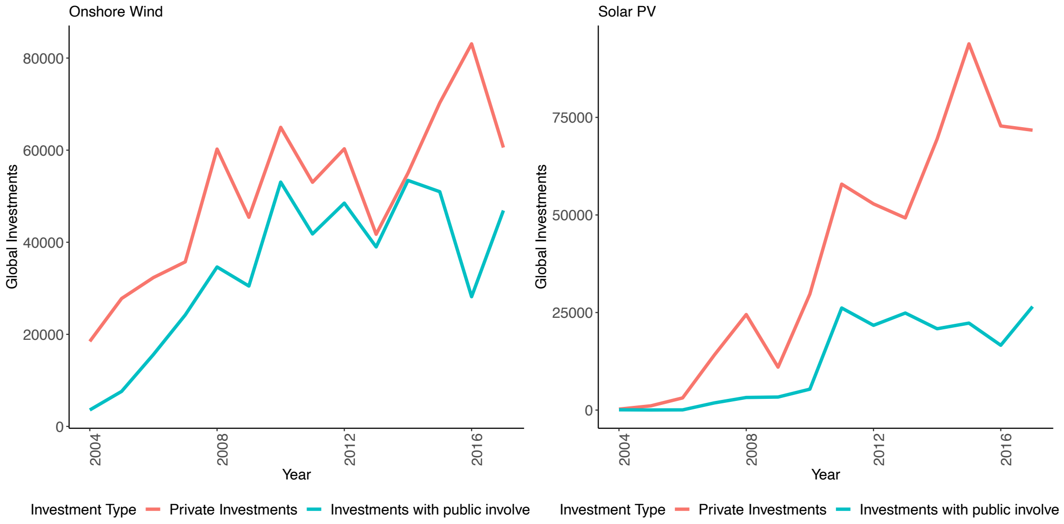
[3] Given a large number of countries with zero patents, log(CumulativePATENTS) = -Inf was changed to 0 and included a dummy variable that takes the form of 1 when log(patents) were 0 in a given country and year and 0 when there was at least one (cumulative) patent. Additionally, given some negative interest rates, these observations were changed to NA (which was only the case for one observation in the dataset).

effects were included to control for country-specific dimensions not captured in the control variables.

The main model relies on ordinary least squares (OLS) regression with regular standard errors. This chapter will further split the period analysed and run the models for different years. The global average total installed costs displayed in Figure 9 show costs were rising between 2004 and 2009, while after 2010 they declined for both technologies. Thus, the models were split into two time periods: 1) From 2004 to 2010 and 2) from 2010 to 2017. Doing so allows us to test whether there was a difference in the strength of the technology-push and demand-pull effect at different points in time.

To further test for the different types of financial investment this chapter utilises the project level data to calculate an aggregate cumulative sum of private investment and cumulative sum of public investments. Public investments are classified as any project where a government agency funded parts of the energy project. It has previously been argued that heterogeneity in the sources of finance matters for innovation outcomes and that public investment has a quantitatively important positive effect on private investment size (Semieniuk et al., 2021).

Figure 11: Yearly public and private financial investments for onshore wind and solar PV projects.



Source: Own elaborations based on BNEF

Figure 11 shows this aggregated global sum in the type of financial investments for onshore wind and solar PV projects for the time period covered. While investments with public involvement never exceeded private investments there are several periods where public investments remained stable or even increased when private investment went down. This chapter aims to test whether this had a significant impact on the total average installed costs per country.

4. Data

The main data consist of a set of country-level variables. For this study data for 24 countries in the case of solar PV, and 32 for onshore wind was used.[4] Data for the main variables of interest Average Total Installed Costs, Cumulative Financial Investments, and Cumulative Patents are taken from the BNEF dataset and Patstat and are explained in more detail below. Table 2 provides summary statistics for the main variables of interest.

Table 2: Descriptive Statistics

Variable	Mean	SD	Median	P25	P75	Min.	Max.
Subsector: Onshore Wind							
Average Total Installed Costs	1675	451	1550	1430	1767	800	6363
Total Financial Investments	1614	4556	322	85	1255	0.8	46971
Investments with Pubic Involvement	522	2466	13	0	162	0	24187
Private Investments	1092	2519	267	47	964	0	22784
Patents (Patstat)	12	32	1	0	6	0	269
Subsector: Solar PV							
Average Total Installed Costs	3603	2581	3000	1600	5121	907.5	24919
Total Financial Investments	1626	5935	121.3	20	744	0.36	57953
Investments with Pubic Involvement	292	1287	4.8	0	52	0	9798
Private Investments	1333	4745	88.6	11	659	0	48464
Patents (Patstat)	21	38	3	0	20	0	205

This table shows the descriptive statistics. The number of observations for onshore wind is 511 and for solar PV 314. Average total installed costs is measured in USD/kW, Total Financial Investment, Investments with Public Involvement, and Private Investments are measured in USD million, Patents shows number of granted patents at the European Patent Office. All variables have data from 2004-2017, except from Patents which has data from 2000 onwards.

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[4] Solar PV countries are Australia, Belgium, Brazil, Canada, China, France, Germany, Greece, India, Israel, Italy, Japan, Malaysia, Mexico, Netherlands, Portugal, South Africa, South Korea, Spain, Thailand, Turkey, Ukraine, United Kingdom, and the United States. Onshore wind countries are Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czechia, Estonia, Finland, France, Germany, Greece, India, Ireland, Italy, Japan, Mexico, Netherlands, Norway, Philippines, Poland, Portugal, South Korea, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, and the United States.

The timeframe between 2004 and 2017 was determined by the availability of average total installed costs and cumulative financial investments determines the sample starting and end years, 2004 and 2017. Given the use of time lags for patent data, patent registrations from 2000 onwards were used for the technology-push variable.

Financial investment data

To understand the demand-pull dynamics, this chapter relies on financial investment data and estimate their effect on cost reductions. Our data relies on the dataset from Mazzucato and Semieniuk (2018). The authors constructed the initial dataset by merging three databases that list different types of finance for energy project asset finance deals using Bloomberg New Energy Finance (BNEF). A further classification of investors by ownership structure and industry classification was added to categorise investments into public and private investments. The initial dataset covers the years 2004 to 2017 and holds data from 83 countries. This timespan covers the important periods of early commercialisation and upscaling of renewable technologies (particularly solar PV) in the 2000s as well as the significant cost reductions after 2010. This allows us to analyse the enabling factors and drivers behind changes in costs.

Financial investments can include both investments in projects that are never finalised as well as brownfield investments through the acquisition of existing projects. To account for these limitations, we only included completed new build projects. We acknowledge that financial investments can be affected by varying financial reporting and accounting practices between different countries leading to potential biases. However, given that the data was taken from Bloomberg's New Energy Finance dataset – a respected data source – we deemed this acceptable.

The final project-level data comprise 32,762 completed new-build projects and BNEF estimates that coverage is upward of 80% of all deals in the period covered (Mazzucato and Semieniuk, 2018). Importantly, the data includes 12,366 public investments. We extracted the data for onshore wind and solar PV energy projects and aggregated the cumulative financial investments in each of the two technologies by country and year.

Patent data

Innovative activities and technology-push dynamics can be proxied using different types of data. R&D expenditures for example can be used to analyse how much is being spent on innovative activities. Patent data can be viewed as a much closer measure of actual innovation and can also be used in a much more disaggregated manner for specific technologies. Nonetheless, the use of patent data is not entirely without problems. Specifically, this relates to three core issues: 1) not all innovations are patentable. Patents protect technological innovations and therefore do not cover organisational or managerial innovation for instance. 2) not all patentable innovations are actually patented. Inventors can choose a range of other intellectual property rights to protect their inventions such as copyrights, trademarks or even purposefully complect technical specifications. Additionally, inventors might choose to not patent their innovations right away in order to keep them secret from other competitors. 3) patents can vary in quality and not all patented innovations are commercialised or adopted. Despite acknowledging these shortcomings, patent data is still deemed to be a useful proxy for technical innovation and has been used in a wide range of studies (Barbieri et al., 2020; Castaldi et al., 2015; Gagliardi et al., 2016; Griliches, 1990; Popp, 2005; Popp et al., 2011)

Raw patent data was extracted from the PATSTAT database of the European Patent Office (EPO) with specific information about renewable energy technologies using the OECD environment-related catalogue (ENV-TECH) (Haščič and Migotto, 2015). PATSTAT aggregates patent data from over one hundred patent offices and reports the date of filing, country origin of patent filing, the patent family, and a set of standard technology codes which classify the technology field. The CPC Y02E classification, which can further be disaggregated into wind energy (Y02E 10/7) and photovoltaic energy (Y02E 10/5) was used. The Y-scheme classification is particularly useful as it allows to identify patents related to wind and solar PV from multiple different patent classes and subclasses (Persoon et al., 2022). For robustness checks this chapter also uses patent data from the OECD Triadic

Patent Families database using the IPC classifications F03D (photovoltaic modules) and H02S (wind motors). Triadic patent families are patents filed at the three major patent offices: the European Patent Office (EPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO). As such, they are often considered high-quality patents (de Rassenfosse et al., 2013, p. 722).

Total Installed Costs

Cost can be measured in various ways when it comes to electricity generation. Measures can include the cost of solar panels or modules or wind turbines, total installed costs, operating and maintenance costs, or the levelized cost of electricity (LCOE). LCOE can be considered the most comprehensive measure as it takes into account certain cost components that have been considered important such as operation and maintenance (Steffen et al., 2020), financing costs (Egli et al., 2018), and economic life extensions (Duffy et al., 2020). As the measure takes differences in expected lifespans of different energy technologies into account it allows for comparisons between technologies. However, by discounting the costs over time to derive a price (USD/kWh) which would need to be paid in order for the power plant to break even at the end of its average expected lifetime is based on several assumptions. In order to discount costs, the weighted average cost of capital (WACC) is used. IRENA, which provides one of the most used sources for LCOE data, is assuming uniform across all OECD countries and China (7.5% in 2010 and declining to 5% in 2020. For the rest of the world a WACC of 10% is assumed in 2010, falling to 7.5% in 2020). This assumption is problematic as research has shown that the cost of capital does not also differ between industrialized and developing countries but also shows large heterogeneity within groups of industrialized and developing countries (Steffen, 2020).

The other main measure for cost comparisons across countries that is used for the calculation of learning curves and cost reductions is the total installed cost. This measure takes into account all upfront financial investments of a new power plant and normalises them as a share of installed capacity (USD/kW). By doing so, improvements in the capacity of the same kind of technology are accounted for. While this measure makes comparisons across different technologies more difficult (as it does not account for differences in expected lifespans) it is suitable for analysing cost changes of a particular technology over time and their rate of change. Hence it is an appropriate measure for learning curves which has been used in the literature (Jamasb, 2007; Lindman and Söderholm, 2012).

Data on total installed costs for each onshore wind and solar PV energy project were taken from the same dataset from Mazzucato and Semieniuk (2018). Costs were normalised by the installed capacity of each project (USD/kW) and aggregated as the average per country and year.

Control variables

Data for the control variables comes from different sources: Exchange rates are taken from the World Development Indicators. Average investment size and average project capacity per country and year are calculated using the BNEF dataset. This is to attempt to capture the potential economies of manufacturing scale through larger financial investments and larger individual projects. The model was run with several additional control variables such as wind or solar PV RDD per GDP, labour costs, share of renewables in electricity generation, and cumulative installed capacity but had to exclude these due to data availability or multicollinearity. Lastly, an autoregressive term which takes the weighted average total installed cost from the previous year was included.

5. Results

5.1. Main Results

Table 3 shows the main results for estimating the effect of technology-push and demand-pull dynamics on changes in average total installed costs for utility-scale solar PV and onshore wind projects. Columns 1 and 5 show the baseline results for the cumulative financial investments and cumulative patent registrations on the costs of onshore wind and solar PV energy projects, respectively. The results show a relatively strong and statistically significant correlation between cumulative financial investments and cost reductions in both solar PV and onshore wind.

Table 3: Regression results for solar PV and onshore wind

	Dependent variable:							
	Weighted Average Total Installed Costs (USD/kW)							
	PV	PV	PV	PV	Onshore	Onshore	Onshore	Onshore
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cumulative Investment	-0.130***	-0.031	-0.116***	-0.048***	-0.035***	-0.054***	-0.041	-0.055***
	(0.034)	(0.023)	(0.043)	(0.016)	(0.009)	(0.011)	(0.027)	(0.011)
Cumulative Patents (PATSTAT)	-0.011	-0.031	-0.335***	-0.014	-0.003	0.006	-0.001	0.009
	(0.031)	(0.024)	(0.058)	(0.017)	(0.010)	(0.011)	(0.023)	(0.011)
Patstat dummy	-0.055	0.078	-0.110	0.090	-0.032	0.016	0.035	0.022
	(0.171)	(0.099)	(0.110)	(0.071)	(0.038)	(0.037)	(0.046)	(0.037)
Average Investment Size		0.083*	0.077*	0.095***		0.057***	0.016	0.052***
		(0.044)	(0.042)	(0.031)		(0.016)	(0.017)	(0.016)
Average Project Capacity		-0.166***	-0.084**	-0.057**		0.035**	-0.004	0.043**
		(0.037)	(0.037)	(0.028)		(0.017)	(0.020)	(0.017)
Exchange Rate		0.301***	1.432***	0.245***		0.102***	0.139	0.093**
		(0.108)	(0.240)	(0.077)		(0.038)	(0.095)	(0.043)
Autoregressive-term		0.561***	0.105	0.155**		-0.003	-0.257***	0.008
		(0.065)	(0.066)	(0.066)		(0.063)	(0.062)	(0.064)
Constant	8.984***	5.037***	9.095***	8.185***	7.759***	7.358***	9.828***	7.147***
	(0.279)	(0.760)	(0.759)	(0.632)	(0.075)	(0.486)	(0.519)	(0.493)
Country fixed effects	No	No	Yes	No	No	No	No	Yes
Time fixed effects	No	No	No	Yes	No	No	No	Yes
Observations	144	144	144	144	266	262	262	262
Adjusted R^2	0.097	0.707	0.845	0.857	0.061	0.214	0.392	0.251

Notes: The table presents the regression results on log-log scale. Each model for solar PV and onshore wind was estimated four times respectively. Firstly, panels 1 and 5 are the baseline results for cumulative financial investment and cumulative patents. Secondly, panels 2 and 6 introduce control variables. Lastly, panels 3 and 4, and 7 and 8 use country- or time-fixed effects. Significance levels are as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

A one percentage point increase in cumulative financial investments is associated with a 0.13 percent decrease in average total installed costs for solar PV projects and 0.035 percent for onshore wind. The larger magnitude of the coefficient for solar PV compared to onshore wind is notable as it indicates a stronger effect of the demand-pull effect in solar PV energy projects. As one would expect, cumulative patents are also correlated with lower average total installed costs, however, not statistically significant. These results hold true when adding our control variables (columns 2 and

6). Importantly, the demand-pull effect in onshore wind energy projects became even stronger once control variables were added.

The non-learning covariates average project capacity and exchange rates have the expected impact: larger project capacity is associated with lower costs while a higher exchange rate is positively associated with average total installed costs. The proxy for economies of scale on the demand side, average investment size, is positively related with average total installed costs.

The results remain largely unchanged when accounting for country- and time-fixed effects (column 3 and 7, and columns 4 and 8 respectively). Interestingly, the coefficient for cumulative patents in solar PV becomes much stronger and statistically significant when accounting for differences in countries. The results show a 0.34 percentage decrease in costs of total installed costs of solar PV projects when patents in solar PV energy have increased by one percent. This is in line with what one would have expected: a stronger technology-push effect, proxied through patent registrations, is related to lower average total installed costs.

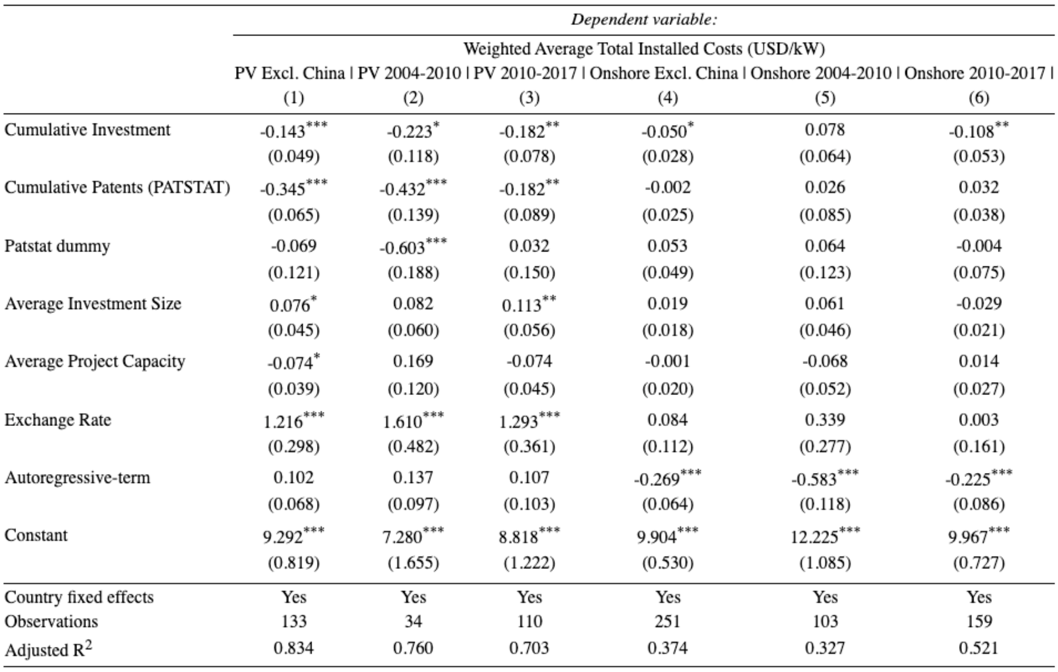
5.2. Robustness checks

In order to check the results for robustness, the model specifications from column 3 and 7, using the control variables and country fixed effects was rerun with the following adjustments: i) excluding China, ii) for the years 2004 to 2010, and iii) for the years 2010 to 2017.

This was done for the following reasons: 1) China accounts for a large part of the global financial investments in onshore wind and solar PV energy projects. Thus, it was decided to excluded China as a potential outlier. Including extreme outliers in OLS regressions can lead to high variance in estimates, making the model less stable. Excluding these outliers, such as China in our case, can improve the model's stability and reliability. 2) As shown earlier, the global average total installed costs of solar PV and onshore wind projects in our dataset rose slightly in the years up to 2009 before it started to decline. By splitting the dataset into two time periods and running the OLS regressions separately for each time period, we can compare the estimated coefficients. This can provide valuable insights into how relationships between variables may have changed over time.

The results for robustness checks are presented in Table 4. For solar PV (columns 1 to 3) the results for cumulative financial investments are similar to the baseline models, while the effect for cumulative patents becomes much stronger for both the model excluding China as well as for the two different time periods. The patent coefficient for solar PV between 2004 and 2010 (column 2) should be interpreted cautiously given the very low number of observations. All other results remain largely unchanged compared to the main results.

Table 4: Robustness checks for solar PV and onshore wind



	Dependent variable:					
	Weighted Average Total Installed Costs (USD/kW)					
	PV Excl. China |	PV 2004-2010 |	PV 2010-2017 |	Onshore Excl. China |	Onshore 2004-2010 |	Onshore 2010-2017 |
	(1)	(2)	(3)	(4)	(5)	(6)
Cumulative Investment	-0.143***	-0.223*	-0.182**	-0.050*	0.078	-0.108**
	(0.049)	(0.118)	(0.078)	(0.028)	(0.064)	(0.053)
Cumulative Patents (PATSTAT)	-0.345***	-0.432***	-0.182**	-0.002	0.026	0.032
	(0.065)	(0.139)	(0.089)	(0.025)	(0.085)	(0.038)
Patstat dummy	-0.069	-0.603***	0.032	0.053	0.064	-0.004
	(0.121)	(0.188)	(0.150)	(0.049)	(0.123)	(0.075)
Average Investment Size	0.076*	0.082	0.113**	0.019	0.061	-0.029
	(0.045)	(0.060)	(0.056)	(0.018)	(0.046)	(0.021)
Average Project Capacity	-0.074*	0.169	-0.074	-0.001	-0.068	0.014
	(0.039)	(0.120)	(0.045)	(0.020)	(0.052)	(0.027)
Exchange Rate	1.216***	1.610***	1.293***	0.084	0.339	0.003
	(0.298)	(0.482)	(0.361)	(0.112)	(0.277)	(0.161)
Autoregressive-term	0.102	0.137	0.107	-0.269***	-0.583***	-0.225***
	(0.068)	(0.097)	(0.103)	(0.064)	(0.118)	(0.086)
Constant	9.292***	7.280***	8.818***	9.904***	12.225***	9.967***
	(0.819)	(1.655)	(1.222)	(0.530)	(1.085)	(0.727)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	133	34	110	251	103	159
Adjusted R^2	0.834	0.760	0.703	0.374	0.327	0.521

Note: This table presents the robustness checks on log-log scale. The model uses specifications using control variables and country-fixed effects (Table 2, panels 3 and 7). Firstly, the model was rerun excluding China (panels 1 and 4). Secondly, only the years 2004-2010 were analysed (panels 2 and 5). Lastly, only the years 2010-2017 were analysed (panels 3 and 6) Significance levels are as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

To further test the model, alternative measures as proxies for the technology-push and demand-pull effects were used. First, triadic patent families as an alternative measure for the demand-pull effect were used. As mentioned above, triadic patent families can be seen as high-quality patents as inventions of high importance are more likely to be patented in all major patent jurisdictions. Second, cumulative installed capacity instead of cumulative financial investments was included. Installed capacity is the standard measure for a learning-by-doing effect but was excluded from the main regression models due to high collinearity with cumulative financial investments. The results can be found in Table 6 and Table 7 of Appendix 3.1.

Interestingly, the demand-pull effect, when proxied with triadic patent families, becomes much stronger and statistically significant for solar PV. Given the fact that triadic patent families can be seen as a measure for the quality of patents, these results can be interpreted as an indication for the importance of few high-quality product innovations rather than the quantity of all solar PV patents. The other results for the alternative measure for demand-pull dynamics are in line with the main findings. When using cumulative installed capacity as proxy for technology-push dynamics, the results stay virtually unchanged compared to the main results.

5.3. Disaggregated private and public investment.

‘First of a kind’ and ‘nth of a kind’ demonstration projects in various capital-intensive sectors often have a high share of public investments (Nemet et al., 2018). Previous studies have looked at how public sources of finance influence scale economies and found that public investments can act as a determinant of scale economies thereby crowding in larger public (Semieniuk et al., 2021). This chapter aims to combine some of these findings with the literature on cost reduction and thus integrate public and private investments as two separate explanatory variables into the models. It is here where the definition of demand-pull as cumulative financial investment becomes most relevant.

Table 5: Effect of public vs private investments on average installed costs

	Dependent variable:							
	Weighted Average Total Installed Costs (USD/kW)							
	PV Full |	PV Excl. China |	PV 2004-2010 |	PV 2010-2017 |	Onshore Full |	Onshore Excl. China |	Onshore 2004-2010 |	Onshore 2010-2017 |
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cumulative Investment with Public Involvment	-0.116***	-0.113**	0.015	-0.152**	0.012	0.011	0.007	-0.002
	(0.041)	(0.043)	(0.063)	(0.068)	(0.011)	(0.012)	(0.024)	(0.016)
Cumulative Private Investment	-0.009	-0.037	-0.125	-0.019	-0.065**	-0.075**	0.059	-0.085
	(0.039)	(0.045)	(0.095)	(0.068)	(0.031)	(0.032)	(0.075)	(0.053)
Cumulative Patents (PATSTAT)	-0.324***	-0.327***	-0.550***	-0.199**	0.007	0.006	0.033	0.033
	(0.058)	(0.067)	(0.166)	(0.089)	(0.024)	(0.025)	(0.088)	(0.040)
Patstat dummy	-0.065	-0.030	-0.609**	0.040	0.032	0.050	0.066	-0.002
	(0.112)	(0.123)	(0.228)	(0.150)	(0.046)	(0.049)	(0.124)	(0.076)
Average Investment Size	0.078*	0.079*	0.056	0.101*	0.016	0.018	0.065	-0.031
	(0.042)	(0.045)	(0.068)	(0.056)	(0.017)	(0.018)	(0.046)	(0.021)
Average Project Capacity	-0.088**	-0.080**	0.099	-0.086**	-0.006	-0.002	-0.062	0.005
	(0.036)	(0.038)	(0.123)	(0.043)	(0.019)	(0.020)	(0.054)	(0.026)
Exchange Rate	1.437***	1.263***	1.944***	1.275***	0.170*	0.112	0.345	0.058
	(0.237)	(0.293)	(0.524)	(0.362)	(0.097)	(0.113)	(0.282)	(0.161)
Autoregressive-term	0.094	0.092	0.108	0.120	-0.256***	-0.269***	-0.582***	-0.217**
	(0.065)	(0.068)	(0.104)	(0.104)	(0.062)	(0.063)	(0.120)	(0.087)
Constant	9.195***	9.305***	7.841***	8.789***	9.896***	9.977***	12.248***	9.837***
	(0.761)	(0.819)	(1.858)	(1.218)	(0.519)	(0.530)	(1.153)	(0.732)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	144	133	34	110	262	251	103	159
Adjusted R^2	0.848	0.836	0.715	0.703	0.395	0.378	0.313	0.511

Note: This table presents different previous model specifications when cumulative financial investments are disaggregated into public or private. Column 1 (solar PV, full dataset) and column 6 (onshore wind, full dataset) are the same model specification from the original country fixed effect model (Table 2 panels 3 and 7). Columns 2 to 4 and 6 to 8 are the same robustness check of excluding China (Table 3, panels 1 and 4). Years 2004-2010 (Table 2, panels 2 and 5). Years 2010-2017 (Table 3, panels 3 and 6) Significance levels are as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

For solar PV the model finds that financial investments with public involvement have a stronger correlation with lower costs and higher significance. Hence, on average utility-scale PV energy projects that have been financed (at least partly) by government institutions have been correlated with lower total installed costs. This holds true across all model specifications except for the period from 2004 to 2010 where the number of observations is so small that we can assume this distorts the results.

For onshore wind projects, this analysis does not find these results. Cumulative financial investments with public involvement are positively correlated with total installed costs but also insignificant. Given the importance of public finance particularly in the early stages of a technology we can assume that the effect of public investments driving down costs in onshore wind energy projects has happened prior to 2004.

6. Discussion

First, the results show a clear correlation between demand-pull dynamics and lower average total installed costs of utility-scale solar PV and onshore wind energy projects (first hypothesis). At the same time, the results also show clear heterogeneity between the two technologies and across time periods. For both technologies, the results for the demand-pull effect were strongest for the period from 2010 to 2017, indicating a potential tipping point at which the overall demand became big enough to shift the relative importance vis-à-vis the technology-push effect. This confirms the third hypothesis that not only does the balance between demand-pull and technology-push *policies* shifted towards demand-pull in recent years (Hoppmann, 2015) but also that the relative effect of demand-pull *dynamics* became more important.

Second, in terms of the technology-push effect, the result show smaller effects of cumulative patent registrations on average costs for onshore wind vis-à-vis solar PV. Once country-fixed effects are accounted for, the effect of the technology-push dynamics is more than twice as large as the effect of demand-pull dynamics for solar PV. This indicates that patents have a significant positive impact on lowering the costs of solar PV projects when accounted for within-country differences. These results hold true when China is excluded as an outlier as well as for the two different time periods. Given that onshore wind energy is a relatively more mature technology than solar PV, this might explain the difference in magnitude for the technology-push effect and compared to the results for onshore wind.

For onshore wind, the relationship between the technology-push effect and costs remained insignificant throughout all model specifications. This is contrary to the results from other studies that have found a positive and significant relationship between more registered patents and lower costs (Schauf and Schwenen, 2021). However, it is important to note that the data analysed only started from 2004 onwards which is later than other previous studies and where the technology-push effect in onshore wind was already less relevant given the age and maturity of the technology vis-à-vis solar PV technologies. The discrepancy in results might be explained by the fact that as argued above onshore wind has been a mature technology for much longer compared to solar PV and that the technology-push effect has become gradually less important vis-à-vis the demand-pull effect (compare Figure 10). This hypothesis is supported by the aforementioned stronger demand-pull effect for onshore wind in the second half of the period analysed.

Third, the model finds the positive association between the technology-push effect and lower total installed costs of solar PV projects to be larger and significant when technology-push is proxied by the triadic patent families count. This indicates a higher importance of high-quality patents for associations with lower average total installed costs. The alternative measure for demand-pull effects, cumulative installed capacity, does not change the results and is in line with previous studies such as Schauf and Schwenen (2021) using this measure. While this in part validates using cumulative installed capacity as a measure for demand-pull and learning-by-doing effects, targeting financial investments directly as a policy outcome might be easier for governments.

Fourth, to the best of our knowledge, this study is the first attempt to integrate a public-private distinction of the type of demand-pull effects on costs into an econometric model (fourth hypothesis). While the short timeframe of the data has limited our ability to research the importance of early public financial investments in onshore wind energy projects, this study has found a stronger and more significant effect of financial investments with public involvement vis-à-vis private financial investments in solar PV energy projects on average total installed costs. Given the aforementioned difference in maturity of the two technologies, these results might be due to the greater importance of public financial investments during earlier stages of diffusion of a technology.

7. Conclusion

This study sought to research the effect of technology-push and demand-pull dynamics on average total installed costs of utility-scale solar PV and onshore wind energy projects. For this, cross-country aggregated data on the average total installed costs of utility-scale solar PV and onshore wind energy projects has been used, rather than trying to find a learning rate that can be used to predict future costs of energy projects this chapter analysed some of the drivers behind past cost reductions. Building on the evolutionary economics and innovation literature, a technology-push effect was proxied with patent registrations and a demand-pull effect through financial investment data.

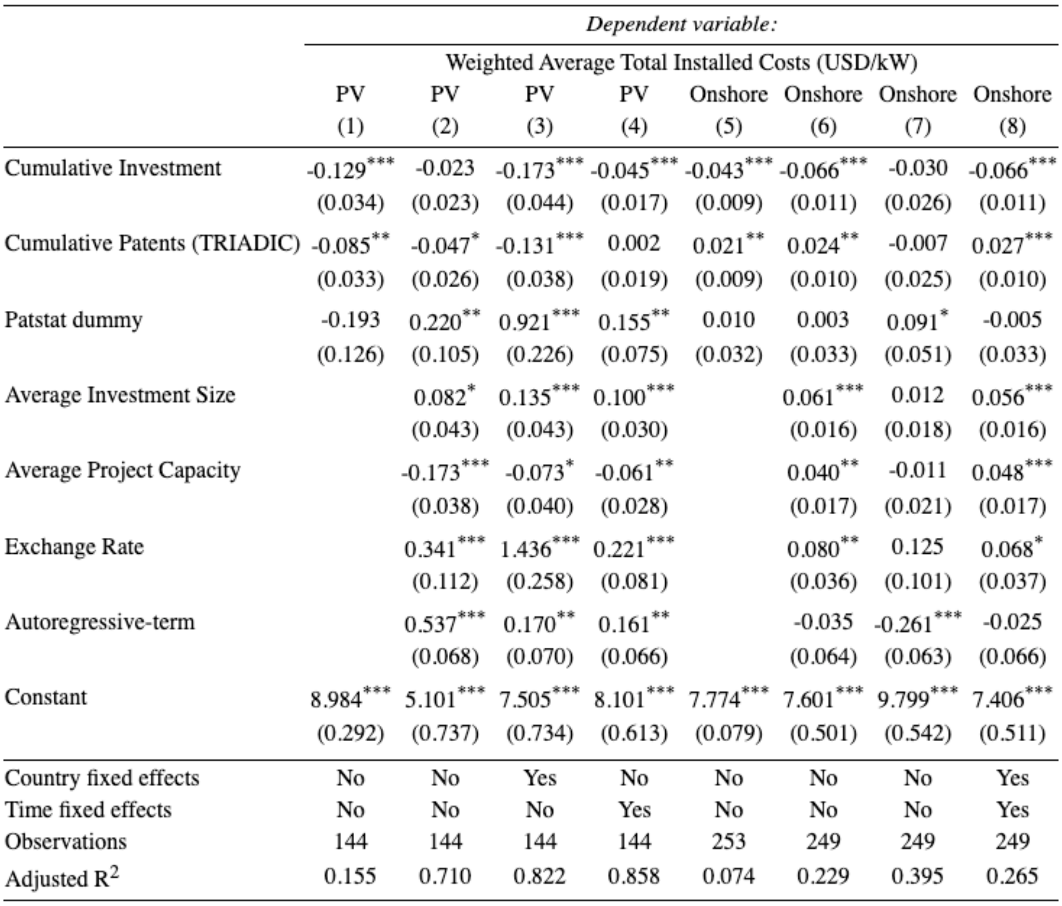
The analysis found that when accounting for within-country variation, technology-push and demand-pull dynamics are both significant and positively related to lower average installed costs for solar PV energy projects. For onshore wind, this chapter finds this significant relationship only for demand-pull dynamics. The results confirm that while both effects are related to lower costs of onshore wind and solar PV energy projects, the technology-push effect seems to be more important during the earlier stages of a technology, while the demand-pull effect becomes stronger for mature technologies. Notably, the results show the technology-push effect to be even stronger for high-quality patents in solar PV energy. Additionally, the chapter found that public investments were particularly important in solar PV projects, given their correlation with lower average total installed costs.

Contrary to the approach of most learning curves, the models in this chapter used financial investment data instead of installed capacity. In a first attempt, this chapter further distinguished between private investments and investments with public participation to understand better the different type of demand-pull dynamics and their relative importance on the cost of onshore wind and solar PV energy projects. The goal was to show the relative importance of these dynamics between the two technologies and across time. While this has been done using a relatively crude measure of private investments and investments with any public involvement, future studies should take a more exact analysis of the share of different types of investments in solar PV or onshore wind energy projects. Unfortunately, the data was not sufficient to carry out a cross-country panel analysis of further disaggregated financial investments in renewable energy cost reductions. Further studies should also extend the analysis to more recent time periods and cover other renewable energy technologies such as offshore, once the data becomes available.

In conclusion, the results highlight a cost-benefit for governments to support innovation and deployment of onshore wind and solar PV energy technologies. Given the high share of upfront costs for such renewable energy projects, this cost benefit is likely to affect the final price of electricity from renewable energy sources. Further study should confirm these results qualitatively while also assessing the economic benefit for domestic manufacturing industries from these technology-push and demand-pull dynamics. This is particularly the case for different new technologies within the solar PV and wind energy sectors. Unfortunately, the data does not allow for a more detailed quantitative analysis of changes in costs of specific types of solar panels, such as first-, second-, or third-generation solar cells or specific types of wind turbine technologies. Analysing different technologies individually would further help to disentangle the relative importance of technology-push and demand-pull dynamics at different points in time.

Appendix 3.1

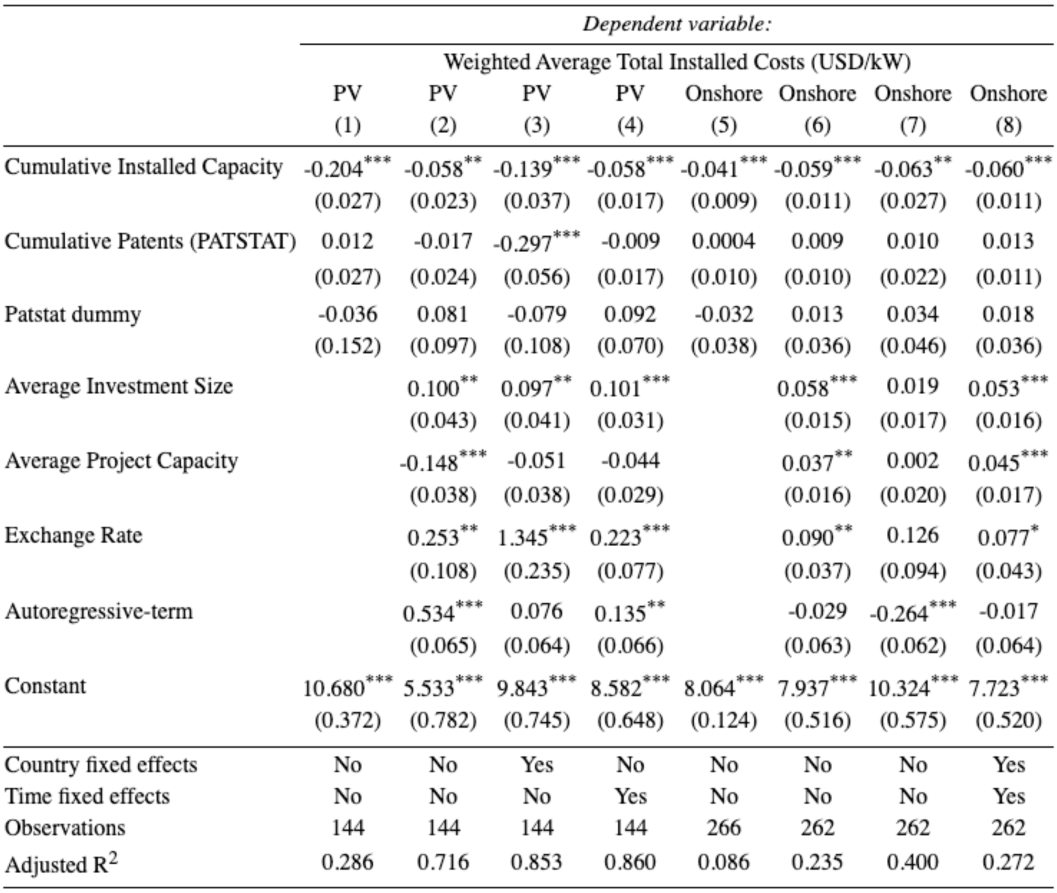
Table 6: Regression results using Triadic Patent Families



	Dependent variable:							
	Weighted Average Total Installed Costs (USD/kW)							
	PV (1)	PV (2)	PV (3)	PV (4)	Onshore (5)	Onshore (6)	Onshore (7)	Onshore (8)
Cumulative Investment	-0.129^{***}	-0.023	-0.173^{***}	-0.045^{***}	-0.043^{***}	-0.066^{***}	-0.030	-0.066^{***}
	(0.034)	(0.023)	(0.044)	(0.017)	(0.009)	(0.011)	(0.026)	(0.011)
Cumulative Patents (TRIADIC)	-0.085^{**}	-0.047^{*}	-0.131^{***}	0.002	0.021^{**}	0.024^{**}	-0.007	0.027^{***}
	(0.033)	(0.026)	(0.038)	(0.019)	(0.009)	(0.010)	(0.025)	(0.010)
Patstat dummy	-0.193	0.220^{**}	0.921^{***}	0.155^{**}	0.010	0.003	0.091^{*}	-0.005
	(0.126)	(0.105)	(0.226)	(0.075)	(0.032)	(0.033)	(0.051)	(0.033)
Average Investment Size		0.082^{*}	0.135^{***}	0.100^{***}		0.061^{***}	0.012	0.056^{***}
		(0.043)	(0.043)	(0.030)		(0.016)	(0.018)	(0.016)
Average Project Capacity		-0.173^{***}	-0.073^{*}	-0.061^{**}		0.040^{**}	-0.011	0.048^{***}
		(0.038)	(0.040)	(0.028)		(0.017)	(0.021)	(0.017)
Exchange Rate		0.341^{***}	1.436^{***}	0.221^{***}		0.080^{**}	0.125	0.068^{*}
		(0.112)	(0.258)	(0.081)		(0.036)	(0.101)	(0.037)
Autoregressive-term		0.537^{***}	0.170^{**}	0.161^{**}		-0.035	-0.261^{***}	-0.025
		(0.068)	(0.070)	(0.066)		(0.064)	(0.063)	(0.066)
Constant	8.984^{***}	5.101^{***}	7.505^{***}	8.101^{***}	7.774^{***}	7.601^{***}	9.799^{***}	7.406^{***}
	(0.292)	(0.737)	(0.734)	(0.613)	(0.079)	(0.501)	(0.542)	(0.511)
Country fixed effects	No	No	Yes	No	No	No	No	Yes
Time fixed effects	No	No	No	Yes	No	No	No	Yes
Observations	144	144	144	144	253	249	249	249
Adjusted R^2	0.155	0.710	0.822	0.858	0.074	0.229	0.395	0.265

This table presents the regression results on a log-log scale using the Triadic Patent Family count. As in Table 2, each model for solar PV and onshore wind was estimated four times respectively. Firstly, panels 1 and 5 are the baseline results for cumulative financial investment and cumulative patents. Secondly, panels 2 and 6 introduce control variables. Lastly, panels 3 and 4, and 7 and 8 use country- or time-fixed effects. Significance levels are as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Regression results using cumulative installed capacity



	Dependent variable:							
	Weighted Average Total Installed Costs (USD/kW)							
	PV	PV	PV	PV	Onshore	Onshore	Onshore	Onshore
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cumulative Installed Capacity	-0.204***	-0.058**	-0.139***	-0.058***	-0.041***	-0.059***	-0.063**	-0.060***
	(0.027)	(0.023)	(0.037)	(0.017)	(0.009)	(0.011)	(0.027)	(0.011)
Cumulative Patents (PATSTAT)	0.012	-0.017	-0.297***	-0.009	0.0004	0.009	0.010	0.013
	(0.027)	(0.024)	(0.056)	(0.017)	(0.010)	(0.010)	(0.022)	(0.011)
Patstat dummy	-0.036	0.081	-0.079	0.092	-0.032	0.013	0.034	0.018
	(0.152)	(0.097)	(0.108)	(0.070)	(0.038)	(0.036)	(0.046)	(0.036)
Average Investment Size		0.100**	0.097**	0.101***		0.058***	0.019	0.053***
		(0.043)	(0.041)	(0.031)		(0.015)	(0.017)	(0.016)
Average Project Capacity		-0.148***	-0.051	-0.044		0.037**	0.002	0.045***
		(0.038)	(0.038)	(0.029)		(0.016)	(0.020)	(0.017)
Exchange Rate		0.253**	1.345***	0.223***		0.090**	0.126	0.077*
		(0.108)	(0.235)	(0.077)		(0.037)	(0.094)	(0.043)
Autoregressive-term		0.534***	0.076	0.135**		-0.029	-0.264***	-0.017
		(0.065)	(0.064)	(0.066)		(0.063)	(0.062)	(0.064)
Constant	10.680***	5.533***	9.843***	8.582***	8.064***	7.937***	10.324***	7.723***
	(0.372)	(0.782)	(0.745)	(0.648)	(0.124)	(0.516)	(0.575)	(0.520)
Country fixed effects	No	No	Yes	No	No	No	No	Yes
Time fixed effects	No	No	No	Yes	No	No	No	Yes
Observations	144	144	144	144	266	262	262	262
Adjusted R^2	0.286	0.716	0.853	0.860	0.086	0.235	0.400	0.272

This table presents the regression results on a log-log scale using cumulative installed capacity instead of cumulative financial investments. As in Table 2, each model for solar PV and onshore wind was estimated four times respectively. Firstly, panels 1 and 5 are the baseline results for cumulative financial investment and cumulative patents. Secondly, panels 2 and 6 introduce control variables. Lastly, panels 3 and 4, and 7 and 8 use country- or time-fixed effects. Significance levels are as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Chapter 4: Changing Technology and Demand Regimes – Green Windows of Opportunity and Structural Cycles in the European Wind Energy Industry.

