# Actors, Institutions and Innovation Processes in New Path Creation

# –

# The Regional Emergence and Evolution of Wind Energy Technology in Germany

Von der Naturwissenschaftlichen Fakultät der
Gottfried Wilhelm Leibniz Universität Hannover

zur Erlangung des Grades
Doktor der Naturwissenschaften (Dr. rer. nat.)

genehmigte Dissertation
von
Diplom-Geograph Jasper Wellbrock, geb. Ammermann

2021

Referent: Prof. Dr. rer. nat. Rolf Sternberg

Korreferent: Prof. Dr. rer. pol. Tom Brökel

Tag der Promotion: 04.03.2021

## Kurzzusammenfassung

Neue Technologien entstehen nicht zufällig im Raum. Dies betont die aktuelle Literatur im Bereich der Evolutionären Wirtschaftsgeographie. Die Evolution der ökonomischen Landschaft ist verbunden mit Prozessen der Pfadkreation, des regional branching und regionaler Pfadabhängigkeit. Die zugrundeliegenden Prozesse und die Rolle von Akteuren sind allerdings nur wenig untersucht und unzureichend verstanden.

An dieser Forschungslücke setzt die vorliegende Dissertation an. Die Arbeit analysiert die Akteure, Mechanismen und Prozesse der Pfadkreation und der Ko-Evolution von Technologie und Institutionen. Das übergeordnete Ziel der Dissertation ist es, eine theoretische Grundlage und empirische Evidenz zur regionale Entstehung und Entwicklung neuer Technologien zu schaffen. Die zentrale Forschungsfrage der Arbeit lautet: Wo, wie, durch wen und unter welchen Bedingungen entstehen neue Technologien?

Basierend auf Forschungen aus der Evolutionären Wirtschaftsgeographie, der Institutionellen Wirtschaftsgeographie sowie den Sozial- und Organisationswissenschaften wird ein überarbeitetes theoretisches und konzeptionelles Rahmenkonzept entwickelt, mit welchem die regionale Entstehung und Entwicklung neuer Technologien analysiert und erklärt werden kann. Das Rahmenkonzept bietet eine akteurszentrierte, dynamische Perspektive und geht über technologische Diversifizierung und Prozesse des regional branching hinaus. Die Dissertation liefert damit einen Beitrag zur aktuellen theoretischen Diskussion über die Pfadkreation und die Bedeutung von Institutionen und institutionellem Wandel für die Evolution neuer Technologien.

Die empirische Analyse basiert auf einer erklärenden Fallstudie über die Entstehung und Evolution der Onshore Windenergietechnologie in Deutschland. Für die Analyse wurde eine qualitative Inhaltsanalyse durchgeführt. Die Daten wurden durch eine Dokumentenanalyse und 40 Tiefeninterviews mit relevanten Stakeholdern gesammelt.

Die Ergebnisse zeigen, dass neben der Energie- und Umweltpolitik auf nationaler Ebene die Pfadkreation stark vom regionalen institutionellen Umfeld beeinflusst wurde. Des Weiteren geben die Ergebnisse qualitative Einblicke in verschiedene Arten von Akteuren und deren Motive und Aktivitäten in einer neu entstehenden Technologie. In Bezug auf die Mechanismen werden in der Arbeit unternehmerische Aktivitäten und die Diversifizierung der regionalen Industrie als Schlüsselmechanismen für die Schaffung neuer regionaler Pfade identifiziert. Diese wurden später durch verschiedene exogene Impulse verstärkt. Die Bedeutung der Prozesse ist jedoch regional unterschiedlich. Die Arbeit zeigt zudem Zusammenhänge und Rückkopplungsmechanismen zwischen der technologischen Entwicklung und dem institutionellen Umfeld auf und stellt fest, dass die Ko-Evolution unterstützender Institutionen wie technische Standards oder das Stromeinspeisungsgesetz und das Erneuerbare-Energien-Gesetz ein wesentlicher Erfolgsfaktor für die Entwicklung der Windenergietechnologie war. Es wurde festgestellt, dass die Ko-Evolution aktiv von Akteuren vorangetrieben wurde, die ihr institutionelles Umfeld geprägt und verändert haben.

**Schlagworte:** Evolutionäre Wirtschaftsgeographie; Pfadentstehung; Institutionen; Ko-Evolution; Windenergie

# Abstract

The recent literature of evolutionary economic geography points out that new technologies do not emerge randomly across space. The evolution of the economic landscape is associated with processes of path creation, regional branching and regional path dependence. However, the underlying processes and the role of the actors are under-investigated and poorly understood.

This research gap is the starting point of this dissertation. The thesis focuses on the actors, mechanisms and processes of path creation and the co-evolution of technology and institutions. The overall aim of the dissertation is to provide theoretical foundation and empirical evidence to understand and explain the regional emergence and evolution of new technologies. The key question of the thesis is: Where, how, by whom and under which conditions do new technologies emerge.

Based on research in evolutionary economic geography, institutional economic geography, and social and organizational science, a revised theoretical and conceptual framework is developed for analyzing and explaining the regional emergence and evolution of new technologies. The framework provides an actor-centered, dynamic perspective and goes beyond technological diversification and regional branching processes. Hence, the dissertation contributes to the current theoretical debate on path creation and the role of institutions and institutional change for the evolution of new technologies.