Abstract

On the basis of reduced costs of renewable energy technologies vis-à-vis fossil fuels, the energy transition has become a huge opportunity for economic growth and job creation. However, in the wind energy sector, rapid cost reductions as well as changes to the demand and fast-changing technology platforms have increasingly exposed European turbine OEMs to international competition and squeezed their profit margins. Key to the success of individual firms or entire manufacturing ecosystems are Green Windows of Opportunity (GWO): favourable, time-limited conditions for technological advancement and international market leadership in sustainable technologies (Lema et al., 2020). While the concept has been largely applied in the context of latecomer countries, the framework is also useful for understanding the behaviour of incumbent firms as they are trying to maintain their market position. This chapter will produce evidence on the determinants of market leadership in the wind manufacturing industry by looking beyond technological change alone. Central to this approach is the recognition that the structure and composition of demand play a crucial role in industrial dynamics. The German onshore and offshore wind energy sectors will be analysed as a critical case study for European wind turbine OEMs. In 2017, Germany switched from a feed-in tariff system to renewable energy auctions. This policy change will be used as a breaking point in the country's regulatory framework and institutional support for the wind turbine manufacturing industry. A mixed methods approach using a range of data including financial data, wind turbine installation capacity, and patents will be used to present stylised facts about the changing dynamics of Technology and Demand Regimes. Furthermore, this will be triangulated with primary data from semi-structured interviews with key actors in the industry.

1. Introduction

The latest IPCC Synergies Report claims with “high confidence” that there are “*potential synergies between sustainable development and, for instance, energy efficiency and renewable energy*” (IPCC, 2023, p. 54). At the same time, the energy transition and the related economic sectors are increasingly seen as a contested area of industrial competition and geopolitical importance where the question becomes which companies will develop and produce the technologies and who benefits economically from the supply chain. In the US, the Inflation Reduction Act and in the EU the Net Zero Industrial Act are recent efforts aimed at giving manufacturers confidence to expand their production facilities. Similarly, individual Member States of the EU such as the German government have stated their ambition to strengthen the domestic manufacturing of renewable energy technologies such as solar PV and wind (BMWK, 2023a, 2023b). These are the latest attempts to match Chinese industrial policy and support Western manufacturers in their competition with their Chinese counterparts, which are an emerging competition not only on costs but increasingly also on the technological frontier.

Wind energy technologies not only play an important part in the decarbonisation of the energy mix, but the wind energy sector also holds large potential for economic value creation. At the same time, over the past decades, both the onshore and offshore wind turbine manufacturing industries have consolidated significantly resulting in changes in the composition of the market and market leaders (Dai et al., 2020). The early leadership of Denmark and the US was first challenged by Germany and Spain in the early 1990s and later by Asian countries, most notably China, in the early 2000s. Particularly Chinese manufacturers and Chinese industrial policy have been at the forefront of challenging European incumbent firms in the wind manufacturing sector. However, there has been no irreversible loss of the European leadership position and Denmark, Spain, and Germany remain key wind turbine manufacturers alongside Chinese entrants in a market comprised of shared global manufacturing leadership. Additionally, there remains disagreement in the empirical literature to what extent Chinese wind turbine manufacturers have managed to upgrade their innovation capabilities (Dai et al., 2020; Nahm, 2021) or whether they still lag behind the technological frontier (Hu et al., 2018; Zhou et al., 2018).

Industrial leadership, usually defined as the share of global industrial production, can change during Windows of Opportunity through changes in technologies, markets, or institutional regimes (Lee and Malerba, 2017). The outcome of these time-limited opportunities depends not only on the individual factors but also on their interlinked and compounding effects as well as endogenous responses of firms and supporting institutions in latecomer as well as incumbent countries (Malerba, 2002; Malerba and Nelson, 2011). Green Windows of Opportunity in the age of transformation toward sustainability are often thought to be affected by institutional change that creates demand for green technologies (Lema et al., 2020). This chapter seeks to analyse industrial dynamics from the perspective of incumbent European wind turbine OEMs (Original Equipment Manufacturers) through the lens of a Structural Cycles analysis. As will be elaborated below, a Structural Cycle framework can help us to analyse technological, demand, and organisational transitions and as such lends itself well to the analysis of Windows of Opportunity.

Particular emphasis in this chapter will lie on changes to the demand for wind turbines and how a new set of developers and owners of wind farms have shifted the Demand Regime during a demand transition and affected the manufacturers of turbines. As discussed as part of the literature review in Chapter 2, Demand Regimes can shift when the dominant customer changes or a new demand class emerges (Capone et al., 2013; Malerba et al., 2016, 1999). In the context of the wind turbine manufacturing industry, this concerns changes in the composition of developers and operators of wind farms. This conceptualisation of demand, while a departure from the conventional focus on final electricity consumption, is significant and sensible for two reasons: 1) energy project developers and operators serve as the intermediaries between the manufacturing supply chain of renewable energy technology and the final consumption of generated electricity. By developing and operating wind energy projects, they create a market for wind turbines, thus shaping the demand for these technologies. 2) in many cases, for example in the European Union and specifically Germany, the government has provided remuneration in the case of feed-in tariffs or market premiums to increase the uptake of renewable energy technologies. Thus, changes in the regulatory framework or remuneration schemes can affect not only the overall quantity but also the structure and composition of demand for renewable energy technologies, i.e. the Demand Regime.

As the disaggregated data on European wind farm developers and operators is surprisingly sparse, we use treat Germany as a ‘critical case study’ (Flyvbjerg, 2006) for the changes in the European wind energy in sector. Similar to most EU Member States, Germany switched from a feed-in tariff system to renewable energy auctions in 2017. We therefore treat this policy change as a breaking point in the country’s regulatory framework and institutional support for the wind turbine manufacturing industry.

We show the effect of the switch to renewable energy auctions on the demand for wind turbines in Germany as well as how this has altered the direction of technological change in the sector. The compounding effect of these dynamics will be analysed concerning their implications for the wind turbine manufacturing industry. By doing so, the following research question will be answered: *How has the structure and composition of demand for wind turbines changed following the adoption of renewable energy auctions in the EU and what impact has this had on European wind turbine OEMs?*

The research question rests on a number of interlinked hypotheses. 1) the quantity and quality of demand for wind turbines was altered following the change in the institutional support system. 2) different types of demand influence the structure of the supply side in the wind turbine manufacturing industry. Hence, when the structure of developers and operators of wind farms changed it affected the structure of supply from a technological as well as an organisational point of view. 3) these dynamics followed time-specific as well as sector-specific cycles and thus developed differently between the onshore and offshore wind energy segments. These three hypotheses will be tested by presenting a number of stylised facts on the example of the German switch from feed-in tariffs to renewable energy auctions. Additionally, semi-structured interviews were used to triangulate these trends and to establish causal effects.

The renewable energy sector, and particularly the wind energy sector, is a unique case where the structure and composition of the demand is heavily influenced by public policy. Energy policy and industrial policy can be used by governments to structure the demand for wind energy technologies which in turn can have a significant impact on technological developments and the supply of these technologies. Without sufficient alignment of both demand and supply side interventions and an understanding of the sectoral dynamics, there is a risk of local manufacturers being unable to benefit from the energy transition.

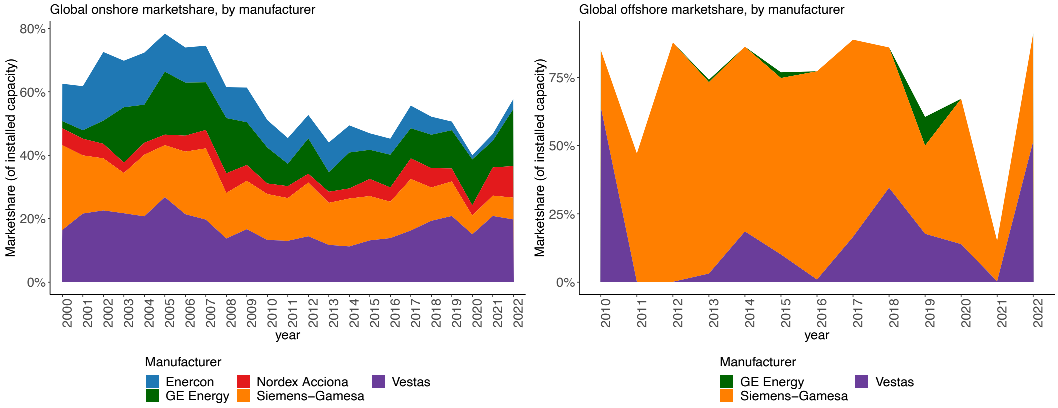
The remainder of this chapter is structured as follows. Section 2 briefly sets the scene by discussing wind turbine OEM market shares as well as their financial performance. The section will further outline why Germany was chosen as a critical case study to analyse the drivers behind the industrial dynamics in the European wind turbine manufacturing industry. Section 3 provides a review of the existing literature on the European wind turbine manufacturing industry. Section 4 presents the analytical framework of the Structural Cycle approach to analyse macro-structural dynamics of technology and demand transitions. Section 5 presents the findings of our analysis in the following format: 1) technological developments in the onshore and offshore wind energy segments globally will be presented. 2) European demand for wind turbines will be mapped out. 3) changes in the German institutional support framework for wind energy projects will be elaborated on. This will be used to further understand changes to the structure and composition of demand for wind turbines including their effects on wind turbine cycles. 4) the effect of these interdependent dynamics on wind turbine OEMs will be explained based on the interviews conducted for this research. Section 6 will discuss the main results while Section 7 concludes.

2. Background:

2.1. The European Wind Turbine Manufacturing Industry

Since the late 2010s' there has been a process of consolidation of manufacturing firms in the wind energy sector with the global as well as individual national industries being centred around fewer and fewer actors (O'Sullivan, 2020). Western OEMs have lost significant market shares in the past 20 years.[5] Figure 12 shows how the main Western manufacturers have been challenged in their global leadership. While the four main remaining European OEMs accounted for over 60% market share in the onshore segment in the early 2000s', this has reduced to under 40% since the 2010s'. In the offshore segment, Siemens Gamesa has maintained its global leadership position but also Vestas constitutes an important actor.

Figure 12: Global market shares by turbine manufacturer



Global onshore marketshare, by manufacturer

Global offshore marketshare, by manufacturer

Source: Own elaborations based on WindPower database. Market shares for both Siemens-Gamesa and Nordex Acciona include projects supplied by both Siemens and Gamesa, and Nordex and Acciona, respectively, prior to their merger.

In the onshore segment, the loss of global industrial leadership by European OEMs can partly be explained by the expansion trends of wind energy in other regions, most notably in China (see Figure 13). Before 2010, the global expansion of onshore wind energy was driven largely by Europe and the US and until it plateaued in 2012. The period from 2013 to 2016 saw a combined

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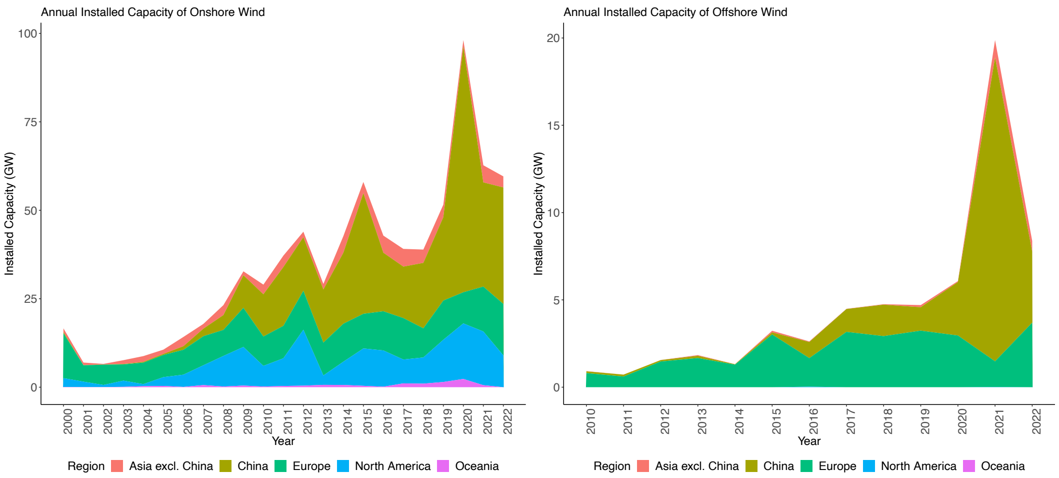
[5] Western OEMs include the four largest European OEMs (Enercon, Nordex-Acciona, Siemens Gamesa, and Vestas) as well as GE. Given GE's renewables division is headquarters in France, GE is sometimes included among the European OEMs but will not be treated as such in this analysis.

expansion of Europe, the US, and Asia. From 2018 onwards the global expansion of wind energy was predominantly driven by installations in China.

In the offshore segment, two such cycles can be identified: First, pre-2017 which was driven by a relatively stable expansion in the European market. Second, post-2017 which was largely driven by the Chinese offshore market similar to the dynamics in the onshore segment.[6]

Figure 13: Global onshore and offshore wind installations.



Source: Own elaborations based on IRENASTAT

Changes to global market shares can therefore partially be explained by the rapid expansion of wind installations in China, benefitting Chinese OEMs. As noted by Backwell (2018), the wind industry remains characterised by two almost separate markets. One in China where mostly Chinese OEMs are dominant, and one for the rest of the world where European OEMs remain among the dominant players.

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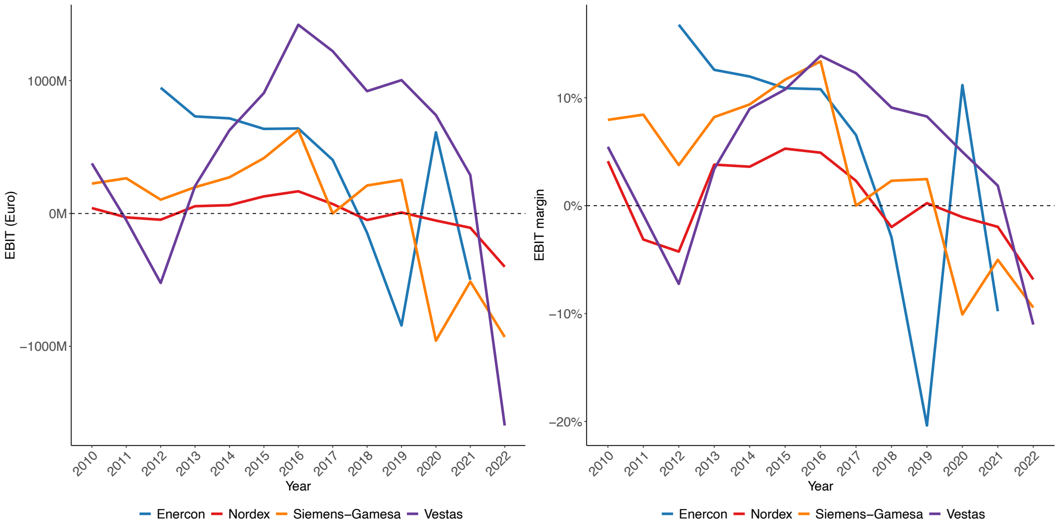
[6] The high spike in Chinese onshore instalments in 2020 can be explained by the 2019 policy release of the Chinese National Development and Reform Commission (NDRC) that ended the Feed-in Tariff in China by the end of 2020 (GWEC, 2022, p. 103). Since then, Chinese onshore wind has been paid based on the regulated price for coal power in each province. Similarly, the Chinese spike in offshore installations in 2021 can be explained by the change in the Chinese remuneration scheme which stated that only offshore wind farms approved before 2018 and grid-connected by the end of 2021 would still receive a feed-in tariff (GWEC, 2022, p. 105). While it is still too early to see the exact effect of these institutional changes manufacturers, competition and turbine growth have increased among Chinese OEMs since the phasing out of the feed-in tariff (Lico, 2024).

Within the European market, European wind turbine OEMs continue to account for 85% of installed turbines (94% in the offshore sector). Nevertheless, since 2017 European wind turbine OEMs have reported decreasing profits which has led to layoffs and shifts in production locations to regions with lower labour costs. The global market leader Vestas reported a net loss of almost €1.2bn in 2022, down 369% from a loss of €428m in 2021. Despite becoming the biggest selling OEM in the German market, the turbine manufacturer Nordex also reported a net loss of €498m in 2022. Siemens Gamesa, who recently announced problems related to their onshore fleet which are expected to cost over €1bn to fix, reported a full-year net loss of €4.6bn for 2023 and required a €15bn rescue package including €7.5bn in state guarantees by the German government. Similarly, Enercon a privately owned OEM has struggled in recent years and received €500m in government support through the German economic stabilisation fund in 2022.

Figure 14 shows the earnings before income and tax (EBIT) for the four main European OEMs as well as their EBIT margins. All OEMs' manufacturing net income and profit margins are even worse when looking at the margins by Segment. For Vestas, in 2022 the service segment showcased a strong performance with 27% revenue growth at 21.4% EBIT margin, but the profitability of the wind turbine sales decreased to negative 13.3% (Vestas, 2022). Similarly, Siemens-Gamesa recorded a service EBIT margin of 17.5% and a wind turbine sales EBIT margin of negative 12.7% in 2022 (Siemens-Gamesa, 2022a). While having an overall EBIT margin of negative 6.8% in 2022, Nordex's service segment reported an EBIT margin of 16.2% (Nordex Acciona, 2023).

Figure 14: OEMs' EBIT and EBIT margin, 2010-2022



Source: Own elaboration based on Orbis data

Crucially, for Enercon, Nordex, and Siemens-Gamesa the profit margin (EBIT margin on the right side of the graph) turned negative much before Vestas. As soon as the profit margin turns negative, the respective OEM made losses from every Euro revenue generated. In such a situation, financial investment in the company through spending on research and development or expansion of production facilities is often hard to justify to potential investors.

These financial difficulties pose a risk for the European wind turbine supply chain as they constrain wind turbine OEMs from making the necessary investments in production capabilities needed to meet the targeted demand by European governments. As argued, regional trends in the global wind energy expansion alone are insufficient in explaining the financial situation of European wind turbine OEMs. Instead, we need to focus on the interlinked changes in technology, demand, and organisational transitions within the European context.

2.2. Germany as a Critical Case Study for the European Wind Turbine Manufacturing Supply Chain

We analyse these interlinked changes in technology, demand, and organisational transitions using the example of the German wind energy sector as a critical case study for the developments in the European wind energy sector. With 31% and 50% of cumulative wind capacity installed in the EU[7] for the onshore and offshore segments respectively, Germany stipulates the largest market for wind energy technologies (IRENASTAT). Given the importance of the domestic market for manufacturers of wind turbines and the relative importance of the German market in Europe, the developments in Germany can be viewed as a key determinant for the structure of European demand and the overall effect on the supply chain.

In 2017, Germany switched from a feed-in tariff system to renewable energy auctions. As mentioned above, the policy change in Germany did not happen in isolation but during a time when all EU Member States were instructed by the European Commission to determine the level of renewable energy remuneration through competitive auctions rather than feed-in tariffs. The effect of changes to the renewable energy support system on the expansion of renewable energy can also be seen in the case of Spain where a memorandum on feed-in tariffs for wind energy was passed in 2012 and led to an almost complete standstill of new wind turbine installations in the country (del Río, 2017).

Germany is often viewed as an international role model for climate action. Over the past twenty years, Germany has positioned itself internationally as a pioneer in energy efficiency, energy security, renewables, and nuclear phaseout. The country's early focus on renewables makes it an interesting case to analyse as German firms have been operating within the wind value chain for a long time and the government has provided long-standing support for the industries. From the start, the support for innovation in renewable technologies in Germany however went much further than seeking to achieve just an increase in the share of renewable electricity in

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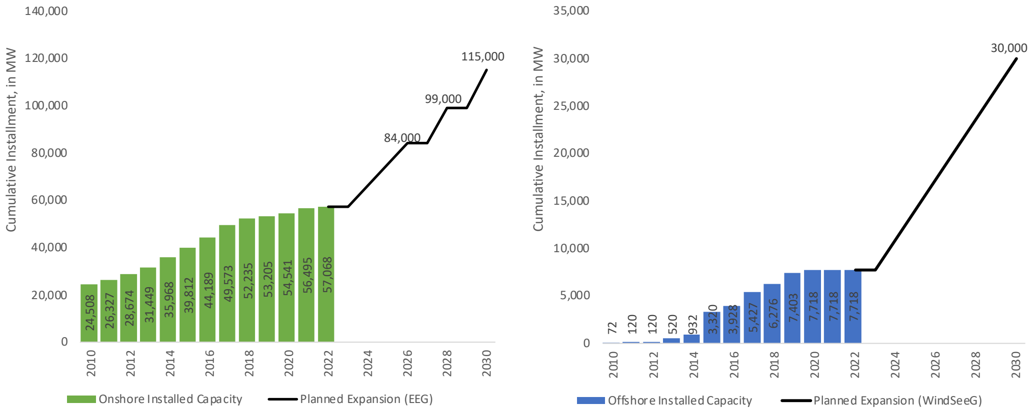
[7] This share reflects the EU without the UK, adding the UK reduces Germany's share in the offshore segment to 27% of cumulative installed capacity.

the German energy mix. The ‘Energiewende’ (energy transition) was intended to ensure Germany’s position as a global leader in the development and manufacturing of renewable technologies and promote the creation of jobs within the industry.

Figure 15: Installed cumulative capacity in Germany and planned expansions.



Source: Own elaboration. Cumulative installed capacity based on the WindPower database and planned expansion targets according to EEG and WindSeeG

The German government has outlined ambitious plans for the expansion of both onshore and offshore wind energy capacities as a critical pillar of its energy transition strategy. Figure 15 shows the cumulative installed capacity of onshore and offshore wind turbines in Germany, as well as the planned expansion targets as defined in the German Renewable Energy Act and the Offshore Wind Energy Act. These plans aim to ensure that by 2030, onshore wind will provide at least 115 GW and offshore wind 30 GW, up from about 57 GW and 8 GW respectively at the end of 2022.

As noted earlier the main European OEMs have all reported negative profit margins in 2022. These diminished profit margins pose a potential threat to the European wind turbine supply chain if, as a result, the wind turbine OEMs do not make the necessary investments to meet the expected future demand for wind turbines. The current production capacities of European wind turbine OEMs are likely insufficient to meet the expansion plans of the onshore and offshore wind energy sectors set by Germany and other Member States of the EU.

3. Literature Review: Empirical studies on the European wind turbine manufacturing industry

Most empirical studies that have analysed the development of the German and European wind manufacturing industry so far have focused on government policies and how they have enabled the emergence of local manufacturing industries. These studies can be grouped into focusing on "direct" (demand-side) policies and "indirect" (supply-side) policies that have supported the expansion of wind energy technologies. The relevance of various support measures aimed at creating a market for renewable energy technologies has been shown by several studies (Bürer and Wüstenhagen, 2009; Darmani et al., 2014; Groba and Breitschopf, 2013; Haas et al., 2011; Jacobs, 2014; Nemet, 2009).

Lütkenhorst and Pegels review several German support policies for renewable energy technologies and assess the costs and benefits associated (Lütkenhorst and Pegels, 2014; Pegels and Lütkenhorst, 2014). They find that in terms of economic and social benefits, the wind industry has performed better than other renewable technology industries in Germany. Similarly, Lewis and Wiser (2007) analyse early support policies across the main wind manufacturing countries.

While reviewing various direct support policies, Lewis and Wiser (2007) find that a sizable domestic market is a prerequisite for a successful local wind manufacturing industry (Ibid, p.19). Similarly, Dechezlepretre and Galachant (2014) find domestic wind deployment policies far more important for the local industry than foreign support policies. Lacal-Arantegui (2019) reviews annual European installed wind capacity to assess the strategies of wind turbine manufacturing companies. Quitzow et al. (2017) compare global production networks in the wind and solar industries and suggest that for wind manufacturing the development of a local industry likely depends on the presence of a strong home market which implies a consolidation of a number of regional production hubs. Reviewing the recent developments in the German wind manufacturing industry Bach et al. (2020) argue that insufficient provision of space by federal governments, bureaucratic red tape, and political disagreement about the minimum distance between new wind turbines are at fault for the recent struggles of the industry, thus confirming the importance of local demand for German manufacturers.

Reichardt and Rogge (2016) review how the German policy mix has influenced corporate innovation activities in the emerging technology of offshore wind in Germany. While they find a general consistency and credibility of the policy mix for corporate innovation activities in offshore wind, they argue that the demand-support through the feed-in tariffs of the EEG and its sufficient level of support and high predictability was most important for German firms in the wind energy sector.

Furthermore, loan programmes, such as the Offshore Wind Energy Loan by the German state-owned development bank Kreditanstalt für Wiederaufbau (kfW) started in 2011, are argued to be instrumental in supporting the domestic manufacturing industry (Lema et al., 2014; Reichardt and Rogge, 2016). In addition to the German feed-in tariff, Nahm (2021, 2017) argues the German wind manufacturing industry and its supplier network benefitted from several supply-side support measures from the 1950s onwards: Firstly, R&D funding for Industrial Collaborative Research (ICR- Industrielle Gemeinschaftsforschung)—research projects firms in the wind sector and public research institutes. Secondly, local credit unions (Sparkassen) provided long-term loans for development projects to further support a demand-pull effect. And lastly, the recruitment of and reliance on high-skill engineers and production workers through Germany's universities and apprenticeship programmes. Interviewing German industry experts, Johnstone et al. (2021, p. 7) find that export promotion and public R&D support were important industrial policy instruments used to promote renewable technologies.

With regards to the development of the wind industry as a whole, Lema et al. (2014) find that as the industry is focusing on bigger projects and bigger turbine sizes, it is also moving away from private equative investment and community-based deployment towards big-business-based deployment (p. 22). This means that the industry consolidation, particularly in the offshore wind segment favours such large players that some industry experts even question whether Vestas' financial power may be too small to compete globally in the long run (Ibid, p. 22). Schmitz and Lema (2015) find similar industrial organisation geared towards economies of scale and the importance of capital and financial power as the main determinants for competitiveness in the wind manufacturing industry.

Wüstenmeyer et al. (2015) show how the offshore segment has decoupled its supply chain from the onshore counterpart and how their respective needs for government subsidies increasingly differ. Analysing the turbine manufacturing industry, Hughes and Quitzow (2018) show how major manufacturers are often vertically integrated with in-house developed production lines. They further argue that while demand-side policies are important for national competitiveness, it is important to understand how firms within global production networks influence learning and competition. Looking at industry life cycles, O'Sullivan (2020) maps how the global wind industry has developed and consolidated over time.

So far, there are only a few studies that look at specific firms operating in the wind manufacturing industry and their business strategies over time. Lema and Lema (2016) find that for emerging wind industry manufacturers, R&D partnerships and acquisitions of foreign firms have become important in addition to traditional technology transfer mechanisms such as foreign direct investments and licensing. Awate et al. (2015) compare the M&A strategies of Vestas and Suzlon as examples of how advanced and emerging MNEs internationalise their R&D.

Focusing on German policy and the shift to an auction-based system, Grashof et al. (2020) assess the effect of this shift on prices. Lundberg (2019) focuses on the types of winners of these auctions and investigates the effect on the overall structure of demand. She finds that uncertain technology costs and strong competition may have encouraged overly aggressive bidding in the first rounds of wind energy auctions in Germany in 2017. In reviewing the policy process behind this shift, Leiren and Reimer (2018) argue that the shift to an auction system was partly due to a desire to protect the market shares of big utility companies, thereby implicitly confirming the resulting change of the structure of demand. Dukan and Kitzing (2021) further assess the impact on financing conditions and the cost of capital for wind energy projects. However, none of these studies have analysed the effect of the switch from feed-in tariffs to renewable auctions on wind turbine OEMs and their supply chains.

So far, the empirical literature has focused on static analyses of the enabling factors for the initial development of a wind turbine manufacturing industry. Far less attention has been given to changing industrial dynamics in the wind energy sector. This gap is surprising given the observed industry consolidation in the wind turbine manufacturing sector and the financial struggles of European OEMs since 2017.

With regard to global changes to the industrial landscape, existing studies have attributed the rise of China in several green technologies to successful responses to Green Windows of Opportunity (Dai et al., 2020; Lema et al., 2013; Mathews and Tan, 2015).

Changes in industrial leadership that can occur through 'Windows of Opportunity', were first described by Perez and Soete (1988). The framework explains how new techno-economic paradigms can enable latecomers to achieve economic leapfrogging. Lee and Malerba (2017) expanded on this idea by incorporating elements from the sectoral innovation system literature to identify three distinct windows: a technological window, a demand window, and an institutional window. In the case of renewable energy technologies, the concept of green Windows of Opportunity is argued to be predominantly relying on institutional support for green technologies (Lema et al., 2020).

In trying to explain China's rise in wind power Haakonsson et al. (2020) attribute recent catch-up by Chinese firms to organisational changes taking place in the incumbent wind turbine lead markets in Europe. Dai et al. (2020) investigate the relationship between technological change at the global level and responses by Chinese latecomer firms through the framework of Green Windows of Opportunity. Their study shows how Chinese firms managed to achieve technological catch-up as the sectoral frontier advanced to new technologies centred around digital and hybrid solutions. While China's rise in wind power is largely attributed to generous feed-in tariffs and other market-creating industrial policies, Dai et al. (2020) argue that technological windows shaped by institutional support rather than domestic market creation enabled Chinese firms to achieve technological catch-up with European OEMs.

However, so far there remains a gap in the academic literature that analyses the concept of Green Windows of Opportunity and their implications for industrial dynamics from the perspective of incumbent firms in the wind turbine manufacturing sector. This chapter aims to fill this gap by analysing European wind turbine OEMs using the concept of Structural Cycle analyses by Andreoni et al. (2016).

4. Analytical framework

As mentioned in Section 3, the framework of Green Windows of Opportunity has been used to explain the industrial upgrading of Chinese OEMs in the wind turbine manufacturing sector. The concept has so far not been applied to understanding the changing dynamics of industrial production of incumbent firms. This is particularly relevant in the case of wind energy technologies, where there is the existence of "*two almost separate markets*"' between China and 'the West' (Backwell, 2018, p. 185). As a result, the financial performance of European incumbent European OEMs is to a large degree independent from the performance of Chinese latecomers. This is different from other renewable energy technology sectors, such as solar PV for example, where Chinese solar panel manufacturers have managed to penetrate the European market to a much larger degree.

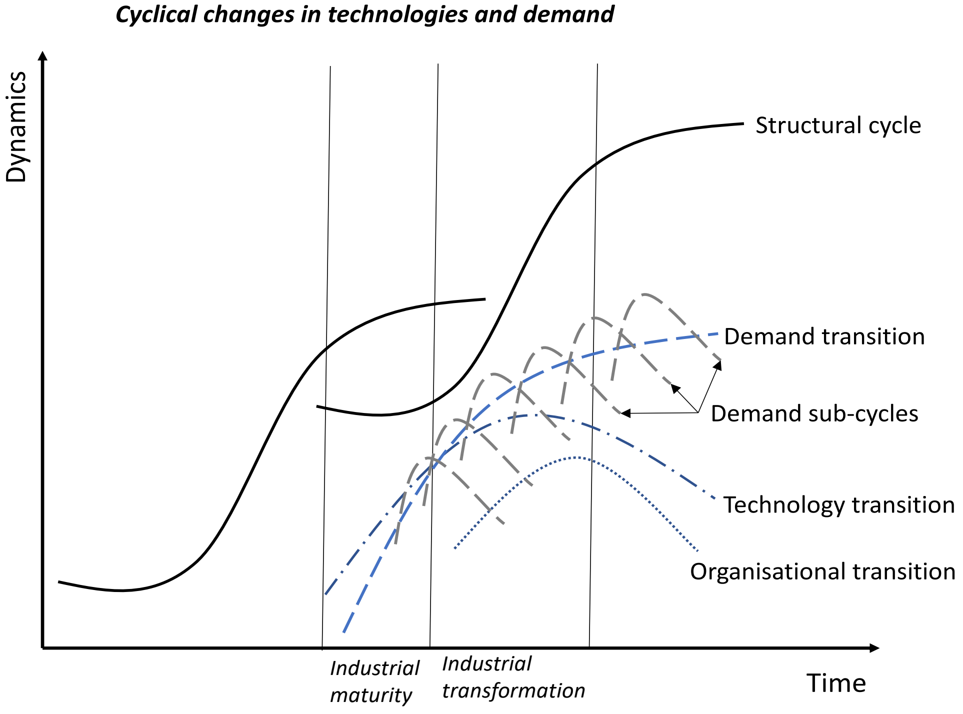
While the Green Windows of Opportunity framework shows how favourable, but time-bound conditions can lead to industrial leadership changes, it so far has not been used to analyse how incumbent firms are affected by and respond to these windows. In order to analyse the dynamics of technology, demand, or institutional-led Windows of Opportunity, this chapter relies on the framework of Structural Cycles (Andreoni et al., 2016) and develops this further. Structural Cycles are the result of coevolving and cumulative dynamics resulting from technology transition and organisational reconfiguration. As such, Structural Cycles can help us to capture stylised facts of different macro-structural and micro-firm-level dynamics within a given sector and link industrial leadership changes. The framework is particularly helpful in understanding changes in the Technology or Demand Regime within a given industry.

On a higher level, the Structural Cycles framework can be used to understand the shifting dynamics between different technologies or energy sources. Figure 16 presents the stylised facts of a new energy technology, such as wind energy, emerging as part of a new structural cycle. During a period of industrial maturity (of the previous technology, not shown in Figure 16), a technology transition will emerge and lead to a period of industrial transformation. The initial framework of Andreoni et al. has focused on a technology transition and subsequent organisational reconfiguration *"that business organisations experience when they shift towards higher-value product segments opportunities"* (Andreoni et al., 2016, p. 888).

We have extended this framework with a subsequent demand transition that follows the technology transition and over time becomes relatively more important vis-à-vis the technology transition during the period of industrial transformation. This happens as the respective technology matures and receives more attention from customers once it becomes economically attractive. This demand transition continues to rise but eventually plateaus as the demand becomes saturated.

However, it is important to note that the technology and demand transitions will have several underlying sub-cycles. For example, the technology of wind turbines is continuously evolving, and newer and bigger turbines constantly emerging. As will become clear in the analysis, the nature of wind energy auctions is such that bigger turbine models often perform better with regard to their LCOE and wind farm developers quickly adopt their preferences whenever a new turbine model emerges. The demand transition is therefore not simply linear but follows an overall emerging direction with different competing technologies and segments. This highlights the importance of a continuous organisational transition in response to the sub-cycles of the technology and demand transition during industrial transformations, which will be explored in greater detail in Chapter 5.

Figure 16: Elements of Structural Cycles



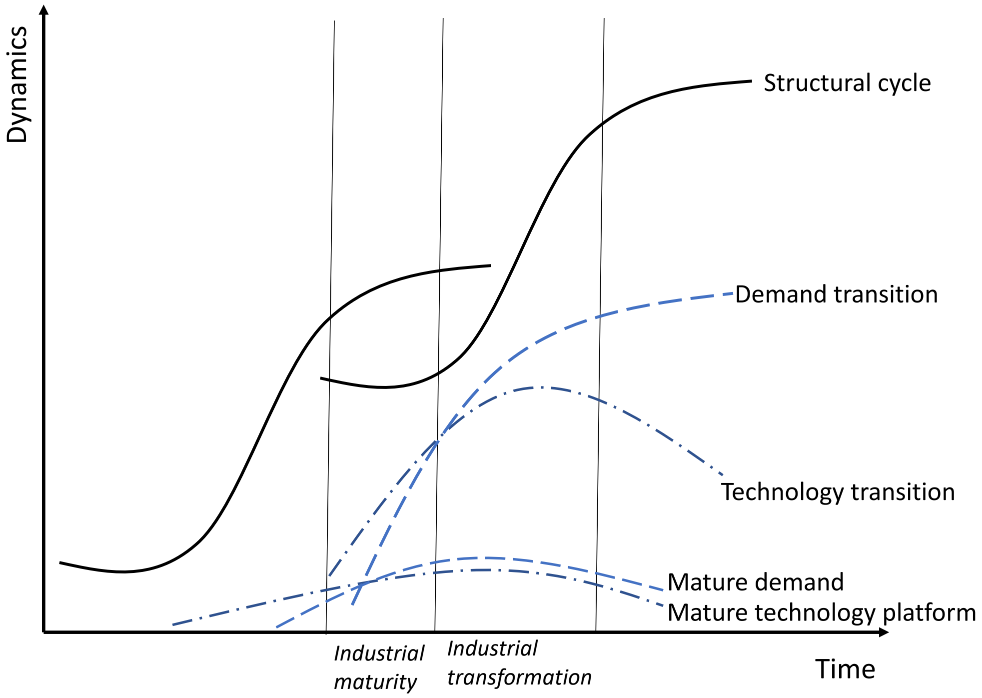
Source: Own, based on Andreoni et al. (2016)

We use this framework of Structural Cycles to investigate potential industrial leadership changes during Windows of Opportunity. In Figure 17 we visually outline how each period of industrial maturity and industrial transformation as part of the Structural Cycle is aligned with opportunities for market and technology challenges from latecomer firms.

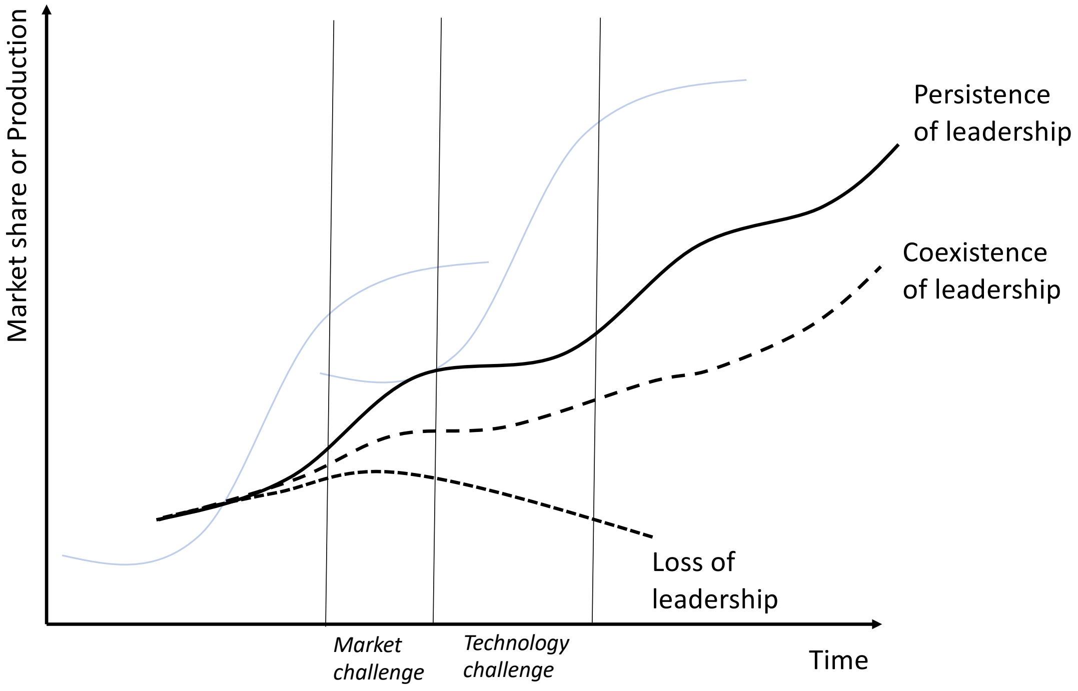
Once the technology transformation starts to plateau and a new technology design or product solution becomes established during a period of industrial transformation, the dynamics of the demand transition become stronger as the technology becomes widely deployed. Following a subsequent industrial maturity, a new technology cycle emerges with demand eventually shifting to new products during a new phase of industrial transformation.

These interconnected dynamics of technological development and changes in demand can be along short or long cycles and whose relative importance can change over time. With regard to technology cycles, Lee (2013) has shown that in technologies with shorter cycles, incumbents are more likely to weaken or face downfall, thereby enabling greater opportunity for catching up. By contrast, sectors with long technology cycles favour 'old giants' (Ibid).

Figure 17: Analytical Framework: Industrial Leadership Changes as a Result of Structural Cycles



Cyclical changes in technologies and demand



Leadership changes as a result to emerging challenges from windows of opportunity

Source: own elaborations based on Andreoni et al. (2016) and Lee and Malerba (2017)

The lower part of Figure 17 illustrates how industrial leadership evolves from the viewpoint of the existing dominant player. The term "persistence of leadership" refers to a scenario where the sector's evolution, steered by the incumbent and its country, successfully maintains its leading position. On the other hand, "coexistence of leadership" occurs when a new entrant challenges the incumbent, leading to a shared market leadership and a consequent decline in the curve. When the incumbent is unable to counter the challenge posed by a new entrant, a change in leadership takes place, resulting in a gradual decrease in the incumbent's market share.

The framework is of course an oversimplification of complex dynamics and overlapping technological developments and changes in the structure and composition of demand, which productive organisations adapt to, and government policies may or may not be aligned with.

4.1. Data and research methods

The Green Windows of Opportunity literature so far does not address specifically how incumbents can be affected by changed dynamics of Technology and Demand Regimes. As this involves complex dynamics of demand transitions, technological change, and policy support, this will be further analysed in the specific country context of Germany. In doing so, the research project aims to understand how exactly transitions in the Technology and Demand Regime have played out in the context of Germany and what effect this has had on the European wind turbine manufacturing industry. For this, the study adopts a mixed-method, multi-tiered and multi-disciplinary approach.

Firstly, a number of stylised facts will be used to map the Structural Cycles in the onshore and offshore wind turbine manufacturing industries. Technological cycles and changes in the structure and composition of demand are difficult to capture. However, there are a number of proxies that can be used for our purposes. Despite some limitations, patent data are a frequent proxy for technological change and developments (Keller, 2004).