The empirical analysis is based on an explanatory case study on the emergence and evolution of the onshore wind energy technology in Germany. A qualitative content analysis was employed. Data were collected by a document analysis and 40 in-depth interviews with relevant stakeholders.

The findings show that besides energy and environmental policies at the national level, path creation was strongly influenced by the regional institutional environment. The findings also give qualitative insights into different types of actors and their motives and activities in an emerging technology. Concerning the mechanisms, the thesis identifies entrepreneurial activities and regional industry diversification as the key mechanisms in new regional path creation. These were later strengthened by various exogenous impulses. The relevance of the processes differs between regions. The thesis also reveals interrelations and feedback mechanisms between technological development and the institutional environment and finds that the co-evolution of supporting institutions like technical standards, the Electricity Feed-in Act and the Renewable Energy Sources Act was a key success factor for the evolution of wind energy technology. It was found that co-evolution was driven by actors who shaped and changed their institutional environment.

**Key words:** evolutionary economic geography; new path creation; institutions; co-evolution; wind energy

## Acknowledgements

First of all, I would like to thank my supervisor Prof. Dr. Rolf Sternberg for providing me the opportunity to work on this project and for his intellectual guidance and patience. I am also very thankful to Prof. Tom Brökel for consenting to be a co-referee and Prof. Dr. Benjamin Burkhard for kindly agreeing to serve as the chairman of the examination committee.

Moreover, I am grateful to my friends and (former) colleagues at the Institute of Economic and Cultural Geography for a very pleasant working atmosphere, many interesting formal and informal discussions, vital coffee breaks and great Christmas theme parties.

Many thanks to all interview partners who were willing who share their time and knowledge with me.

Finally, I would like to thank my parents and my brother for providing me with good education and supporting me in all my academic endeavors, for their belief in me, and for encouraging me to follow my own path.

Last, but certainly not least, I would like to thank my family: My dear wife Kathrin for her unbelievable and unconditional support, love and patience, and for our time together. Without her, I would never have made it to where I am today. Thank you. And my daughters Hanna and Frieda for their smiles and laughs, and for taking care of the necessary distraction. Although they delayed the research progress to some extent, they have made my efforts worthwhile. I am glad that, from now on, we will have more moments together again.

# Table of Contents

# List of Figures

## List of Tables

## List of Abbreviations

| | |
|---|---|
| BauGB | Baugesetzbuch (Federal Building Code) |
| BDEW | Bundesverband der Energie- und Wasserwirtschaft (German Energy and Water Association) |
| BEE | Bundesverband Erneuerbare Energien e.V. (German Renewable Energy Federation) |
| BMBF | Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research), since 1994, formerly BMFT |
| BMFT | Bundesministerium für Forschung und Technologie (Federal Ministry for Research and Technology), until 1994, later BMWi |
| BMU | Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry of Environment, Nature Protection and Reactor Safety) |
| BMWi | Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy) |
| BWE | Bundesverband WindEnergie e. V. (German Wind Energy Association) |
| CDU/CSU | Christlich Demokratische Union / Christlich-Soziale Union (Christian Democratic Union / Christian Social Union (Bavarian sister party)) |
| DENA | Deutsche Energie-Agentur (German Energy Agency) |
| DEWI | Deutsches Windenergie-Institut (German Wind Energy Institute) |
| DFIG | Doubly-fed induction generator |
| DFVLR | Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (German Aerospace Research and Testing Establishment), until 1997, later DLR |
| DGW | Deutsche Gesellschaft für Windenergie (German Society for Wind Energy) |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre); since 1997, formlery DFVLR |

| | |
|---|---|
| EEG | Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act) |
| EESG | Electrically excited synchronous generator |
| EWE | Energieversorgung Weser-Ems AG, a regional energy supply company |
| FGW | Fördergesellschaft Windenergie e.V. (Federation of German Wind Power) |
| GROWIAN | GROWIAN (abbreviation for Großwindanlage, "large wind power plant") was a publicly funded onshore wind turbine with a capacity of 3 MW, which was installed in 1983 in Kaiser-Wilhelm-Koog at the western coast of Schleswig-Holstein. |
| HAWT | Horizontal axis wind turbine |
| HSW | Husumer Schiffswerft, German wind turbine manufacturer |
| ISET | Institut für Solare Energieversorgungstechnik e. V. (Institute for Solar Energy Technology), until 2009, later IWES |
| IWES | Fraunhofer-Institut für Windenergie und Energiesystemtechnik (Fraunhofer Institute for Wind Energy and Energy System Technology), since 2009, formerly ISET |
| IWB | Interessenverband Windkraft Binnenland e.V. (Inland Wind Power Association) |
| kWh | Kilowatt per hour |
| MNC | Multinational corporation |
| MW | Megawatt |
| M&A | Mergers and Acquisitions |
| PMG | Permanent magnet generator |
| R&D | Research and Development |
| RES | Renewable energy sources |
| SCIG | Squirrel cage induction generator |

| | |
|---|---|
| SPD | Sozialdemokratische Partei Deutschland (Social Democratic Party of Germany) |
| StrEG | Stromeinspeisungsgesetz (Electricity Feed-in Act) |
| TU Berlin | Technical University of Berlin |
| UCTE | Union for the Co-ordination of Transmission of Electricity |
| VAWT | Vertical axis wind turbine |
| VDEW | Verband der Elektrizitätswirtschaft (German Electricity Association) |
| VDMA | Verband Deutscher Maschinen- und Anlagenbau (German Engineering Federation) |
| WAB e.V. | Windenergie-Agentur (Wind Energy Agency), a business network for the offshore wind energy in Northwest Germany |