Wind patent applications were taken from the PATSTAT database and aggregated by sector, office, as well as individual firms to analyse technological cycles.

To capture the changing dynamics of the demand transition, wind turbine installations will be mapped and presented through different descriptive statistics. For this, data from the WindPower database was used, which holds detailed project-level data on location, capacity, and manufacturer for a total of 766GW of onshore installations and 54GW offshore as of 2022, which corresponds to 92 per cent and 87 per cent of installed onshore and offshore capacity respectively according to IRENASTAT (IRENA, 2023).

Secondly, the descriptive analysis will be triangulated with an in-depth case study of Germany to capture nuanced changes in the dynamics of the demand transition. For this, changes in the renewable energy remuneration scheme and their effect on the overall expansion of wind power in Germany as well as the type of developers and their preferred turbine configurations will be elaborated on. In 2017, Germany as well as many other EU countries, switched from a feed-in tariff to an auction system to determine the level of renewable energy remuneration. This shift will be treated as a breaking point in the regulatory framework while Germany will serve as a critical case study for wider developments in the EU.

Lastly, the findings of the first two approaches will be related to the financial performance of the main European wind turbine OEMs. Rapid cost reductions of wind energy technologies as well as changes to the demand and fast-changing technology platforms have increasingly exposed European wind manufacturers to international competition and squeezed their profit margins. This analysis includes data from annual financial reports of the European wind turbine OEMs and 18 semi-structured interviews throughout 2023 with industry experts, firm representatives, as well as officials from government organisations (see Appendix 4.1 for an overview of semi-structured interviews). The research also benefitted from a number of informal discussions with representatives from wind turbine OEMs and their suppliers at the WindEurope annual conference in Copenhagen in 2023.

5. Analysis: Macro-structural trends in the wind turbine manufacturing industry and shifting Demand Regimes in Germany

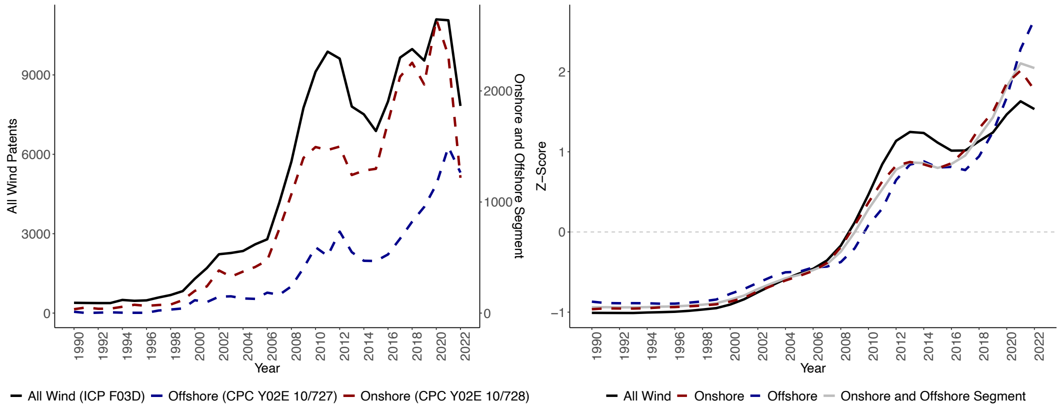
5.1. Technological change in the wind turbine industry

To measure technological cycles, patent data is often used as a proxy. Figure 18 shows patent applications for all wind turbine-related patents (classified as ICP class F03D), as well as the onshore and offshore segments (classified as PCP class Y02E 10/728 and 10/727). In the wind sector, three distinct cycles of changes to the technology frontier and subsequent plateauing can be identified during which technology-led windows of opportunity may have occurred (Figure 18). Looking at global patent applications for wind turbine technologies, there is clear evidence for the technology transition reaching three peaks in 2002, 2012, and 2020.

Starting in the 1990s and with the emergence of onshore wind turbine technologies brought the first innovation cycle. This resulted in the deployment of small and medium-sized turbines used for onshore wind energy generation. The onshore wind technology first plateaued in the early 2000s before expanding again between 2006 and 2012. This second period also coincided with the emergence of offshore wind as a new high-tech technology domain.

From 2015 onwards, we can identify a third cycle of technological development that emerged in the wind sector. While the overall wind technologies as well as the onshore segment plateaued in 2020, the offshore segment is seemingly still evolving rapidly.

Figure 18: Global patent applications and standardised cyclical components

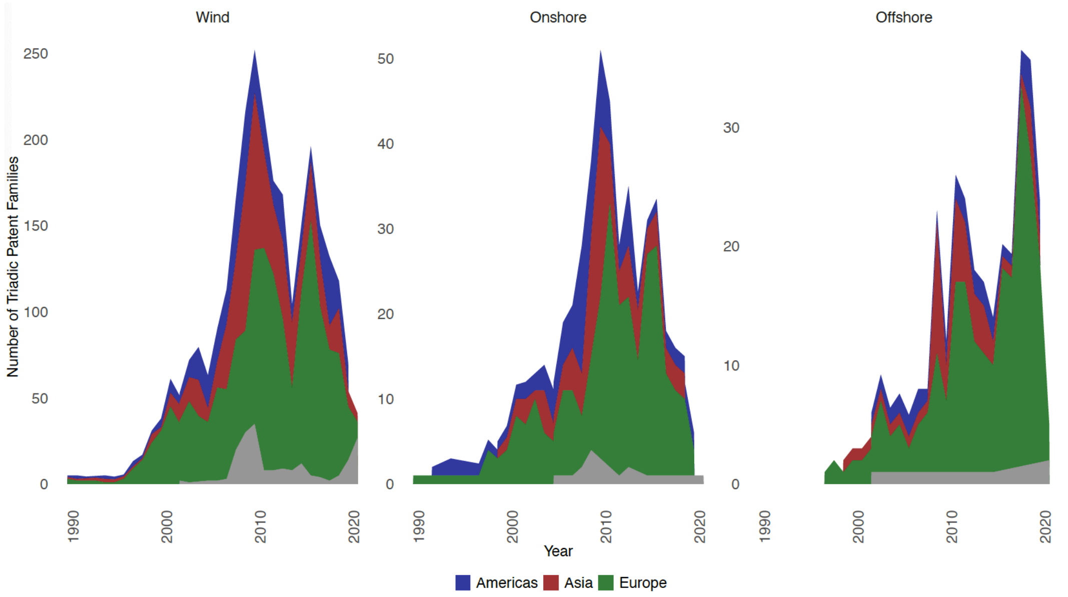


Source: Own elaborations based on PATSTAT global patents.
All Wind represents patents classified as ICP F03D. Onshore represents patents classified as CPC Y02E 10/728. Offshore represents patents classified as CPC Y02E 10/727. While both classifications relate to wind energy, CPC Y02E 10/727 and 10/728 are framed within the context of climate change mitigation and renewable energy technologies. In contrast, IPC F03D is more broadly focused on the engineering and mechanical aspects of wind motors or turbines. Z-scores are calculated based on 5-year moving averages of patent applications.

To confirm the trends in technological dynamism we can compare the cyclical components of patent applications of the wind turbine industry and segment level. The right side of Figure 18 examines the z-scores of patent applications within the wind energy sector. There are similar trends in z-scores across all categories, with periods of increase and decrease occurring at roughly similar times. This suggests that factors influencing innovation in wind energy affect both onshore and offshore technologies similarly. The presence of cyclical patterns is confirmed, with z-scores rising and plateauing over time. A significant uptick in z-scores starting around the year 2000 suggests a period of increased innovation. Furthermore, the onshore and offshore segments move largely in tandem, suggesting that drivers of patent activity have impacted both segments equally. However, the offshore segment appears to have a sharper increase in recent years, which may suggest a recent focus or advancements in offshore wind technology.

To understand whether technological transitions corresponded with a change in technological leadership, we analysed patent applications by the location of the applicant. A large number of wind patent applications in recent years have been at the Chinese Patent Office. Unfortunately, the Chinese Patent Office does not publish data on the location of the applicant, making any further analysis of this data difficult. To account for this lack of location, PATSTAT suggests relying on ‘international patents’ that are filed in more than one jurisdiction. Triadic patent families are counted as patents filed at the EPO, USTPO, and JPO, thus excluding single-nation filings. Triadic patents have the further advantage that they are often recognised as ‘high quality’ patents. One limitation of triadic patent families is their timeliness, due to the time lag between priority and grant date.

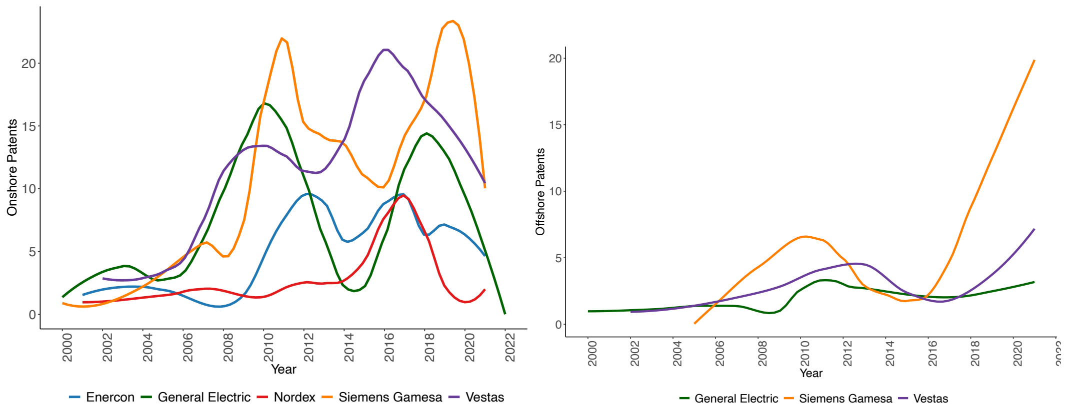
Figure 19: Triadic Patent Families by Segment and Location of the Priority Applicant



Source: Own elaborations based on PATSTAT data.
Triadic patent families were counted as PATSTAT DCOBD families filled in US, EU, and Japan, with information on company location taken from the priority application.

Figure 19 gives the triadic patent families by segment and location of the applicant. Overall, the technological cycles proxied by patent data show no obvious loss of leadership of European firms in the technological domain. The innovative activity of European wind turbine OEMs can further be seen from the individual patent filings to the EPO of each manufacturer (Figure 20). The trends confirm that each European OEM was participating in the technology transitions identified in Figure 18.

Figure 20: Onshore and offshore patent applications by the main Western OEMs and segment



Source: Own elaborations based on PATSTAT data. Lines were smoothed using LOESS.

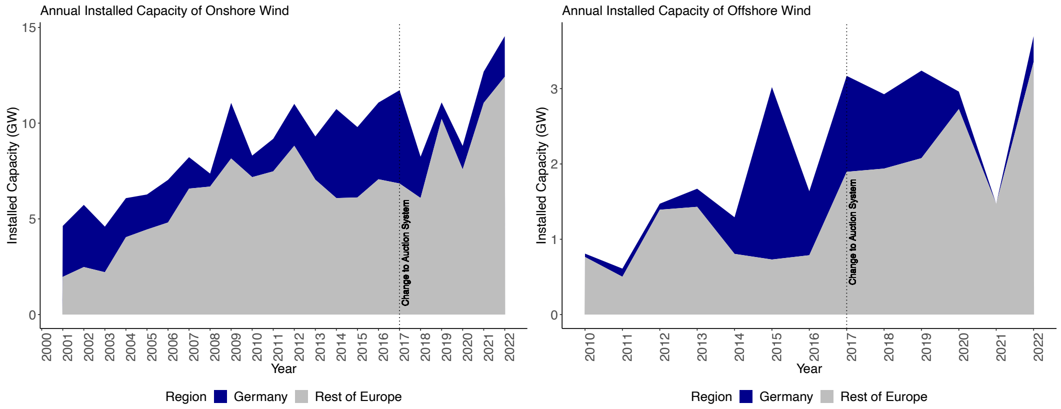
5.2. Changes in the structure and composition of demand for wind turbines

To disentangle further the drivers of industrial dynamics within the European wind turbine manufacturing industry, this section will analyse changes in the structure and composition of demand for wind turbines in Europe.

Figure 9 gives the amount of annual installed capacity in the European onshore and offshore wind energy sectors, with the share of German installations highlighted. In terms of onshore installations, Germany was responsible for a significant share of European capacity in the early 2000s' as well as during the period from 2010 until 2017 when renewable energy auctions were introduced in most EU Member States to determine the level of renewable energy remuneration. Since then, German demand dropped significantly and has not yet managed to reach similar levels.

In the offshore segment, demand has generally been a lot more volatile given the sector reached cost-competitiveness with other energy sources only recently. Nonetheless, while German offshore installations once accounted for more than 50 per cent of annual European installations, the share of German offshore projects has dropped to virtually zero in recent years. The longer lead time for offshore wind projects is important to understand the dynamics in the segment following the shift to the auction system. As it can often take four to five years for an offshore wind farm to be built following the contract award in the tender process, the projects awarded in the first offshore wind auctions are only being installed now with the respective project start dates anticipated to be in 2025 (Ørsted, 2023; RWE, 2022). Thus, the effects of the switch to the renewable energy auction system on the wind turbine installations came into effect much later in the offshore segment vis-à-vis the onshore segment.

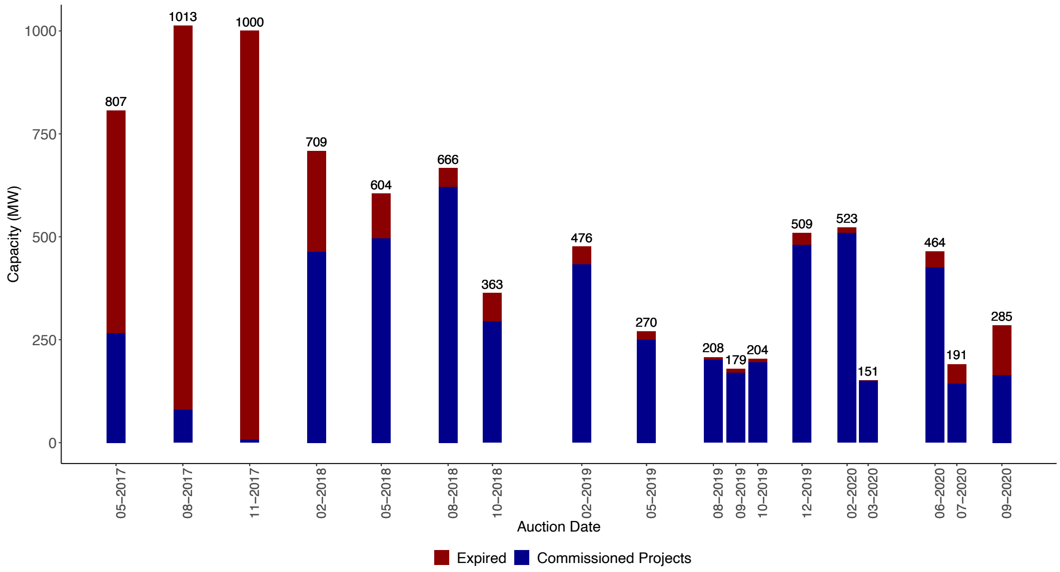
Figure 21: Demand dynamics in the European and German wind sector



Source: Own elaborations based on IRENASTAT

In the onshore segment, the decrease in the rate of German wind energy installations and thus a reduction of the overall quantity of demand following the shift to the auction system can be explained by two factors: 1) auction systems naturally put a cap on the expansion of renewable energy technologies as for each auction round only a predetermined amount is being tendered. 2) the first rounds of wind energy auctions in Germany in 2017 allowed bids without having secured the relevant permits. As a result, there were a high number of speculative projects that were never constructed despite being successful in the auction (Interview #17, Industry Association). As wind farms need to be constructed and operating within 30 months of winning an auction in order to qualify for the market premium, some of the awarded support expired. While this has since been changed in the auction design, it has negatively affected the realisation rate of the initial auction rounds where nearly all awarded support expired by 2022, as can be seen from Figure 22.

Figure 22: Realisation rate of awarded capacity of previous German onshore wind auctions



Source: Own elaborations based on FA Wind

However, as was argued previously, it is not just the overall quantity of demand that matters for industrial dynamics but also the structure and composition of the Demand Regime that lead to changes in industrial structures. Representatives from OEMs as well as industry experts described the switch from feed-in tariffs to renewable energy auctions in 2017 as a fundamental shift that completely changed the market, particularly in the onshore segment (Interview #4, Industry Expert; #11, OEM; and #13, OEM). To further understand these effects as a result of the switch to renewable energy auctions on wind turbine OEMs and industrial dynamics, the following section will present a case study of the specific changes to the Demand Regime for wind turbines in Germany.

5.3. Renewable energy remuneration in Germany

In 1990 Germany created the world's first renewable energy feed-in tariff to support small operators of renewable energy plants by guaranteeing them priority access to the national electricity grid and paying them a guaranteed feed-in tariff for the next 20 years. These renewable energy remuneration schemes are aimed at encouraging the deployment of renewable energy technologies, such as wind turbines, and thus directly influence the demand by project developers and operators for these technologies, as higher remuneration increases the profitability and attractiveness of investing in renewable energy projects.

Under the feed-in tariff system, the operators of the renewable energy installations receive a predefined, guaranteed tariff for each kilowatt-hour (kWh) of electricity they generate and feed into the grid. In Germany, the tariffs were determined by the government and offered long-term payment guarantees, usually over a 20-year period. The tariffs were designed to be high enough to incentivise investment in renewable technologies and decrease over time to reflect the falling costs of these technologies. Feed-in tariffs thus offer long-term contracts to renewable energy producers based on the cost of generation of each technology.

In 2012 Germany introduced a market-premium model as a significant change to the original feed-in tariffs. Rather than paying a fixed feed-in tariff which lies above the price of electricity to anyone supplying electricity to the grid, the market premium gives producers of renewable electricity to sell their electricity directly to any end-user. The market-premium regulates the difference between the average prices of renewable energy that are sold on the energy market and the price of energy according to the feed-in tariff at the time. For example, in late 2019 the price for wind energy according to the EEG was 6.2ct/kWh. If the average price for electricity on the energy exchange market is below this, the EEG surcharge will cover the difference. As the market premium is calculated as the difference between the EEG and the average price of electricity, producers who feed their electricity into the grid during peak demand hours when the price is higher can therefore make a bigger profit. The aim was to incentivise the market-oriented behaviour of owners of renewable power plants to feed electricity into the grid at times when demand was high.

Until 2016, the German government determined the value of the feed-in tariff and later the market-premium if electricity is sold directly on the spot market. Since 2017, renewable energy remuneration has been determined through a competitive approach based on renewable energy auctions. This switch was in line with the European Commission’s Guidelines on State Aid for Environmental Protection and Energy 2014-2020 (EEAG), which instructed Member States to determine the amount of remuneration through market based systems. Under the new system, project developers submit bids to build renewable energy installations of a certain size and at a certain price. The bids are selected on a least-cost basis, with the lowest bids receiving a market premium on top of the electricity market price. Investors can submit their bids during the auction rounds, which are announced by the Federal Grid Agency (Bundesnetzagentur - BNetzA). The lowest bids win the auction until a specified capacity under auction is met, although a ceiling price is specified by the BNetzA in advance.

The payment duration for the market premium retains its original span of 20 years, although the premium's amount now hinges on the awarded sum following a successful bid. The BNetzA operates on the principle of favouring the most economical bids in the auction. While the feed-in tariff saw continuous demand for OEMs, auctions are only held 4 times per year meaning demand has been less constant and more unpredictable (Interview #6, Industry Association). This is particularly relevant as it makes financial commitments and investments by wind turbine OEMs difficult in the face of this uncertainty.

5.3.1. Shifting Demand Regimes in the German onshore segment

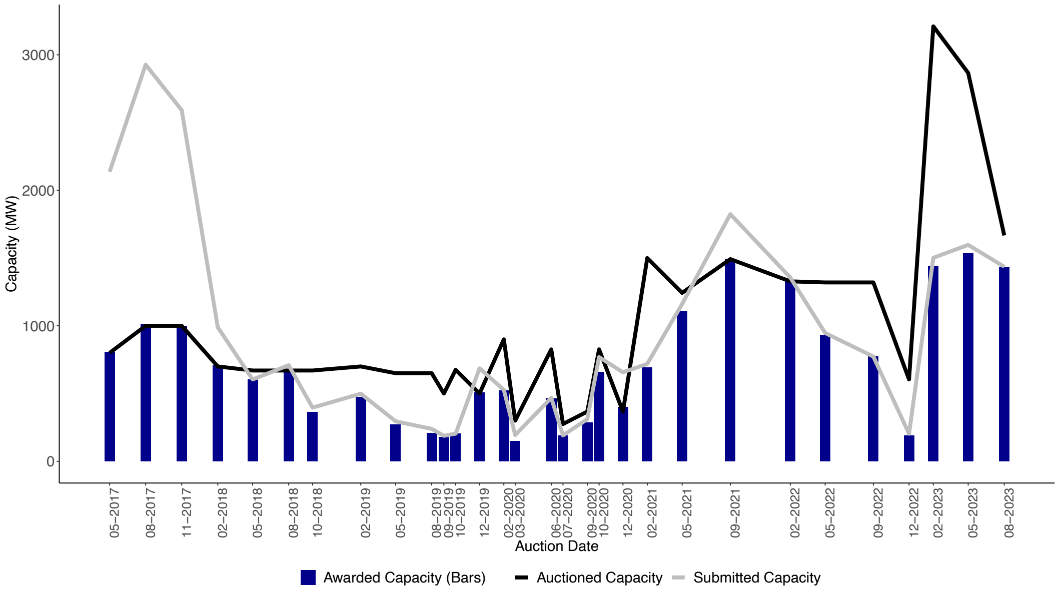
The initial auctions under the new system were oversubscribed with the total submitted capacity far exceeding the auctioned capacity (see Figure 23). In such a situation where there are more bids than possible projects, there is likely going to be a shift towards larger players that can afford to lose the costs associated with submitting a bid which can include legal fees and permit costs of €100.000 per projects (Interview #12, public research institute; Interview #13, OEM).

> "*The auction system favours larger players as it comes with additional cost preparations. This is particularly the case when the auction size is artificially*

reduced and there is less capacity auctioned than developers interested"

(Interview #9, Industry Association).

Figure 23: German auction capacity and submitted / awarded capacity for onshore wind.

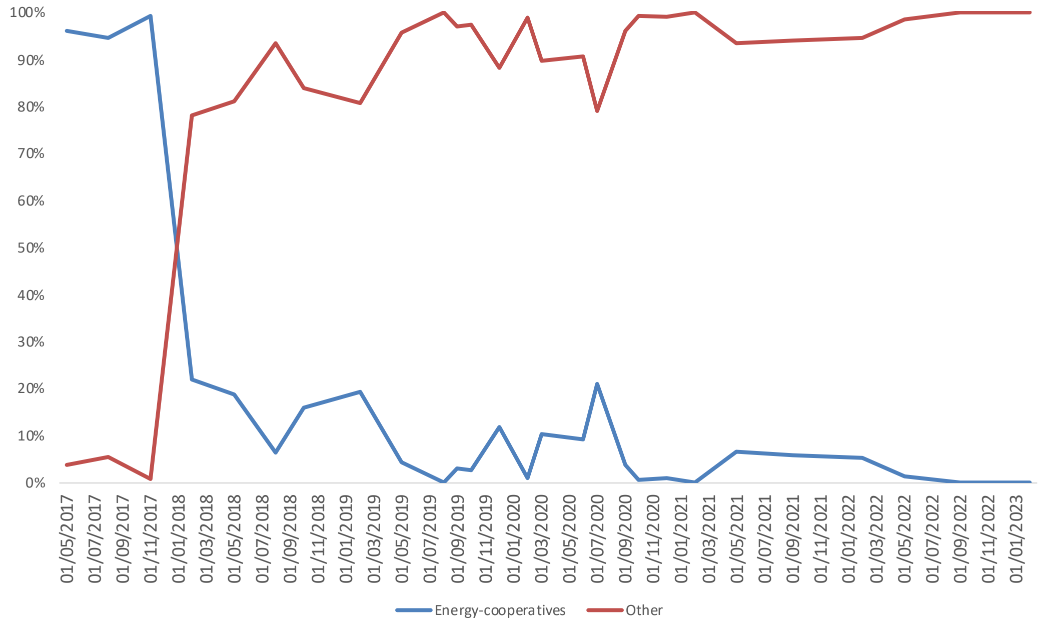


Source: Own elaborations based on Bundesnetzagentur data

Since 2018 there have been several onshore auction rounds that were undersubscribed, meaning there was more capacity auctioned than interest from wind farm developers. Based on the interviews conducted, there are different reasons for this. 1) regulatory changes and local opposition to wind projects have slowed the permitting process, making it harder for projects to qualify for auctions (Interview #5, Industry Association). 2) supply chain issues and the unstable supply of transformers and semiconductors have resulted in developers not participating in auctions as they cannot guarantee the delivery of the wind farm. This is particularly the case as following the low realisation rate of initial auctions, penalties have been introduced that apply if the respective wind farm is not operating within 30 months of winning the tender (interview #17, industry association). 3) interviewees suggested that large European energy companies and multinational utilities have also increasingly shifted to emerging markets (Interview #2, Public Research Institute).

With the advent of the auction-based system, the landscape of wind farm developers and owners has started to tilt towards larger corporations and utilities (Đukan and Kitzing, 2021; Grashof, 2019). While the available data for Germany does not allow for detailed analysis of the exact type onshore wind farm developers and operators, several interviewees from both within the industry and with external experts stated that the change to the auction system went hand in hand with a consolidation of developers and a change away from energy cooperatives towards larger developers (Interview #2, Public Research Institute; #5, Industry Association; #7, OEM; #9, Industry Association; #16, Industry Association; #17 Industry Association). The data on the German onshore auction results in Figure 24 confirms this trend with a clear shift away from energy cooperatives and towards 'other' developers submitting the winning bids to the onshore wind energy tenders since 2018. Unfortunately, the data published by the German Federal Grid Agency (BNetzA) does not further distinguish the different types of developers. However, it was confirmed during interviews that these bids were coming from increasingly larger developers (Interview #16, Industry Association).

Figure 24: Share of energy-cooperatives winning tenders in German onshore auctions.



Source: Own elaborations based on BNetzA

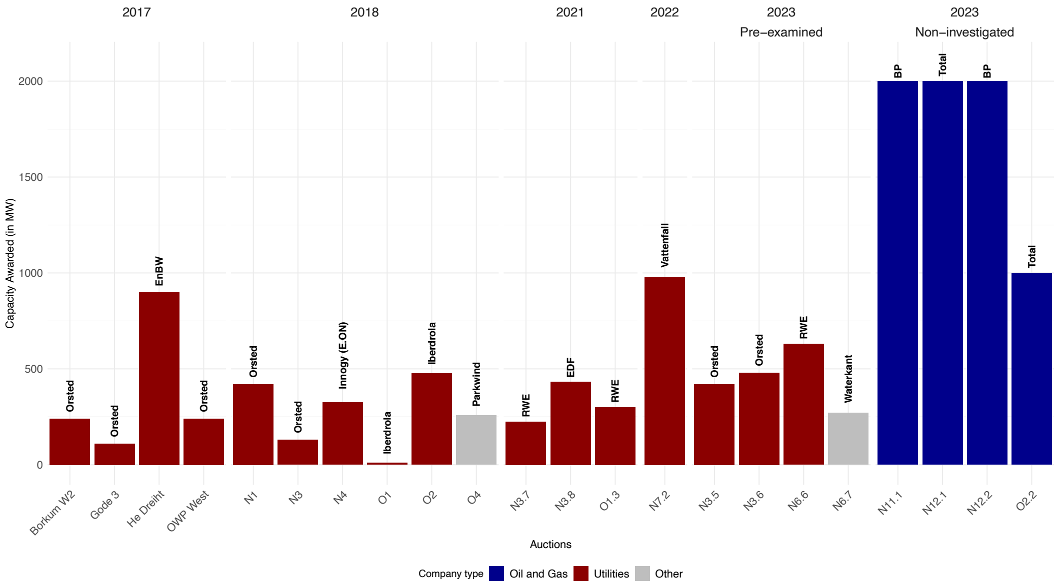
5.3.2. Shifting Demand Regimes in the German offshore segment

As noted above, due to the much longer lead time of offshore wind energy projects, the effects of the shift to the auction system on the segment became visible much later. The German offshore projects built until 2020 were all projects that were awarded prior to the introduction of the auction system. Since 2020, the number of new installations has dropped to virtually zero (as can be seen in Figure 21). The German offshore expansion was further dampened after there were no auctions held in 2019 and 2020, which has led to many in the industry referring to a "threat breakage" or standstill in the German offshore industry (Interview #17, Industry Association). This standstill was the result of the switch in the remuneration scheme, which was described by many offshore industry actors as insufficiently prepared. As a result, many investors and developers had to put on hold or reschedule already initiated projects (Weber, 2022). Only since 2021 has it been possible again to advance completely new projects. Between 2018 and 2020, developers built only those wind farms that still fell under the old system as part of a transitional agreement with the government. 2021 was the first year where auctions took place under the new system introduced in 2017. Recent auction rounds of 2021,2022, and 2023 saw the successful award of 956, 980, and 8800MW, respectively.

In terms of auction bids, the first competitive auction in 2017 was notably oversubscribed, with winning bids reaching zero-cent bids. Zero-bids are where the developer does not receive any additional remuneration from the government but instead relies entirely on merchant prices on the electricity wholesale market. An important caveat in these bids is the fact that developers do not have to pay for the grid connection, which can account for up to 40% of the project making it as expensive as the offshore wind turbine (Interview #2, Public Research Institute). As projects that won the tender in 2017 only have to be operating by the latest 2024, many of the developers rested their bids on the expectation that there either would be a rise in electricity wholesale prices or that the LCOE of offshore wind projects would go further down by the time the projects are operating. Zero-bids have been described as explicitly based on the anticipation that turbine classes would increase and thus be able to produce electricity at a cheaper level (Backwell, 2018, p. 113).

Although the offshore segment has always favoured much larger developers, there are also trends of developer consolidation observable. While earlier German offshore wind farms were partly developed by comparatively smaller actors such as WPD, Trianel or cooperatives of municipal utilities, the offshore wind auctions since 2017 have predominantly been awarded to big utility companies. This trend towards larger developers can be expected to continue given the recent tender awards to the traditional oil and gas conglomerates BP and Total.

Figure 25: German Offshore Auction Results:



Source: Own elaborations

5.4. Changes in wind turbine cycles as a result of shifts in the German Demand Regime for wind energy

The changes in the renewable energy remuneration scheme and related changes to the Demand Regime for wind turbines have also had further effects on the size of wind turbines preferred by developers participating in wind energy auctions. The price-based auction system has resulted in downward cost pressure that are largely placed on OEMs, which have responded by developing larger and more efficient turbines (BWE, 2018). Several industry experts interviewed mentioned price-based auction designs as a driver of increasingly bigger turbines. This was explained as, on average, larger turbines would always achieve lower LCOE:

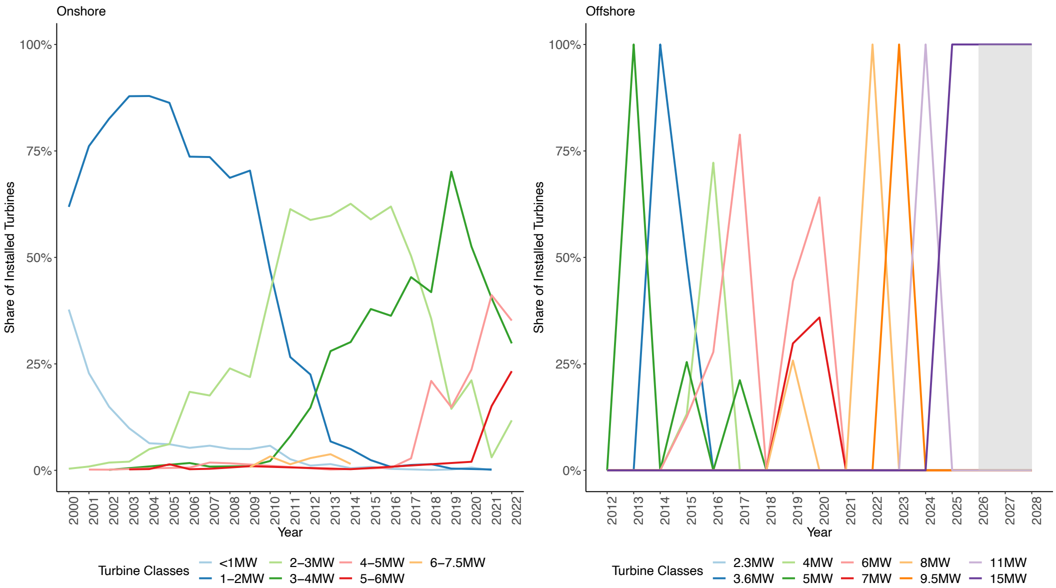
> *"The cost pressures of the auction system have increased the speed of the technological developments which in turn has led to quality issues" (Interview #12, Public Research Institute).*

> *"Price has been king. The auction model has started a race to bigger turbines where tenders are won on a cost basis with bigger turbines winning. On the one hand, this is of course a success, but OEMs are under such cost pressure they source inputs from the cheapest sources often at the expense of local supply chains and bring new products to the market without significant service feedback on previous models" (Interview #8, Industry Expert).*

Figure 26 gives a visible representation of the changing technology cycles in the German onshore and offshore wind turbine sectors, measured by capacity classes of installed turbines. The onshore segment shows clear patterns of cycles with new turbine classes emerging in the early 2000s, 2010s, 2017, and 2020 and each class becoming the dominant turbine design soon after. Two trends are noteworthy here: Firstly, these cycles have both become shorter in later years, i.e. new turbine classes are emerging faster than in previous cycles. Secondly, the rate of adoption has become faster, as can be seen from the steeper curves of later cycles. However, to some degree there remains a co-existence of turbine models in the onshore segment.

In the offshore segment, the cycles of technology classes are even shorter. Additionally, new offshore turbines clear the entire market to a much greater degree compared with the onshore segment with a bigger turbine class quickly accounting for almost all yearly installations. The period 2015 and 2020 (which covers projects awarded before the change to the auction system) saw a slightly slower rate of introduction of new turbines and greater co-existence of turbine classes. This has changed in recent years: For projects starting to operate in 2022 and onwards, the dominant turbine design changes almost on a yearly basis. Additionally, the new offshore wind turbine models seem to make previous models redundant at a much faster pace. Figure 26 clearly shows how the technology for onshore and offshore turbines measured as the turbine size keeps evolving with developers continuously demanding bigger turbines.

Figure 26: Technology cycles in German wind energy installations



Source: Own elaborations. Onshore turbine classes were calculated based on the capacity and the number of turbines per project of operating wind farms from the WindPower database. For the offshore segment, projects were manually researched with turbine models assigned based on project press releases and included wind farms that are not yet operating. Wind farms from 2026 onwards (grey area) have been awarded and announced but the final investment decision (FID) has not yet been taken.
Shares are calculated as the sum of installed capacity per turbine class as a share of total installed capacity.

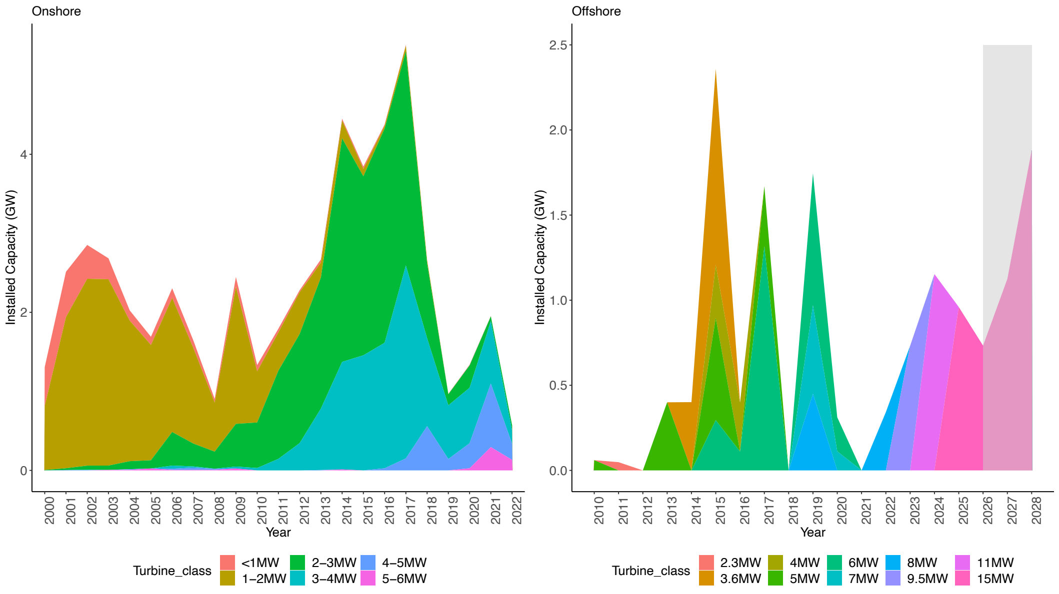
The continuous evolvement of the respective turbine size can pose a problem for manufacturers if this means each turbine class never reaches enough demand in order to become profitable before a new class emerges.

> *“OEMs are having to develop new turbine models every 2-3 years, with costs of 2 - 2.5 bn€ development costs for each new turbine model.”*
> *(Interview #5, Industry Association)*

Figure 27 plots the total demand by turbine class in Germany, measured as the total installed capacity. It shows that since 2017, not only are new turbine models emerging faster, but for onshore wind farms, newer turbine models have not reached the same level of demand as previous models when a new class emerges.

The lower levels of demand for individual turbine classes are particularly problematic for OEMs and their suppliers. Production facilities are often built solely for one particular turbine class. A lack of standardisation means that the production facilities of OEMs and suppliers often have to be retooled entirely for new and bigger turbine designs (Interview #4, Industry Expert). Interviewees from both OEMs and industry associations mentioned that this lack of standardisation was a main factor for existing production overcapacities by the European OEMs (Interview #6, Industry Association; #12, Public Research Institute; #13, OEM). Although there can be modularisation to some degree, constantly changing technology platforms and increasing turbine sizes require manufacturers to make significant changes to their production facilities, leaving older factories at times unused.

Figure 27: German wind turbine installations by turbine class



Source: Own elaborations. Onshore turbine classes were calculated based on the capacity and the number of turbines per project of operating wind farms from the WindPower database. For the offshore segment, projects were manually researched with turbine models assigned based on project press releases and include wind farms that are not yet operating. Wind farms from 2026 onwards (grey area) have been awarded and announced but the final investment decision (FID) has not yet been taken.
Shares are calculated as the sum of installed capacity per turbine class as a share of total installed capacity.

6. Discussion: The effect of changes to the demand for wind turbines and shorter technology cycles on wind turbine OEMs

Germany's shift away from the feed-in tariff to an auction-based model has been described by representatives from OEMs as well as industry experts as an overnight shift which completely changed the market (Interview #3, Industry Expert; #12, Public Research Institute; #13, OEM; and #14, OEM).

All European OEMs stated to have been affected by the change in demand for larger turbines following the auction system and linked this to their profitability during interviews. A particular challenge for OEMs was described as the rate at which new turbines are being developed and brought to the market:

> "*The latest turbine model usually clears the market, meaning that short innovation cycles lead to reduced profitability.*" (Interview #9, Industry Association)

> "*New products have been brought to the market at an eyewatering speed, often at the cost of sufficient service feedback from previous models*" (Interview #8, Industry Expert)

The quotes above from an industry expert and representative of an industry association highlight the problems that may arise from increasingly shorter technology cycles. The continuous evolvement of turbine platforms is particularly challenging for OEMs as long lead times between orders and delivery often exceed the current technology cycles (Interview #3, OEM).

At the same time, the changed structure and composition of demand are affecting wind turbine OEMs. Fewer and larger developers in both the onshore and offshore segments have increased market power over OEMs and can exercise greater cost pressure on their suppliers. All interviews with OEMs stated that the shift to the auction system clearly increased cost-pressures from them as tenders are being awarded on a cost-only basis (Interview #7, OEM; #10, Industry Association; #11, OEM; #13, OEM; #14, OEM).

Squeezed profit margins of developers mean that developers ask for either cheaper turbines or bigger turbines. Both outcomes are not great for OEMs

> *as it takes time to properly test products and set up the supply chain.”*
> *(Interview #7, OEM)*

As a result, OEMs are having to focus their R&D activities largely on short-term incremental innovation centred and developing larger turbines rather than evolving the technological frontier (Interview #12, Public Research Institute). Interviewees from industry associations as well as independent industry experts regarded the technological frontier, particularly related to offshore solutions, to still be located with European OEMs but warned there was no place for complacency. This is particularly the case in terms of cost where Chinese turbines perform much better:

> *The gap between Europe and Chinese technology is rapidly decreasing. More importantly, the average price per MW for a European turbine is around €950.000-1.000.000 while Chinese turbines are manufactured and supplied to Europe for around €450.000 (Interview #5, Industry Association).*

The importance of profitability for future industrial leadership and market shares can be seen from the response of OEMs. Vestas and Siemens-Gamesa, the respective leading OEMs in the onshore and offshore segment, have both stated in their 2022 annual reports that expansions needed for the successful delivery of the energy transition will depend on profitability (Siemens-Gamesa, 2022b; Vestas, 2022).

7. Conclusion

This chapter endeavoured to advance theoretically the understanding of the importance of Remand Regimes and how the structure and composition of demand can be a key driver for industrial dynamics. The ‘Demand Regime’ was proposed as an analytical concept that captures this structure and composition of demand and their changing dynamics over time.

The literature on Windows of Opportunity has shown the types of macro-level conditions including demand-led opportunities that enable changes in industrial market leadership. In the context of green technologies, the literature has shown the importance of institutional changes in opening opportunities for industrial transformations as well as their implications for subsequent demand and technology windows. However, so far, the concept had not been applied to incumbent firms. This chapter has tried to fill this gap by analysing the effects of a specific policy change in the context of Germany on demand and technological developments in the wind energy sector and their implications on turbine OEMs.

The switch to the auction system for the remuneration of wind energy in Germany changed not only the composition of developers and owners of wind farms but also altered the demand for wind turbines both in terms of quantity as well as different types of turbines. Particularly the wind turbine cycles in the offshore segment at which new and bigger wind turbines are introduced have become shorter since the introduction of the auction system. In the onshore segment, the overall quantity of demand for wind turbines in Germany dropped following the switch to the auction system. While new and bigger turbines are not necessarily a problem in itself (and in many respects are desirable from a cost point of view), they can cause problems for OEMs if there is a lack of sufficient demand to become profitable on each turbine platform.