# 1 Introduction

## 1.1 Background and research topic

The emergence and spatial evolution of new technologies and industries is a key issue in economic geography. Technological development and the creation and diffusion of knowledge and innovation are considered to be of the major sources of economic growth. Over the past decade, an evolutionary perspective of economic development has gained increasing importance in analyzing and explaining the evolution of technologies, institutions or industries (BOSCHMA/FRENKEN 2006; ESSLETZBICHLER/RIGBY 2007; HASSINK ET AL. 2014; HENNING ET AL. 2013; MARTIN 2010; MARTIN/SUNLEY 2006). Evolutionary economic geography offers a dynamic, explanatory perspective on economic, technological and institutional change. Drawing on evolutionary economics, path dependence and lock-in are central concepts for studying the economic landscape. An evolutionary perspective emphasizes the path-dependent nature of technology, economic and regional development. Path dependence theory, as associated in particular with the work of ARTHUR (1994) and DAVID (1985), builds on the idea that "history matters". It is argued that initial choices, small events or historical accidents trigger a self-reinforcing process and positive feedbacks through which a path may become locked in (ARTHUR 1994; DAVID 1985; HASSINK 2005; MARTIN/SIMMIE 2008; MARTIN/SUNLEY 2006). The evolution of a technology is characterized by a multiplicity of potential technological paths. A technological path or trajectory is a result of a series of subsequent decisions and events (DOSI 1982, 1988). Or, in other words, a technological path is a result of a firm's technological solutions and user decisions.

The concept of path dependence provides a theoretical framework to explain why technologies, products, institutions and decisions follow specific trajectories in different regions. It is argued that the emergence of a new technology in a region strongly depends on the pre-existing economic, technological and institutional structures in that region (MARTIN/SUNLEY 2006; MARTIN 2010; NEFFKE ET AL. 2011). New activities are not random, but related to existing activities. Evolutionary approaches emphasize, in particular, the role of technological relatedness between industrial paths in a region. The process, when a new industry grows out of the existing industrial structure of a region, is also seen as a regional branching process (BOSCHMA/FRENKEN 2011a; BOSCHMA ET AL. 2013; NEFFKE ET AL. 2011).

However, the theoretical debate on the classic concept of path dependence has drawn substantial criticism. One major point of criticism relates to the strong emphasis on initial conditions, historical accidents and random processes reducing path dependency on small events and coincidences (GARUD/KARNØE 2001a; HASSINK ET AL. 2019; MARTIN 2010; MARTIN/SUNLEY 2006; SYDOW ET AL. 2009). This turns the emergence of a new industrial and technological path into an accidental, serendipitous event. Another limitation of the concept is that it pays little attention to endogenous mechanisms of technological change and development and underestimates the active role that actors might play in generating novelty (GARUD/KARNØE 2001a; MARTIN/SUNLEY 2006; SIMMIE 2012). Thus, path dependence theory does not provide a sufficiently adequate explanation for how new paths emerge.

Because of this, GARUD and KARNØE (2001a) introduced the concept of path creation as an alternative perspective on path dependence. Emphasizing the active role of human agency in shaping technological paths, this offers a sociological perspective on the emergence of new technologies and industries. Path creation suggests that paths can be deliberately created by actors as they are able to shape their environment and deviate from an established trajectory. In contrast to path dependence theory, initial conditions are influenced and constructed by actors (GARUD/KARNØE 2001a, 2003; GARUD ET AL. 2010; MARTIN 2010). Thus, actors can influence the creation and development of new technological paths. Although the sociological path creation perspective does not address regional aspects, it is a promising approach to explain how economic actors like entrepreneurs and firms create new opportunities for new technological development. In recent years, the concept has gained growing interest in evolutionary economic geography and is increasingly discussed in the literature (HASSINK ET AL. 2019; MACKINNON ET AL. 2019; MARTIN 2010; MARTIN/SIMMIE 2008; MARTIN/SUNLEY 2006) and applied in analyzing new path development (BINZ ET AL. 2016; CHLEBNA/SIMMIE 2018; DAWLEY 2014; DAWLEY ET AL. 2015; SIMMIE 2012; SIMMIE ET AL. 2014; STEEN 2016; STEEN/HANSEN 2018). In economic geography, path creation refers to “the emergence and growth of new industries and economic activities in regions” (MACKINNON ET AL. 2019: 114). Since many mechanisms of path creation like entrepreneurial activities, diversification, labor mobility or social networking are mostly localized at the regional level, path creation has a strong regional dimension.

Over the last decade, evolutionary economic geography has discussed the concept of co-evolution and its potential to explain the spatial evolution of the economic landscape (BOSCHMA/FRENKEN 2009; GONG/HASSINK 2019; SCHAMP 2010; STRAMBACH 2010). The concept refers to the interrelations of technological, social and institutional change (GEELS 2004) and opens up a systemic perspective as to "how technology is shaped by social, economic, and political forces alike; and how, in the same process, technologies and technology systems shape human relations and societies.“ (RIP/KEMP 1998: 328). It is generally assumed that institutions co-evolve with technologies in a path dependent way (BOSCHMA/FRENKEN 2006; MURMANN 2003; NELSON 1994; RIP/KEMP 1998; STRAMBACH 2010).