While this chapter has only analysed the dynamics following institutional changes in the specific context of Germany, they can be seen as a critical case study for wider European developments. Not only does Germany account for a large part of European wind turbine installations, but the German policy changes were also in line with specific guidance from the European Commission in 2014 to adopt renewable auctions and can therefore be seen as a part of a wider institutional change in Europe at that point time.

Overall, there has been a notable consolidation and concentration of actors on the demand side as well as a shortening of technology cycles. This has led us to conclude that it has been primarily changes in the structure and composition of demand that were driving the changes in wind turbine technologies and related turbine platforms. The result of this has been increased financial pressure on wind turbine OEMs.

With regard to our stated hypotheses, we have confirmed that 1) there was a change in the structure and composition of demand for wind turbines following the change in the institutional support system for wind energy. 2) This shift in the Demand Regime has in turn affected the structure of supply, i.e. European wind turbine OEMs from a technological as well as an organisational point of view. 3) These dynamics followed time-specific as well as onshore and offshore segment-specific cycles.

Without adapting to the changes to the structure and composition of the demand following the policy change, there is a risk that European OEMs will miss out and will not be able to supply the turbines needed for future expansions in onshore and offshore wind. At the same time, industrial policy measures will have to be aligned to these changed conditions to avoid future industry consolidations and further loss of global market shares. This further warrants an analysis of how European wind turbine OEMs in the onshore and offshore segments have adapted to the changes analysed in this chapter.

Appendix 4.1

Overview of semi-structured interviews

#	Affiliation	Role	Industry	Date
1	Management Consultant	Principal for Industrial Goods Practice	Industry Expert	15.03.2023
2	DLR	Former Head of Energy Economics	Public Research Institute	24.03.2023
3	MHI Vestas	Former CEO	OEM	15.05.2023
4	Wood Mackenzie	Wind Energy Supply Chain Expert	Industry Expert	11.07.2023
5	WindEurope	Director of Industrial Affairs	Industry Association	02.08.2023
6	German Industry Association	Analyst Energy Policy	Industry Association	05.08.2023
7	Vestas	Public Policy Specialist	OEM	11.08.2023
8	Durham University	Ørsted Professor in Renewable Energy	Industry Expert	04.09.2023
9	WindEurope	Chief Policy Officer	Industry Association	05.09.2023
10	WAB	Managing Director	Industry Association	05.09.2023
11	SGRE	Head of Market Intelligence	OEM	11.09.2023

12	Fraunhofer IWES	Director	Public Research Institute	14.09.2023
13	Enercon	Policy Analyst	OEM	04.10.2023
14	Enercon	Policy Analyst	OEM	04.10.2023
15	Financial advisor for renewable energy	Director	Industry Expert	28.11.2023
16	FA Wind	Consultant Wind energy systems	Industry Association	29.11.2023
17	BWO	Managing Director	Industry Association	15.12.2023
18	Nordex	Member of the supervisory board	OEM	Written communication, December 2023

Appendix 4.2

Guiding questions for semi-structured interviews

General questions

- How would you describe the effects of the policy shift from feed-in tariffs to auctions in Germany and the EU in 2017?
- Do you / your firm tend to view the shift to the auction model more positively or negatively? What are the main reasons for this assessment?
- Has the transition to an auction-based system altered the market structure, particularly in terms of the developers, owners, and operators of wind farms? If so, how?

Technological questions

- How do you view the current technological developments in the wind sector, specifically with regard to the size of wind turbines?
- Do you consider Europe still at the forefront of technological innovation in wind turbine manufacturing?

Demand questions

- Do larger developers and operators of wind farms have greater leverage to negotiate lower prices, especially during periods of overcapacity? Or is cost pressure primarily driven by the price-based auction system?
- Are European OEMs currently operating at full capacity, or are they experiencing overcapacities? If overcapacities exist, what are the main causes, and are there differences between the onshore and offshore segments?

Organisational questions

- What are the main factors contributing to the decrease in profit margins for OEMs since 2017?

Chapter 5: Organisational Restructuring in Response to Shifts in the Demand Regime in the European Wind Turbine Manufacturing Industry

Abstract

The Windows of Opportunity literature has shown how global patterns in industrial production can change following shifts in institutions, technologies, or demand (Lee and Malerba, 2017). At the micro-level, changes in technology and demand can open new opportunities for value capture that require organisational reconfigurations both internal to the firm and with regard to their supply chain organisation. These organisational transitions follow similar cyclical patterns to those of technology transitions (Andreoni et al., 2016). This chapter analyses how European wind turbine OEMs have adapted to changes in Technology and Demand Regimes following the shift from feed-in tariffs to renewable auctions in the European Union since 2017. The analysis of this chapter shows how these OEMs have had to reorganise organisational structures in response to changes in the wind energy Technology and Demand Regimes. A key question this chapter tries to answer is the extent to which corporate strategies around cost reductions in response to the shift in the Demand Regime shaped the organisational restructuring of European wind turbine OEMs or to what extent a need for external finance drove the organisational restructuring. Overall, these dynamics pose European OEMs as an interesting case to analyse in order to understand how changes in technology platforms, demand composition, and institutional support frameworks can affect the producers of renewable energy technologies. Understanding how technological developments and changes in the composition of demand require and produce organisational reconfigurations within firms and with regard to their supply-chain organisation is a key aspect of this approach.

1. Introduction

Understanding how firms react and reorganise themselves in response to changes in institutions, demand, or technologies is crucial for the outcome of so-called ‘Green Windows of Opportunity’. As outlined in Chapter 4 of this PhD, the increased cost pressure from customers of wind turbines and increasingly shorter cycles of technological developments have had significant effects on the supply chains of wind turbines. This has made it increasingly difficult for OEMs (Original Equipment Manufacturers) to be profitable, and they had to react to this. Analysing these organisational responses can provide valuable lessons for state interventions and industrial policy, which can be aligned or misaligned with the changing needs of firms.

Evolutionary economics has convincingly argued that the enduring and distinct competitive edges among companies stem more from organisational variances, particularly in their capacity to innovate and leverage innovation, rather than mastery over specific technologies (Nelson, 1991). The dynamic capabilities literature has explored these differences between companies further and argued that it is a firm’s “*ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments*” that explains differences among firms (Teece et al., 1997, p. 524).

The dynamics in the European wind turbine manufacturing industry pose an interesting case to analyse how firms adapt to changes in technology platforms, demand composition, and institutional support frameworks. At the micro-level, technology and demand transitions can open new opportunities for value creation that require organisations to react and adapt (Andreoni et al., 2016). Often this requires organisational restructuring that can happen both internally to the firm as well as externally with regard to their supply chain organisation (Guerrieri and Pietrobelli, 2004). This organisational restructuring follows similar cyclical patterns to those of technology and demand transitions. For example, the wind turbine OEM Nordex shifted its production facilities to other countries as part of cost optimisation efforts, while the OEM Enercon adopted a different cheaper technology to respond to changed demand conditions. Additionally, these coevolving transitions and restructurings are neither isolated nor can they happen all at once (Lazonick, 2022). Thus, they are both collective as well as cumulative and can be affected by the need for corporate finance to support these transitions. As will be elaborated on further below in Section 4, organisational restructuring can include different strategies such as buyouts, divestitures, outsourcing, relocation, or downsizing. At the same time, expansionary strategies through mergers or acquisitions can also be part of organisational reconfigurations

This chapter will focus on organisational restructuring in response to changes in demand, which so far has been largely neglected in the academic literature. By building on the findings of Chapter 4 of the PhD, this chapter seeks to understand how European wind turbine OEMs have responded to changes in the Technology and Demand Regimes. This will be done by answering the following research question: *How have European wind turbine OEMs restructured their internal organisation as well as external supply chain structure following changes to the structure and composition of demand for wind turbines?*

The research question rests on several interlinked hypotheses. 1) European OEMs have moved production abroad or reduced their vertical integration following the switch to the auction system in the EU. 2) European OEMs had to give up strategic control in order to ensure external financial commitment for this organisational restructuring. 3) The misalignment of technological, demand and organisational transitions can explain the financial difficulties and loss of market leadership of some European OEMs 4) The extent and direction of these organisational responses differ between OEMs operating in the onshore segment and those operating in the offshore segment as well as depending on their ownership structure.

These hypotheses will be tested by analysing primary data from the annual reports of three of the main European OEMs, Siemens Gamesa, Nordex, and Enercon. These three OEMs pose an interesting juxtaposition in both their business segments and technologies as well as strategic choices and ownership structures. Particular focus will lie on the respective OEM's i) corporate strategy and finance, ii) changes to their manufacturing footprint, and iii) mergers, acquisitions, joint ventures or partnerships in the period before and after the change to the auction system in most European countries in 2017. 18 semi-structured interviews were conducted throughout 2023 as well as several informal conversations with industry experts, which were used to inform the research and to triangulate the findings from the annual reports (see Annex 5.1. for an overview of these interviews). A key question this chapter tries to answer is the extent to which corporate strategies around cost reductions in response to the shift in the Demand Regime shaped the organisational restructuring of European wind turbine OEMs or to what extent a need for external finance drove the organisational restructuring (cf. Lazonick and Prencipe, 2005). By doing so, the chapter tries to uncover the main drivers of organisational change in the wind turbine manufacturing industry and the degree to which changes on the demand side following the change to the auction system have influenced changes on the supply side. The goal of this chapter is not just to make sense of how the wind turbine manufacturing industry has evolved but also to contribute to a better understanding of the most effective ways to influence these industrial transformations. The proposed framework of Structural Cycles augmented with the focus on the role of corporate finance in organisational restructuring can help to understand how government policies have to be aligned with the evolving technological and organisational shifts within certain sectors.

The remainder of the chapter is structured as follows: Section 2 gives a brief overview of the emergence and development of the wind turbine manufacturing industry. Section 3 reviews the literature on the European and Chinese wind turbine manufacturing value chain. It also reviews the existing micro-founded theories of firm organisation and how this has been analysed in relation to interdependent processes of technological transitions within the concept of Structural Cycle analyses. Section 4 elaborates on how the analytical framework of Structural Cyles will be used in the context of the European wind turbine manufacturing industry and what data sources were used for the analysis. Section 5 covers the analysis, firstly comparing organisational restructuring within the onshore segment, and secondly comparing these organisational restructuring within OEMs operating in the onshore as well as offshore segments. Section 6 discusses the main results while section 7 concludes.

2. Background: Expansion and slowdown of the European wind turbine manufacturing industry and emerging contradictions between Europe and China.

Today's wind industry emerged mostly out of a small number of Danish firms selling mostly to farmers and energy cooperatives. Vestas, initially an agricultural machinery company, began experimenting with wind turbines in the 1970s. During the 1980s, the Danish wind industry took off after US federal and state regulatory policies and tax cuts created the so-called "California Wind Rush" and the Danish manufactured turbines emerged as the leader in quality and design (Backwell, 2018, pp. 11–14). As interest in wind power and Danish turbines grew worldwide, Vestas formed a joint venture with the Spanish company Gamesa, which up until then had been operating as an aerospace and engineering company in 1994. Although the joint venture lasted only a few years, it gave Gamesa the opportunity to enter the industry through licencing agreements of the 'Danish design' for wind turbines. In Germany, Enercon and Nordex emerged as wind turbine OEMs that became popular suppliers for Germany's small-scale developers and cooperatives that drove the early expansion of wind energy.

In the early 2000s, industrial giants General Electric (GE), Siemens, and Alstom entered the wind industry by acquiring smaller manufacturers: In 2002, GE bought energy company Enron which had filed for bankruptcy a few months before (Enron had previously entered the turbine manufacturing business by acquiring the wind turbine OEMs Zond in the US, and Tacke in Germany). Following GE's move into the wind sector, Siemens acquired the Danish manufacturer Bonus and started pushing for offshore wind turbine solutions. Alstom acquired the Spanish manufacturer Ecotècnia in 2007 and started developing their own offshore wind turbine. The entry of these industrial giants, which had existing close relationships with big utility companies as well as much bigger balance sheets, made life much harder for the pure players like Vestas, Gamesa, or Nordex (Backwell, 2018, p. 33).

Soon after, in 2010, China became the largest market in terms of cumulative installed capacity. In its early days, the Chinese expansion in the wind sector was mostly dependent on Western-produced turbines by Vestas, Gamesa, Suzlon and Nordex, which together held more than 70 per cent of the market share. However, this expansion was accompanied by a fast-growing base of domestic turbine suppliers. Often learning through licensing agreements with European OEMs and supported by favourable domestic support policies and state-owned financial institutions, Chinese manufacturers managed to benefit from large economies of scale and thus were able to supply turbines at a much lower cost.

While this expansion saw Chinese manufacturers such as Goldwind, Guodian, Sinovel, and Sewind enter the ranking of the global top 10 wind turbine OEMs by 2012 (BNEF, 2013), European manufacturers largely left the Chinese market. The decline can be attributed to a range of factors: Chinese OEMs became increasingly successful in their domestic market through competitive pricing, cutting-edge technology, the ability to offer customised solutions, efficient servicing, as well as strong relationships with local governments (Backwell, 2018, p. 52). The competitive landscape was particularly challenging due to excess capacity among Chinese firms, coupled with a market slowdown during 2011–12, which significantly decreased profit margins.

As a result, the Spanish manufacturer Acciona sold its stake in a joint venture with the Chinese Aerospace Science and Technology Cooperation in 2009, GE ended a joint venture with Harbin Electrical Machineries in 2012, and Nordex stopped their plans for a joint venture with Huadian in 2012. Vestas and Gamesa continued supplying turbines to the Chinese market, while Siemens started a joint venture with their long-term partner Shanghai Electric for the production of blades and nacelles. Nonetheless, their market shares remained relatively low compared to those of their Chinese competitors.

While the Asian markets expanded, wind energy expansion in the US and Europe slowed down. Particularly the rate of new onshore installations in Spain, Germany, and the UK declined from 2010 onwards, which led to overcapacities of many turbine OEMs. After a decade of constant expansion, worsening financial results and profit warnings led to a number of restructurings by wind turbine OEMs. For example, in 2012, Vestas announced to cut 2335 jobs and broke up their technology R&D department with parts moved into the growing Global Solutions and Services division and others combined into a smaller general manufacturing division (Backwell, 2018, p. 128). Similarly, Gamesa announced a major restructuring including cutting 1800 jobs (20% of the workforce) in late 2012 as a response to a Spanish wind turbine installation memorandum and a new regulatory environment. This period of crisis was followed by a strong recovery between 2014 and 2016 (partly due to the expansionary effects before the phasing out of many generous feed-in tariff subsidy regimes in 2017 as analysed in the previous chapter). With new record installations, manufacturers' balance sheets had recovered but with the previous slump industry consolidations and organisation restructuring both through mergers and acquisitions as well as changes to make vs. buy strategies had increased. "*Despite booming installations, competition in the global wind market [was] more intense than ever and Western turbine OEMs [were] getting ready for the future by stepping up M&A activity*" (Aris Karcanias, Senior Managing Director at FTI Consulting, quoted in Backwell, 2018, p. 146).

Vestas and Mitsubishi Heavy Industries (MHI) announced a joint venture in 2013 and created a new company MHI-Vestas Offshore Wind, to compete in the fast-growing offshore segment. One year later, Gamesa and AREVA also signed a new offshore joint venture Adven, to compete with MHI-Vestas' and Siemens' offshore turbines. In the onshore segment, GE bought the energy business from Alstom as well as LM Windpower, at the time the largest independent rotor blade manufacturer in 2014 and 2017, respectively. Through the acquisition of Alstom, GE expanded its onshore business as well as integrated the offshore turbine Haliade into its portfolio.

In 2016, Nordex announced a merger with Acciona Windpower, in which Nordex acquired Acciona Windpower from its parent company Acciona Group, while Acciona Group acquired a 29.9 per cent stake in Nordex, thereby making it the biggest shareholder. Lastly, following the increase in competitive pressure from the Nordex-Acciona and GE-Alstom mergers, Siemens decided to improve their position in the onshore segment by merging with Spanish manufacturer Gamesa and Siemens Gamesa subsequently buying 50% of Adven from Areva.

The period between 2013 and 2016 saw a major consolidation and restructuring of the wind turbine manufacturing industry, with the emergence of a number of bigger OEMs. However, as will be elaborated in greater detail below, there remains a variety of strategies between manufacturers as well as between the onshore and offshore segments. OEMs have continuously responded to changing dynamics in demand and related over-capacities, supply chain disruptions and changes to profit margins by restructuring their internal as well as external organisation.

As the wind turbine manufacturing industry consolidated and OEMs reorganised themselves to remain competitive, differences in wind turbine technologies affected these processes and shaped firms’ strategies. Although wind energy technology has matured significantly since its initial invention, significant technology differences remain. A main distinction between wind turbine designs is their use of a gearbox or direct-drive solutions (Li and Chen, 2009). The gearbox wind turbine incorporates a gearbox situated between the rotor and the generator, which amplifies the rotor's rotational speed before it reaches the generator. Since 1991, advancements in wind turbine technology have led to the creation of gearless direct-drive wind turbine solutions. Designed to bypass common issues like gearbox failure and reduce transmission losses, the rotor of direct-drive wind turbines is directly coupled with the generator. Direct drive turbines can further be divided into two categories: the permanent magnet direct drive and the electrically excited direct drive. Initially, electrically excited solutions used to be the dominant design for direct drive turbines as permanent magnets were expensive. Later, when prices dropped, permanent magnet solutions became the dominant technology for direct-drive wind turbines (Polinder et al., 2013).

The two most important distinctions between gearbox wind turbines and direct drive wind turbines lie in their cost of energy and reliability. While wind turbines using a gearbox solution are usually cheaper and thus achieve lower costs of energy, direct-drive designs have much higher reliability. Direct drive solutions have gained popularity, particularly for offshore wind turbines given their increased reliability and reduced need for maintenance and repairs. However, gearbox solutions continue to be popular, especially in onshore wind turbines and manufacturers are continuously developing the gearbox technology.

There remain different preferences by the main European OEMs with regard to the technology they use. Since 1984 Enercon has produced highly original direct-drive wind turbines with a synchronous generator that eliminates the need for permanent magnets. Having traditionally focused on gearbox designs for onshore solutions, Nordex presented a direct drive offshore wind turbine in 2011 but abandoned the project again soon after. Vestas has specialised in geared drivetrain solutions, citing lower rare earth intensity and cost benefits as the main reason (Vestas, n.d.). Siemens built its first direct-drive onshore turbine in 2009 and began testing the prototype for its 6MW direct-drive offshore turbine onshore in 2011. The company has specialised in direct drive solutions since but differences in turbine portfolio and different approaches to technology became a major issue in the merger between Siemens and Gamesa. Contrary to Siemens, Gamesa (in its offshore joint venture Adwen) used a mid-speed gearbox approach. As will be elaborated in the analysis below, Siemens Gamesa chose to keep both technologies with different solutions for the onshore and offshore segments. Overall, the different technologies of gearbox and direct drive solutions offer an interesting case to analyse implications for organisational integration and reconfiguration when OEMs choose to engage in technology transitions.

3. Literature Review

The following section will discuss three main groups of literature: 1) the literature on the emergence and development of wind energy and its supply chain will be summarised. This literature has largely followed the dynamics in the industry with the focus initially being on the emergence of the industry in Europe and the US, and more recent contributions largely focused on latecomer developments by Asian, and particularly Chinese firms. 2) Micro-founded theories of firm organisation within evolutionary economics will be introduced. This will be used to refocus the debate on the organisational restructuring of incumbent firms adapting to changed market conditions. 3) The concept and literature focusing on organisational restructuring as part of Structural Cycles will be presented. 4) This element of Structural Cycles will be augmented with an additional aspect centred around the role of different sources of corporate finance in organisational restructuring finance.

3.1. Emergence and development of the global wind energy industry

Initial academic studies on the wind sector focused primarily on the emergence of wind energy technologies in Denmark and Germany. Balat (2011) shows how European countries used different policy measures to support the emergence of a domestic wind energy manufacturing industry and fostered domestic supply chains. Ek and Söderholm (2010) analyse the role of technological learning through public R&D policies in the early beginnings of the European wind industry between 1986 and 2002. With regard to the offshore segment, Dedecca et al. (2016) analyse different market strategies among different actors within the emerging European wind energy supply chain and along development and diffusion patterns. Lema et al. (2014) show how innovation paths in the wind energy sector have differed between Germany and Denmark as a result of differences in government policies, demand and production conditions, as well as the political economy between the two countries.

As wind energy technologies matured and the industry internationalised, the academic literature also increasingly focused on the globalisation of production and in particular global value chains in the wind energy industry. Lema et al. (2011) analyses the key actors of the wind power industry and differences in the manufacturing supply chain between Europe and China. They find that while there is considerable competition among lead OEMs, opportunities for collaboration along the value chain are increasing. Haakonsson and Kirkegaard (2016) analyse strategies for internationalisation among core, semi-core, and noncore component manufacturers in the European and Chinese wind turbine industry. Their analysis reveals that while European lead firms prefer to integrate components and protect their technologies by maintaining robust relationships with their primary suppliers, Chinese OEMs are more inclined towards modularising component technologies and engaging with highly specialised suppliers via modular connections, thereby adopting a more open and flexible strategy.

Nahm (2017) finds how industrial legacies are shaping learning and specialisation in distinct innovation capabilities of wind energy supply chain in Germany, the US, and China. At the same time, he argues that by specialising in their respective niche parts of the supply chain, firms in Germany, the US, and China were able to collaborate together to a greater extent (Nahm, 2021).

Following the impressive success story that saw China "*rising from nowhere in the mid-2000s to world market leadership by 2009*" (Tan and Mathews, 2015), the academic literature has focused predominantly on Chinese upgrading and the role of Chinese companies in the global wind energy supply chain. On the one hand, the literature has focused on Chinese government policies, particularly the role of the feed-in tariff, in establishing a domestic industry and upgrading the Chinese wind energy supply chain. Li et al. (2023) analyse how the wind energy industry emerged in China and how the Chinese government put great emphasis on the establishment of a domestic wind industry supply chain through specific policy measures. Particularly, China's 2005 Renewable Energy Law is often credited with the country emerging as a global leader in the wind energy industry (Quitzow et al., 2017; Wang et al., 2012).

On the other hand, a number of studies have focused on Chinese firms upgrading through integration into global value chains. Lema and Lema (2016) as well as Lewis (2012) demonstrate how acquisitions, joint ventures, and R&D partnerships played an important role in enabling Chinese firms to catch up with European incumbents. Haakonsson and Skepinov (2018) link the national innovation systems literature with firm capabilities and analyse how technology transmission and re-localisation of the production of components occurred across national innovation systems from Europe to China. Dai et al. (2020) demonstrate the ways in which Chinese companies accomplished technological advancement as the wind energy industry moved towards new technologies focused on digital and hybrid solutions. While the significant growth of wind power in China is often credited to substantial feed-in tariffs and other policies aimed at market creation, Dai et al. argue that it was primarily technological opportunities enabled by institutional backing, rather than the creation of domestic markets, that facilitated Chinese companies in catching up technologically with European Original Equipment Manufacturers (OEMs).

As a result of the rise of Chinese OEMs and component manufacturers, knowledge-intensive business service providers of the wind energy industry emerged in Europe and specialised in the designing and testing of wind turbines as well as control system software, as has been documented by Haakonsson et al. (2020). This allowed Chinese OEMs to benefit from European technology developments and innovate based on of accecing this technology, ultimately enabling them to catch up with Western OEMs. Nonetheless, a strong European wind turbine manufacturing industry and supply chain continues to exist despite the rise of Chinese competitors. Particularly outside of China, European wind turbine OEMs have remained in a strong position and managed to enter new markets either through the acquisition of local developers or through the expansion of their own production facilities through local subsidiaries (Lacal-Arántegui, 2019).

The academic literature, however, is surprisingly sparse on European wind turbine OEMs adapting to changed market conditions particularly in their domestic industries rather than in response to Chinese competition. To understand how European wind turbine OEMs have adapted and changed their strategies as the industry matured and changed, this chapter will build on evolutionary economics and the theory of the firm and adopt an enhanced Structural Cycle approach.

3.2. Micro-founded theories of firm organisation

Evolutionary economics theories acknowledge a diversity in the behaviours of firms within similar industries, driven by profit-seeking motives rather than strict rational profit maximisation. Schumpeter (1934) highlights that firms must innovate to stay competitive and survive, leading them to seek innovations to boost profitability. This profit-seeking nature and competitive environment drive firms to develop and change routines over time, learning in the process. This evolution can result in both similarities and differences among firms in the same industry (Helfat, 2018). Similarities arise from imitation, while differences stem from unique learning processes influenced by each firm's context, competencies, and assets.

Building on Penrose's (1959) definition of a firm as a collection of productive resources managed by administrative decisions, the resource-based view explains value creation through learning processes. This view focuses on how firms accumulate and reconfigure resources in response to new opportunities, creating structural learning and transformation in production structures (Andreoni, 2014). The resource-based view aids in understanding internal organisational structures and firm restructurings through capacity expansion, mergers, acquisitions, or joint ventures. It also highlights learning dynamics external to the firm, shaping industry organisation and supply chain structures (Guerrieri and Pietrobelli, 2004; Richardson, 1972).

Writing on the economics of diversification, Penrose (1959) defines diversification as the expansion of a firm's activities into new product lines, markets, or industries that are distinct from its existing core business.

Opportunities to produce new products or serve new markets can arise from both changes to the productive services and technologies available to the firm as well as changes in external supply and demand conditions. In addition to technological change, a firm's justification for diversification and related organisational restructuring often lies in temporary fluctuations or permanent adverse changes in demand. Under-utilisation of resources and fluctuations in earnings often cause firms to adapt in order to permit a fuller utilisation of production capacities and stabilisation of profits. A specific form of diversification is the case of either backward or forward vertical integration, where a firm starts to produce products previously bought from suppliers or starts producing new products closer to the final consumer.

Firms can be assumed to be using their resources in those segments where they assume the highest profitability while accounting for risk and uncertainties. "*A firm is essentially a pool of resources the utilization of which is organised in an administrative framework*. [And,] *in a sense, the final products being produced by a firm at any given time merely represent one of several ways in which firms could be using its resources, an incident in the development of its basic potentialities*" (Penrose, 1959, pp. 149–150). Thus, firms change their level of diversification and vertical integration over time and adapt to changing conditions by restructuring their internal and external organisation.

3.3. Organisational Transitions as part of Structural Cycles

Andreoni et al. (2016) have used the concept of Structural Cycles to analyse the interdependent processes of technology transitions and subsequent organisational transitions in the packaging industry. The concept links structural economic theories with micro-founded theories of the firm and industrial organisation by the resource-capability literature. Integrating these approaches helped the authors to understand how technological change and new production opportunities triggered learning processes, which led to the restructuring of organisational configurations in the Emilian Packaging Valley in Italy.

Building on Andreoni et al. (2016) Structural Cycles can be described as "*transformational phases of both technological transition and changes to the composition of demand that lead to internal and external organisational restructuring of firms and as they shift towards higher-value product segments*". For example, the integration of automation and new ICT technologies with existing production systems has opened new opportunities in higher-value product segments and subsequent firm reconfigurations.

Their findings highlight two main dynamics: 1) The integration of electronics, information, and communication technologies with traditional mechanical technologies allowed firms in the packaging industry to move towards higher-value product segments, such as the pharmaceutical packaging segment. 2) This technology transition and the new opportunities it created led to organisational changes within firms such as the packaging OEM IMA. These changes included a process of 'verticalisation' of critical production tasks and the formation of strategic partnerships with local producers and public institutions (Ibid).

The theoretical framework thus lends Itself well to the analysis of organisational responses to technological and demand transitions. The idea of Structural Cycles is not just an analytical method for understanding transformation processes through technological revolutions, but can also help with the right choice of policies for the government to intervene and support these processes (Andreoni et al., 2016). By liaising closely with the private sector, governments' industrial policies can play a key role in enabling firms to capture value-capture opportunities and retain their competitive advantage. At the same time, the misalignment of industrial policies could lead to the loss of industrial leadership. Understanding how governments try to align their policies with the evolving needs of private sector organisations and manage the arising conflicts is key to understanding the success or failure of policies aimed at the energy transition (Andreoni et al., 2016; Andreoni and Chang, 2019). Such alignment of government policies requires governments to take on entrepreneurial characteristics during processes of technological transitions and subsequent organisational restructuring.

3.4. The role of corporate finance in organisational reconfiguration

The literature on firm capacity as an evolutionary process as discussed in Section 3.2 emphasises "learning-by-doing" through routine integration and strategic processes. The Theory of Innovative Enterprise integrates business history and economic theory, focusing on how firms invest in and organise around new technologies and their impact on economic outcomes (Lazonick, 2015). This approach underscores firms' role as primary agents of economic change, highlighting strategic decisions to develop and utilise new technologies for sustained growth and competitive advantage. As such, organisational processes are at the core of dynamic capabilities. However, at the same time, corporate strategy and external finance play vital roles in how a company integrates, develops, and reconfigures skills to meet the challenges of changing environments (Lazonick and Prencipe, 2005).

The decision on which competencies to integrate, build, and reconfigure is made by the organisation's leadership or strategic decision-makers. Funding to support these innovative strategies and organisational reconfiguration can be mobilised through various financial mechanisms, which might include internal resources, external investments, or a combination of both. While managing internal revenues strategically is essential, it frequently needs to be complemented by external financial sources such as stock issues, bond issues, or bank loans. The key challenge lies in how those who hold strategic control can access and secure external funding dedicated to supporting the ongoing innovation process.

Lazonick and Prencipe (2005) have analysed how the engine manufacturer Rolls-Royce adapted their strategic control and financial commitment at different stages. Key questions of the analysis include who determines the types of competencies to be developed and reconfigured, and how financial resources are allocated to support these innovative approaches. Hence, strategic control and financial commitment in the allocation of resources are seen as the main determinants of the success of innovative enterprises (Ibid).

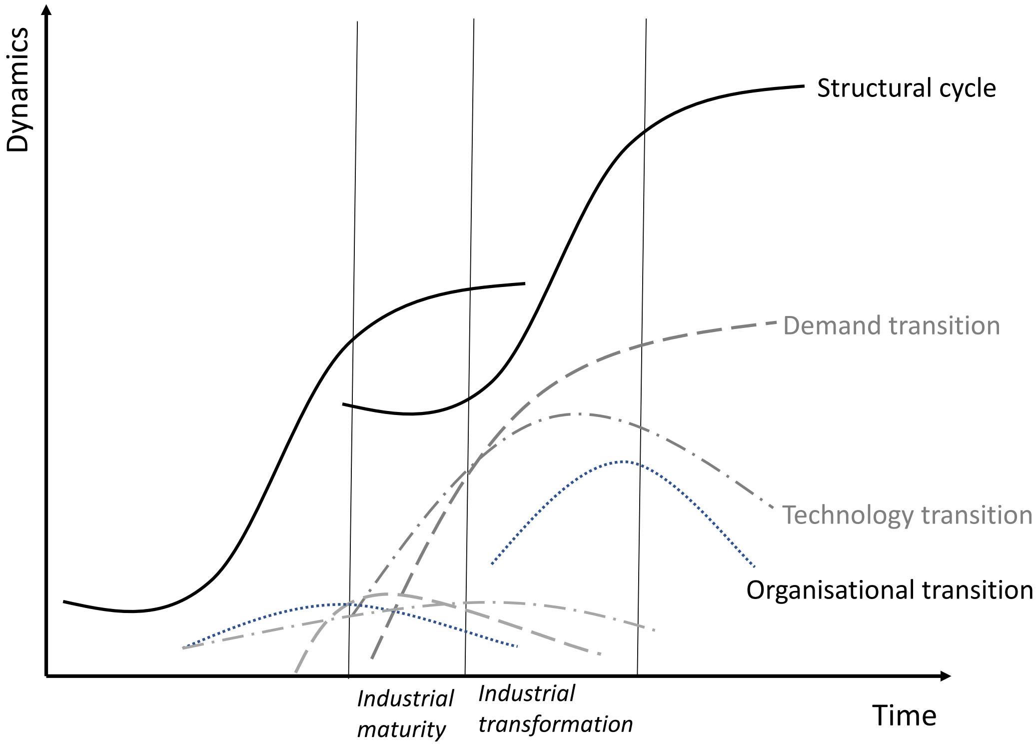
4. Analytical Framework and Data Sources

Although the Structural Cycle approach by Andreoni et al. (2016) does not explicitly consider a separate demand dimension, the approach acknowledges that industrial transformation also involves changes in the quality and composition of demand. While of course interlinked with technological developments, these changes in the Demand Regime can develop at a different rate to the rate of technological change and differ across locations. Understanding how technologies for wind energy as well as the demand for wind turbines have evolved in a 'glo-cal' (both global and local) nexus and how firms have responded to these changes can help us understand how individual companies, as well as entire regions, can succeed or fail at capturing Windows of Opportunity.

Since the switch from feed-in tariffs to renewable energy auctions in 2017 in the EU, the European wind energy sector not only underwent technological transitions but crucially also a demand transition. The Demand Regime in the wind sector, which consists of the composition of developers and operators of wind farms as well as the overall quantity of demand, changed fundamentally following the switch to renewable auctions. This led to larger developers and utilities becoming the dominant demand class with increased cost pressures leading to shorter turbine cycles.

The below figure outlines the organisational restructuring co-evolving with technology and demand transitions as part of the Structural Cycle. The main analytical challenge is to assess how these technological, demand, and organisational changes occur along "*time-specific patterns and in specific organisational settings*" (Andreoni et al., 2016, p. 887). This includes understanding how technological change and changing resource-capability dynamics can lead to new value product segments within the same industry as well as organisational restructuring in specific settings of a local production system.

Figure 28: Analytical Framework of Structural Cycles



Source: Own, adapted from Andreoni et al. (2016)

Organisational restructuring can occur both internally as well as externally to the firm and manifest itself in different ways: i) buyouts, ii) divestitures, iii) outsourcing, iv) relocations, v) downsizing, or vi) bankruptcy (Lazonick, 2006). 1) A buyout is when a company's management buys enough shares to separate their unit from the larger corporation, turning it into an independent entity. 2) Divestiture involves a corporation selling off a part of its business. 3) Outsourcing refers to a situation where a company contracts with another entity to perform tasks or services that it previously handled in-house, thus reducing its vertical integration. 4) Relocation means moving a business activity from one location to another, significantly changing the workforce in the process. 5) Downsizing is the reduction of a company's workforce to lower costs without specifically exiting a market, ceasing a particular activity, or leaving a geographic location. 6) bankruptcy is declared when a company cannot meet its financial obligations to creditors, which can follow any of the previously mentioned restructuring strategies. However, organisational reconfigurations can also follow expansionary strategies. A particular type of such expansionary organisational reconfiguration is through acquisitions or mergers. Acquiring another firm can enable both access to new technological capabilities as well as access to new markets. Additionally, it can change the position of existing producers and thus reduce competition. While this can give the firm a competitive edge vis-à-vis its competitors it does not come without risks given the associated costs with these restructurings.

At the same time, different firms may choose different strategies for organisational restructuring. The analytical framework will integrate this analysis of strategic control and financial commitment discussed in Section 3.4 as drivers of organisational restructuring into the framework of Structural Cycles. Applying this to the wind turbine manufacturing industry can help us to further analyse the reasoning behind the different forms of organisational restructuring.

A firm’s ability to react to the uncertain, collective, and cumulative dynamics of technology and demand transitions depends on i) their strategic control, ii) organisational integration, and iii) financial commitment (Lazonick, 2022). 1) strategic control is crucial for innovation to occur amidst the uncertainties of technological development and changes in demand. This involves corporate executives who manage resource allocation possessing the capabilities to invest strategically in innovation. 2) Organisational integration focuses on unifying individuals within a complex organisational structure to participate in and contribute towards the innovation process. Organisational integration becomes particularly important after organisational restructurings. Particularly if the strategy is to decrease vertical integration or downsize, this can reduce a company’s capacity to integrate and thus negatively affect innovation. 3) Financial commitment is about securing the long-term investment and ‘patient capital’ that supports ongoing learning and innovation within the company.

We primarily analyse the organisational reconfiguration of three European wind turbine OEMs in response to the shifted Demand Regime in the wind energy sector, as analysed in Chapter 4 of this PhD. The main analysis is based on the annual reports of these OEMs. OEMs were chosen as the level of analysis as they were described by interviewees as often dictating the dynamics in the industry with wider implications for the entire supply chain. In order to understand how their strategies as well as internal and external organisational structure have changed we analysed their annual reports and press releases or other official communications between 2010 and 2023 (2017 onwards in the case of Siemens Gamesa). Additionally, we analysed key financial variables for each OEM to find stylised facts on organisational restructurings. Data for this was taken from the ORBIS database as well as the respective OEM's financial reports. Furthermore, we triangulated the analysis with data from 18 semi-structured interviews with representatives from the main European OEMs and industry associations conducted throughout 2023. The research also benefitted greatly from several informal conversations at the annual WindEurope conference in Copenhagen in April 2023.

5. Analysis

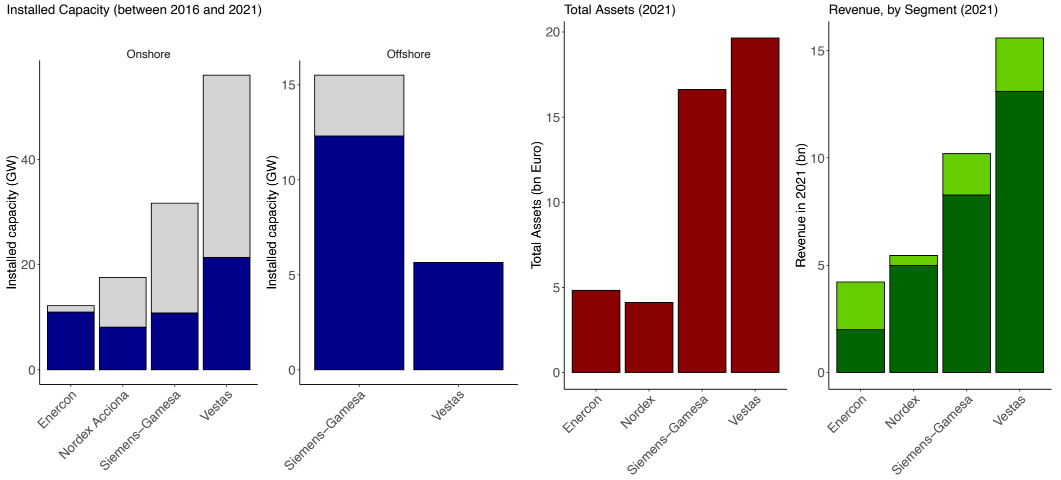
5.1. Industrial dynamics in the European wind turbine manufacturing industry and emerging differences between the main European OEMs

The four largest European wind turbine OEMs by total installed capacity are Vestas, Siemens Gamesa, Enercon, and Nordex Acciona. In 2022, Vestas installed 12.4GW, SiemensGamesa 6.4GW, Nordex 4.7GW, and Enercon 1.39GW wind turbines onshore (BloombergNEF, 2023). In the offshore segment, Vestas replaced Siemens Gamesa as the market leader with 1.9GW and 1.4GW installed capacity respectively. An initial important distinction between the main four European wind turbine OEMs is their ownership structure. Nordex Acciona, Vestas, and Siemens Gamesa are all publicly traded, while Enercon is privately owned by the Aloys Wobben Foundation. The main shareholder of Nordex Acciona with 47 per cent of the shares is Acciona, which in turn is majority owned by the Entrecanales family. Vestas is publicly traded with the major shareholder being BlackRock, which owned more than 5 per cent of the share capital at the start of 2024. Since 2023, Siemens Gamesa has had Siemens Energy AG as its sole shareholder.

To get a further understanding of the heterogeneity across the main European OEMs, it is worth starting with a comparison of their size as well as business focus. Figure 29 gives an overview of their geographical focus as well as size in terms of total assets and the respective business segment. The blue bars on the left side show the distribution between onshore and offshore installed capacity between 2016 and 2021, as well as the share of capacity installed in Europe versus the rest of the world (RoW). While Enercon and Nordex focus entirely on the onshore segment and traditionally almost exclusively on the European market (although this has changed in recent years as will be elaborated on below), Siemens Gamesa and Vestas also engage in the offshore business and have a much more global focus in the onshore segment. Enercon has gone the furthest in their focus on high-quality products and unparalleled service models. While this strategy was highly successful in Germany under the feed-in tariff system, it also has left the company exposed to the German sector to a much greater degree than its competitors.

Total assets (shown in red bars) give an overview of the general size of the four companies. The revenue by segment in the green bars (revenue derived from turbine sales vs revenue derived from service segment) shows the degree to which companies have shifted away from pure turbine OEMs towards integrated service providers. All four main European OEMs are increasingly generating large shares of their revenue from the subsequent (post-installation) operation and maintenance of wind turbines. Through the provision of downstream services through full-service agreements which cover the operation, maintenance and repairs of wind turbines, European firms have carved out new business strategies which make up between one-third (Nordex Acciona, 2022; Siemens-Gamesa, 2022) and half (Enercon, 2022) of their overall revenue by now.

Figure 29: OEM Overview

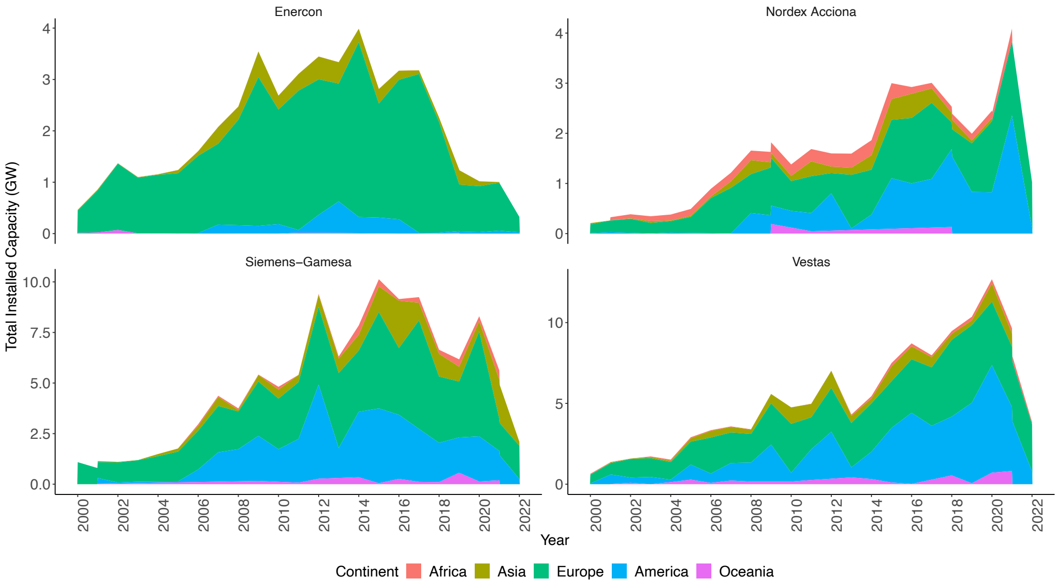


Source: Own elaboration based on Orbis data and OEMs' financial reports

Furthermore, the four main European OEMs have followed very different expansion and M&A strategies. While Vestas abandoned its joint venture MHI Vestas in the offshore segment with Mitsubishi Heavy Industries after a few years, Siemens Gamesa's and Nordex Acciona's mergers had very different motivations. The merger between Nordex and Acciona was largely market-driven whereas Siemens' merger with Gamesa was based on the idea to achieve a greater combined size. Lastly, Enercon's recent acquisition of the Dutch company Lagerwey can largely be described as technologically driven.