From an evolutionary perspective, the development of new technologies can be considered as a co-evolutionary process of technological, industrial and institutional change. This is a central assumption of the dissertation. The thesis argues that evolutionary economic geography provides a framework to explain the regional emergence and evolution of technologies and industries through time as a process of regional path dependency. However, the literature on path creation suffers from at least three shortcomings. First, little is known about the mechanisms of regional path creation. Recent approaches highlight the pre-existing economic, technological and institutional structures in a region which enable or constrain the emergence of a new path. Most studies explain the emergence of a new regional path on a macro level by diversification of existing technologies into related activities (BOSCHMA/FRENKEN 2011a; BOSCHMA ET AL. 2013; NEFFKE ET AL. 2011). The influence of the broader regional environment and resources on the emergence of a new industry or technology has been inadequately researched. Thus, there is clearly a need for more detailed empirical examinations of regional activities and processes of path creation and the enabling and constraining factors. This would help to gain a better understanding of how and under which conditions new technologies emerge and, therefore, to rethink policies and promotion programs.

Second, although it is increasingly acknowledged in the literature that new paths do not emerge randomly, but are created by strategic action, the role of the actors in new path creation has so far gained little attention. With few exceptions (such as DAWLEY 2014; MIÖRNER/TRIPPL 2017; SIMMIE ET AL. 2014), research on the evolution of new technologies and industries has neglected the active role of individual and collective actors in emerging paths. Furthermore, little attention has been paid to the influence of nonindustrial actors like universities and research institutes (TANNER 2014) and policy interventions (DAWLEY 2014). In-depth studies, which focus on the actors who shape technological pathways by creating new knowledge and innovations, are even more limited in number. Paying greater attention to the role of various actors and their activities in path creation can provide new insights into micro-level processes of path creation and how these actors shape new regional path development. This is important for both academia and policy.

Third, although it is widely accepted that institutions influence economic development and the relations between economic actors, most studies inadequately address the interplay between actors and the institutional environment. Over the last ten years, there has been an intense debate amongst scholars on the role of institutions in the further development of evolutionary economic geography (BOSCHMA/FRENKEN 2009; ESSLETZBICHLER 2009; ESSLETZBICHLER/RIGBY 2007; MACKINNON ET AL. 2009; RAFIQUI 2009; STRAMBACH 2010). The concept of co-evolution provides a promising framework for the consideration of institutions in economic evolution and for analyzing the interactions and interrelations between economic actors and their institutional environment (MURMANN 2003). From this point of view, institutions are not exogenously predetermined and static, but instead co-evolve with technological development and industrial dynamics. Although the idea of co-evolution is increasingly applied in economic geography, it tends to be fuzzy and abstract (SCHAMP 2010; GONG/HASSINK 2019). In particular, it remains unclear whether co-evolution is a "natural", adaptive process that takes place spontaneously during the evolution of a technology or instead is the result of a process affected deliberately by economic actors. Addressing this gap will enhance the understanding on how different actors influence their institutional environment in order to create favorable conditions for new path development.

## 1.2 Aims and objectives of the study

It is obvious that there are serious shortcomings in the field of economic geography concerning the emergence of new technological and industrial paths. This is where the present dissertation aims to make a contribution. The study aims to better understand the regional emergence and evolution of new technologies. The dissertation argues that, for an evolutionary approach in economic geography, there is a need to pay greater attention to the institutional environment and the role of actors in the emergence and evolution of new technologies. Therefore the key question of this study is: where, how, by whom and under which conditions do new technologies emerge?

Such a study calls for an in-depth exploration of processes, actions and interactions shaping the emergence and evolution of a technology. Thus, the empirical research is based on an explanatory case study on the emergence and evolution of the onshore wind energy technology in Germany between the 1970s and 2015. Based on the micro level of economic actors, this dissertation analyzes which actors, processes and mechanisms have led to the regional emergence and evolution of the wind energy technology.

The first objective of this dissertation is to address a conceptual shortcoming in evolutionary economic geography. This thesis aims to contribute to advance theory development through modifying and refining extant theoretical concepts. The literature has so far largely neglected the role of institutions and institutional change and how these affect the evolution of new technologies or industries; this neglect has caused much criticism within the scientific community (MacKinnon et al. 2009; Pike et al. 2016). Hence, the first objective of the dissertation is to develop a revised theoretical and conceptual framework that explains the regional emergence and evolution of new technologies and therefore takes into account the interactions and interrelationship between technology, institutions and industrial structure. Therefore, the dissertation suggests a co-evolutionary perspective on the emergence and spatial evolution of new technologies and industries.

Second, to get a better understanding of path creation, the study empirically examines how new regional paths emerge. By analyzing wind energy technology, the dissertation investigates the actors, mechanisms and processes of path creation. Who are the actors engaged in path creation and which drivers are behind it? Insights on the motives of pioneering actors help to understand why they are involved in the development of a new technology. Although the research focuses on wind energy technology, the findings have relevance for other technologies. A better understanding of the mechanisms of path creation – especially in sustainable or renewable energy technologies – is of high importance for policy makers to promote regional industrial change and encourage technological transitions.