Enercon and Nordex have traditionally been much more focused on the European market, particularly their domestic German market. This has slightly changed in recent years for Nordex who expanded into the American market from 2013 onwards (as can be seen in Figure 30). Despite an overall larger global presence, Siemens Gamesa and Vestas are also very reliant on their domestic European market and have virtually no presence in the Asian market. This exposure to the European market underlines the importance of understanding the shifts in the European Demand Regime for these OEMs.

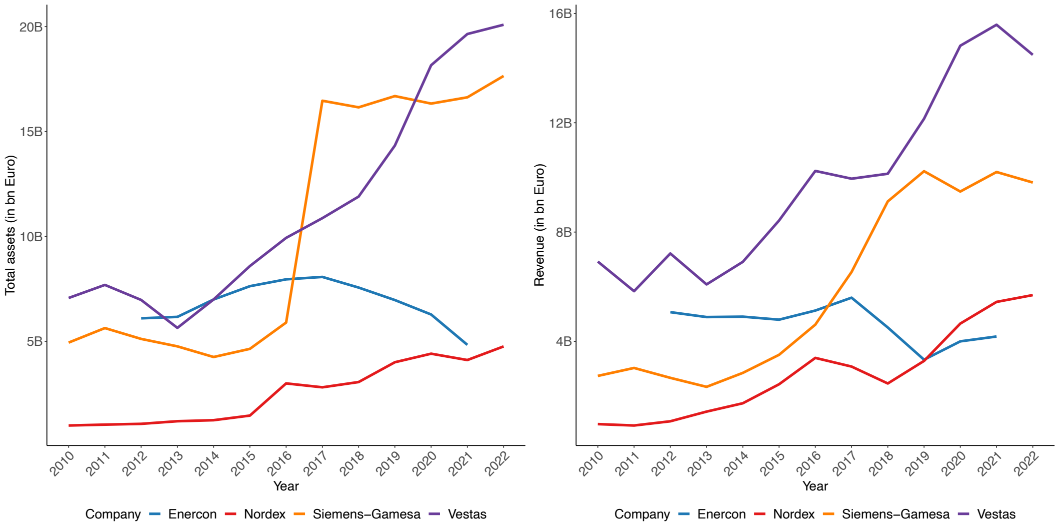
Figure 30: OEMs' Market Shares by Continent



Source: Own elaborations based on WindPower database.

Apart from Enercon, all other three OEMs seem to have invested over the last couple of years, indicated by an increase in total assets over time. The left side of Figure 31 shows that the value of total assets has decreased for Enercon since 2017. The data for Siemens Gamesa shows the total assets of Gamesa up until 2016. The large jump in total assets in 2017 can be explained by the merger with Siemens. Vestas has invested the most over the last 10 years with their total assets growing from around bn€ 5 to over bn€ 20. Nordex also increased its total assets by nearly five-fold from around bn€ 1 to nearly bn€ 5 in 2022. As one would expect, these increased investments have also led to increased revenues. The right side of Figure 31 gives the revenue of the respective OEM during the same period as the figure on the left. Despite falling total assets, Enercon has managed to increase its revenue in 2020 and 2021.

Figure 31: OEMs' Total Assets and Revenue, 2010-2022

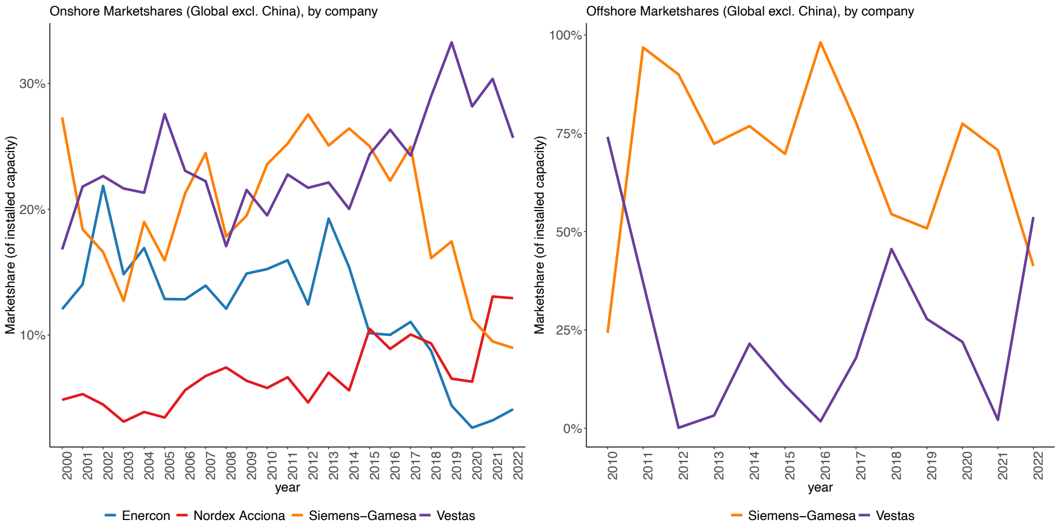


Source: Own elaboration based on Orbis data

Despite increases in total assets and revenue, all four OEMs have started to experience decreased profits and profit margins since 2016. This, indicates potentially failed organisational reintegration following their restructuring. At the same time, the different trajectories of the European wind turbine OEMs in Figure 31 also suggest that different strategies for organisational restructuring were followed.

The period of financial difficulty of European wind turbine OEMs has also coincided with changes to their market shares. Figure 32 presents the changes in market shares by installed capacity outside China. China is often seen as an entirely different market to the rest of the world given the difficulty for non-Chinese manufacturers to penetrate the market (Backwell, 2018, p. 185). Thus, it makes sense to analyse how market shares have developed globally excluding China. The figure shows how particularly Enercon and Siemens Gamesa have lost significant market shares in the onshore segment over time, while Vestas and Nordex managed to improve their position.

Figure 32: Global installed capacity market shares (excl. China) by Enercon, Nordex, Vestas, and Siemens Gamesa



Onshore Marketshares (Global excl. China), by company

Offshore Marketshares (Global excl. China), by company

Source: Own elaboration based on The WindPower database. Siemens Gamesa and Nordex Acciona show their respective combined market share prior to the mergers.

The first significant drop in Enercon's market share between 2013 and 2015, which saw the company's market share decrease from around 20 per cent to 10 per cent, can be explained by the growing expansion of wind energy around the world. Enercon has traditionally had a very strong focus on the domestic German market, thus an increased expansion of wind energy in other parts of the world was always going to affect the company's market shares. The more interesting drop in Enercon's market shares occurred between 2017 and 2020 following the change to the auction system. As will be elaborated in greater detail below the changes following the switch in the remuneration scheme in many European countries have had a significant effect on Enercon. Contrary to this, Nordex has managed much better to to reconfigure their internal and external organisation to the changes in the industry which are reflected in its increased market shares in recent years following the initial effect. Siemens Gamesa's loss in onshore market shares is also intriguing. Driven mostly by the sale of Gamesa turbines, the company achieved to establish itself as a leader in the onshore segment between 2010 and 2015 but experienced an equally drastic loss of market shares in the post-2017 period, after which it was taken over by Vestas. This development is in contrast to the dynamics in the offshore segment where Siemens Gamesa has managed to remain in a global leadership position.

5.2. Nordex: 'Leaving the niche' and reducing costs by going global

Despite having initial plans to enter the offshore market, German manufacturer Nordex has been focused entirely on the onshore segment, although with a changing geographical focus and with different strategies over time. The company has traditionally specialised in the production of wind turbine nacelles as well as rotor blades. In 2010 it assembled 25% of its products in its own facilities with the remaining 75% sourced from suppliers as a system integrator with relatively low degree of vertical integration. Nordex has so far bet on cheaper gearbox turbine designs, apart from a brief test project that developed a direct drive offshore turbine but was abandoned after a few years. The following case elaborates how Nordex, through a number of strategic organisational restructurings, has managed to respond to the changes in the wind turbine sector since 2017. The success of Nordex's strategy can be seen from the increases in their wind turbine market shares from 2020 onwards.

Europe has traditionally been the most important market although the company has at different times tried to enter various foreign markets. In 2008, Nordex USA was established and by 2010 the company had production facilities in Germany, the US, and China. However, following surplus capacity of turbines in the wind energy market and a slower-than-expected growth of demand, the company stated a firm focus on the European market in 2011. The same year, Nordex changed its strategy for Asia where it abandoned its own expansion and localisation strategy and set the new strategic goal of setting up a joint venture with a Chinese state-owned utility company to achieve full access to the Chinese market. In 2012, Nordex closed its own rotor blade factory in China and downsized their overall international footprint. Referring to the smaller structure and focus on being a mid-sized company, then CEO Jürgen Zeschky wrote in his letter to Nordex's shareholders in the 2012 annual report:

> *"I am confident that with the leaner structures which we have implemented, we will be able to make full use of the advantages which we have in the marketplace. This is because we have always been successful as a mid-sized company. Customers don't expect Nordex to be a big corporation but rather, a flexible engineering partner that is able to respond quickly and understands all aspects of their business."* (Jürgen Zeschky in, Nordex, 2013)

The new strategy meant that Nordex fully abandoned its offshore development programme and no longer considered utilities as their main customer but rather, focused on mid-sized and small developers, as well as a greater focus on the service segment with higher profitability rates. The systemic return to being a mid-sized company was continued in 2013 and 2014 with restructurings of their foreign activities in the US and China where production facilities were repurposed as service and maintenance depots. The main production facilities for nacelles and rotor blades have henceforth been in Rostock, Germany with a large proportion of components sourced from external suppliers. Seeking to eliminate occasional shortfalls in the supply chain for large and complex blades, Nordex expanded their Rostock facility into a "lead factory" and implemented a "build to print" strategy with three international partners (Nordex, 2015).

In May 2015 following the resignation of Jürgen Zeschky, Lars Bondo Krogsgaard became the new CEO and in October 2015 Nordex announced an agreement with Spanish infrastructure group Acciona on the acquisition of Corporación Acciona Windpower S.L. (AWP). In the first annual report following the announced merger with Acciona, Lars Bondo Krogsgaard announced a drastic change in the company's strategy:

> *"Our strategy of operating in the market as a focused niche player with the structures of a mid-sized company has been a success. Yet, the global wind power industry is evolving rapidly. New challenges are calling for new answers from us. […] Our niche strategy worked well in the past, but the future will favour scale players with a broader geographical focus than Nordex and Acciona Windpower would have on their own"* (Lars Bondo Krogsgaard in, Nordex, 2016).

The reference to the ‘rapidly changing wind industry’ and ‘new challenges’ in the above quote can be interpreted as a clear reference to the changing institutional framework in Europe and related technological developments and changes to the structure and composition of demand for wind turbines in Europe. The European Commission adopted new guidelines on state aid and public support for environmental protection and energy in April 2014. The reviewed guidelines gave clear instructions to Member States to introduce market mechanisms such as renewable energy auctions and market premiums instead of feed-in tariffs. Hence, wind turbine OEMs were aware of the upcoming changes and were able to adapt to the resulting changes to the industry. While the merger between Nordex and Acciona Windpower was described as primarily motivated by synergies between products and markets, it was also in response to upcoming changes to the industry as a result of the introduction of renewable auctions in many countries (Interview #18, OEM).

The merger was described as having several complementarities in markets (Nordex’ focus on Europe with AWP’s focus on emerging markets), customers (Nordex’ small and medium sized customers, and AWP’s large developers and IPPs), products (Nordex complex and land constrained projects with AWP’s projects without land constraint), and technologies (Nordex’s focus on blades and AWP’s focus on concrete towers). Following the announcement of the merger, Nordex also stated explicitly that it wanted to serve both local individual municipal (energy cooperatives) windfarms as well as utilities.

As part of the merger, Acciona S.A. transferred its wind power subsidiary Acciona Windpower to Nordex in the form of a combined cash/non-cash capital contribution. In return, Nordex agreed to pay Acciona €366.4 million in a one-off cash payment and issued 16.1 million new Nordex shares, for a combined value of €419 million, which equated to a 16.6% stake in the German company. Consequently, Acciona Group became a leading shareholder in Nordex with a 29.9% stake.

With regard to adapting to changes to the structure and composition of demand following the changes in the institutional frameworks in most

European countries, the 2015 annual report mentions for the first time an upcoming shift to renewable auctions in the European renewable energy remuneration scheme but does not offer a specific opinion on this shift. Nordex has always followed a strategy with a large focus on reducing costs. For example, in 2010, the company launched a program to cut product costs in response to lower turbine prices in the market and conducted an internal reorganisation program ("N-ergize") aimed to cut structural costs. Similarly, in 2013 the "Core 15" programme was implemented in order to cut turbine costs by €100,000 per turbine and aimed at further reducing these costs by 15% by 2015. However, from 2017 onwards and with the introduction of renewable auction systems in most European countries, cost reductions become a clear part of the company's strategy and narrative. This shows a clear link between the changes in the structure and composition of demand and the related greater importance of cost reductions since the introduction of the auction system to organisational responses by European OEMs such as Nordex.

In his first letter to the shareholders, the new CEO Jose Luis Blanco, who had previously been Acciona Windpower's chief executive, stated "*In our domestic market of Germany, the introduction of a new auction system is also set to heavily impact prices in the current year and our programme for reducing the cost of energy will not be able to fully compensate for this development*" (Jose Luis Blanco, in Nordex, 2017, p. 5). Similarly, several interviews with the company's managers reference the importance of achieving low costs of energy:

> *"[The cost of energy] is downright essential. […] Many regions are increasingly replacing fixed feed-in tariffs with auctioning systems. This means that the provider with the most favourable offer will get the deal."* (Melanie Verheyen, Cost of Energy Manager, cited in Nordex, 2017, p. 11).

> *"One of the main challenges [for Nordex] is the provision of the lower cost of energy, which we are working on continuously, using all the resources available."* (Norbert Dwenger, Head of Global Sales, cited in Nordex, 2017, p. 14).

> *"We understand that reducing the cost of energy is not only a tool but also an answer to future market trends."* (Eugenio Luis Solla Feijomil, Head of Nacelle, cited in Nordex, 2017, p. 18).

The above quotes show the central role cost reductions have taken for wind turbine OEMs since 2017 and how they were seen as a key driver for success in the competition with other OEMs. The reference to the introduction of auction models in most countries by the Cost of Energy manager further underlines how the change to the institutional framework has lasting effects on the structure of the wind industry, both from a demand and a supply perspective. The strategic choices by Nordex around 2017 are in line with the results from the previous chapter where the technological development in the onshore segment plateaued in 2017 and a change in the quantity as well as structure and composition of demand for onshore wind turbines increased the need for cost reductions for OEMs.

On the one hand, Nordex adapted by restructuring its internal structure not least through the merger with Acciona Windpower. Through the merger, Nordex Acciona increased production sites substantially. In addition to the factories in Germany, in 2016 the company was producing nacelles and rotor blades in two factories in Spain, nacelles in Brazil and India, as well as through mobile production units for towers. Additionally, two concrete tower production facilities were planned in Brazil, while subcontractors used one factory in Brazil and one in India with Nordex supplying the moulds.

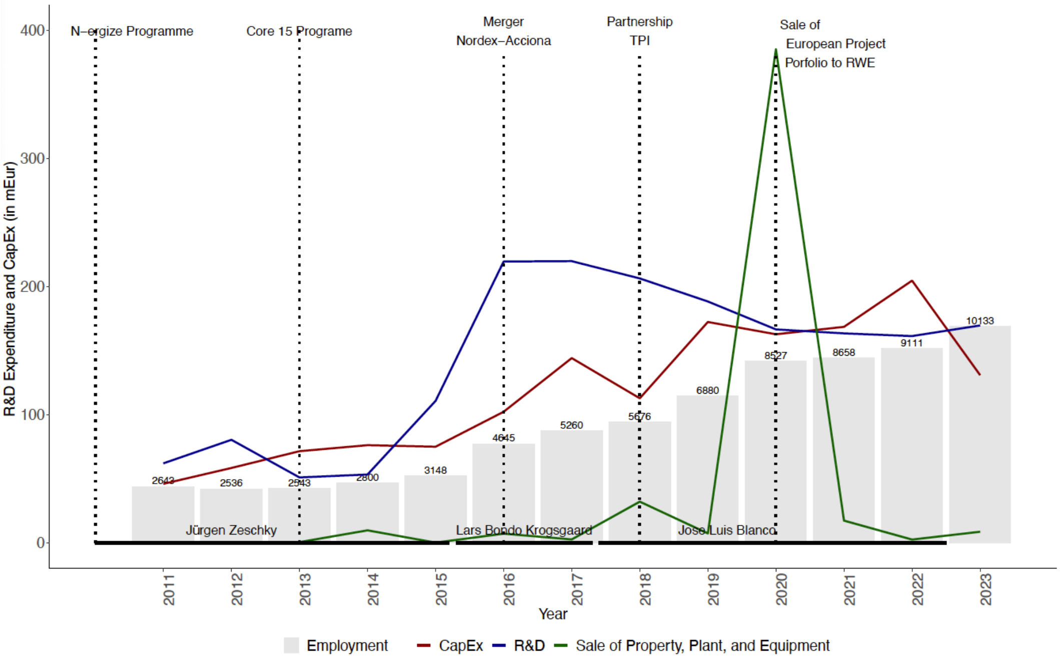
On the other hand, following the merger, the company also changed its supplier network and outsourced certain activities to ensure greater cost competitiveness. Further outsourcing plans for concrete towers using subcontractors in Mexico and South Africa were announced for 2017. From 2017 onwards, Nordex Acciona changed its corporate strategy to include "*The transformation of the supply chain to further lower the cost of wind turbine systems*" and "*systematically and continually reduce COE [cost of energy] of its products*." (Nordex Acciona, 2018, p. 30). The strategy was centred around limited vertical integration, flexible procurement strategies, and increasingly sourcing components from low-cost countries. In 2017, the company further implemented a cost-saving programme to reduce structural costs and stated the declining demand for wind turbines following the shift to the auction system as the main reason for this. Nonetheless, the company continued to invest and opened a new competence centre for rotor blade R&D in Denmark that focuses particularly on producing innovative and cheap production technologies for rotor blades.

Since 2018, Nordex has continued with the shift to a global presence as German turbine sales continued to decline and subsequently expanded their supply chain in other countries. New production facilities for blades were opened in India and Mexico in 2018 for both local demand as well as export. A new fully owned concrete tower production facility was opened in Brazil, and a new joint venture was set up in Argentina for a new wind turbine assembly line. The majority of Nordex blades are now produced by independent producers according to Nordex design specifications. For example, blade production in Mexico was continued through a new partnership with US manufacturer TPI, in addition to existing collaborations in Turkey and India. This strategy has been described by Nordex as an ‘asset light approach’ where the number of production sites and capital commitments required are carefully managed and optimised (Nordex Acciona, 2019). As a result, Nordex has been “*expanding its supply chain in so-called ‘best cost countries’ to enable more international and flexible production and procurement”* (Nordex Acciona, 2019, p. 68). At the same time, Nordex announced it would have to wind up several existing projects with less favourable cost structures.

The decrease in demand in the German market since 2017, which also led to the insolvency of a main competitor Senvion, and the overall decrease of profits as a result of cost competitiveness and aggressive pricing of contracts had significant impacts on Nordex Acciona’s solvency (Weston and Knight, 2019). Following the volatile market dynamics resulting from the Senvion insolvency, Nordex aimed to improve its financial situation by exclusively offering additional shares to Acciona S.A. This raised funds of €99 million for Nordex and increased Acciona’s share to 36.27% in 2019. The strategic move was aimed at signalling confidence to stakeholders and supporting future growth, especially for the Delta 4000 platform, which had a significant order backlog. Following further profit warnings, Acciona provided further equity of € 139.2 million in return for new shares, which increased its stake to just under 40%. In 2023, this stake was further increased to just under 50% as part of a debt-to-equity swap in which Acciona S.A. exchanged receivables worth around €347 million for new shares.

To further strengthen the group's capital structure and address the impact of the COVID-19 pandemic on its operations, Nordex Acciona decided to sell its European wind project development portfolio to the German energy supplier RWE in 2020. The deal was worth € 402 million and included a project pipeline of 2.7GW in France, Sweden, and Poland (Nordex Acciona, 2021). Crucially, the deal allowed Nordex to refocus on its core business and finance profitable growth in the manufacturing of wind turbines.

Figure 33: Organisational Reconficutions at Nordex



Source: Own, based on Nordex Consolidated Financial Statements and Annual Reports

In 2022, Nordex also took the initiative "*to respond to competition and shifts in demand*" (Nordex Acciona, 2023, p. 77) by aligning their production footprint: two blade and nacelle factories in Spain were closed entirely and the production of rotor blades in Germany ceased, while rotor blade and turbine production facilities in India were expanded further. The German factory in Rostock was reorganised for the continuous production of nacelles, hubs and drivetrains. Additional nacelle production is conducted in China via a local partner.

Overall, the case of Nordex shows that while the company adapted early to the switch to the changes in the remuneration system for wind energy by restructuring internally and externally. The changing market dynamics still forced the company to give up strategic control due to the need for further external finance. The increased stake of Acciona S.A. means that the power of Nordex Acciona's CEO Jose Luis Blanco, who had been the chief executive of Acciona Windpower prior to the merger, was further cemented and increased the strategic control of Acciona vis-à-vis Nordex. Nonetheless, the strategic choices of Nordex appear to have been successful with the company managing to increase its market share vis-à-vis its competitors from 2020 onwards. Despite the differences in markets, customers, and technologies Nordex and Acciona managed to successfully integrate following their merger in 2016. Importantly, although Nordex did reduce some of its vertical integration and shifted production to best-cost countries, the company has continued to increase its capital expenditure and retained a large strategic control.

5.3. Enercon: Reducing vertical integration and adopting new technologies

Similar to Nordex, Enercon is a German manufacturer that has focused entirely on the onshore segment and was equally exposed to changes in the European remuneration schemes given its strong focus on the domestic German and European markets. The case of Enercon is interesting as it provides an example of a company reacting too late to changed demand conditions. The company has lost significant market shares since the early 2010's (see Figure 32) and only recently underwent a major organisational restructuring and technological change as will be elaborated below.

Contrary to Nordex, Enercon was owned and managed by its founder Aloys Wobben until 2012. At the end of 2012, Aloys Wobben transferred the entire ownership of Enercon to the Aloys Wobben Stiftung (Aloys Wobben Foundation) and Hans Dieter Kettwig became the new CEO. The transfer of ownership to a foundation has been described as a move "*which ensures the business remains independent and has a corporate strategy that is focussed on the future*" (Enercon, n.d.). As an industrial foundation, Enercon has been much less exposed to consolidations in the wind turbine manufacturing industry.

Traditionally, Enercon is known for its high vertical integration along the entire value chain and extensive service contracts for its turbines. They have also gone the furthest in the wind turbine manufacturing industry in terms of offering a full-package approach where Enercon often operates its own wind parks, undertakes the installation of turbines, organises the logistics, conducts service, operation and maintenance, has its own insurance and thus sells the entire wind package (Lema et al., 2014). As mentioned above, Enercon was also one of the first wind turbine OEMs to embrace a direct drive technology and has developed a highly original design using a direct-drive solution that also eliminated the need for permanent magnets and which has become very popular among smaller developers and energy cooperatives for their reliability and high quality.

Enercon's main production sites are in Germany but the company has several production facilities in other countries as well as an extensive network of service providers. Historically, Enercon India and Wobben Windpower Indústria e Comércio in Brazil were the most important subsidiaries supplying wind turbines to local markets as well as components for Enercon in Germany (Enercon, 2007). Following a patent infringement case with Kenetech Windpower Inc, the US International Trade Commission imposed an import ban for Enercon in 1996, which lasted until 2010 and has meant the company has no presence in the US until this day. In 2010, the company expanded its production facilities in Canada and Turkey and held exclusive contracts with suppliers in Germany, Sweden, Portugal, Canada, and Turkey.

The company's corporate strategy has always been focused on close relationships with both suppliers as well as customers and "*ensuring future success through quality and innovation – based on a stable foundation*" (Enercon, 2008, p. 24 translated from German). As a result, a large focus of the company's R&D has been on improving its turbine reliance and Enercon has become known for its high quality and as the "*Mercedes of wind turbines*" (Interview #12, public research institute).

Enercon's annual report 2010 states the market developments and expansion of manufacturers in China, the US, and India as a potential risk and states the expectation that this will lead to overcapacities of OEMs. As a result, the company stated to focus only on those markets where it had established a presence in the European market and in particular in Germany, France, and Sweden (Enercon, 2011, p. 35). Following a legal dispute with their Indian subsidiary Enercon India in 2007, the Enercon group ended the joint venture and left the Indian market entirely. Only following a court ruling of an international arbitration court in 2017 did Enercon return to India in 2020.

With regards to changes in the structure and composition of demand, Enercon stated in their annual report for 2011 for the first time that they acknowledge a trend towards bigger turbines and bigger projects that would suit larger customers such as utilities and investment groups better. At the same time however, Enercon stated that they firmly believed in smaller customers that plan and build individual turbines or small wind parks and that those customers were the main driving force behind innovations and quality improvements in the energy transition (Enercon, 2012). The focus on high-quality turbines for the domestic German and other European markets, together with the concentration on smaller customers has remained a key aspect of Enercon's strategy. In 2012, the company underwent an organisational reconfiguration in which the WRD Wobben Research and Development GmbH was created as a separate research entity with an innovation centre and connected testing facility for wind turbines.

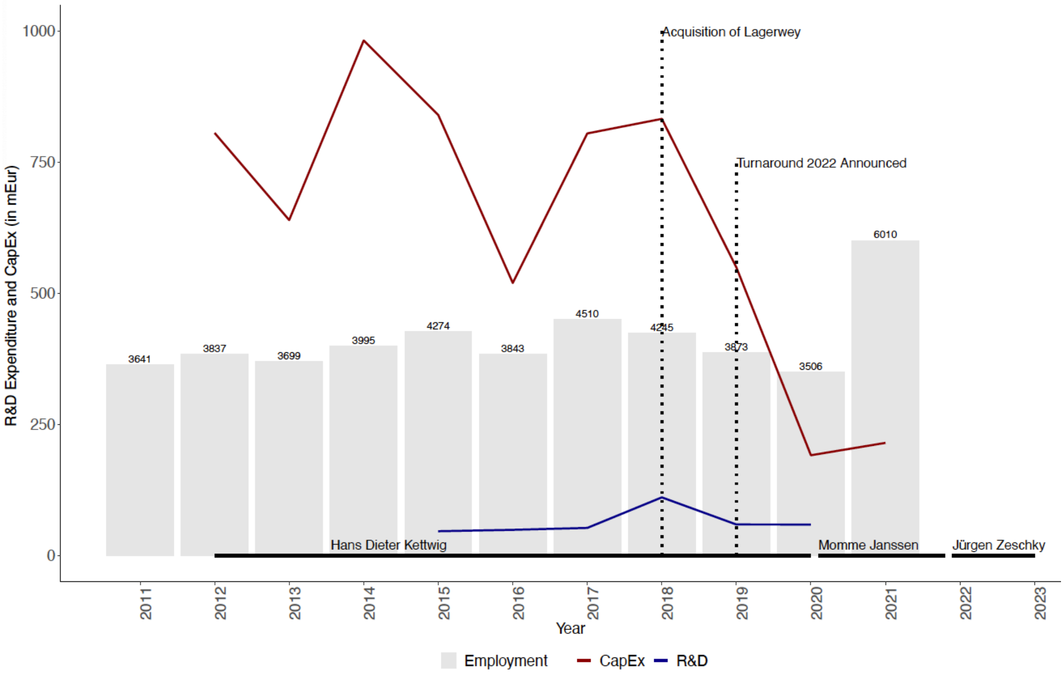
In 2013, Enercon for the first time acknowledged in their annual report that ongoing discussions in Germany around the costs of the energy transition and related changes to the feed-in tariff were increasing (Enercon, 2013, p. 31). Following the initial discussions around changes to the German feed-in tariff and wider renewable energy remuneration schemes in the EU, Enercon stated that policy changes could potentially have an impact on the company's business operations (Enercon, 2014, p. 33). While the annual report states that Enercon is participating constructively in the discussions on finding the right policy framework, it states that through increased investments in new production and new production facilities, Enercon is In a position to react quickly to changed industry conditions.

The Initial effect of the announced switch to the auction system in Germany on Enercon was a sharp rise in sales. This can be explained by the fact that wind energy projects that received permitting before 2017 and were built and operating before the end of 2018 still received remuneration under the previous feed-in tariff system. Enercon acknowledged this anticipatory effect at the time but stated then that the impact of the policy change on wind park developers could not yet be gauged (Enercon, 2017, p. 5). Despite referencing expected increases in the complexity of turbines, technologies, and customers in relation to the auction model, Enercon continued to focus on smaller developers as their main customer and named close relationships with their customers as the main reason for why Enercon was less exposed to volatility of demand for wind turbines in several non-European markets at the time and the resulting over-capacities of wind turbine OEMs (Enercon, 2017, p. 12).

In 2018, Enercon acquired the Dutch wind turbine OEM Lagerwey and began a technology transformation. At the time, Enercon explained this as a strategic investment to expand their wind turbine portfolio as well as the opening up of new emerging markets. It also meant that Enercon acquired and integrated permanent magnet generator technologies into its portfolio. As a result, Enercon gave up its original design around synchronous generator direct drive wind turbines and worked on integrating the Lagerwey technology into its turbine portfolio henceforth. The acquisition of a new direct drive technology by Enercon is insofar interesting as it happened during a time when the technological dynamics in the onshore segment plateaued. At the same time, the acquisition of a permanent magnet technology for direct drive turbines can be seen as a move toward more cost-effective solutions due to the technology's advantages for scalability and modular platform solutions compared with synchronous generators. Although an Enercon turbine using permanent magnet technologies was not introduced until a few years after the acquisition, it was described as a cost-effective alternative: "*The E-175 EP5 features the tried-and-tested Enercon direct drive and a highly-efficient, yield-optimised permanent magnet generator, making it another attractive option for our customers and an alternative to the gear-based competition. In most of the market regions across the world, the cost of energy is the deciding criteria*" (Enercon COO Frederic Maenhaut, cited in ReNews, 2022).

The acquisition and integration of Lagerwey corresponded with Enercon starting to more explicitly refer to increasing cost pressure in the industry. While up until 2017 the economic assessment of the wind industry section in the company's annual report exclusively focused on wind turbine expansion in various markets, the annual report of 2018 for the first time included a section on the trends of levelised costs of energy (LCOE) for onshore wind (Enercon, 2019, pp. 8–12) as well as an analysis of LCOE reduction in Enercon's wind turbines (Ibid, p. 14). This is in line with the developments in the industry from 2017 onwards that made cost reductions much more important for OEMs as analysed in the previous chapter but came much later than the strategic adaptions Nordex took in anticipation to the changes in the quantity and quality of demand.

Figure 34: Organisational Restructuring at Enercon



Source: Own, based on Enercon and Wobben Research and Development Konzernjahresabschlüsse.
Note: (1) Due to different reporting obligations, Enercon (or its holding company UEE Holding) does not publish R&D data. The annual reports state that all research is conducted by a separate entity Wobben Research and Development (WRD). The R&D numbers in the graph above only reflect expenses incurred by WRD and published in their income statement and thus might not capture the full R&D expenditure of Enercon. (2) Enercon has multiple suppliers that exclusively serve Enercon. As such, a large number of indirect employees are not reflected in the official data published by Enercon and might not be reflected in the above graph.

The reduction of the European market, and in particular Enercon’s domestic onshore market in Germany which decreased by 80 per cent over two years between 2017 and 2019[8], had significant effects on Enercon’s market shares. Enercon’s European market share subsequently reduced to 10.9% in 2019 (down from 26,2% in 2018). In response to these developments, Enercon tasked the management consultancy Olyver Wyman GmbH to develop a wide-ranging organisational restructuring programme “Turnaround 2022” (Enercon, 2020). As a result, the company cut around

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[8] In 2017, Germany added 4.871MW of newly installed wind energy capacity. By 2019, this had decreased to 859MW (IRENASTAT)

3000 jobs[9], equating to 17 per cent of its direct and indirect employees at the time and moved production to cheaper markets. A key aspect of the ongoing restructuring programme is the internationalisation of Enercon's purchasing activities. As part of this, new production facilities through local partnerships were constructed in Turkey and India. In its 2019 annual report, Enercon described the restructuring efforts as the following:

> *"The aim is, to purchase or have own production facilities in so-called best-cost countries. The procurement activities in Germany will be scaled back further. As part of a long-term, extensive make-or-buy analysis, the in-house production activities carried out together with production partners are also examined. The focus lies particularly on the manufacturing of the new E-138 wind turbine, which relies on a completely reorganized supply chain from the outset. As part of cost-out programs, attention is also paid to optimizing the cost of energy for existing product lines."* (Enercon, 2020, p. 19, translated from German)

This shows that, albeit slightly later, Enercon adopted very similar organisational restructuring to those of Nordex and started using a similar strategy of producing in 'best-cost' countries. In 2020, Enercon secured financing until the end of 2023 through agreements with banks on the condition to complete the restructuring programme within the set timeframe of three years (Richard, 2020). As a result of the Turnaround 2022 restructuring, Enercon stopped producing rotor blades in its factories in Aurich and Magdeburg, Germany and moved production outside of Germany. Commenting on the ongoing restructuring Enercon's COO, Jost Backhaus said in an interview with Enercon's Magazin Windblatt:

> *"Our supply chains are more international than ever. We produce components in Poland, Portugal, Turkey, India, China and other Asian countries – no longer predominantly in Germany as in the past. Because produce more parts in 'best cost' countries, we were able to significantly lower production costs and thus meet crucial precondition for restoring our*

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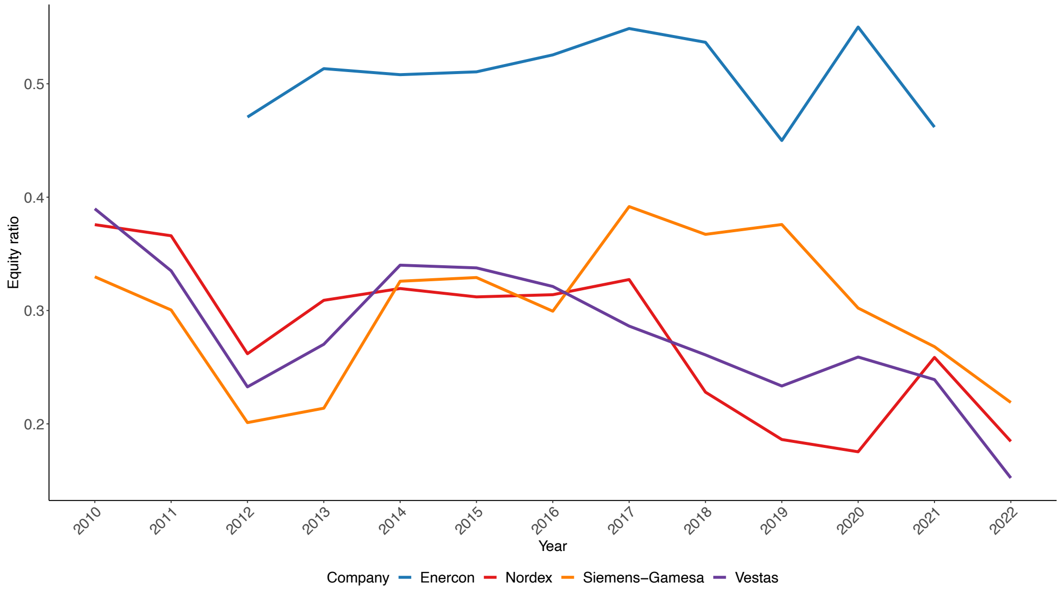
[9] Note that Enercon has a complex web of subsidies and many of these employees were not directly employed by Enercon. Hence, these numbers are not reflected in Figure 34.

> *international competitiveness."* (Jost Backhaus, quoted in Enercon, 2021, p. 18)

With the start of 2020, Enercon replaced its long-standing CEO Hans-Dieter Kettwig with Momme Janssen, who continued the organisational restructuring of Enercon. Following Janssen's installation as the new CEO, Enercon for the first time did not explicitly name developers of individual wind turbines or smaller wind farms as an important customer group but only acknowledged the continuous trend towards larger utilities and investor groups (Enercon, 2020, p. 19). As part of the ongoing restructuring process, Enercon sold its project planning and operation of windfarm subsidies to a new joint venture Atteric with the utility company EWE. The disintegration of the planning and operating segment was explained by Enercon as a refocus of its core business around wind turbine manufacturing and service.

Figure 35: OEMs' Equity Ratio



Source: Own elaboration based on Orbis data

Despite the sale of project rights to the joint venture, which increased Enercon's revenue by €500 million and thus temporarily improved the company's profits and equity ratio, their liquidity situation deteriorated as a result of the ongoing restructuring programme. Nonetheless, their equity ratio still remains higher than their competitors' due to the fact that Enercon remains owned by an industrial foundation. The company has also stated it expected the debt to equity ratio to stay above 40 per cent in the future (Enercon, 2022, p. 24).

In November 2021, Jürgen Zeschky, previous CEO of Nordex, was announced as Enercon's new incoming CEO and tasked with the continuation of the restructuring programme. In 2022, Enercon stated that if the structural, strategic and operational measures of the "Turnaround 2022" do not increase profitability, the existence of the company would be in question. Further measures of the restructuring included a thinning out of its product portfolio and a greater focus on standardised serial production of turbines, expansion of production facilities in China, as well as a new R&D strategy that focused primarily on expanding research activities in India and the Netherlands (Enercon, 2022). A central goal of the restructuring remains the optimisation of LCOE in existing turbine models.

Enercon's technology in wind turbines was changed around the same time as the organisational restructuring with the introduction of permanent magnet technology direct drive turbines as well as its new E-Nacelle and expanded modular platform system, with a built-in electrical system aimed at optimising assembly and costs. The E-nacelle is designed to house the electrical systems responsible for converting the energy generated by the turbine's generator. The primary focus of this development was on optimising production, transport, and installation by making the nacelle fully equipped with all mechatronic systems at the factory and thus plug-and-play enabled. Enercon is currently adopting the E-nacelle technology for all turbine platforms and has reconfigured the previous production facilities in Aurich and Magdeburg as "mechatronics centre of excellence" and "generator centre of excellence" as the primary plants for the production of nacelles. The development of Enercon's E-Nacelle shows how the company not only reconfigured existing production processes for existing technologies in response to changed demand conditions but also adapted its technologies and products.

Albeit later than some of its competitors, the case of Enercon clearly shows how the company engaged in a technology transition as well as organisational reconfiguration in response to changed dynamics in the industry, particularly on the demand side and with regard to greater emphasis on the cost of energy. Enercon's acquisition of Lagerway can be seen as a strategic decision to address these issues by acquiring new and complementary capabilities. At the same time, the company reduced its vertical integration and changes its internationalisation strategy by shifting production to suppliers and contractors in 'best cost' countries. The case highlights the problems that can arise from the integration of a new technology when simultaneously the organisational structure is disintegrating, thus reducing the company's ability to integrate the new technology successfully.

Despite this internal and external reconfiguration and the related need for external financing, Enercon managed to retain a large degree of strategic control through its status as an industrial foundation. This strategic control of Enercon's managers can further be seen in Enercon's latest announcement of making Udo Bauer, previously COO of the company, the new CEO with Jürgen Zeschky moving to CEO of the board of directors of the Aloys Wobben Foundation.

5.4. Siemens Gamesa: 'One segment, one technology' strategy and the problems with organisational integration

To compare different strategies between the onshore and offshore segments, this last section will analyse the strategic choices and organisational restructuring of Siemens Gamesa following their merger. This case particularly highlights the problems of organisational integration following a merger and the difficulties that can arise from differences in technologies or market focus.

Due to the fact that their geographical focus was already much more international, the introduction of renewable energy auctions in Europe impacted the wind turbine OEM Siemens Gamesa less extremely than it did Nordex and Enercon. As of 2020, Siemens Gamesa had main engineering centres in the US, Denmark, and India, and operated manufacturing factories in Germany, Portugal, Spain, Denmark, the UK, Morocco, the US, Brazil, India, and China. At the same time, however, most countries have by now adopted auctions as the preferred renewable remuneration regime and Siemens Gamesa has also adapted both internally and externally to new market conditions and changed dynamics of demand and supply in the industry.

Siemens Gamesa, together with the Danish manufacturer Vestas, is one of two of the largest European manufacturers in the offshore wind turbine segment, where the industry has mostly been focused on increasing the size of wind turbines. The fact that developers of offshore wind farms usually do not have to pay grid connection fees as well as the anticipation of future reductions in LCOE has made the development of bigger turbines even more important for OEMs in the segment. The following section will analyse how Siemens Gamesa has reacted to the changes in the remuneration scheme for renewable energies and related changes to the structure and composition of demand as well as technological developments. Engaging in the offshore segment requires much more financial capital as can be seen in Figure 31 from the much higher total assets of Siemens Gamesa and Vestas. Some have even questioned whether Vestas will have enough financial power to compete globally in the offshore segment (Lema et al., 2014).

On 17 June 2016, Gamesa and Siemens entered into an agreement to combine their wind business, with the merger coming into effect in early April 2017. Following the completion, Siemens owned 59% of the enlarged company's shares and Iberdrola 8% with the remainder freely floated. The headquarters of the combined company are based in Spain, as is the onshore business; the offshore business is based between Hamburg (Germany) and Vejle (Denmark). Particularly challenging proved the question of how to integrate Adwen, the offshore joint venture between Gamesa and AREVA. Gamesa and Adwen had both used gearbox solutions for their wind turbines while Siemens Wind Power had primarily focused on direct drive technology for their wind turbines. At the time of the merger, Adwen was dedicating significant resources to develop an 8MW turbine, using the world's largest wind turbine gearbox at the time. This development raised questions about its integration within Siemens' offshore portfolio, which was also developing its own 8MW direct drive turbine (Backwell, 2018, p. 112).

CEO of the combined company became Markus Tacke, previous CEO of Siemens' Wind Power and Renewables Division who subsequently described Siemens Gamesa's decision-making as "cost-focused" (Siemens-Gamesa, 2018). Similarly, Chairwoman Rosa María Garicía, in her first letter to the company's combined shareholders acknowledged "*a slowdown of main markets such as India and US and low prices at record levels as a consequence of the global market transition to auction systems have impacted the wind industry worldwide. […] forcing [Siemens Gamesa] to make important decisions regarding the company's processes, business models and implement stringent cost reduction programs*." (Siemens-Gamesa, 2018, p. 5). This shows, Siemens Gamesa was from the start aware of the wide-ranging changes of the shift to the auction system and focused on cutting costs. Initial organisational restructurings included the closure of a rotor blade factory in Canada, the establishment of a new blade factory in Morocco, and the opening of a new offshore nacelle factory in Germany with a combined investment of 297 million Euros.

Following a decrease in profitability in 2018, Siemens Gamesa announced a wide-ranging restructuring programme "L3AD2020". One key focus of the restructuring was cost reduction with a target of saving 2 billion Euros by 2020. The programme also stated a clear "one segment, one technology" strategy in which onshore turbines would rely on a gearbox technology, while offshore turbines would be built with a direct drive turbine. This meant that Siemens Gamesa also kept its geographical split between operational units with the the onshore business based in Spain and its offshore business units based in northern Germany and Denmark. While keeping this geographical split can be seen as an early sign of difficulties with the organisational integration between Siemens and Gamesa, keeping the two technologies was justified by Siemens Gamesa with having distinct advantages in the two segments. Direct drive technologies in offshore turbines would give greater reliability in harsher offshore conditions, while the gearbox design in onshore turbines would offer simplicity and lower prices of turbines.

The strategy of achieving the lowest cost of energy in the onshore segment can further be seen in Siemens Gamesa's 2019 annual report where the company's onshore activities are described as being focused on efficiency and cost reductions to make onshore wind "*one of the cheapest sources of energy*", while the offshore business is described as "*developing the most sophisticated turbines*" with activities focused on innovation and new technologies (Siemens-Gamesa, 2020, p. 5). In 2019, the company also expanded its service segment through the acquisition of selected onshore wind turbine assets and IP of Senvion. The acquisition was further aimed at reducing dependencies on suppliers sourcing from Asia and optimising costs for projects in Europe.

At the start of 2020, Siemens Energy acquired all the shares of Siemens Gamesa held by Iberdrola. Following lower financial results than expected, particularly in the onshore segment, Siemens Gamesa installed Andreas Nauen as the new CEO, who focused on a new strategy for profitability in the onshore segment. To achieve a turnaround in the onshore segment, the company implemented a new corporate strategy ("LEAP") to prioritise profitability over volume. While the company's offshore and service segments performed well, partially through the development and commercialisation of new offshore platform "SG 14"[10], the onshore segment continued to report losses despite a new onshore turbine platform "5.X" which was launched in 2019. The 5.X platform was of particular significance for the manufacturer as it was the first true post-merger product that Siemens Gamesa developed through international collaboration and technologies from both former standalone companies.

However, continuous problems with higher failure and repair rates than expected prevented a faster industrialisation of the 5.X platform and impacted Siemens Gamesa's financial performance throughout 2022. After failing to improve the company's situation, Andreas Nauen was replaced as

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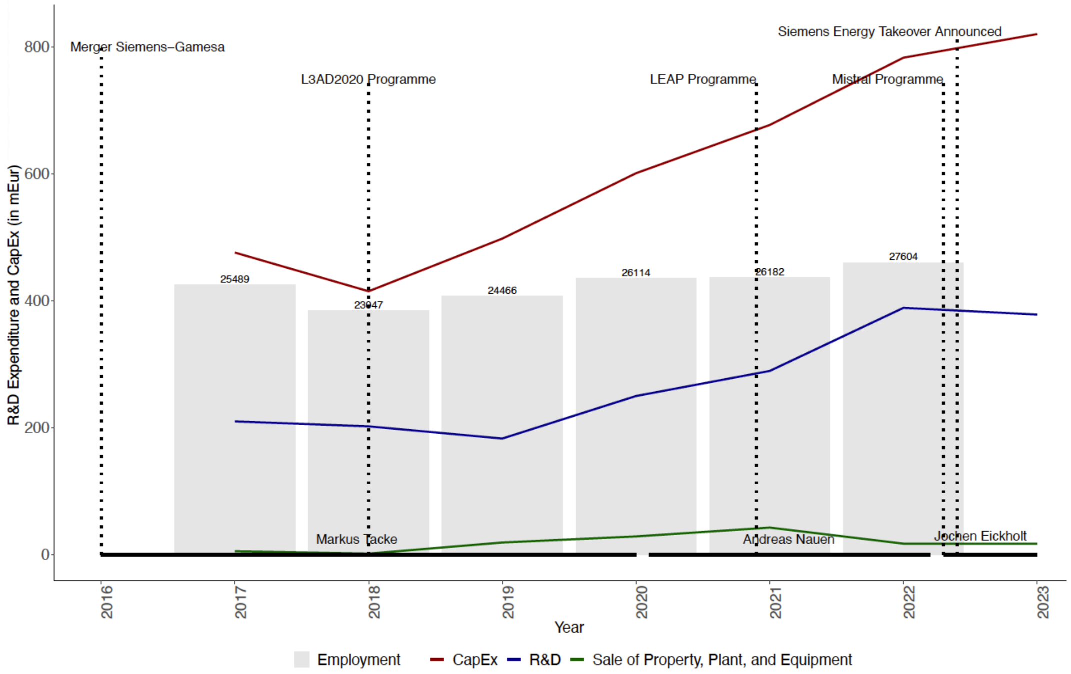
[10] With a 222-meter diameter rotor with 108-meter-long blades, the SG 14 222 was the largest operating turbine in 2021.

the CEO in March 2022, after only one year by Jochen Eickholt, a board member of majority shareholder Siemens Energy. Additionally, Siemens Energy board member Tim Dawidowsky was installed as COO and Christian Bruch, CEO of Siemens Energy, was appointed as the new chairman of the board of directors of Siemens Energy. The company further installed Richard Luijensijk, who had joined Siemens Wind Power in 2005, as the new CEO for the onshore business. Siemens Energy's actions to exercise power over the management of Siemens Gamesa was a sign of the company increasing its strategic control vis-à-vis the former Gamesa management by installing their own managers in the leadership team.

Figure 36: Organisational Restructuring at Siemens Gamesa



Source: Own, based on Siemens Gamesa consolidated annual financial statements

Under Jochen Eickholt as CEO, the company announced a further restructuring programme "Mistral". With the programme, the company aimed to achieve greater harmonisation and standardisation between segments by creating one technology development team and one manufacturing team across the wind turbines segment and the operation and maintenance segment. This also included a streamlined product portfolio, with the number of turbine designs reduced, and to standardise technology across components like blades, drive trains and electrical systems. As part of this restructuring, Siemens Gamesa also reduced its workforce by 2900, including 1900 in Europe.

In May 2022, Siemens Energy further announced its decision to launch a voluntary takeover of the remaining shares of Siemens Gamesa not already owned by Siemens Energy and stated its intention to pursue a delisting of Siemens Gamesa from the Spanish stock exchanges. Despite its majority stake of 67%, Siemens Energy was finding it difficult to exercise sufficient control and influence with Siemens Gamesa's operational problems and was facing increasing shareholder pressure to take full control of the wind turbine OEM (Burger and Steitz, 2022). The full take-over of Siemens Gamesa by Siemens Energy was completed in July 2023, with Siemens Energy CEO Christian Bruch stating at the time "*This is an important step in preparing for full integration. Besides, the turnaround program at Siemens Gamesa, Mistral, needs further rigorous execution, even though we see first moves in the right direction*" (Siemens Gamesa, 2023). He further stated that within the full ownership structure, it would be easier to tackle problems in a more consequential way and give stronger access to financing for Siemens Gamesa. At the same time, he said that a delisting of the company was needed to give support managers to focus entirely on the financial turnaround. As a result of the takeover, Siemens Gamesa is required to reduce structural costs by €400 million by the end of 2026.

Siemens Energy further installed two taskforces, one internally at Siemens Gamesa and another one from members of the supervisory board of Siemens Energy, tasked with responding to quality issues in the onshore segment. In August 2023, Siemens Energy announced problems with Siemens Gamesa's onshore wind turbines could cost up to 4.5 billion Euros to repair and Siemens subsequently received a €15 billion rescue package backed by the German government. CEO Jochen Eickholt admitted that the manufacturer had "*tried very quickly to do lots of things at the same time*" and sold turbines that were "*insufficiently tested*" (quoted in. Richard, 2023a). The growing exercise of strategic control by Siemens Energy was further proven by reports of Siemens Energy CEO Christian Bruch dismissing the engineers behind Siemens Gamesa's faulty 4.X and 5.X onshore wind models (Richard, 2024). While still unconfirmed by Siemens Gamesa in July 2024, the manufacturer is supposedly considering designing an entirely new onshore wind turbine platform (Richard, 2023b).

Overall, the developments at Siemens Gamesa show the difficulties the company had with the technological and organisational integration following the merger and having two different strategies in terms of technological developments and cost reductions between the onshore and offshore segments. One interviewee from Siemens Gamesa described the company as "*a good case to look at the industry and the two segments on how to do it and how not to do it*" (Interview # 11, OEM):

> *"Being the industry leader in offshore enabled Siemens Gamesa to keep innovating and pushing the technological frontier, which on the one hand required competitors to follow but more importantly also ensured high reliability of 95% of its test turbines and a very high performing fleet. However, in onshore where our market position was much weaker, Siemens Gamesa was chasing the market leader Vestas and maybe had to cut some corners and maybe didn't do enough testing resulting in lower reliability."* (Head of Market Intelligence, Siemens Gamesa).

In terms of production strategies, and in particular make vs buy strategies, the interviewee also stated that due to the different risk profiles of the offshore and onshore segments, there were different outsourcing strategies. Whereas a project failure in onshore wind projects might have negative impacts in terms of the company's milestones, it is much less financially risky than the failure of offshore wind projects where the project is connected to a much larger supply chain including ports and vessels. As a result, greater vertical integration and higher control of the supply chain are seen as more desirable in the offshore segment (Interview #11, OEM).

At the same time, Siemens Gamesa's decision to keep two separate technologies and separate strategies for the onshore and offshore segments shows how the company viewed the developments in the two segments differently. Particularly the dynamics in the onshore segment caused several organisational restructurings and changes to the company's manufacturing footprint in response to lower-than-expected profit margins. Contrary to this, the offshore segment was much more focused on technological developments and achieving cost reductions through newer and bigger turbine models. The case serves as an example of the difficulties of organisational integration and how this can negatively affect the overall performance of the company.

6. Discussion: Similarities and differences in the organisational transitions of European Wind Turbine OEMs

The analysis of this chapter has focused on the internal and external organisational reconfiguration of three European wind turbine OEMs and their emerging similarities and differences. Most of these reconfigurations were found to be directly or indirectly related to the macro-meso dynamics of institutional change, technological developments, and changes in the structure and composition of demand in the wind energy sector. At the same time, the comparative analysis of wind turbine OEMs' responses to changes in Europe's auction system has also revealed a multifaceted and dynamic industry landscape with a variety of organisational restructuring as part of Structural Cycles.

The Green Windows of Opportunity literature has argued that opportunities in the green transitions rely to a large extent on public policy (Lema et al., 2020). The strategic adjustments undertaken by Nordex, Enercon, and Siemens Gamesa confirm the critical influence of shifts in the regulatory framework and subsequent changes in market demand and technological developments as analysed in the previous chapter. Yet, the analysis in this chapter points to how differences emerge among actors even when they are affected by the same regulatory changes. This attests to the importance of the Structural Cycles framework and in particular the importance of industrial policy alignment to technological, demand and organisational transitions.

The analysed organisational reconfigurations show how European wind turbine OEMs adapted to i) changes in the structure and composition of demand for wind turbines, ii) related technological developments, and iii) increased importance of cost reductions. Particularly Enercon and Nordex, who due to their domestic focus on the European, and especially the German market were much more exposed to the effects of the changes to the auction system adapted their strategies and organisational configuration in response to this.

Nordex's transition towards focusing on larger developers as their main customers, alongside a strategic pivot towards cost reduction and an asset-light approach, illustrates a proactive response to regulatory changes and competitive challenges. The company's strategic merger with Acciona Windpower and international expansion further reflect an adaptive strategy aimed at diversifying market risks. At the same time, the company managed to expand and invest and, as a result, achieved cost reductions through economies of scale. Similarly, Enercon's shift towards larger utilities and investor groups as main target customers underscores the company's focus on maintaining its competitive edge through organisational restructuring. Enercon's strategic acquisition of Lagerwey and subsequent organisational restructuring initiatives further demonstrate a strategic realignment towards cost optimisation and international market penetration. Both companies clearly stated the importance of cost reductions for competition and therefore moved production to ‘best-cost’ countries. Additionally, both companies ‘*left the niche*’ not only in terms of geographical focus but also in terms of scale and customer base. However, the fact that Enercon entered a technological transition and organisational reconfiguration later than its main competitor might explain why Enercon has lost market shares vis-à-vis Nordex since 2017 as could be seen in Figure 32.

The comparison between the two companies is particularly interesting as it shows that their different ownership structure did not have a significant impact on their need to adapt. Being an industrial foundation has so far, however, protected Enercon from any potential takeover attempts and the company did not participate in the previous industry consolidation. It also meant that despite the need for external finance, the company was able to retain strategic control to a large degree compared to Nordex which issued new shares and increased the stake of Acciona in order to ensure solvency.

Similar dynamics of giving up strategic control in return for external finance were found in the case of Siemens Gamesa where Siemens Energy increasingly exercised control over the management board and eventually fully integrated the company. Operating in both the onshore and offshore segments, Siemens Gamesa has also displayed clear differences in strategies between the two segments. Their different strategies for cost reductions and technological developments confirm how the two segments have been affected differently by the change to the auction system. The company's differentiation strategy between onshore and offshore segments, emphasising cost competitiveness in the former and technological advancement in the latter, showcases a nuanced understanding of segment-specific dynamics.

Both Siemens Gamesa and Enercon also attempted to integrate new technologies into their product portfolio at the same time as the internal and external organisational structure changed. Following the merger, Siemens Gamesa decided to keep both gearbox and direct drive turbine designs but faced problems with their first true post-merger onshore wind turbine that integrated technologies from the two companies. Although Enercon continued to rely on direct drive solutions, the acquisition of Lagerwey brought in new capabilities and resulted in a switch to permanent magnet designs. While this alone cannot explain their worsening of market shares vis-a-vis their main European competitors (see Figure 32), it shows the difficulties that can come with engaging in simultaneous technological transitions and organisational restructuring.

Overall, the organisational restructuring in both the onshore and offshore segments was found to be primarily caused by changes to the structure and composition of demand following regulatory changes in Europe, rather than exclusively in response to the external threat of Chinese competitors entering the European market. Thus, it can also be argued that the policy changes towards auction systems have had a direct effect on wind turbine OEMs and their production networks as well as supply chains. Particularly in the case of Germany, where the manufacturers Enercon and Nordex had a majority of their production facilities, the effects of the policy change and resulting cost pressures as well as the reduction in demand were the reason for the supply chain moving abroad.

7. Conclusion

The landscape of the wind turbine manufacturing industry has changed rapidly in recent years. The transition to auction-based remuneration schemes has evidently prompted wind turbine OEMs to critically reassess their strategies, operational models, and technological focus. The wind energy sector is on the cusp of a substantial revival in 2024, following a period of difficulty since 2017 and especially during the COVID-19-impacted supply-chain crisis. Over the past years, input costs have surged dramatically. This situation has been further complicated by continuous permitting delays and inefficient auction designs in various countries, adversely affecting the earnings of wind farm developers and turbine OEMs.

The anticipated resurgence is bolstered by an all-time high in wind turbine order backlogs, a global surge in policy initiatives, and intensified government actions to fast-track wind energy development in pursuit of climate objectives. To meet the growing demand for wind energy, manufacturers and their suppliers must increase production and construct new facilities. The findings of this chapter are relevant to inform industrial policy for the wind energy sector.

The strategic choices and organisational restructuring of three of the main European OEMs highlight a collective move towards cost optimisation, technological innovation, and strategic restructuring to align with market demands and regulatory frameworks. This shift underscores the importance of flexibility, innovation, and strategic foresight in sustaining competitiveness in the rapidly evolving renewable energy sector. Furthermore, the analysis reveals the important role of strategic mergers and acquisitions, and global supply chain optimisation through changes to a manufacturer’s vertical integration in the wind turbine manufacturing industry.

At the same time, these changes highlight not only differences in production patterns since the shift to the auction system but also the importance of industrial policy alignment. Particularly in the onshore segment, there has been a drastic change in the structure and composition of demand for wind turbines which OEMs have adapted to. This requires industrial policy measures to equally adapt to the changing needs of firms and productive organisations. For example, by providing financial support for the retooling of existing production facilities. Such industrial policy alignment, or lack thereof, can significantly impact firms' ability to retain competitiveness and leadership in the renewable energy sector.

In conclusion, the wind turbine manufacturing industry's adaptation to the shift to the auction system underscores the dynamic interplay between changes in regulatory frameworks, demand, and technologies and the implications of this for subsequent organisational restructuring. The experiences of Nordex, Enercon, and Siemens Gamesa, highlight the critical importance of strategic agility, technological innovation, and market diversification in sustaining growth and competitiveness in the renewable energy sector. As the industry continues to evolve, the ability of manufacturers to anticipate and respond to changes in technologies or the composition and structure of demand will remain crucial.

Appendix 5.1

Overview of semi-structured interviews

#	Affiliation	Role	Industry	Date
1	Management Consulting	Principal for Industrial Goods Practice	Industry Expert	15.03.2023
2	DLR	Former Head of Energy Economics	Public Research Institute	24.03.2023
3	MHI Vestas	Former CEO	OEM	15.05.2023
4	Wood Mackenzie	Wind Energy Supply Chain Expert	Industry Expert	11.07.2023
5	WindEurope	Director of Industrial Affairs	Industry Association	02.08.2023
6	German Industry Association	Analyst Energy Policy	Industry Association	05.08.2023
7	Vestas	Public Policy Specialist	OEM	11.08.2023
8	Durham University	Ørsted Professor in Renewable Energy	Industry Expert	04.09.2023
9	WindEurope	Chief Policy Officer	Industry Association	05.09.2023
10	WAB	Managing Director	Industry Association	05.09.2023
11	SGRE	Head of Market Intelligence	OEM	11.09.2023

12	Fraunhofer IWES	Director	Public Research Institute	14.09.2023
13	Enercon	Policy Analyst	OEM	04.10.2023
14	Enercon	Policy Analyst	OEM	04.10.2023
15	Financial advisor for renewable energy	Director	Industry Expert	28.11.2023
16	FA Wind	Consultant Wind energy systems	Industry Association	29.11.2023
17	BWO	Managing Director	Industry Association	15.12.2023
18	Nordex	Member of the supervisory board	OEM	Written communication, December 2023

Appendix 5.2

Guiding questions for semi-structured interviews

General questions

- How would you describe the effects of the policy shift from feed-in tariffs to auctions in Germany and the EU in 2017?
- Do you / your firm tend to view the shift to the auction model more positively or negatively? What are the main reasons for this assessment?
- Has the transition to an auction-based system altered the market structure, particularly in terms of the developers, owners, and operators of wind farms? If so, how?

Organisational questions

- What are the main factors contributing to the decrease in profit margins for OEMs since 2017?
- How have European wind turbine OEMs adapted to the policy changes and developments since 2017? Can you provide specific examples?
- After the announcement of the shift to the auction model in 2014, did your firm undertake any strategic considerations or actions? If so, what were they?
- Were certain investment decisions, acquisitions, or mergers influenced, at least in part, by knowledge of the upcoming auction model?
- Are there any industrial policies, particularly on the supply side, that have been implemented to support OEMs in response to the shift to auctions and the resulting demand and technology changes? How effective have these policies been?

Chapter 6: Renewable Energy Remuneration Schemes and the Political Economy within the Demand Regime: The Case of the German Offshore Wind Act and the Shift to Negative Bidding.

Abstract

Central to the success of renewable energy have been government subsidies aimed at creating markets for these technologies. However, as these technologies have become more mature, governments are starting to scale back their support measures and increasingly rely only on the market for future expansions of renewable energy. Recent changes to the offshore wind auctions in Germany have removed most subsidies for developers and instead rely on a bidding system where developers compete by offering to pay for access to future wind farm locations. The shift was heavily criticised by the European wind turbine OEMs who argued Germany's new offshore wind auction system would increase the costs of wind energy projects and negatively impact supply chains. To understand the political economy behind this shift in the German offshore wind energy remuneration scheme, we propose a framework to understand the implications of different renewable energy pricing regimes and their underlying pricing regimes. We test this framework by analysing the vested interests, capabilities and powers to shape the German offshore wind energy Demand Regime. This will be done at two different points in time in 2020 and 2022 when the German Offshore Wind Act was amended, respectively. The German government has stated that all renewable energy subsidies shall be discontinued once the phase-out of coal energy is complete. Thus, the offshore wind sector - as the first renewable energy sector without a renewable energy remuneration scheme - can serve as an important case study for other renewable energy technologies. The framework and analysis of this chapter will contribute to the emerging literature on the political economy of renewable energy.

1. Introduction

Central to the expansion of renewable energy technologies so far have been government subsidies and support measures aimed at creating demand for these technologies as they are competing with conventional sources of energy. These remuneration schemes were initially centred around feed-in tariffs (FiTs), however, many governments have since shifted to renewable energy auctions as their main policy measure to manage and support the expansion of renewable energies (IRENA, 2017). Auctions are often viewed as a natural successor to FiTs in the evolution of renewable energy technology support policies once the technologies become more mature. This is because auctions are seen as a way to introduce greater competition and thereby ensure further cost reductions in renewable energy technologies. The success of auctions in driving down costs can be seen in the offshore wind sector, where developers are increasingly submitting “zero-cent bids” for tenders. On the back of bigger and more cost-efficient wind turbines, some developers are willing to sell their electricity at “merchant prices”, i.e. electricity at wholesale prices on the spot market without any government support. This trend has also led some governments to overhaul their renewable auction designs and remuneration schemes more generally.

With zero-cent bids becoming more regular in the offshore wind segment, governments around the world including in Germany have started to scale back their support regimes and instead rely only on the market for the expansion of renewable energy. For some auctions, governments have even started considering developers’ willingness to pay money to be awarded a tender through so-called “negative bidding” or second bid components. Under such a system, developers of wind farms no longer receive a potential subsidy on each unit of electricity produced. Instead, bidders are expected to offer a concession payment for each unit of installed capacity. The winners of the auction receive the exclusive right to apply for planning approval, i.e. the permit to construct and operate a wind farm in a specific location.

While some observers have described these developments as a success and endorsement of the auction system, others have raised concerns. On the one hand, critics have pointed out that the cost reductions of renewable energy technologies have not been able to shield electricity customers from the price jumps in the gas and coal market in recent years (Neuhoff et al., 2024).[11] On the other hand, relying entirely on the private sector to conduct the renewable energy transition has been described as an enormous risk, because developers might abandon projects if their return on investment turns out lower than expected (Christophers, 2022a). This is of particular concern for the wind turbine manufacturing industry supply chain, which would be negatively affected if awarded projects are not realised (WindEurope, 2023a). In a sign of times, Ørsted, the world's largest offshore wind developer recently abandoned two key wind farm projects and booked impairments of US$4bn, stating higher interest rates and changed assumptions around tax credits (Millard, 2023). Similarly, Vattenfall abandoned a UK-based offshore wind project in July 2023 saying it was no longer financially viable.

The benefits of certain renewable energy remuneration schemes vis-à-vis others and their underlying pricing regimes[12] have received increased academic attention (Recent examples include: Beiter et al., 2024; Kröger et al., 2022; Neuhoff et al., 2024). However, the political economy of the different proposals – particularly concerning the risk profile and profitability implications within each pricing regime - has so far been neglected. This chapter aims to fill this gap by answering the following research question: *How can the profitability implications of different renewable energy pricing*

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[11] As well be elaborated on below, the generation costs of gas and coal-fired power plants continue to determine the price of electricity in most hours.

[12] Renewable energy pricing regimes refer to the diverse set of policy frameworks and market mechanisms designed to determine the compensation rates for renewable energy generation. These regimes encompass a variety of financial incentives and pricing structures aimed at promoting the integration and sustainability of renewable energy sources within the power market. Examples of such regimes include, but are not limited to: Feed-in Tariffs; Market Premiums; Contracts for Difference (CfDs); Merchant Prices (where prices are obtained directly from the spot market without any additional financial support); or Negative Bidding: (where producers bid on concession payments for the rights to build a renewable energy project in a specific location).

regimes explain the political economy behind changes to Germany's offshore wind remuneration schemes and auction designs?

This research question builds on the hypothesis that the different actors involved anticipate the outcomes of the different pricing regimes and thus try to shape the policy formulation process. To answer this research question, this chapter proposes a framework summarising the main differences and implications of the various renewable energy remuneration schemes. The empirical analysis will test the assumptions of this framework and the degree to which different actors were able to shape the German offshore wind pricing regime according to their interests.

The chapter will use Germany's Offshore Wind Energy Act (WindSeeG) as a case study of the different actors involved, such as the government, wind farm developers and operators, wind turbine OEMs, and various renewable energy industry associations. The German Renewable Energy Law (Erneuerbare Energien Gesetz - EEG) and its various amendments aimed at increasing competition through price-based auction designs have been researched extensively by academic studies (Lauber and Jacobsson, 2016; Leiren and Reimer, 2018). However, the recent developments in terms of moving to a negative bidding system in the offshore segment mark a significant shift from previous renewable energy remuneration. The implications of this for renewable energy expansion have so far not been analysed through the lens of political economy.

The German government has officially stated that renewable energy subsidies shall be discontinued once the phase-out of coal energy is complete (EEG, 2023, § 1a)). Thus, analysing the political economy of the German offshore wind auction – a renewable energy technology that is increasingly considered competitive (Jansen et al., 2020) – can serve as an important case study for other renewable energy technologies. The findings of this Chapter will contribute to a better understanding of how Demand Regimes in renewable energy technologies are shaped and contested by different actors involved.

The rest of the chapter is structured as follows: Section 2 will provide an overview of the different renewable energies pricing regimes and their associated risks. In section 3, the case study selection of Germany and specifically its Offshore Wind Act will be explained. Section 4 reviews the existing literature on the political economy of renewable energy finance and renewable energy remuneration schemes. Section 5 outlines the research design and proposes the analytical framework. Section 6 tests this framework by comparatively analysing the discussions around the amendments to the Germany Offshore Wind Act in 2020 vis-à-vis 2022. Section 7 will discuss the findings and compare them to the results of the German offshore wind auction. Section 8 will conclude.

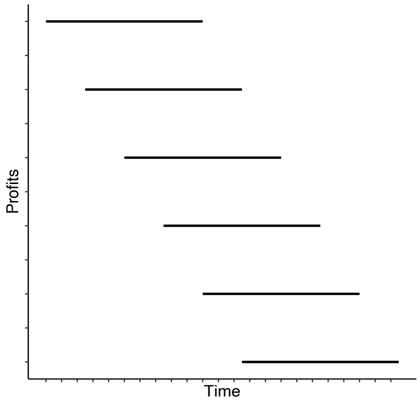
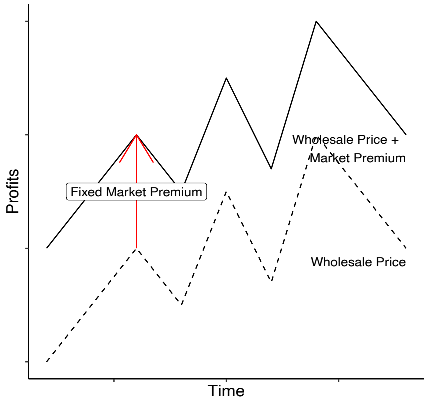
2. Background: Renewable Energy Pricing Regimes and Their Associated Risk Distribution

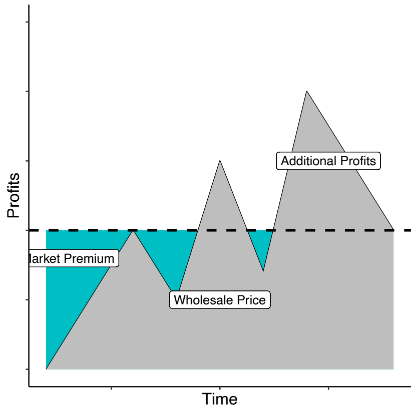
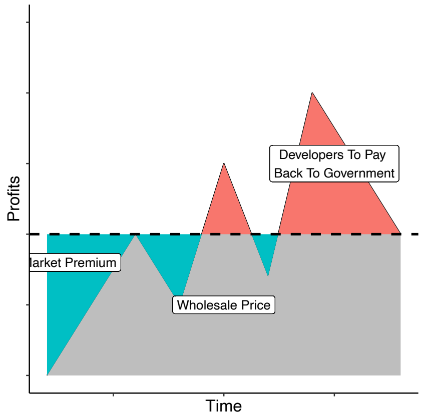
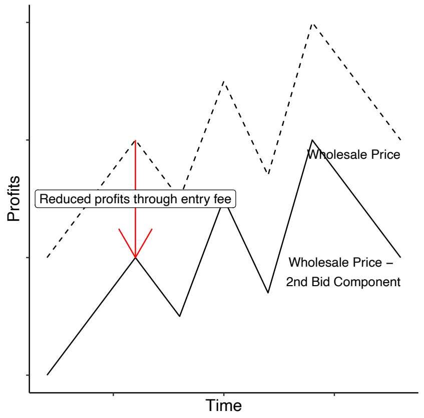
Historically, it has mostly been government support that created an initial market for renewable energy technologies and drove their expansion through subsidies or various guarantees. Government subsidies have played a crucial role in addressing the challenges of financial uncertainties and reducing the perceived risks in renewable energy investments. Often these subsidies were tied to preferential access for renewable electricity to the electricity grid, thereby addressing market failures and helping to level with playing field with fossil fuels.

The type of government support of course varies across countries but often also changes significantly over time. Usually, most countries have used FiTs in the early stages of renewable energy technologies and move towards market premiums or renewable auctions to add greater competition and market forces as the respective renewable energy technology matures. As renewable energy technologies have matured many governments have switched to market premiums and auction models for continued government support for the expansion of renewable energy. Table 8 gives a brief overview of different subsidy regimes and how they differ from one another.

FiTs once were the most popular mechanism for supporting renewable energy technologies in many countries. A FiT guarantees operators of renewable energy systems a fixed payment per unit of renewable electricity produced. The value of the tariff is set by the government but reassessed over time. Long-term contracts give developers financial security and enable them to source higher-quality products designed for maximum yield. As such, FiTs have been described as more than simple market creation tools but also as important levers for raising capital (Gross, 2023, p. 291). In countries like Germany and Denmark, this has also enabled a wide variety of actors with many smaller developers and energy cooperatives with higher risk aversion benefiting from the scheme. As these subsidies apply to anyone building a renewable energy system, the growth of renewable energy under a FiT is uncapped.

Table 8: Different Renewable Energy Remuneration Schemes and the Respective Pricing Regime

Feed-in tariff (with adjustments over time) A FiT system pay the operators of renewable energy sources an above market rate for each kWh electricity produced. Prices set by the government for fixed periods of time with adjustments over time. Usually, this will be lower for systems that are installed later (hence lower remuneration for later projects).	
Fixed Market Premium A fixed market premium (sometimes also called renewable obligation system) is an additional payment to operators of renewable energy systems on top of the wholesale electricity price. Prices are determined by the market but supplemented with a fixed market premium, determined either by the government or through auctions.	

Sliding Market Premium (One-sided CfD) Prices are set by the market but with a ‘floor price’ determined through auctions. Operators of renewable energy systems receive additional compensation through the sliding market premium if the electricity price falls below the contract price. If market prices exceed the contract price, operators get to keep additional profits.	
Two-sided CfD Prices are determined by auction. If electricity prices fall below the contract price, the government compensates for missing revenues. If the contract price is exceeded, the operator transfers excess revenue to the government. Thus, CfDs can be viewed as long-term swap contracts that trade short term volatile prices for a stable long-term price with payments similar to a FiT.	
Negative bidding / second bid component Under a negative bidding system, developers bid for seabed leases. Prices depend on future electricity prices. The payment to the government through the second bid component reduces the overall profits of the renewable energy project. The additional costs will be discounted and either result in lower profitability for the operator or partially passed on to the final consumers.	

Source: Own elaborations

To increase competition and greater reliance on market dynamics, many countries switched from a FiT to a (fixed) market premium. Under this scheme, operators are incentivised to sell their electricity on the spot market and receive an additional market premium. The market premium is calculated as the difference between monthly average market prices and the FiT. Thus, revenues are calculated as the sum of the spot price and the market premium. If spot market prices are higher than the previous month's average market prices, producers receive higher remuneration than under the FiT. However, if the spot market prices are lower or even below zero, operators earn less. The expansion of renewable energies can be assumed to be similar to that under the FiT system with uncapped growth but ideally reduced prices for consumers. To increase competition, governments are increasingly using auctions to determine the level of market premium paid to operators. Renewable energy auctions have also introduced caps to the expansion of renewable energy as only a certain amount of capacity is tendered in each auction round.

At the same time, there has been a shift towards sliding market premiums or one-sided Contract-for-Difference (CfD). Under the sliding market premium, operators of wind farms are guaranteed a fixed minimum payment. The market premium paid out changes in the current system depending on the average electricity price and market value factors: If the average energy source-specific market value of the electricity generated increases, the sliding market premium decreases and vice versa. This is in contrast to a fixed market premium, in which operators receive a fixed payment of € per MWh in addition to the wholesale price (see Table 8 for a comparison of the two types of market premium). Under the auction system, developers of renewable energy projects bid in technology-specific tendering processes in which a market premium is determined. While higher bids submitted would lead to higher remuneration, the probability of winning the bid decreases. While renewable energy auctions have increased competition and market dynamics for the pricing of renewable electricity, they have also decreased the variety of actors with larger companies in a favourable position by this system. In times of low electricity prices operators are additionally supported through the sliding market premium, however, if electricity prices rise unexpectedly - as was the case in 2021 amidst global fuel inflation- the operators can keep the profits. While the sliding market premium gives developers a guarantee of minimum revenue, there are associated risks for the renewable energy transition if developers speculate on high electricity prices as a prerequisite for their projects.

Additionally, the functionality of the sliding market premium in giving price guarantees to developers can be undermined if developers submit zero-cent bids to win the auction, thus cancelling the mechanism and instead relying on merchant prices on the spot market for revenues.

This is different in a two-sided Contracts for Difference system, which is thought to offer better financing conditions for wind park developers and operators and mitigate some of the financial risks from volatile electricity prices (Richstein et al., 2022; WindEurope, 2022a). Under a two-sided CfD system, operators receive the same compensation per electricity output for the duration of the contract. If the price of electricity falls below the strike price the government pays an additional remuneration, whereas if the electricity is above the strike price developers have to transfer any excess proceeds back to the government. As such, they do not stipulate a real subsidy but rather long-term swap contracts that trade short-term volatility for long-term price stability (Beiter et al., 2024). The mechanism eliminates the risks of zero-cent bids, however, it still carries risks for the energy transition if there are ceiling prices that are deemed too low or the CfDs are not indexed to changing costs and inflation. Similar to other auction designs, this system generally favours larger developers who in turn require larger and more cost-efficient turbines to submit the lowest possible tender bids while still making a profit.

Lastly, some governments have started to rely on negative bidding auctions in which developers pay for the right to develop a renewable energy power plant in a specific location. This has been used particularly for offshore wind auctions, where apart from the subsidized grid connection, developers receive remuneration only in the form of market prices of electricity. It can therefore be seen as a pricing regime based on merchant prices with additional costs for developers for the lease payment for the offshore wind farm location. For governments, this means reducing the potential costs of renewable energy subsidies while for consumers the result can be mixed. If the money raised during negative bidding is used for example to reduce the renewable electricity levy used by some countries on residential electricity consumption, this could reduce the costs faced by consumers. At the same time, developers will likely cope with their higher costs either by passing them on to their suppliers or transferring them to their customers.

Different renewable energy remuneration schemes have important impacts on the revenue and profitability of renewable energy projects. At the risk of grossly oversimplifying complex dynamics, we can say that profits of renewable energy projects largely depend on three factors: Firstly, their costs, which in the case of solar or wind farms are almost entirely upfront costs and are highly dependent on the cost of capital. These costs of can further be affected by the availability of critical raw materials, which in the case of wind turbines include rare earths and core materials for glass fibre that are almost entirely dependent on exports from China (WindEurope, 2023b). Secondly, revenues from electricity sales once the renewable energy system is operating.[13] Thirdly, government subsidies or price guarantees can either reduce the upfront costs or supplement revenues from electricity generation. Thus, in the case of a negative bidding auction design and in the absence of any private sector Power Purchasing Agreements (PPAs)[14], profits of renewable energy projects depend entirely on the first two factors.

It is important to note that different pricing regimes can exist at the same time, given the length of guarantees of FiTs or market premiums. For example, even after the switch from a FiT to a market premium system using renewable auctions, projects that were commissioned before the switch will continue to receive payments until the end of the period specified under the FiT. Similarly, in the context of Germany's new auction design for offshore wind farms, this system does not apply to wind farms that were awarded before 2023. These projects will continue to benefit from a market premium

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[13] How quickly a project can get built after an auction price is determined is another important factor that often lies at the heart of project cancellations (Guillet, 2023). However, for the sake of simplicity we will ignore this for now.

[14] Power Purchasing Agreements (PPAs) are contracts between project developers and (usually corporate) buyers of electricity in which the electricity price is fixed. They give developers partial security from volatile electricity prices and make it possible to build projects in the absence of regulated tariffs. As such they are increasingly seen as the panacea for renewable energy and preferred by governments.

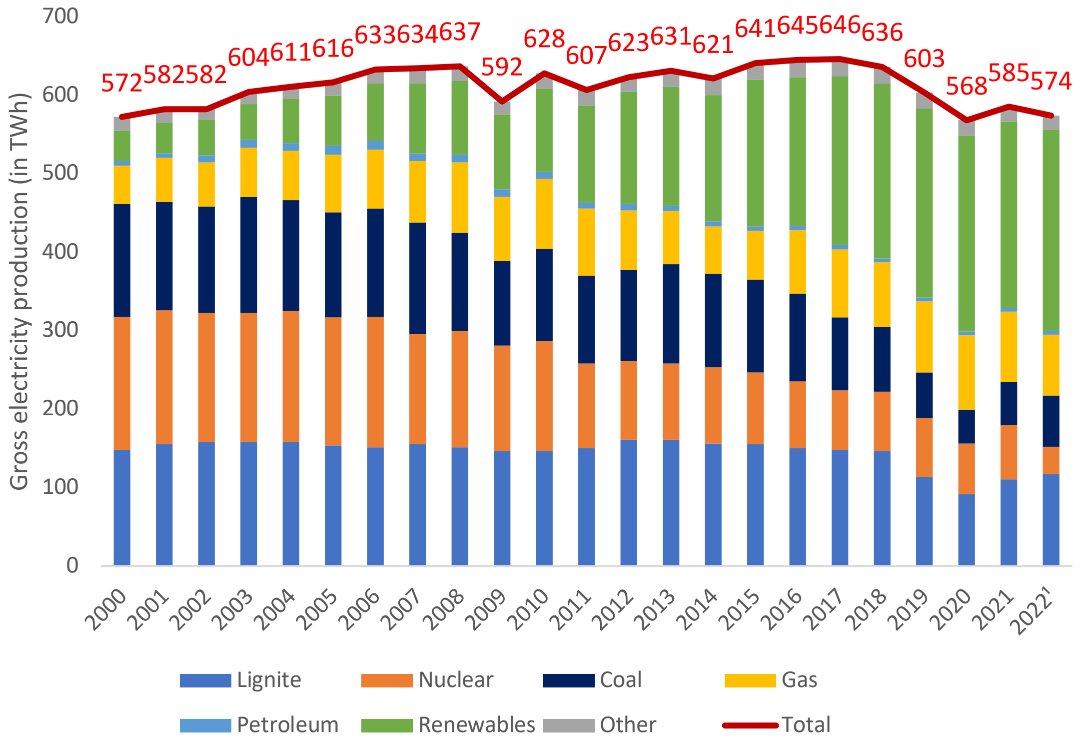
provided they have won an auction which has guaranteed them a subsidy payment.

3. Case study selection

With its prominent *Energiewende* (‘energy transition’), Germany offers an interesting example to analyse the political economy behind changes to their renewable energy remuneration schemes and their implications on the industry. Germany’s *Energiewende* was first and foremost driven through the introduction of FiTs aimed at the creation of a market for renewable energy technologies. The aim of the German FiT system was to support and increase the share of renewable electricity in the energy mix. By reviewing these remunerations on a scheduled annual or monthly basis, the German government added cost pressure on the manufacturers of wind turbines and solar panels as the policy rewarded cheaper producers. By linking the degression of deed-in tariffs to the amount of newly installed capacity, excess profits or rent extraction by renewable energy producers can be reduced (Kwon, 2015). However, crucially, the FiT gave developers greater security on their financial returns and thus de-risked their investments.

The success of the *Energiewende* in changing the electricity mix can be seen in the growing share of renewables in Germany’s gross electricity production. The share of renewables in electricity production increased from only 7% in 2000 to 45% in 2020. With the latest amendment of the EEG, the government set out its ambition to increase this to 80% by 2030. This is to be achieved through the expansion of other renewable energy sources, through an expansion of the installed capacity to 115GW onshore wind projects and 30GW offshore wind projects by 2030. A central part of the German Energiewende since its very beginning has been the remuneration of renewable energy sources first through the FiT and later through the market-premium and renewable auctions.