The third objective of this dissertation is to better understand the subsequent path dependent development and how a new technological pathway becomes established. The study empirically investigates the roles of different economic actors, innovation strategies and activities and the relevance of mechanisms of inter-firm technology and knowledge transfer for the evolution and spatial diffusion of new technologies. In other words, which actors and processes are responsible for the stabilization of a certain pathway. This provides new insights relevant to both science and policy.

The fourth objective is to explain the role of institutions and institutional change in the evolution of new technologies and explore the interactions between actors, institutions and technological development. Therefore, the dissertation suggests a co-evolutionary perspective. Although the idea of co-evolution is increasingly applied in economic geography, there is no general explanation of the mechanisms and drivers behind this process. Thus, the fourth aim of the dissertation is to empirically investigate and explain how the co-evolution of institutions with technological development affects the creation and development of a new technological pathway.

Moreover, this dissertation aims to contribute to the growing empirical work in economic geography dealing with energy transitions, renewable energy technologies and eco-innovation (e.g. COOKE 2012; ESSLETZBICHLER 2012; HANSEN/COENEN 2015; TRIPPL ET AL. 2020).

Based on a review of existing literature, the following six research questions were formulated:

(1) RQ 1: *What pre-existing conditions and changes in the institutional environment and what region-specific conditions (economic, technological and institutional conditions) are most important for the local emergence of wind energy technology?*

(2) RQ 2: *Who are the actors engaged in path creation and what are the motives of the different actors to engage in a new technology? How do their motives influence path creation processes?*

(3) RQ 3: *How do new regional technological paths emerge? To what extent has the emergence and development of wind energy technology been influenced by diversifying from technologically related industries?*

(4) RQ 4: *Which actors and processes have contributed to the establishment of the pathway of wind energy technology?*

*a) Who are the main actors in the innovation processes? What role do suppliers of wind turbine components play in innovation processes?*

*b) What kind of inter-firm knowledge transfer mechanisms have contributed to wind energy technology diffusion?*

(5) RQ 5: *How and under what circumstances does co-evolution arise? To what extent does co-evolution result from strategic actions of economic actors, users, policy makers and other organizations and how large is the impact of strategic actions on the institutional environment?*

(6) RQ 6: *How can evolutionary economic geography and the inclusion of institutions and institutional changes contribute to analyzing and understanding the interrelationship between strategic actors and the institutional environment and its influence on the evolution of a new industry and technology?*

The first five research questions are oriented toward the four phases of the conceptual framework. The last research question is a theoretical one and will be answered in the revised theoretical and conceptual framework.

The empirical focus on wind energy technology provides a useful and relevant case study for the exploration of the emergence and evolution of a technology. Wind energy technology in its modern form is still a relatively young technology that started to emerge in the late 1970s (KAMMER 2011; SIMMIE ET AL. 2014). As a result, many pioneers are in principle still available for interviews. This enables a detailed investigation of the processes and framework conditions at the time of the emergence as well as in later stages of development. Moreover, there are large regional differences in Germany in the expansion and use of wind energy and in relation to the spatial development of the wind industry. This raises the question of the role of regionally specific conditions. In addition, the technological development path offers an interesting subject of investigation. In wind energy technology, the technological path is characterized by the technological key elements of a wind turbine. As the core technologies and components may differ, a diversity of technological paths can evolve as sub-trajectories in the field of wind energy technology (HAU 2014).

A further important point is the economic, social and political significance. Environmental problems, climate change and global warming have gained considerable attention and are a growing concern all over the world. The development and implementation of renewable energy technologies are seen by governments and academia as a core strategy for mitigating greenhouse gas emissions and reducing global warming (IEA 2017a; REN21 2017). In

Germany, wind energy, especially onshore, plays a central role in energy transition (BMWI/BMU 2010: 9).

## 1.3 Structure of the thesis

The dissertation was prepared in the context of the research project "Wind energy technology in Lower Saxony - A comparative approach to explain path creation and path dependence in a renewable energy". It was funded from 2013 to 2016 by the Ministry for Science and Culture of Lower Saxony, grant no. AZ. 76202-17-10/12. Originally, the research project was designed as a collaborative research project between Oxford Brookes University (James Simmie and Camilla Chlebna) and Leibniz University Hannover. The aim was to conduct two individual comparative case studies on the development of the wind energy in Germany and Britain, each with a different point of focus. Unfortunately, the collaboration could not be achieved. A literature review and the first interviews suggest considerable differences in the policy context, institutional environment, and technological and industrial development in onshore wind energy between the two countries. The author refrained from a comparative case study and instead focused on a single in-depth case study on the German technological development path.

This thesis is organized into ten chapters. Following this introduction, chapter 2 provides background on wind energy technologies from a political and technical perspective. Chapter 3 gives a summary of the empirical state of research on the emergence of wind energy in Germany and other countries. Chapter 4 reviews and discusses literature concerning the regional evolution of technologies, especially relating to path creation theory. Based on this, chapter 5 presents the theoretical and conceptual framework of this analysis. The research design and methodology, as well as data collection and analysis processes, which were used to address the research questions, are outlined in Chapter 6.