Figure 37: Gross electricity generation in Germany by energy source, from 2000 to 2022



Source: Own, based on data from the Federal Statistical Office of Germany

As the costs of renewable energy technology drastically fell, the core justification for these subsidies became increasingly questioned. In 2014, on the back of growing austerity measures as well as an increasing belief that market forces alone would be enough, the German government drastically cut the remuneration for wind and solar PV (Gross, 2023, p. 306). Subsequently, in 2017, the government replaced the FiTs with an auction system in which the remuneration for wind and solar PV energy projects was determined through a competitive bidding system. Also elsewhere around the world, renewable energy auctions are becoming increasingly popular: while only 6 countries used an auction system in 2005, 131 countries held auctions in 2021 (REN21, 2022, p. 48). Not only did this shift the structure of developers and owners of wind and solar farms towards larger companies able to finance the upfront costs of auctions (del Rio et al., 2020; Hauser et al., 2014), but it also placed further cost pressures on the OEMs to reduce the levelized cost of electricity even further (see previous Chapter for a discussion on this).

In the first tender after the switch to the auction system in 2017, three of the four winning bids were awarded contracts at a bid price of 0ct/kWh (EnBW for 900MW wind park He Dreit, Ørsted for OWP West and Borkum Riffgrund West 2, with 240MW each). While these bids meant Ørsted and EnBW had to generate their revenue entirely from the sale of electricity on the spot market, the developers still benefitted from the subsidised grid connection of the respective wind farm, which in turn is financed by electricity consumers via an offshore network levy. Nonetheless, these zero-cent bids came as a surprise to many industry experts including the German government itself. The dynamics also caused considerable problems for German lawmakers at the time. According to the German offshore wind auction design, the lowest bid from the previous auction determines the maximum allowable value for the next round. Those developers wishing to participate, therefore had to offer zero cents and, as a result, realise their project without a market premium. On the back of this apparent risk appetite from developers, the German government started to consider other pricing regimes.

At the time, this also raised the question of what criteria should be used to award contracts. As a temporary solution, a lottery system was proposed for the case of more zero-cent bids than capacity auctioned. However, there was a large consensus that this approach was unsatisfactory and changes to the auction system were proposed before the next auction round in 2021. The main discussions at the time centred around the introduction of either a second bid component (a negative bidding system) or the introduction of contracts for difference, which at the time were already used in other countries such as the UK since 2015.

Since 2023, Germany has had two different offshore wind tender systems: One for pre-investigated sites that have been examined by the Federal Maritime and Hydraulic Agency (BSH), and one for non-investigated sites. Based on the investigation, the Federal Network Agency (BNetzA) publishes reports which interested developers can use to submit bids for the amount of compensation they need. Those developers that need the lowest level of subsidy win the bid. However, if multiple bids are tied for the lowest value, such as in the case of several “zero-cent bids” the winning bid is determined through two different systems: For Centrally pre-investigated sites, the award is determined based on the willingness to pay lease prices and a set of qualitative criteria. The bidding price will account for 60 of 100 available points, with the remaining 40 distributed among the following qualitative factors: utilisation of green electricity and hydrogen in wind turbine manufacturing, meeting an education and training quota, establishing a power purchase agreement, and considering biodiversity and nature protection during turbine installation. For non-investigated sites, the tender is awarded solely on the developers’ willingness to pay, which is determined through a dynamic auction system.

The introduction of this auction design using negative bidding or a second bid component for offshore wind shifts the financial risks from the government to the private sector. This is intriguing insofar as it happened at a time when the wind energy sector, particularly wind turbine OEMs, was increasingly calling for de-risking measures to ensure investments (WindEurope, 2023c). Germany previously considered a negative bidding auction design for offshore wind in 2020 but the proposal was dropped following strong rebuttals from manufacturers and developers at the time. The fact that Germany adopted a negative bidding auction design instead of CfDs in 2023 is also in contrast to developments in the EU, where the latest proposals for reform of the EU Electricity Market Design state CfDs as the preferred mechanism for renewable energies (Council of the European Union, 2023).

4. Literature review

4.1. Political Economy of Renewable Energy Finance

There is an emerging literature on the political economy of renewable energy financing (Baker, 2022; Knuth, 2021), especially as government support schemes for renewable energy are increasingly scaled back and the sector is expected to stand on its own feet (Christophers, 2022a). This means, that for individual wind farms, the returns on investment must be sufficient for developers to be able to raise the necessary capital. Recent estimates for wind farms put the debt-to-equity in the range between 70-80% debt and 20-30% equity (Brindley, 2020, p. 11). At the same time, wind farms by large utility or energy companies are increasingly using a project finance model with a special-purpose vehicle structure where a specific project such as a wind farm is turned into an individual asset and debt is raised against future electricity sales generated from the project (Bridge et al., 2020, p. 733). Therefore, creditors' and investors' claims are restricted to the specific project rather than to the wider assets and projects of the wind farm owners and operators (Ibid). Banks and other investors have an intrinsic hesitation towards investments in renewable energy projects as most costs have to be shouldered upfront and returns are uncertain (Christophers, 2022a, p. 1525; Hirth and Steckel, 2016; Schmidt, 2014). Compared to fossil fuel based electricity plants, which have an upfront CapEx ratio of around 15%, offshore wind projects are upfront capital intensive with 65% of expenses incurred upfront and only 35% of project expenses over its lifetime incurred during operations (Beiter et al., 2024).

A second critical consideration for this is price volatility and the importance of the so-called “last-unit” in electricity markets (Christophers, 2022a, p. 1530). Even in countries with large shares of nuclear or renewable energy in the electricity mix, it is often fossil fuels that are used as the backup technology to ensure sufficient capacity. Thus, the price of fossil fuels still dictates the price of wholesale electricity (Zakeri et al., 2022). For fossil fuel-based energy projects this means that investors can have greater security about their financial returns because if input prices such as the cost of coal or natural gas rise, their revenues from selling electricity are also likely going to rise. Equally, fossil fuel power plants can decide when to produce power and can at any point decide not to burn fossil fuels if it is not profitable to do so. In the case of renewable electricity, revenues and thus profits for project developers, operators, and owners are more volatile as well as unpredictable and can involve both significant losses as well as windfall profits (Harrison, 2022, p. 1725). Under the FiT scheme and to a certain degree under the market premium system, the risk from volatile electricity prices was minimized. However, in the case of zero-cent bids or negative auction designs, markets are expected to take on this risk.

4.2. Review of different renewable energy remuneration schemes and their approaches to derisking investment

The increasing use of auctions to support the renewable energy transition has gone hand in hand with a greater academic focus on the policy measure. Del Rio and Kiefer (2023) provide an extensive literature review of the academic research on the purpose and effectiveness of auction designs in renewable energy. The authors summarize two main streams of literature explaining the rise of auctions as a policy measure: a functionalist view, which focuses on the advantages of auctions such as alleged cost-effectiveness; and a political economy view, which stresses the importance of political and industrial influences behind the adoption of auctions (del Río and Kiefer, 2023, p. 4).

On the effectiveness of auctions for renewable energy transitions, there is general agreement that auctions are support-cost-efficient (del Río and Kiefer, 2023, p. 7). The International Renewable Energy Agency, as well as several academic publications, state a link between switching to auctions and greater competition and cost reductions (del Río and Linares, 2014; Grashof, 2021; IRENA, 2017, p. 17; Lackner et al., 2019). Similarly, greater competition through auctions is assumed to increase innovation (Bento et al., 2020; Haufe and Ehrhart, 2018).

However, at the same time, studies have found that auctions can decrease actor diversity and have negative impacts on local industries and supply chains. Del Río et al. (2020) find that auctions affect the number and diversity of project developers and component manufacturers. Despite being a competitive bidding system, a sliding market premium has been described as an asymmetrical hedge in which producers of renewable energy are protected against low prices but electricity consumers are not protected to the same extent against high electricity prices (Richstein et al., 2022).

In the case of Germany, the switch to renewable energy auctions has been explained with the desire to drive down costs of renewable energy remuneration through greater competition (Grashof and Dröschel, 2018, p. 5). An important argument against the FiT was the rising costs of renewable energy subsidies, which eventually legitimised the shift to the auction system (Leiren and Reimer, 2018, p. 38). Similarly, Lauber and Jacobsson (2016) argue that the discussions around the renewable energy remuneration schemes in Germany can be grouped into two coalitions: those who were in favour of thinking about the total costs of the energy transition, lengthy learning periods, and market formation to reduce costs on the one hand, on those who focused on short-term consumer costs, short learning periods, and cost reductions from R&D instead of the creation of a market. Lauber and Jacobsson argue that with several amendments to the remuneration scheme, the latter group increasingly gained the upper hand which served the interests of those industries threatened by a market formation of renewable technologies (Lauber and Jacobsson, 2016, p. 159).

Leiren and Reimer (2018) further argue that the shift to the auction system happened at a time when renewables were increasingly taking away market share from the big utility companies which in turn were threatened by bankruptcy. Renewable energy in Germany was growing at a much faster rate than anticipated with anyone able to receive remuneration under the FiT and growth was thus uncapped. Under the auction system, growth of renewables is limited by the specific targets set by the government and the market can either meet or fall short of this target. Therefore, the shift to the auction system slowed this expansion through quotas that were put up for tender and thus put an initial limit to the amount of renewable electricity that could receive government subsidies (Morris and Jungjohann, 2016, p. 373).

So far, the academic literature has not considered the political economy of different renewable energy auction designs. CfDs have increasingly been proposed as a favoured procurement instrument for utility-scale renewable energy projects (European Commission, 2022). This has also increased the academic interest in CfDs and how the mechanism relates to other pricing regimes (Beiter et al., 2024) as well as its potential benefits to electricity consumers (Kröger et al., 2022). When carefully designed, CfD auctions are thought to be an effective instrument for risk management in electricity markets. However, there remains little research on the implications of different renewable energy auction designs and how this shapes the demand for renewable energy technologies such as wind turbines.

The role of risk considerations in renewable energy is gaining growing attention in energy policy (Christophers, 2024; Kitzing, 2014; Wüstenhagen and Menichetti, 2012). Different risk components are often incorporated into existing cost-benefit analyses. These include modifying discount rates or capital costs (Đukan and Kitzing, 2021; Steffen, 2020) or calculating a 'risk-adjusted' levelized cost (Levitt et al., 2011). This has also led to increased academic interest in the implications of different renewable energy remuneration schemes and pricing regimes (Butler and Neuhoff, 2008; Couture and Gagnon, 2010). Kitzing (Kitzing, 2014) and Schallenberg-Rodriguez and Haas (2012) both compare FiT with market premiums with regard to their risk implications for investors. They both find that FiT consistently require lower direct support levels than market premiums, while still offering the same investment appeal due to reducing market risk for investors.

Nonetheless, the shifting risk profiles from investors to the state, as seen with different renewable energy remuneration schemes are not without critique. Gabor (2023, 2021) criticises increasing de-risking strategies, especially in the context of green industrial policy, revealing a trend that increasingly favours private capital investment while side-lining broader public interests. She notes that global financial mechanisms are being shaped to align with climate change agendas in ways that prioritise risk reduction for private investors. Remuneration schemes such as FiTs or market premiums are thus seen as mechanisms that enable investors to profit from environmental projects without bearing significant risks. As a result, public institutions bear significant financial risks, while private investors benefit disproportionately from the guarantees and financial instruments designed to make green investments more attractive. Moreover, Gabor cautions that by prioritizing financial instruments and guarantees appealing to private investors, states might relinquish some control over their green industrial policies (Gabor, 2023).

Critiques of de-risking often assume that such measures are unnecessary, yet some level of de-risking is generally required (Christophers, 2024). However, de-risking renewable energy does not always equate to unwarranted government generosity. For instance, as was discussed earlier certain pricing structures like CfDs can result in reciprocal payments to the government, not just pay-outs. That said, de-risking is not without issues. Concerns around justice, equity, and public sector capacity building highlight that external support for private renewable energy projects can be problematic, depending on which organisations shoulder the burden and how risks and rewards are distributed. While de-risking remains broadly necessary in the current global electric power landscape, it does come with its own problems of capture and conflicts of interest. However, industrial policy has always entailed elements of de-risking and can account for conflict management.

4.3. The political economy of green industrial policy and conflict management

Green industrial policy, just like traditional industrial policy, will create conflicts among various actors and institutions (Andreoni and Chang, 2019; Chang and Andreoni, 2020). The more selective a policy is in choosing ‘winning’ sectors or technologies, the more likely open conflicts are. As this process inevitably redistributes resources, resistance can often formulate against policy proposals that can hinder the intended outcomes. However, industrial policy is never a single policy measure and a carefully crafted policy mix can help resolve conflicts of interest between various organisations, including differing factions within the government (Chang, 1994a; Chang and Rowthorn, 1995).

This is particularly the case in the renewable energy transition where conflicts arise not only between producers of fossil-fuel-based and renewable technologies but also on the basis of the costs of electricity consumed by industrial producers. Political resistance towards renewable energy technology support measures is likely to come from groups affected by ‘stranded assets’, whose value of reserves of oil and gas or coal, and related infrastructure would be decreased by those policy measures (Jakob and Semieniuk, 2023). These vested interests can make the implementation of climate policy harder or time-inconsistent (Kalkuhl et al., 2020). Additionally, resistance can come not only from those incumbent industries affected directly through capital stocks related to fossil fuels but also via financial markets (Braun, 2022; Christophers, 2022b). Therefore, the renewable energy transition involves complex shifts with a multitude of actors and interest groups each with varying degrees of power, interests, and capabilities to influence the transition.

Similar to traditional industrial policy, this is likely to create conflicts: It necessitates choosing between sectors, technologies, and sometimes even specific firms within the same industry (Chang and Andreoni, 2016). This selection process naturally leads to persistent questions regarding why the government invests in a particular industry, rescues some sectors while abandoning others, or prioritises one technology over another. Such scrutiny reflects how, within a particular political settlement, powerful organizations can significantly influence government industrial policies and the distribution of societal rents (Khan, 2010, 2013). Understanding power relations has been argued to be of particular importance for successful industrial policy (Grey, 2013; Whitfield et al., 2015). The state's conflict resolution role aligns closely with its entrepreneurial function because conflicting interests are more likely to align when the government provides a clear focal point for organising economic activities during significant changes (Chang, 1994).

This highlights the importance of understanding the political economy influencing the renewable energy transition and green industrial policies. Despite this, there remains a gap in the academic research regarding the detailed differences and nuances among various renewable energy remuneration schemes. To understand what preferences different stakeholders, have for each remuneration scheme, we need a more nuanced understanding of their underlying pricing regimes and what implications they have for different stakeholders involved.

5. Analytical Framework

This chapter aims to link some of the emerging literature on renewable energy remuneration schemes with insights from the political economy of industrial policy studies on power, interests, and capabilities. As discussed above, industrial policy has often functioned as a tool for conflict management (Andreoni and Chang, 2019; Chang and Andreoni, 2020). However, in order for this to be effective, an understanding of how different actors have different interests, powers, and capabilities is essential. This chapter proposes the following framework as a guiding lens for analysing how and why different actors might favour certain pricing regimes and what implications these have.

Table 9 summarises the main pricing regimes with regard to i) the respective government rationale, ii) risk allocation, iii) associated financial risks for private sector investors, iv) who the likely wind farm developers are, v) their preferred wind turbine types, and vi) general implications for the energy transition. This framework will be used to guide the analysis and will enable a deeper understanding of why different stakeholders favoured certain renewable energy pricing regimes over others. The table hypothesises which market players are likely to invest and which types of renewable technologies, such as specific wind turbine models, are likely to be favoured. Understanding these dynamics helps in anticipating how shifts in electricity pricing under different regimes can directly influence the broader energy transition.

Table 9: Implications of Different Pricing Regimes

Renewable energy pricing regime	Government rationale	Risk allocation	Associated financial risk for investors	Project developer profile	Technological preference	Implications for the energy transition
Feed-in Tariff (FiT)	Promote renewable energy development and guarantee stable returns for investors	Government/ consumers bear risk (De-risking)	Low risk of investment losses	Mix of players incl. smaller developers & energy cooperatives	Wind turbine OEMs can 'retro-engineer' to the tariff and adapt their prices	Uncapped expansion. Can lead to oversupply and higher costs
Fixed Market Premium	Greater reliance on market mechanism to reduce market disruption	Developers bear risk (Partial de-risking through government supplement)	Possibility of windfall profits for investors in case of high electricity prices	Mix of players	If government set: as FiT If set through auctions: as CfD	Inefficient in terms of costs, leads to higher electricity prices for consumers
Sliding Market Premium **(One-sided CfD)**	Reduce the cost of renewable energy expansion while providing minimum prices for investors	If auctions result in market premium, government bears partial risk. If auctions result in zero-cent bids, developers bear risks	High financial risks for investors in case of zero-cent bids and projects based on merchant prices	Larger developers with expensive capital willing to take risks on volatile electricity prices	More efficient turbines, designed for lower cost	Expansion capped by auctioned amount. Risk of unrealised projects if developers speculate on windfall profits
Two-sided CfD	Reduces costs to consumers in times of high electricity prices while providing revenue certainty to investors	Government and developers share risk of price volatility	Smaller risks for investors due to price certainty.	Depends on eligibility criteria for auctions	More efficient turbines, designed for lower cost	Expansion capped by auctioned amount. Greater security of delivery of projects due to fixed prices
Negative bidding (e.g., for seabed leases)	Earn government revenue through the licencing of leases	Developers bear risks (de-risking still possible e.g., through subsidised grid connection)	Highest risk for investors due to electricity price volatility	Favours speculative capital with long time horizon	Most efficient turbines, designed for lowest possible cost	Volatile electricity prices can result in higher investment risk and higher financing costs. Projects might not be realised if electricity prices fall too low

Source: Own elaborations.

Additionally, the table hypothesises different potential intended and unintended consequences of certain remuneration schemes and their underlying pricing regime vis-à-vis market actors. It is important to stress that not all actors might necessarily be aware of all consequences at any one point and their position on certain pricing regimes might change as they obtain further information or become aware of further implications.

In terms of associated financial risks for investors and implications for the energy transition, a negative bidding system carries the greatest risk as (in the absence of individual Power Purchasing Agreements) developers might never build the respective renewable energy power plant if they deem the revenues from electricity prices too low. This is particularly the case when the auction is held before the permitting process or for not pre-investigated seabed leases and thus involves a long permitting and development phase. If future electricity prices are high enough, the project can be expected to be built and the developer can receive windfall profits. If electricity prices are not as high as expected, the developer might abandon the specific project.

To unpack how certain actors have viewed different pricing regimes over time, the research will centre around two complementary approaches. The first concerns the review and analysis of documents such as government reports, discussion papers, company statements and press releases of renewable energy technology manufacturers and utilities, as well as newspaper articles. Particularly, this involved mapping the differences between proposed and passed amendments to the German Offshore Wind Act in 2020 and 2022 as well as the review of hundreds of documents submitted by industry actors in response to proposed amendments to the Offshore Wind Act. This analysis focuses on both how the offshore wind auction system has changed as well as the interests and powers of the actors involved. The second approach is centred around triangulating these documents with semi-structured interviews with relevant stakeholder from the offshore wind sector. In Germany, most industry actors communicate their positions on government policies through industry associations (Interview #13, utility company).

Different actors might not always have full information on the different implications of a specific pricing regime and their stance might change once they gain further insights. This makes the triangulation of published documents with interviews crucial and can further enhance the analytical discussion of the above framework. Interviews were conducted with relevant stakeholders such as members of the German parliament or members of their offices, renewable energy associations, as well as managers from utility companies between September 2023 and April 2024 (see Appendix for an overview of interviews conducted). Furthermore, the analysis also benefitted from many informal conversations and discussions with industry experts and consultants who provided expert opinions on the electricity market to the German government.

The following section will analyse the two amendments to Germany's Offshore Wind Act in 2020 and 2022 and the vested interests that influenced the policy formulation process at the time.

6. Analysis

6.1. First Amendment to the German Offshore Wind Act in 2020

Following the 2017 federal elections, the "Fourth Merkel Cabinet" under a grand coalition between the SPD and CDU was sworn in on March 14, 2018. The new cabinet changed the leadership of the Ministry for Economy and Energy from a SPD-led ministry under Sigmar Gabriel (2013-2017) and Brigitte Zypries (2017-2018) to a CDU-led ministry under Peter Altmaier. The CDU, contrary to the SPD, preferred the introduction of a second bid component to ensure effective competition among offshore wind developers and in order to minimise and eventually phase out renewable energy subsidies.

Based on the expectation of further zero-cent bids, the Ministry for Economic Affairs (BMWi) in 2018 commissioned a study to examine the further development of the market premium system under the Offshore Wind Act. The study conducted by several research institutes considered several renewable energy remuneration schemes including sliding or fixed market premiums as well as CfDs. It stated that CfDs would combine guaranteed revenues with lower financing costs and ultimately low risks to electricity consumers due to repayments by producers in case of high electricity prices. However, the report also concluded that a market premium model was better suited for the gradual phase-out of subsidies than a CfD model, which doesn't allow for zero-cent bids (Fraunhofer ISI, 2020, p. 24).

On the back of this report, the federal government proposed an amendment to the existing Offshore Wind Act in June 2020. The motivation for amending Offshore Wind Act was the aforementioned difficulty in dealing with zero-cent bids. Under the existing legal framework at the time, the ceiling price for bids was based on the lowest bids in the previous auction round. Hence, given that the auctions of 2017 and 2018 received zero-cent bids only zero-cent bids would be allowed in the next upcoming auction. This was deemed as inappropriate as future wind auctions would include sites with very different conditions and it could not be assumed that all projects can be realised without any subsidies. At the same time, the government did expect some auctions where there would be more than one zero-cent bid in which case there would need to be an auction design that differentiated these bids.

The amendment proposed to increase the ceiling price for auction bids but also proposed the introduction of a second bid component centred around a dynamic bidding system with several rounds to determine the developers' willingness to pay for the rights to develop an offshore wind park (Bundesregierung, 2020, p. 3). Prior to this, several wind energy industry associations had advocated for the introduction of CfDs in an open letter to the BMWi. The letter, which was signed by the managing directors of the main wind energy industry associations BWO, `Foundation Offshore Wind Energie, BWE, and WindEurope, also called on the ministry to enter discussions with the industry on the best way forward. When the proposal for the amendment nonetheless included a second bid component and only gave a two-day deadline for industry actors to respond, it was heavily criticised by the German wind energy industry associations for not engaging with their requests: "*Anyone who sets such deadlines shows that they are not interested in a serious discussion of [CfDs] or even want to prevent it*." (Stefan Thimm (BWO), translated from German and cited in Kühn, 2020).

Following the first passing in parliament, the proposal was sent to Germany's second chamber the Bundesrat, which represents the governments of the regional states. Both the Bundesrat, as well as a motion tabled by the Greens called for the introduction of CfDs instead of a negative bidding system (BT 19/22081, BT 20588). However, both motions were subsequently rejected by the German government (BT 19/22081, BT 24027).

In September 2020, the Parliamentary Committee for the Economy and Energy held a public hearing on the proposed amendments with several expert interviews from industry representatives. This included written as well as verbal statements from representatives of the utility company EnBW, the wind turbine OEM Siemens Gamesa, the Association for Offshore Wind Farm Operators BWO, the Association for Machinery and Equipment Manufacturers VDMA, the union for metal workers IG Metall, the European Energy Exchange AG EEX, as well as the consultancy Consentec.

Based on the statements provided by the invited experts, there was no clear consensus either for the introduction of CfDs or a second bid component. The statements by EEX and Consentec both advocated against CfDs and stated that a second bid component was the logical evolution of the existing sliding market premium model: "*[The second bidding component] is a model that allows renewable energies to be gradually integrated more and more into the market. [Under a CfD model] we shield the bidders from the market […] and the hurdle to fully adopting renewable energies into the market, if you consider this to be a political goal, will not decrease but remain just as high as in the past*" (Ausschuss für Wirtschaft und Energie, 2022, p. 5 [translated from German]).

This underlines the importance of the question of who should bear the main risks of renewable energy projects. The BWO and Siemens Gamesa both advocated for CfDs citing their success in other European countries as well as a more likely realisation of awarded projects due to better financing conditions. VDMA further supported the introduction of CfDs as they feared Germany was otherwise losing its competitive position as an investment location for manufacturers vis-à-vis other countries with a CfD system (Ausschuss für Wirtschaft und Energie, 2022). IG Metall and the utility company EnBW cautioned against a switch to CfDs but equally criticised the proposed negative bidding system. EnBW further stated that from an individual project perspective, CfDs might be the more attractive solution but that they were afraid of CfDs becoming the norm also for other renewable technologies (Ibid).

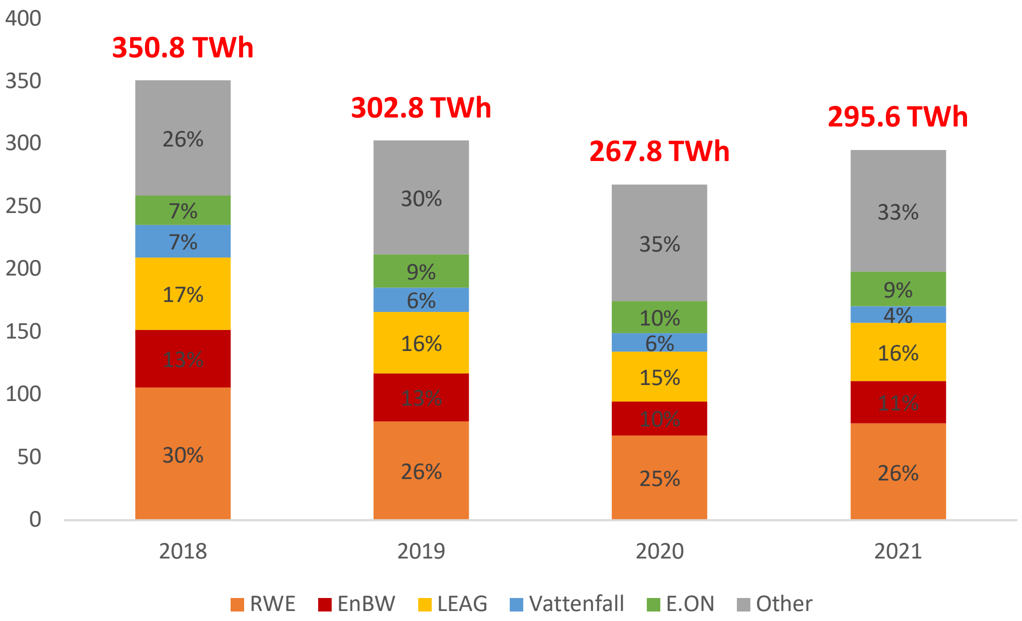
In addition to the statements in the Parliamentary Committee for Climate and Energy, the proposals by the German government and the BMWi also led to a large rebuttal from most German utility companies. The utility companies RWE, Vattenfall, and Ørsted, together with the industrial manufacturers Wacker Chemie, Trimet Aluminium, and Covestro stated their dissatisfaction with the proposals in a letter to the Minister for the Economy, Peter Altmeier. Throughout 2020, the big utility companies continued to lobby against the proposals of the BMWi and instead demanded the introduction of CfDs. Sven Utermöhlen, COO Wind Global Offshore at RWE Renewables at the time, stated: *"The [proposed] model endangers the expansion goals for offshore wind and makes the projects more expensive than necessary - to the detriment of the electricity consumer"* (Uthermöhlen, 2020).

RWE further commissioned a study by the consultancy Enervis Energy Advisors to design an auction system centred around CfDs. During interviews with representatives from RWE, it was revealed that this study was particularly important for the company to understand the consequences and implications of different remuneration schemes (Interview #13, #14, utility company).

Given that RWE and Vattenfall had previously lost the German offshore wind auctions of 2017 and 2018 against the zero-cent bids from EnBW and Ørsted, it made sense that they opposed a pricing regime that was likely going to increase the risks for financial investors. This can further be seen from RWE heavily criticising the bidding strategy of their competitors at the time (Maksimenko, 2020). Vattenfall's situation was particularly affected by the fact that they held the entry rights for certain offshore wind parks. When the remuneration scheme was first changed to an auction system, Vattenfall had transferred pre-developed projects to the German government in return for the guarantee to be able to exercise project development rights against the winning bids. Thus, a change in the offshore wind pricing regime to a negative bidding system would have required Vattenfall to match the winning concession payment in order to exercise their entry right: *"The draft law not only allows negative bids as a second bid component, but even proposes to use them as the decision criterion for the award of the contract. We see this as a clear breach of trust. We handed over the projects under different assumptions, now the rules are being changed to our disadvantage. The right of the last entry [that Vattenfall was guaranteed] is of course invalidated."* (Gunna Groebler, CEO Wind at Vattenfall, quoted in Energate, 2020, [translated from German]).

While Vattenfall never directly threatened to sue the German government, it indirectly implied on several occasions they would consider options if the proposed second bid component were to be passed in parliament (Bathke, 2020; Hanke, 2020). Although EnBW was slightly more critical of CfDs as a suitable alternative, the overall consensus among the large utility companies was a strong disapproval of the government's plans to introduce a negative bidding system. The near-unanimous protest from the utilities as well as the main renewable energy associations against the introduction of a second bid component in the offshore auction design was successful in the end. The power of the 'big five' utilities in Germany and thus their ability to influence political decisions can further be seen from their market shares in the production of electricity in Germany and their resulting importance for German energy security. According to Figure 38, the ‘Big Five’ utilities accounted for 65% of German electricity production in 2020.[15]

Figure 38: Electricity volumes generated by electricity producers, 2018-2021.



Source: Bundesnetzagentur and Bundeskartellamt Monitoring Reports

Although the request for the introduction of CfDs as an alternative remuneration scheme and price regime was rejected, the introduction of

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[15] Although this is down from 80% market share held by RWE, E.ON, EnBW, and Vattenfall (excluding LEAG) in 2009 when renewables only accounted for around 15% of electricity production (Monopolkommission, 2021, p. 10), it is important to note that the Federal Competition Agency (Bundeskartellamt) views the market for the first-time sale of electricity as having two distinct categories: (i) for electricity generated from conventional sources and renewables not remunerated through the EEG; and (ii) electricity generated from renewables and remunerated through the EEG. Figure 3 only reflects the former. As a result of this approach, the market share of the big utilities only captures the 295TWh of electricity that is not remunerated through the EEG or produced for own consumption (compared to the 574TWh gross electricity generated in 2021, see Figure 2). On the other hand, the Bundeskartellamt’s Monitoring Report for 2022 has stated elsewhere that the big five utilities still only accounted for 6.4% of production capacity and 3.6% of renewable electricity generated and remunerated under the EEG in 2021 (Bundesnetzagentur and Bundeskartellamt, 2022, p. 53). It is difficult to reconcile this discrepancy because a large part of the installed renewable capacity of the big utilities does not fall under EEG remuneration because it was either awarded based on 0ct/mWh bids or otherwise covered through PPAs. It therefore does not fall into either category (i) or (ii). As a result, the market share of the big utilities shown in Figure 3 is likely to be artificially low. Overall, however, the reporting of the Bundesnetzagentur and the Bundeskartellamt does show the market power and therefore political influence the big utilities hold in Germany.

the second bid component was removed from the final amendment. Instead of either the second bidding component model or a CfD model, the law implemented a lottery procedure: “in the event of several zero-cent bids, the winning bid will be determined by lot.” (WindSeeG § 23). It was further stated that the German government would examine the need for further adjustments by 2022. Specifically, the law instructed the German government to monitor the tendering models for offshore wind farms in other EU member states in order to be able to identify any possible need for adjustment (WindSeeG §23a). The final version of the amendment can be viewed as a win for those who had advocated against the second bid component. Although CfDs were not implemented as the alternative model, it stipulated a victory against the CDU-led BMWi, which had preferred a negative bidding system in order to further integrate renewables into the market.

6.2. Second amendment to the German Offshore Wind Act in 2023

Following the 2021 elections to the German parliament, a governing coalition was formed between SPD, Greens, and FDP. The coalition agreement stated that the new federal government would make the expansion of renewable energies a central project in its government work. It further promised to ensure that the economy receives competitive electricity prices for industrial companies while consistently using its own renewable energy potential. The importance of addressing climate change and promoting renewable energy was further emphasised by creating a new cabinet-level Ministry for Economic Affairs and Climate Action (BMWK) headed by the Vice Chancellor of Germany, Robert Habeck.

In March 2022, the BMWK published a draft bill for the Second Amendment to the Offshore Wind Act as part of a wider draft bill for Emergency Measures for an Accelerated Expansion of Renewable Energies and Other Measures in the Electricity Sector. Particularly, this included measures aimed at expanding renewable energy and reducing the country’s reliance on Russian fossil fuel imports. This came out of the Russian sanctioning of European gas companies and the rising prices of electricity following the

Russian invasion of Ukraine. Much of the political discussions around the easter package were thus tied to cost of electricity for industrial and residential consumers. As a result of these discussions, the renewable electricity surcharge for residential consumers of electricity was removed from the EEG and the renewable remunerations are henceforth financed through a special fund as part of the Climate and Transformation Fund (KFT).

With regards to offshore wind, the initial proposal for the second amendment of the Offshore Wind Act stated that the funding regime for the expansion of offshore wind energy was being completely redesigned. To this end, two different tender designs were proposed for different areas: The centrally pre-investigated areas were to be put out to tender over twenty-year CfDs. The areas that have not been pre-investigated centrally would be advertised based on qualitative criteria, one of which would be a one-off payment, determined through a one-time 'blind auction' (BMWK, 2022). The introduction of a second bid component as part of those qualitative criteria was explicitly proposed concerning its ability to reduce electricity costs and thereby further market integration and acceptance of offshore wind energy (BT Drucksache 20/1634). Thus, the new government proposed a combination of the two different systems that were debated in 2020.

The redesign of the remuneration scheme and chosen price regime became a contentious point among the coalition parties. SPD and Green had long been advocating for the introduction of CfDs. Contrary to this, the FDP had previously voiced opposition towards the introduction of CfDs as this was seen as a continuation of renewable energy subsidies, which the party had a strong interest in phasing out (Interview #6, political party).

Following the publication of the draft bill, the BMWK initiated a stakeholder engagement process and invited relevant industry actors to react to the draft bill by mid-March. In total, the BMWK received 124 opinion statements from various industry associations, federal state ministries, research institutes and other industry players, which are all publicly available through the BMWK. However, as these reactions concerned a package of bills for the electricity market, only some of these provided opinions on the proposed introduction of CfDs in centrally pre-investigated sites and an auction system based on qualitative criteria and payment for not centrally pre-investigated sites. 21 statements were found to address the introduction of CfDs in the offshore segment.

The Association for Machinery and Equipment Manufacturers VDMA, the German Business Organisation for the Energy and Water Industry (BDEW), the Federation of German Consumer Organisations (VZBV), the Association for the Non-Ferrous Metal Industry, (WVM), and the WWF all welcomed the proposed changes to a CfD system. However, a number of statements were critical or at least sceptical of the introduction of CfDs: This included the European Power and Energy Exchanges Epex Spot and EEX, the European Federation of Energy Traders EFET, the utilities BnEW and Statkraft, and the Association of Local Utilities of Municipalities (VKU), as well as several industry associations including the Business Association for Wind Energy systems (WVW), the German Solar Industry Association (BSW Solar), Association of Energy Market Innovators (BNE), the German Renewable Energy Association (BEE), German Wind Energy Association (BWE).

The main critique of CfDs in these statements was twofold: 1) several renewable energy associations advocated against the introduction of CfDs in offshore wind citing this would pave the way for CfDs in other renewable energy technologies. This was particularly the case for those renewable energy associations that represent other forms of renewable energy, such as onshore wind and solar PV. Given that other renewable energy auctions have so far not received any zero-cent bids, a switch to a CfD system was therefore viewed by some renewable energy associations as undesirable as it would have potentially reduced profits for renewable energy project operators. 2) CfDs were criticised predominantly by the utilities and energy exchanges for preventing PPAs. Interviewees raised that in the German context, CfDs would prevent green certificates required by many industrial customers of electricity as a statement of the origin of the electricity could not be issued once the electricity is remunerated and fed into the grid[16] (Interview #7, industry expert; interview #8, industry association).

Despite these reservations by some notable industry actors, the published draft bill continued to propose CfDs for auctions of centrally pre-investigated sites. In April 2022, Minister Habeck formally introduced the cabinet draft to the German Parliament. Following debates in parliament and the Bundesrat, several parliamentary committees discussed the amendments in special hearings in May 2022. Leading the discussion was the Committee for Climate Protection and Energy. Similar to the hearing in the Committee for the Economy and Energy in 2020, this hearing included expert statements from several industry experts and associations. This included the industry associations BDEW, BWO, DIHK, BDI, BEE, and DENA, among others. Each association gave a brief oral statement during the hearing with accompanying written statements published by the German Bundestag

Most statements to the committee analysed as part of this research were found to be critical of the proposed introduction of CfDs. The BEE criticised the proposal for CfDs on the basis of its cost implications for customers as well as what the implications of introducing CfDs in the offshore sector would be for other renewable, while the BDI was critical given it sees CfDs not as a market-based approach. Similarly, DENA and the DIHK questioned how effective CfDs were as a measure compared with PPAs, particularly in light of companies increasingly requiring green certificates. The issue of CfDs preventing the issuing of green certificates was confirmed as a main reason for the opposition of the DIHK during an interview (Interview #8, industry association). BWO and BDEW were generally in favour of CfDs but suggested that price caps should be set higher and advocated for the use of indexed contracts given the increases in input costs for wind turbines.

With regards to the proposed auction model for non-pre-investigated sites, most statements did not react directly to the proposed introduction of a

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[16] Under a CfD model, the operator of a wind farm has to feed any electricity produced into the grid. As a result, it cannot be used by companies that rely on green certificates for their fulfilment of sustainability criteria. Companies thus would have to acquire these certificates elsewhere.

qualitative bidding component based on willingness to pay. Only BDEW and BWO explicitly criticised these plans strongly with reference to the cost implications for the supply chain. Both associations suggested instead the introduction of a cap on the payments such as €50m / GW as is the case in other European countries.

Following the hearing, a second, revised draft of the amendment for the Offshore Wind Act was published. Two different auction designs for centrally pre-examined sites and non-investigated sites were kept. However, the revised draft no longer mentioned the introduction of CfDs for the auction model for centrally pre-investigated sites. Instead, the revised draft proposed to award tenders for centrally pre-investigated sites based on a selection of qualitative criteria (i.e., an auction design that had previously been proposed for non-pre-investigated sites). For not centrally pre-investigated sites, the auction model was now based on a second bid component using a dynamic bidding procedure.

This late change in the proposal was unexpected given previous near-unanimous calls for CfDs from the offshore industry. It also came as a surprise even to those who had previously advocated for a second bid component in the offshore auction design (Interview #7, industry expert). Furthermore, it is surprising that the Greens-led BMWK removed CfDs from the proposal given the party had previously tabled a motion for the introduction of CfDs to the offshore wind auction system and heavily advocated for the use of the mechanism in other areas (such as Carbon Contracts for Difference). Bündniss90/The Greens stated that the proposals for CfDs were dropped explicitly at the request of the FDP (Deutscher Bundestag, 2022). The proposals for the auction design for non-investigated sites based on a set of qualitative criteria including the willingness to pay were unchanged.

Throughout the process, the FDP remained critical of CfDs and voiced its opposition towards the proposed bill, despite being part of the coalition. *"We negotiated a second bid component for not pre-investigated sites as a development from the already existing subsidy regime. […]. We strongly opposed CfDs as the state should not take on risks in a volatile electricity* *market if others are willing to take on these risks. (Interview #6, political party)*. Similarly, Lukas Köhler, deputy chairperson of the FDP parliamentary group, stated on the position of the party: "*The FDP is sceptical towards a new funding regime through contracts for difference in the electricity sector, especially since in the coalition agreement we agreed on the end of all subsidies for the renewable with completion of the coal phase-out, ideally in 2030*" (translated from German and cited in Hanke, 2022)

These positions show how the FDP viewed CfDs as a form of continued subsidy for the offshore wind industry. Contrary to this, the SPD took a more nuanced view where their main goal was to ensure benefits to the domestic supply chain through prequalification and qualitative criteria in the auction design, regardless of a CfD or market premium regime (Interview #9, political party). Nonetheless, it came as a surprise that a Greens-led ministry introduced a second-bid component and did not manage to introduce a CfD system together with their coalition partner SPD, given both parties had strongly advocated for such a system. This raises the question of what fiscal political or political economy factors changed that impacted the coalition of interest for CfDs compared to the first amendment to the Offshore Wind Act in 2020 that can help explain this outcome.

Importantly, up until 2022, the market premium was financed through a renewable electricity levy (EEG Umlage) placed on consumers, although there have been exceptions for heavy energy-reliant industries. After the energy crisis following the Russian invasion of Ukraine, the electricity levy was abolished in order to reduce the costs to final consumers and is since financed through a special fund (Energy and Climate Fund) by the federal government. Hence, the levy is no longer financed through higher energy prices but through the federal budget. This raises the question of whether the government viewed the introduction of a second bid component as a source of additional government revenue.

However, a freedom of information request to the BMWK submitted as part of this PhD research revealed that the ministry had commissioned two studies that elaborated on the implications and advantages or disadvantages of implementing a CfD system compared with a second bid component under a sliding market premium model. A particular question was how much government revenue could be expected to be generated under the two systems. The first of those two studies, conducted by Consentec and Fraunhofer ISI, concludes that an auction design centred around CfDs where part of the project risks are taken on by the government, would likely increase the probability of achieving the stated renewable energy expansion goals. The study further concluded that due to the higher capital costs for developers in a model with a second bid component, it could initially be expected that the payments offered by developers would be lower than the sum of the (discounted) repayments that can be expected from a CfD model.

The second study on behalf of the BMWK conducted by economic consultants Prognos AG and others, further estimated how much revenue the government could expect to generate under a CfD system or a payment from developers through a second bid component in different electricity price scenarios. The study estimated a payment of at least €500 million per 1GW auction through a second bid component. This was contrasted with discounted repayments under a CfD system between €500 million and €3.1 billion, depending on the scenario. This also echoes the results of a study by the German Institute for Economic Research (DIW Berlin) which estimated that the introduction of CfDs would have saved electricity consumers a total of €800 million (Kröger et al., 2022). This shows that depending on the price of electricity and the respective CfD strike price, a CfD system can generate more government revenue that a negative bidding system.

Nonetheless, notable voices were criticising the planned introduction of CfDs. Veronika Grimm, since April 2020 member of the influential German Council of Economic Experts[17], together with colleagues published an

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[17] The German Council of Economic Experts is an academic body that advises the government on economic policy issues. Set up by in 1963, it is mandated with the task of providing an impartial expert view in the form of periodic assessments of macroeconomic developments in Germany. The Council consists of five members who are specialists in

opinion piece which heavily criticised the initial plans of the government to change the renewable energy remuneration scheme from a market premium to CfDs (Löschel et al., 2020). In it, the authors criticised that the proposed move away from the market premium would go against market-based competition and reverse that the state compensates renewable energy according to market conditions.