Chapter 7 and 8 present the empirical findings of the analysis on the emergence and evolution of the wind energy technology in Germany and answers the research questions. Chapter 7 is structured into three sections according to the conceptual framework. The first section starts with an analysis of the initial conditions under which the new wind energy technologies could emerge and evolve over time (chapter 7.1). The second section presents the findings about actors and mechanisms of path creation (chapter 7.2). Section 7.3 elaborates on the influence and interactions of different actors in innovation processes and the relevance of mechanisms of technology and knowledge transfer for the evolution and spatial diffusion of wind energy technology. Chapter 8 concentrates on the co-evolution of wind energy technologies and the institutional environment and explores the extent to which co-evolution is the result of strategic actions of economic actors, users, policy makers and other organizations.

Chapter 9 discusses the theoretical framework in light of the case study. Finally, the major results of the thesis are summarized and conclusions are drawn from the case study in chapter 10. In this final chapter, the contribution to the literature, a discussion of the findings concerning to theory and previous studies, the limitations of the study as well as implications for future research are discussed and policy implications are presented.

# 2 Wind energy technologies

## 2.1 Wind energy and energy transition

In September 2010, the German Federal Government adopted the Energy Concept and made the fundamental decision to cover the future energy supply from renewable sources. It describes the orientation of Germany's energy policy up to 2050, particularly measures to expand the use of renewable energy sources and the grids and increase energy efficiency. Although the Energy Concept originally intended to extend the life of Germany's nuclear power plants as a so-called "bridge transition technology" (BUNDESREGIERUNG 2010: 3), after the Fukushima nuclear disaster in 2011, the German government decided on a radical energy turnaround. A part of the Energy Concept was revised and the government returned to the previously agreed phase-out timeline meaning that all nuclear power plants will be shut down by the end of 2022 (BMWI 2018: 6).

With the Energy Concept, the federal government set itself ambitious targets for the future energy transition in Germany ("*Energiewende*"). These goals include a reduction in greenhouse gas emissions by 40% by 2020 and 80 to 95% by 2050 – compared to the level of emissions in 1990. Another target of the Energy Concept aims to increase the share of renewables in the energy sector and especially in the power sector, meaning that the share of renewable energy in gross electricity consumption should be at least 35% by 2020, 50% by 2030 and 80% by 2050 (BUNDESREGIERUNG 2010: 5). The share of renewables in gross electricity consumption has steadily grown over the last few years from around 6% in 2000 to 36.2% in 2017 and has already exceeded the 2020 goal (35%) in 2017 (BMWI 2018: 12).

Wind power, especially onshore, is one of the most important drivers of Germany's transition to renewable energy. In 2019, wind power produced about 127.2 TWh (onshore: 102.6 TWh; offshore: 24.4 TWh). As a result, wind power surpassed both nuclear and brown coal within one year and became the main electricity source in Germany for the first time. By the end of 2019, 29,456 onshore turbines with a total capacity of nearly 54 gigawatts (GW) were in operation across the country (DEUTSCHE WINDGUARD GMBH 2020: 3) (see figure 1).

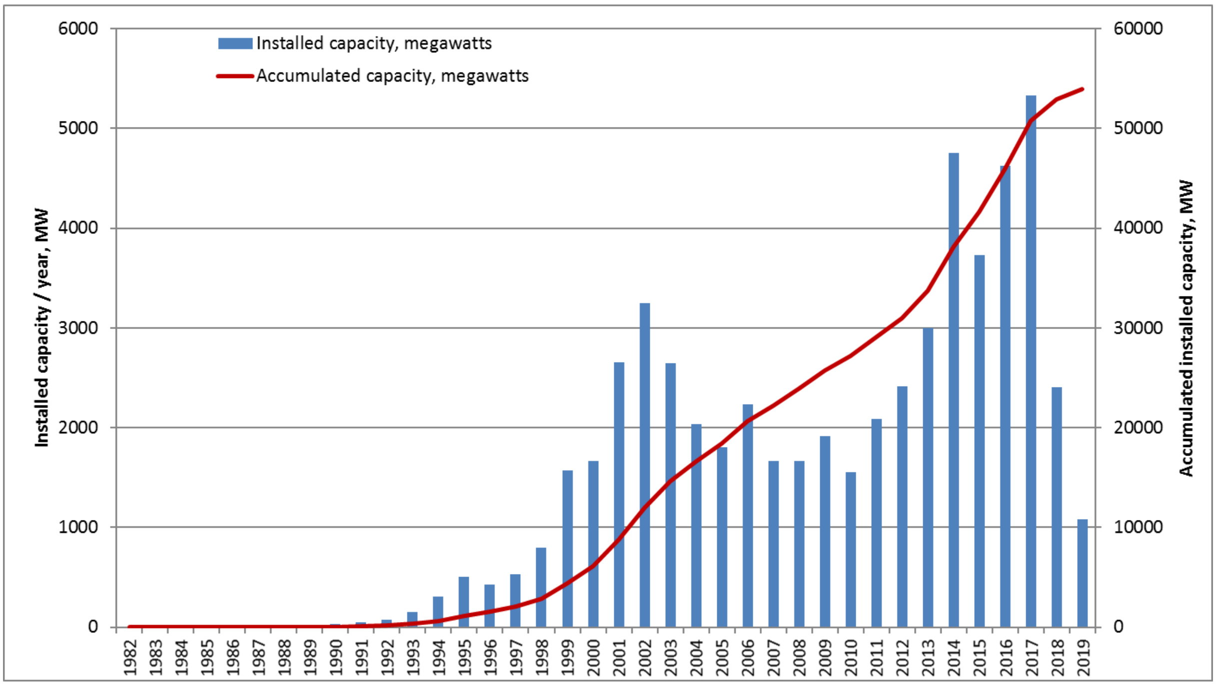


**Figure 1: Development of the installed capacity from onshore wind energy in Germany (in MW)**

Source: Own illustration based on DEWI (various years) and DEUTSCHE WINDGUARD GMBH (various years)

The German wind industry has a high economic relevance through its creation of jobs, revenue, and other businesses, which contributes to the national and regional economy. According to a study by consultancy PROGNOS (2019), commissioned by turbine manufacturer GE and the engineering association VDMA Power Systems, onshore wind power is associated with a high employment effect across the various stages of the value chain. In 2019, 64,200 people were employed in the core areas of the German onshore wind energy industry (project planning, research, manufacture, assembly and installation, operation and maintenance). This makes onshore wind power the most important renewable energy source, both in terms of installed capacity and in terms of the number of employees. By far the largest sub-area is the manufacture of systems and components: almost half of the workforce in onshore wind power was employed here (29,700). This area is characterized by the manufacturers of generators and wind turbines, such as Enercon, Vestas, Nordex and GE Wind Energy. Besides, there is a diverse supplier industry that manufactures components such as bearings, gears, electrical, measurement and control technology, rotor blades, towers and special tools. The increase in importance of onshore wind energy can also be seen by other economic parameters. The added value of companies from the cross-sectional industry in the core areas rose from a good 4 billion euros in 2010 to almost 7 billion euros in 2017. The turnover generated in onshore wind power increased from 15 billion euros to 26 billion euros in the same period. According to calculations by PROGNOS AG, tax revenue also increased noticeably (PROGNOS AG 2019).

## 2.2 Technological background

A wind turbine turns wind energy into electricity using the aerodynamic force created by the rotor blades. The rotor of the wind turbines converts the power represented by the wind into rotational power. The rotational power is then transferred to the generator, either directly or through or through a gearbox. This translation of aerodynamic force to rotation of a generator creates electricity. Based on different generator and power control systems, four main turbine designs can be distinguished. The central characteristics are given in table 1.

**a) Danish design (stall control)**

The Danish design dates back to the pioneering work of Johannes Juul in the 1950s in Denmark. In the 1980s and 1990s, it was applied by many Danish wind turbine manufacturers and dominated the market. The turbine concept is based on an upwind, three-bladed rotor with stall regulation and an asynchronous generator directly coupled to the grid. The generator speed is dictated by the grid frequency (50 Hz or 60 Hz) and the turbine operates at a (nearly) constant speed. The necessary limitation of power during storms is achieved by a stall effect. This so-called stall control system is the simplest and most robust control system which makes the turbine very robust and reliable. It has fewer components than other designs, uses low-cost electrical parts and is therefore significantly cheaper. The Danish design is characterized by a fixed blade pitch, which means that the rotor blades are fixed at a specific angle and cannot rotate around their longitudinal axis (EWEA 2009: 68; GASCH/TWELE 2011: 450).

**b) Advanced Danish design**

The mechanisms for power regulation to avoid overloading the wind turbine system were introduced in the extension of the Danish design. In this case, power control is achieved through active stall or passive pitch control by altering the angle of the rotor blades. The passive pitch control technique automatically adjusts the pitch angle of the blade to limit the power transfer. Another technique for regulating power output is active stall control. Here, the blades are pitched initially into stall in order to limit power – in contrast to traditional pitch regulation where the blades are pitched out of stall (EWEA 2009: 68). Like the original Danish design, turbines of this type also operate at a fixed speed using an asynchronous generator.

**c) Variable speed wind turbines with pitch control**

With a variable speed concept using pitch control, the rotor speed can adjust (accelerate and decelerate) depending on prevalent wind velocities and directions. The variable speed operation is achieved by decoupling the electrical grid frequency from the mechanical rotor frequency. This requires the implementation of power electronic converters. To regulate the rotor speed and the power output, pitch control by rotating the rotor blades around their longitudinal axis is used. The electronic controller monitors the power output at any given wind speed and controls the pitch angle of the rotor blades. For example, pitch control adjusts the angle of the rotor blades when wind velocities or directions change. Aerodynamic advantages are achieved, the dynamic loads on the mechanical drive train are reduced and the power output is levelled. Among variable speed wind turbines, the squirrel cage induction generator (SCIG) and the doubly-fed induction generator (DFIG) are the most commonly applied generator concepts (EWEA 2009: 89; GASCH/TWELE 2011: 70; HAU 2014: 479).

**d) Direct drive**

The direct drive (gearless) wind turbine also utilizes a variable speed concept with the peculiarity that the turbine does not require a gearbox. The generator is directly connected to the rotor hub and to the grid through a full-scale frequency converter. The frequency converter achieves reactive power compensation and smooth grid connection. Most direct drive designs are based on permanent magnets generators (PMG), which allow a compact design and a higher part-load efficiency of the generator. Alternative to the PMG technology, some direct drive turbines build on an electrically excited synchronous generator (EESG). The idea and main advantage of direct drive designs is to reduce the number of components of a turbine by removing the gearbox and therefore eliminate gearbox problems, reduce maintenance, and increase reliability (EWEA 2009: 87; HANSEN/HANSEN 2007: 86; IWES 2012: 59).