Particularly some industry associations, such as the German Renewable Energy Association BEE and the German (onshore) Wind Energy Association BWE, advocated heavily against the introduction of CfDs. In February 2022, the BEE released a study on the implications of introducing CfDs for renewable energies. The study argued that the introduction of CfDs would increase the risks for investments in renewables, cause additional economic costs, undermine the market-friendly operations of renewable energy systems, prevent green certificates and PPAs, and limit the overall diversity of actors. The two associations were particularly concerned it would lead the way to CfDs becoming the norm in other renewable sectos, which was deemed to be undesirable.

After the passing of the second amendment of the Offshore Wind Act in parliament, the industry organisations BWE, BWO, Stiftung OFFSHORE-WINDENERGIE, VDMA and WAB released a joint statement saying "*A central weakness of the amended Wind-on-Sea Act is the new tender design, which puts the price for the expansion of areas in the North and Baltic Seas first and foremost. Due to the freeze on expansion in recent years, Germany has fallen behind in international comparison. This makes it all the more important to have a functioning system that removes obstacles in the international competition for resources, skilled workers and investors*" (BWO, 2022). However, the statement did not explicitly call for CfDs as an alternative model.

The European association WindEurope went further in this regard by strongly criticising the introduction of an uncapped negative bidding process instead of CfDs (WindEurope, 2022b). Given that WindEurope's

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the field of economic theory and economic policy, and who are appointed every five years by the Federal President on the recommendation of the Federal Government.

position is heavily influenced by the manufacturers of wind turbines, this stance is not surprising as CfDs decrease a project's exposure to volatile electricity prices, as discussed in Table 9. Thus, CfDs provide greater security for the delivery of projects.

Overall, however, the calls for CfDs were notably fewer than during the discussions in 2020. The changed stance on CfDs was particularly notable with the utilities. As discussed in the previous section, in 2020 both RWE and Ørsted argued for the benefits of CfDs for the offshore wind industry. Two years later the two companies were less vocal about their position on CfDs. During an interview in April 2022, CEO of RWE Renewables Markus Krebber only criticised the proposals for the Offshore Wind Act for not providing the right incentives needed to market large amounts of green electricity to industrial customers at attractive prices (FOCUS online, 2022).

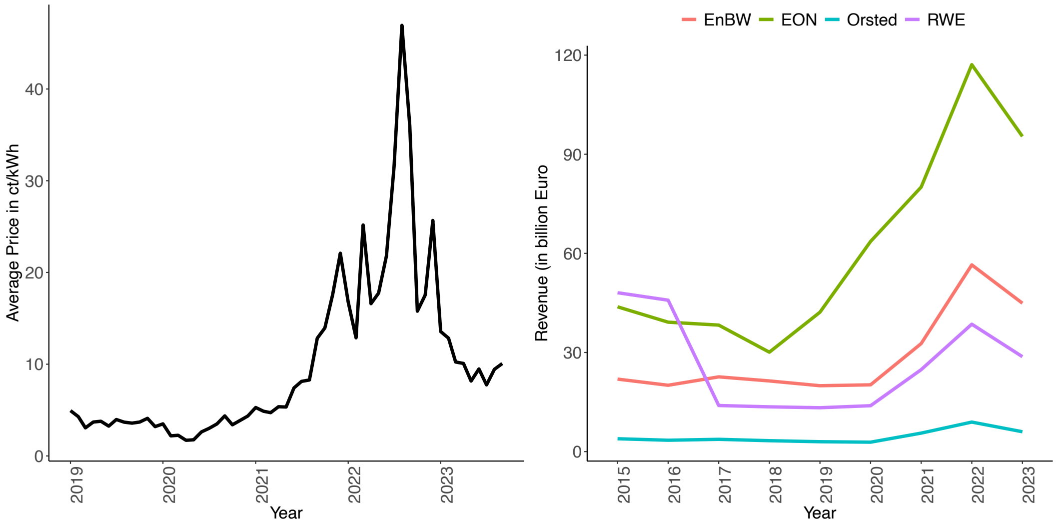
Similarly, in 2020 Vattenfall had lobbied heavily against the second bid component (partly due to their perceived violation of their entry right to upcoming auctions as elaborated above). In 2022, Vattenfall stated that the introduction of CfDs were a step in the right direction but criticised that the proposed model included a ban on double marketing (Jung, 2022). This restriction (EEG 2021 §80) prevents electricity producers from switching between CfD and direct marketing, i.e. selling of electricity without additional compensation on the spot market or through PPAs when prices were high. Instead, the company called for CfDs to be voluntary and warned of "a corset of state-controlled CfD auctions for a large part of fossil-fuel electricity" (Vattenfall, 2023, p. 5).

Of the large utilities, EnBW went furthest in their opposition to CfDs in 2022. Given EnBW's success with zero-cent bids in the previous auction round, the company was already more critical of the introduction of CfDs in 2020 than other utility companies. However, in 2022, it voiced much stronger opposition to the proposed amendments to the offshore wind auction system. Most notably the company published a study by Christoph Maurer for the EnBW Energy and Business Club that summarised the negative consequences of a switch to a CfD system compared to a continuation of the sliding market premium system (Maurer, 2022).

During interviews with two senior managers from EnBW, it was stated that according to them there was no need for the socialisation of risks in the offshore segment but rather that tenders should be awarded to those bidders with the highest risk tolerance (Interview #10, #11, utility company). Those taking on the risks of volatile electricity prices could then maximise their profits through the most efficient market integration of renewable electricity (Interview #11, utility company). At the same time, it was stated that a pricing regime with a price-based negative auction could, in some instances, be preferable as it reduces competition by limiting bids to developers with a high-risk tolerance (Interview #10, #11, utility company).

This underlines a stark contrast in the utility companies' positions toward CfDs between 2020 and 2022. The proposed changes to a CfD system coincided with a period when energy prices had been at a record high since the end of 2021. In October 2021, EU energy ministers met to exchange views on the increase in energy prices and discuss possible mitigating measures at the national and EU level. The Russian invasion of Ukraine on February 24th, 2022 exacerbated this crisis even further. Given the importance of fossil fuels as the "last-unit" in electricity markets (Christophers, 2022a, p. 1530), this led to highly volatile electricity prices. Figure 39 shows how the sudden increase in electricity prices also increased the revenue of the large utility companies. While the figure gives only revenue (as opposed to profits) for all electricity operations, the profits of renewable energy projects increased likely even more due to renewable energy being a "price taker".

Figure 39: Average monthly electricity wholesale price in Germany, and revenue from electric operations of selected utility companies



Source: Own based on Ember (2023) and LSEG Workspace/Refinitiv data. Electric operations represent revenue from regulated sales of electric power through local distribution establishments.

As a result, it raised the prospect of windfall profits for the producers of renewable electricity. In Germany, these windfall profits became possible as the renewable energy remuneration scheme operated under a sliding market premium, where producers of electricity got to keep any additional profits from selling their electricity on the spot market (Carp, 2022). The situation was so unusual that, within a few days, some utility companies managed to earn as much as they would in several months under normal circumstances. (Interview #5, industry association).

Given the high prices of electricity, the economic interest of producers of electricity including the utilities changed towards PPAs. This shift was confirmed during interviews conducted for this chapter. Interviewees mentioned, for example, that the BWO had a strong stance in favour of CfDs until the Russian invasion of Ukraine occurred. Following the Ukraine invasion, there was a significant rise in electricity prices, which led to a shift in sentiment among the association’s members. The members began to express their desire to move away from offering CfDs, emphasising their preference to see financial returns due to the changed market prices (Interview #5, industry association). Others also confirmed the increased focus on PPAs instead of CfDs by the utility companies following the increase in electricity prices (Interview #7, industry expert; Interview #9, political party).

In June and August 2023, Germany held its first offshore wind auctions under the new model for non-investigated and pre-investigated sites, respectively. With 6,8 €bn and 5.4€bn respectively, BP and Total Energies acquired the rights for a combined capacity of 7GW on non-investigated sites. The results from the first results under the new auction system came as a surprise to many industry observers (Amelang, 2023). By placing much higher bids than what has traditionally been offered, BP and Total are hoping to challenge the market shares of traditional energy utilities.

Both RWE and Ørsted criticised the results of the latest auction round for being unsustainable and increasing the risks for project delivery. Markus Krebber, CEO of RWE stated in response to the auction results: "*We participated in that auction and we would have loved to win. However, bid prices reached levels, where our return expectations would not be met even in very optimistic scenarios, so we pulled out*" (quoted in Chetwynd, 2023).

For the centrally pre-examined 1.8GW auctioned, the winning bids came from RWE, and Waterkant Energy (a bidding entity owned by the asset manager Luxcara). In addition to qualitative commitments centred around decarbonisation and sustainability, the bids were awarded based on companies' willingness to pay 784€M for the rights to develop the wind farms.

7. Discussion: German Offshore Wind Auction Results Over Time

This research aimed to understand the political economy behind the shift in the German offshore wind energy remuneration scheme by analysing the vested interests, capabilities, and powers that shaped the policy formulation process. For this we proposed a framework that hypothesised the differences and implications of different renewable energy remuneration schemes and their respective pricing regimes with regard to i) the respective government rationale, ii) risk allocation, iii) associated financial risks for private sector investors, iv) who the likely wind farm developers are, v) their preferred wind turbine types, and vi) general implications for the energy transition. We tested the framework by conducting a comparative analysis of two amendments to the German Offshore Wind Act in 2020 and 2022.

For this, we reviewed and analysed how various stakeholders reacted to the proposed amendments and engaged in the parliamentary process. The results show how certain actors had greater risk appetite vis-à-vis others and thus favoured remuneration schemes such as a one-sided CfD with zero-cent bids or a negative bidding system, which benefit developers with access to expensive capital willing to take risks on volatile electricity prices.

Our analysis found how in 2020 the industry unified and gathered behind their opposition against a second bid component, which would have shifted the risks of renewable energy projects almost entirely to the private sector. In 2022, the opposition against a second bid component was much weaker given the changed position of certain actors on the alternative proposal for a CfD system. This was found to be intricately linked to the profitability implications of the various renewable energy remuneration schemes for certain actors such as the wind farm developers and owners. While CfDs can give developers greater security through fixed prices, they can also prevent windfall profits in times of high electricity prices. The possibility of windfall profits in 2022 changed the position of certain actors such as utility companies on CfDs.

To further test our assumptions on the implications of different renewable energy pricing regimes, we can review the auction results under different systems in Germany. The results of the most recent auction under a new pricing regime for offshore wind in Germany are in stark contrast to the auction results under previous regimes. Table 10 summarises all German offshore wind farms commissioned since 2014[18]. The table states the main developer or owners (who received a FiT or won the respective auction)

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[18] Note the commissioning date concerns the date when the respective wind farm was approved or won a subsidy under the respective auction system.

and the main type of wind turbine used for each wind farm, grouped by the respective pricing regime under which they were commissioned.

The comparison of the different pricing regimes and the main developers and turbines used in each confirm several of the assumptions from Table 9. Firstly, it confirms that a FiT pricing regime favours a mix of players including smaller players, as stated in the framework of Table 9. Under the FiT regime in Germany between 2014 and 2017, a number of smaller developers and owners such as municipal utilities (Stadtwerke) developed offshore wind farms. The results of the latest auction for pre-investigated sites that relied on a set of qualitative criteria were largely similar to the results of the auctions under the market premium system with the winning bids coming from mostly large utilities. For the auction of non-investigated sites using a second bid component, the winning bids from Total and BP confirm that those developers with the highest risk appetite and access to capital are likely to win under such negative bidding system.

Table 10: German Offshore Wind Farms

Offshore Wind Pricing Regime in Germany	Wind farm	Main Developer / Owners	Wind turbines
Feed-in Tariff: Before 2017	Alpha Ventus	EWE, RWE, Vattenfall	Areva 5MW
	EnBW Baltic 1	EnVW, municipal utilities	Siemens 2.3MW
	BARD	Ocean Breeze Energy	BARD 5.0
	Riffgat	EWE, ENOVA	Siemens 3.6MW
	Meerwind Süd-Ost	WindMW	Siemens 3.6MW
	Trianel Windpark Borkum 1	Trianel (municipal utilities)	Areva 5MW
	Amrumbank West	RWE	Siemens 3.6MW
	Butendiek	WDP, insitutional investors	Siemens 3.6MW
	Dan Tysk	Vattenfall and municipal utilities	Siemens 3.6MW
	EnBW Baltic 2	EnBW and institutional investors	Siemens 3.6MW
	Nordsee Ost	RWE	Senvion 6MW
	Borkum Riffgrund 1	Orsted, Greencoat	Siemens-Gamesa 4MW
	Global Tech 1	ENTEGA, municipal utilities	Areva 5MW
	Nordergründe	WDP	Senvion 6MW
	Sandbank	Vattenfall, municipal utilities	Siemens-Gamesa 4MW
	Nordsee 1	RWE, Northland Power	Senvion 6MW
	Wikinger	Iberdrola	Siemens 5MW
	Veja Mate	Veja Mate consortium	Siemens 6MW
	Gode Wind 1 & 2	Orsted, institutional investors	Siemens 6MW
	Arkona Becken Südost	RWE, Equinor, Credit Suisse	Senvion 6MW
	Merkur Offshore	institutional investors	GE 6MW
	Borkum Riffgrund 2	Orsted, Gulf Energy	Vestas 8MW
	Hohe See	EnBW, Enbridge, Canada Pension	Siemens 7MW
	EnBW Albatros	EnBW, Enbridge, Canada Pension	Siemens 7MW
	Deutsche Bucht	Nordthland Power	GE 6MW
	Trianel Windpark Borkum 2	33 Municipal Utilties	Senvion 6MW
Market Premium: 2017-2022	Baltic Eagle (02)	Iberdrola	Vestas 9.5MW
	Gode 4 (N3)	Orsted	Siemens-Gamesa 11MW
	O1	Iberdrola	NA
	Kaskai (N4)	Innogy (E.ON)	Siemens-Gamesa 8MW
	Arcadis Ost (O4)	Parkwind	Vestas 9.5MW
	Borkum Riffgrund 1 (N1)	Orsted	Siemens-Gamesa 11MW
	He Dreiht	EnBW	Vestas 15MW
	Norther Energy OWP West	Orsted	Siemens-Gamesa 11MW
	Borkum Riffgrund W2	Orsted	Siemens-Gamesa 11MW
	Gode 3	Orsted	Siemens-Gamesa 11MW
Qualitative criteria (for pre-investigated sites): 2023 onwards	Nordesee Cluster A (N3.5)	Orsted	Vestas 15MW
	Nordsee Cluster A (N3.6)	Orsted	Vestas 15MW
	Nordlicht 2 (N6.6)	Vattenfall	Vestas 15MW
	N6.7	Waterkant	Ming Yang 18.5MW
	Nordlicht 1 (N7.2)	Vattenfall	Vestas 15MW
	Nordsee Cluster A (N3.7)	RWE	Vestas 15MW
	N3.8	EDF	Vestas 15MW
	Windanker (O1.3)	Iberdrola	NA
Negative bidding (for non-investigated sites): 2023 onwards	N11.1	BP	NA
	N12.1	Total	NA
	N12.2	BP	NA
	O2.2	Total	NA

Source: Own elaboration based on The WindPower database and 4C Offshore.

Secondly, it confirms that certain remuneration schemes and their underlying pricing regimes vis-à-vis others have further implications for the demand for wind turbines. The auction results from Germany show that there is an emerging trend of the growing importance of larger turbines under the market premium and negative bidding system. While this trend is of course impacted by a time dimension and the offshore wind turbine technology maturing further, the importance of larger and more cost-efficient turbines was confirmed through interviews with offshore wind farm developers (Interview #5, #10, #11, #13, #14). In July 2024, the asset manager Luxcara announced a preferred supplier agreement with the Chinese OEM Ming Yang for the supply of 16 turbines to their Waterkant offshore wind farm. The bidding entity Waterkant won the auction for site N6.7 in 2023 under the new system of centrally pre-investigated sites using a combination of qualitative criteria and their willingness to pay a lease price (see Table 10). In 2024, Ming Yang's offshore turbines were the world's largest available offshore wind turbines with a capacity of 18.5 MW. The supply of Ming Yang's turbines to the Waterkant wind farm will also be the first time a Chinese OEM will supply offshore wind turbines to the German market.

Thirdly, while the latest auction round using a second bidding component is too recent to see the full implications for the energy transition, the risk with the current auction designs is that these offshore wind farms might never be built if the financial returns turn out lower than expected (Ambrose, 2021). To participate in centrally pre-investigated site auctions, companies must provide a security deposit of €200,000 per megawatt of installed capacity. For sites not centrally pre-investigated, this security deposit lies at €100,000 per megawatt. The 7GW of not centrally pre-investigated sites auctioned in 2023 thus hold a combined security deposit of €700 million. This bond is meant to ensure that the winning bidder adheres to the development milestones outlined in the Offshore Wind Act and the timely completion of each offshore wind farm. Failure to meet these milestones would result in penalties and could ultimately allow authorities to seize the security deposit. However, the bidder is exempt from paying penalties if they can demonstrate that project delays were caused by factors beyond their control. Given the long permitting and development phases of offshore wind projects and the unpredictability of volatile electricity prices, not pre-investigated sites have therefore been described as “a one-way option for developers” (Interview #4, industry expert).

Developers accepting penalty fees or even the loss of their security deposit is a possibility, particularly as the payment system of the latest German offshore auction offers staggered and delayed payment options most of the lease payments are only due after the wind farm starts producing electricity (Aegir Insights, 2023). With lease payments split between a 10% upfront payment after one year of the award date and the remaining 90% staggered into annual payments over a 20-year period from the commissioning of the plant, investors would have the possibility of walking away from the project if financial returns are not as high as expected.

For example, BP is “expecting returns of 6-8%, [which] are consistent with [their] renewables and power growth engine on an unlevered basis” (BP executive vice president of gas and low-carbon energy Anja-Isabel Dotzenrath, quoted in Dykes, 2023). The final investment decision for the project will be made in 2027. As a result of the relatively much smaller security deposit, the tender can be viewed more as an option rather than a fixed commitment. Big Oil companies like BP and Shell have previously invested in ramping up their renewable business segments but abandoned these plans again after profits were deemed not high enough (Malm, 2016, pp. 370–371).

8. Conclusion:

This chapter set out to analyse the political economy behind different renewable energy remuneration schemes and their underlying pricing regimes. This was done on the example of the German Offshore Wind Act and its two recent amendments.

The analysis in this chapter confirms the importance of understanding the political economy of different renewable energy pricing regimes. Central to this political economy is the allocation of risks between renewable energy project developers and the government as well as the respective associated financial risk for investors.

In the case of the German Offshore Wind Act, supporters of a negative bidding auction design succeeded only after powerful actors such as utility companies and industry associations had temporarily changed their stance on CfDs. This shift occurred due to rising electricity prices, which increased the possibility for windfall profits, which would have been reduced under CfDs. Consequently, important actors such as the utilities accepted the alternative system of a second bid component in 2022.

The findings are of particular importance at a time when the discussion around electricity market design both in Germany as well as at the EU-level are ongoing. These results also further confirm the power of utilities in Germany, which already played an influential role in the initial introduction of renewable energy auctions and the abolishment of the FiT (Leiren and Reimer, 2021, 2018), and whose power has remained significant in the German context as can be seen from Figure 38.

While this chapter analysed the case of CfDs and negative bidding in the specific context in Germany through a comparative case study of two different points in time, further research should look into other contexts. At the same time, with growing interest in CfDs, there has also been a greater focus of the academic literature on the different specifications of how CfDs can be designed. Future research will likely benefit from a greater understanding of CfDs in general as well as the implications of different auction designs.

Appendix 6.1:

Interview Overview

Interview	Affiliation	Role	Industry	Date
1	WAB	Managing Director	Industry Association	05.09.2023
2	WindEurope	Chief Policy Officer	Industry Association	05.09.2023
3	Fraunhofer IWES	Director	Industry Expert	14.09.2023
4	Financial advisor for renewable energy	Financial Advisor for Renewable Energies	Industry Expert	28.11.2023
5	BWO	Senior Executive	Industry Association	15.12.2023
6	FDP	Scientific Advisor for Energy	Political Party	08.03.2024
7	Consentec (Consultancy)	Founder	Industry Expert	18.03.2024
8	German Chamber of Commerce	Head of Energy, Environment, Industry	Industry Association	26.03.2024
9	SPD	Member of Parliament	Political Party	10.04.2024

10	EnBW	Senior Manager	Utility company	17.04.2024
11	EnBW	Senior Manager	Utility company	17.04.2024
12	BEE	Head of Renewable Energies	Industry Association	18.04.2024
13	RWE	Senior Manager	Utility company	26.04.2024
14	RWE	Senior Manager	Utility company	26.04.2024

Appendix 6.2:

Guiding research questions for semi-structured interviews

- What is your company's general position on various auction designs (sliding market premium, second bid component, CfDs)? What are the respective reasons?
- What are the implications of different auction models or remuneration schemes for wind farm developers (particularly on profitability and implications for preferred wind turbine models)?
- Do different remuneration systems affect developer's behaviour in auctions? Do they have an influence on preferred wind turbines?
- Has your company's position on renewable energy remuneration schemes changed since 2020? If so, were there specific reasons or market changes that can explain this?
- Specifically, I am interested in the legislative process for the Second Amendment to the Offshore Wind Energy Act and why Contracts for Difference (CfDs) were removed from the law.
    - To what extent did you or your company participate in the legislative process?
    - How do you assess the outcome of the legislative processes of the Offshore Wind Act in 2020 and in 2022?
    - Have the results of the auction rounds in 2023 changed your company's position?

Chapter 7: Conclusion and Policy Implications

1. Introduction

This PhD and its findings are a timely contribution to the existing literature and policy discussions given the renewed interest in green industrial policy in the EU and beyond. In her State of the Union speech in September 2023, the European Union Commission President Ursula von der Leyen specifically addressed the importance of wind energy and the wind turbine manufacturing industry for the EU. Speaking on the proposed EU Industrial Strategy, she stated that the EU's ambition was to ensure that clean tech industries were "*made in Europe*" (von der Leyen, 2023). To reach the EU‘s target of 42.5% renewable energy in Europe's energy consumption by 2030, the Commission estimates that the total onshore and offshore wind installed capacity will need to double to 500GW. To make sure this target can be met, the Commission published an EU Wind Power Package in October 2023 aimed at supporting the European wind turbine supply chain. This package was introduced in addition to the EU Net Zero Industry Act, which allows Member States to support businesses' CapEx expenditures aimed at developing net zero supply chains.

The EU Wind Power Package sets out six pillars of proposed actions centred around Member States' i) acceleration of deployment, ii) improved auction design, iii) access to finance, iv) support against international competition, v) skills, and vi) industry engagement (European Commission, 2023). To address the prevailing financial difficulties of EU wind turbine OEMs, the proposals explicitly state the under-utilisation of OEM production capacities is due to insufficient and uncertain demand for wind turbines in the EU. To address this, the Commission proposed to improve and accelerate the permitting of European wind energy projects and to increase future project pipeline visibility. Building on the reform of the EU Electricity Market Design[19], the EU Wind Power Package calls for pre-

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[19] The reform of the EU Electricity Market Design was first proposed by the European Commission in March 2023 (COM2023 148) and agreed by the European Parliament and

qualification or non-price award criteria to be used in Member States' onshore and offshore wind auctions. Additionally, the EU Wind Power Package sets out several recommended actions to improve the EU wind sector's access to finance by i) enabling access for wind turbine manufacturing to the EU Innovation Fund, ii) instructing the European Investment Bank to introduce de-risking tools and guarantees, and iii) allowing Member States to utilise the flexibility of EU Stade Aid rules until the end of 2025. To further protect the domestic wind turbine manufacturing sector, the European Commission also pledged to monitor possible unfair trade practices by non-EU OEMs and to promote the adoption of additional EU standards for all participants in the wind sector.

The policy proposals of the EU Wind Power Package were widely well-received. Most EU Member States, as well as important industry actors including European OEMs (Nordex, Vestas, Siemens Gamesa), developers (EDP, Enel, Equinor, Iberdrola, Ørsted, RWE, Vattenfall) and industry associations (WindEurope, BDEW), signed the European Wind Charter to commit to the proposed actions. The wind energy association WindEurope called the EU Wind Power Package a "*game changer*" for Europe (WindEurope, 2023a).

Despite the overall positive response from industry to the EU Wind Power Package, the question arises whether or not these policy proposals will sufficiently address the findings and policy implications emerging from the research of this PhD. The following Section 2 will briefly summarise the main *empirical* findings and their interdependencies. The main *theoretical* contributions of this PhD will be summarised in Section 3. Together these findings can be used to assess the above outlined industrial policies by the European Commission. Section 4 will then draw further policy implications not currently addressed by EU or German industrial policy.

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the Council in April and May 2024. The legislation calls for the implementation of CfDs, or equivalent schemes with the same effects, to encourage energy investment in the EU and ensure price stability.

2. Summary of the empirical chapters and their main findings

2.1. What has driven cost reductions in renewable energy projects?

One contribution of this PhD has been to further investigate the drivers of past cost reductions in renewable energy projects. While learning curves are an existing and popular method in both academia and policy debates to forecast trends in cost reductions, their methodological limitations were criticised as oversimplistic and too reductionist. Instead, building on concepts from the evolutionary economics literature, we analysed the effect of technology-push and demand-pull dynamics on renewable energy cost reductions through a cross-country econometric study of onshore wind and solar PV energy projects. These findings are presented in Chapter 3. A positive relation between demand-pull dynamics, proxied by cumulative financial investments and lower average installed costs, was found for both onshore wind and solar PV projects. For both technologies, the demand-pull effect became stronger in the latter half of the full period between 2004 and 2017 that was analysed. Using financial investments as a proxy for demand-pull dynamics further allowed us to distinguish between types of finance. Although this was done on a relatively binary distinction between private investments and investments involving public actors, this revealed a nuanced picture confirming that the *type* of financial investors in renewable energy matters (Semieniuk et al., 2021). More importantly, the analysis also indicated a changing relative importance in the types of financial investors over time, with private investments becoming more important for cost reductions as renewable energy technologies mature. This justified a further investigation of dynamics at play on the demand side for cost reductions on renewable energy projects and their implications for the manufacturers of renewable energy technologies.

2.2. How have the Technology and Demand Regimes in the wind energy sector changed since the adoption of renewable energy auctions in Europe in 2017 and what effect has this had on wind turbine OEMs?

In Chapter 4, we investigated the technological developments and cyclical elements on the demand side through a comparative study of the European onshore and offshore wind turbine manufacturing industries. This responds to Malerba et al.'s (2016) call for greater academic inquiry into the nature and importance of Demand Regimes. Using the critical case study of demand for wind turbines in Germany, this analysis was done with regard to changes in the onshore and offshore wind energy sectors since the switch in 2017 from feed-in tariffs to renewable energy auctions. Renewable energy auctions were found to have increased cost pressures resulting in the need for European wind turbine OEMs to build ever bigger and simultaneously more cost-effective turbines. We argued this policy change and the resulting shifts in the structure and composition of demand are central to understanding the industrial dynamics in the wind turbine manufacturing sector.

Both European wind turbine OEMs and European policymakers often warn of competition from Chinese imports in the wind turbine manufacturing sector. A common argument has been that the cost advantages of Chinese OEMs are undercutting European OEMs and threatening domestic manufacturing industries. However, the findings from Chapter 4 point to internal changes within the structure and composition of European demand as the main cause of the financial difficulties of European wind turbine OEMs. When Germany switched from a feed-in tariff to wind energy auctions in 2017, this set about a process of shortening wind turbine manufacturing cycles and increased cost competition among European wind turbine OEMs.

2.3. How have wind turbine OEMs responded to cost pressures and changes in demand?

European wind turbine OEMs have had to respond to increased cost pressures and decreased profit margins, by adapting their internal and external organisational configurations. We analysed these organisational transitions as part of so-called Structural Cycles in the wind turbine manufacturing sector in Chapter 5. The organisational reconfigurations of three main European wind turbine OEMs, Enercon, Nordex, and Siemens Gamesa, were analysed and found to have been made directly in response to the macro-meso dynamics of institutional change, technological developments, and changes in demand, reported in Chapter 4. A common theme of all these organisational reconfigurations was either the closure of EU production facilities or the move to cheaper production locations, often outside of the EU. This process often involved giving up strategic control of certain activities or elements of the wind turbine supply chain. At the same time, the analysis in this Chapter revealed diverging approaches between firms even when they are affected by the same regulatory changes. In particular, this analysis has revealed the important role of strategic mergers and acquisitions as well as specific technology choices for OEMs.

2.4. What is the political economy of renewable energy remuneration schemes and how can this help us understand future changes in Demand Regimes?

The analyses from Chapters 3 to 5 reveal the importance of demand itself, and also the structure and composition of the Demand Regime. This is the case not only for renewable energy cost reductions but also for the structure of supply of renewable energy technologies such as wind turbines. In Chapter 6 we unpacked the political economy underpinning one of the main policy measures shaping the Demand Regime for offshore wind turbines, namely renewable energy remuneration schemes. This was analysed using the case study of the German Offshore Wind Act. By analysing the vested interests, powers, and capabilities of different actors in the German offshore wind sector, Chapter 6 showed how certain actors advocating for specific directions in the German offshore wind energy remuneration scheme vis-à-vis others. Although the offshore wind sector is a particular case, the German government has stated that it wants to discontinue all renewable energy subsidies once the coal phase-out is complete. Thus, understanding the implications of different types of renewable energy remuneration schemes and their underlying pricing regimes can hold important lessons learned also for other renewable energy technologies beyond the offshore wind sector.

3. Theoretical contributions

In addition to the empirical findings, the PhD makes important theoretical contributions and aims to fill several gaps in the existing literature. This section will elaborate on these contributions and implications for future research in renewable energy sectors and green industrial policy.

3.1. Structural learning in renewable energy technologies

The PhD contributes to a better understanding of cost reductions and structural learning in renewable energy technologies. So far, most of the literature centred around renewable energy learning curves has been centred on a reductionist approach and there has been a lack of research integrating macro and micro approaches to structural learning, organisational aspects, and industrial dynamics. The overall results of the different empirical chapters demonstrate a multifaceted and multi-tiered process of structural learning, driven by interrelated technological advancement, changes to the structure and composition of demand, and institutional support through strategic policy interventions. Different methodologies with distinct research methods were adopted in each respective chapter. However, the combined PhD thesis shows why an integrated approach focusing on different units of analysis and utilising mixed methods (with both quantitative analyses and qualitative data triangulation) is essential for understanding cost reductions and structural learning in renewable energy technologies.

3.2. Green Windows of Opportunity in renewable energy technologies

Analysing the technological advancements in wind turbines and the structure and composition of demand for wind turbines in Europe has further contributed to the existing academic literature on Green Windows of Opportunity (Dai et al., 2020; Lema et al., 2020). This was done by utilising the Green Windows of Opportunity framework to study the perspectives of incumbent firms in the wind turbine manufacturing industry. The analysis has shown how incumbent OEMs had to adapt to the changing demand patterns for wind turbines, including turbine design preferences and technology cycles within the European markets. The internal changes to the structure and composition of demand within the European market were found to be more important drivers for the financial performance and industrial market position of European wind turbine OEMs than the threat of competitors from latecomer countries. At the same time, this analysis confirmed the importance of government policies and institutional-led Windows of Opportunity in renewable energy technologies. Existing literature on Green Windows of Opportunity largely views changes to industrial leadership as the outcome of *exogenous* changes in technology, demand, or institutions (Ferraz et al., 2022). The PhD has further contributed to the importance of understanding *endogenous* change with firms, by reference to internal dynamic capabilities and organisational configuration of firms in order that they can benefit from Windows of Opportunity.

3.3. Further development of the Structural Cycle framework and the role of Demand Regimes

Through the analyses in Chapters 4 and 5, we have further developed the existing framework of Structural Cycle analysis introduced by Andreoni et al. (2016). The analyses in Chapters 4 and 5 reinforce the importance of a multi-tiered approach, by which macro-structural dynamics of technology and demand transitions, are viewed alongside micro-founded theories of firm capabilities and organisational change in renewable energy technology manufacturing sectors. In particular, this approach involved further developing the notions of the structure and composition of demand. The importance of Demand Regimes as analogous to Technology Regimes had already been brought forward a long time ago (Malerba et al., 2007). However, so far the academic literature has largely ignored the importance of structural and cyclical elements within the demand side (exceptions include Garavaglia et al. (2012) for the pharmaceutical industry and Malerba et al. (1999) for the computer industry). This PhD has therefore contributed further to the understanding of the role of the Demand Regime in renewable energy technology sectors by extending the analysis to the onshore and offshore wind turbine manufacturing sectors. The role of public policy was found to be particularly relevant in shaping the structure and composition of demand for wind turbines. Therefore, the findings hold important insights for industrial policy in renewable energy technologies and how policies need to be aligned with technological and organisational changes over time as well as with the changes in demand and cycles of investment within the economic sector they are designed to target.

3.4. Importance of the institutional political economy of renewable energy remuneration

Demand Regimes in renewable energy technologies are largely shaped by government policies such as feed-in tariffs or renewable energy auctions. This makes the interests and ability of different actors to influence industrial and energy policies an important aspect to uncover. In Chapter 6 we have conducted an institutional political economy analysis of the Demand Regime for offshore wind turbines in Germany. In doing so we proposed a framework on the main renewable energy pricing regimes and their rationale and implications with regard to risk allocation, associated financial risks for private sector investors, who the likely wind farm developers are, their preferred wind turbine types, and general implications for the energy transition. Particularly the allocation of risks between renewable energy project developers and the government as well as the respective associated financial risk for investors was found to be central to understanding the motivation of different actors shaping the Demand

Regime. Overall, this analysis has contributed to the emerging literature on the political economy of renewable energy.

4. Policy implications

The results of this PhD indicate that industrial policies, particularly those designed to address the demand side, need to be carefully designed to ensure they drive the exact type of change desired. This section summarises the main policy implications from the research findings of the PhD and compares them against the current industrial policies for renewable energy technologies in the EU.

4.1. It's the type of demand that matters

The EU's goal to reach 500GW of installed wind energy capacity by 2030 together with the EU Wind Power Package which aims to accelerate deployment and reduce barriers to permitting is a step in the right direction to address the low levels and uncertainty of demand for wind turbines in the EU. The positive relationship between cumulative financial investments and cost reductions in renewable energy projects suggests that policymakers should focus on enhancing financial instruments and mechanisms that attract investments in this sector. This could include offering tax incentives, grants, or loans to stimulate demand-pull dynamics. However, a nuanced understanding of the type of financial investment in renewable energy projects is critical. In particular, it is important to understand the nature of commercial entities that are developing and operating renewable energy projects (such as wind farms) in order to understand the potential effects of the Demand Regime on industrial dynamics in the sector. The stylised facts emerging from this PhD show that the business of manufacturing wind turbines is becoming increasingly difficult for European OEMs under current demand conditions in the EU. This is in line with Christophers (2024), who argues that the business of deploying wind and solar energy is not financially attractive to most investors.

4.2. Non-price criteria in renewable energy auctions to reduce price-based competition

Renewable energy auctions in the EU remain predominately price-based tenders. The results from this PhD have shown how the widespread switch to price-based renewable energy auctions in the EU has shortened the wind turbine cycles and started a ‘price war’ among wind turbine OEMs. In order to support the European wind turbine manufacturing industry, renewable energy auctions should be designed to award tenders based on non-price criteria. The EU Wind Power Package states that due to being able to manufacture on average 20% cheaper, Chinese OEMs are becoming a serious threat to the domestic supply chains. To address this, the EU Commission has proposed to use pre-qualifications and non-price criteria in renewable energy auctions, effectively aimed at barring Chinese OEMs from entering the EU market. The Net Zero Industry Act already instructs EU Member States to use 30% of non-price criteria in renewable energy auctions. This effectively allows Member States to favour European OEMs. However, the fact remains that European OEMs have been struggling financially despite accounting for 85% of the EU wind energy market (94% in the offshore sector). If the remaining 70% of award criteria continue to be entirely price-based, the competition and cost pressure among European OEMs is likely going to continue, even if Chinese OEMs will in theory be denied access to the EU market. Carefully designed CfDs indexed by inflation and commodity prices could help to address the implications for European wind turbine OEMs within the EU market. Auction designs based on value creation rather than just price could further support the European wind turbine supply chain.

4.3. “Made in Europe” industrial policy aimed at the entire supply chain.

Ursula von der Leyen’s call that “the future of [Europe’s] clean tech industry has to be made in Europe” was well received by the European wind turbine manufacturing industry (WindEurope, 2023b). However, there remains a lack of clarity on what level of production this is to be achieved. The analysis of Chapter 5 of this PhD focused on the European wind turbine

OEMs and their organisational reconfiguration in response to changed market demand and increased cost. For Europe's wind turbine OEMs, the calls for "made in Europe" are undoubtedly interpreted to be at the level of the assembled turbine. However, all OEMs investigated in Chapter 5 showed a trend of decreasing vertical integration and increased sourcing inputs from non-EU countries or shifting parts of their production outside of the EU. Industrial policy measures should therefore target the entire supply chain including wind turbine components. There remain bottlenecks in key supply chain elements such as offshore foundations and power cables or installation vessels that are booked up for several years ahead, which threatens to further undermine the goal of truly "made in Europe" wind turbines. Expanding production capabilities and investments in ports, grids, vessels, cranes and skilled workers will be needed to ensure a strong European wind turbine manufacturing industry. In addition to this, industrial policies should support the organisational transitions of wind turbine OEMs by providing frameworks for strategic mergers and acquisitions, which were shown in Chapter 5 to be of central importance.

4.4. The continued importance of price controls and re-risking

In 2014, the EU first instructed its Member States to switch from feed-in tariffs to renewable energy auctions. The main objective was to correct "serious market distortions and increasing costs to consumers" by introducing market-based mechanisms and increasing competition among renewables (European Commission, 2014). Nonetheless, mechanisms such as market premiums and contracts for difference (CfD) have since been used by most EU Member States and continue to constitute a form of price control. Despite the resurgence of price control mechanisms in policy and academic debates (Weber, 2021), these mechanisms are criticised by both the left and right sides of the political spectrum. Free-market-based advocates such as the FDP in Germany see CfDs as a continuation of subsidies and a form of unwanted state interference. Others have criticised these mechanisms as unnecessary de-risking of private sector investments by the government (Gabor, 2023).

By analysing the implications of different renewable energy remuneration schemes and their respective pricing regimes, the results from Chapter 6 have shown the potential implications for shifting the risks of renewable energy projects onto the private sector. From an EU perspective, de-risking in the energy transition is not only about ensuring the expansion of renewable energy but also addressing energy security and dependencies from other countries. Chinese wind turbine OEMs have achieved substantial technological catch-up, progressing from 'following' to 'running alongside,' and now to 'leading' in wind technology development globally (GWEC, 2023, p. 54). In the past two to three years, Chinese OEMs such as Mingyang, Goldwind, and Haizhuang have introduced offshore turbines ranging from 16 to 18 MW, surpassing those of European OEMs. In February 2023, Envision launched a 10 MW onshore turbine, and two weeks later, SANY unveiled the 230/8-11MW prototype, currently the largest onshore wind turbine in the world. De-risking or controlling the price of renewable electricity not only supports the deployment and expansion of renewable energy but also has important implications for renewable energy technology OEMs such as wind turbine manufacturers. Therefore, it can serve as a crucial policy instrument to prevent the formation of dependencies on other countries in the wind energy sector.

4.5. Conflict management and industrial policy in the renewable energy transition

Understanding the vested interests and capabilities of the multitude of different actors can help design the right types of remuneration schemes. Policymakers need to be aware of the context-specific challenges they face when changing institutions and policies that could impact how resources are allocated amongst various groups (Andreoni and Chang, 2019). Resistance from certain interest groups might be so strong that they can undermine certain policy goals. Importantly, support or resistance can come from different groups or sub-groups, whose interests might be aligned or not aligned with the industrial policy measures. An important policy implication from this PhD is that conflicts can arise not only between existing '*sunset*' interest groups around fossil-fuel extraction and new '*sunrise*' interest groups centred around renewable energy (Semieniuk et al., 2021), but also within '*sunrise*' groups. '*Sunrise'* groups can include i) different types of renewable energy technologies, as well as ii) different actors within a technology such as offshore wind farm developers and offshore wind turbine manufacturers. Certain actors with access to expensive capital and willingness to take risks on volatile electricity prices might push for renewable energy pricing regimes that favour actors with greater risk appetite. However, policy makers in countries like Germany who stated their ambitions to discontinue renewable energy subsidies in the near future should be aware of the implications of shifting the risks entirely to the private sector.

5. Limitations and further research

This PhD has aimed to contribute to our understanding of the drivers of cost reductions and industrial dynamics in renewable energy technologies using the case study of the wind energy sector. This was done using a mixed-methods and case study approach as detailed in Section 3 of Chapter 2. The justification for this approach stemmed from the complexities of the analysed dynamics as well as available quantitative data. One of the primary limitations of this research is the availability and quality of disaggregated quantitative data on financial investments in renewable energy technologies and renewable energy project developers. Although the mixed-methods approach was designed to mitigate this issue by triangulating against qualitative insights, the reliance on existing datasets may still constrain the scope of quantitative findings. Future research could benefit from the development of and utilisation of more comprehensive datasets on wind farm developers that span longer periods and cover more countries.

The notion of the demand regime in the wind energy sector was elaborated on using the critical case study of Germany. With better available quantitative data on the developers and operators of wind farms, future research should expand the analysis to cover the structure and composition of demand for wind turbines across Europe. This could, for example, be done using social network analyses or history-friendly models. History-friendly models are simulation tools used to replicate and understand the evolutionary dynamics of industries by incorporating detailed historical events, firm behaviours, and market interactions. These models utilise both quantitative data—such as market shares, R&D expenditures, and sales figures—and theoretical frameworks that capture processes like innovation and competition (Pyka and Nelson, 2018). History-friendly models could be a pivotal addition in modelling industrial dynamics in renewable energy technologies by simulating how different policy interventions, technological advancements, and market conditions could influence the growth and transformation of the renewable energy sector.

While the mixed-methods approach used in this PhD provides a nuanced understanding of specific contexts through case studies, the generalisability of these findings to other contexts or industries may be limited. Qualitative methods, particularly the use of in-depth interviews, are necessarily subject to researcher interpretation and potential bias. While triangulation and methodological rigour aim to minimise these biases, they cannot be eliminated entirely. Case studies can also be very context-specific and may not easily translate to different settings. By comparing the industrial dynamics between the onshore and offshore wind energy segments, the PhD has added a comparative element. However, conducting further comparative sector-specific and region-specific studies would allow for a more detailed examination of the unique characteristics and challenges faced by other renewable energy industries and regions.

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Chapter 1

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