**Table 1: Wind turbine concepts**

| Type | Danish design | Advanced Danish design | Variable Speed | Direct drive |
|---|---|---|---|---|
| **Generator** | asynchronous | asynchronous | synchronous, asynchronous, or DFIG | PMG or EESG |
| **Power control** | stall | active stall/ pitch | pitch | pitch |
| **Speed control** | fixed speed | fixed speed | variable | variable |
| **Drive train** | gear-driven | gear-driven | gear-driven | direct drive |

Source: Own illustration based on GASCH/TWELE (2011) and IWES (2009)

## 3 Empirical state of research

Because of the distinct political and social importance, wind energy has attracted the interest of economic geography. In the past two decades, several studies have focused on the emergence of wind energy technology and industry. Many of these have also adopted an evolutionary perspective to analyze path creation. Most studies, however, focused on the evolution of the wind industry rather than technological pathways. KAMMER (2011), for example, provided a comprehensive insight into the history and development of the global wind energy industry. The work focused on the production of wind turbines, along with the sub-sectors in project development and planning and operation of wind farms. KAMMER (2011) covered a period from 1970 to 2009 and outlined the global expansion of the industry, based on qualitative descriptions of company histories and corporate relations.

Despite the increasing number of studies, only little research has been conducted on the role of different actors in the evolution of wind energy technologies. Notable exceptions are investigations by GARUD and KARNØE (2003), SIMMIE (2012) and SIMMIE ET AL. (2014). Since Denmark has been a pioneer in the development and utilization of wind energy, most empirical studies on the evolution of wind energy technologies concentrate on the Danish case (BUEN 2006; GARUD/KARNØE 2003; KARNØE 1990; MENZEL/KAMMER 2011; SIMMIE 2012). In their comparative study on the emergence and development of the wind turbine industry in the United States and Denmark GARUD and KARNØE (2003) identified two processes of path creation and engagement of actors. In Denmark, technological development was based on learning through trial and error and tight interactions between various stakeholders. These actors included manufacturers, universities and research institutes, policy makers and other public actors. The technological path, which GARUD and KARNØE (2003) called "bricolage", started with small, low capacity wind turbines based on a low-tech design. Interactions and learning processes enabled continuous improvement of existing technologies through incremental innovations, and the size and capacity of wind turbines was gradually scaled up. In contrast, the technological path in the United States followed a knowledge intensive strategy to create a technological breakthrough or radical innovation. Whereas the Danish "bricolage" approach followed a bottom-up strategy of wind turbine development, the US case was characterized by a top-down approach. The government tried to induce firms to develop a high technology turbine design and offered extensive wind power programs and market subsidies. GARUD and KARNØE (2003) called this approach a strategy of breakthrough.

In the US pathway, interactions between manufacturers, researchers, users and policy makers were weak. GARUD and KARNØE (2003) showed that, although the US strategy could draw on a rich knowledge base and was more expensive with higher financial incentives, the Danish strategy prevailed over the US approach through the 1980s and 1990s: the Danish wind turbine design proved, at that time, to be superior and Danish manufacturers became world market leaders. In this context, SIMMIE (2012) stressed the role of actors in new path creation in the Danish wind industry. He explained how inventors and innovators have shaped the institutional environment to overcome path dependent barriers to the new technological pathway.

Many studies have dealt with policies and institutional change at the national level (BERGEK/JACOBSSON 2003; BRUNS ET AL. 2008; JACOBSSON/LAUBER 2006; MUSGROVE 2010). CAMPOS SILVA and KLAGGE (2013) analyzed the development of the Chinese wind industry and showed how politics and public policies have supported the evolution of the industry and how the state has shaped global organizational and spatial dynamics of the wind industry. In her analysis of wind energy politics and governance processes in Germany, OHLHORST (2009) emphasized the social and political context and institutional change in the 1970s and 80s as an important trigger for the emergence of the wind energy. The accident of Chernobyl, the anti-nuclear movement, the oil price crises and climate change debate created a change in awareness that led to an increasing interest in wind energy. Studies on the evolution of the German wind energy industry also highlighted the importance of policy instruments and institutional change at the early stages of path development, in particular the Electricity Feed-in Act of 1990, as an important driver for the wind energy sector (BERGEK/JACOBSSON 2003; CARPENTER ET AL. 2012; JACOBSSON/LAUBER 2006; SZARKA/BLÜHDORN 2006). For example, CARPENTER ET AL. (2012) and SIMMIE ET AL. (2014) argued that the different development paths of the wind energy industry in the UK and Germany resulted from the institutional environment and policy initiatives in the early stage of technological development and market formation. A recent study by CHLEBNA and SIMMIE (2018) confirms these findings. They also argue that divergent path development in both countries is the result of different institutional environments. This relates to formal institutions and political structures – a highly centralized government system in Britain versus the Federal system in Germany – but also to informal institutions like the attitude towards nuclear power. In Germany, governmental funding and a growing influence of environmental movements provided favorable conditions for pioneers who began to experiment with wind energy technologies. So, during the 1970s and 1980s, a small wind industry emerged in Germany. In the 1980s, in Britain a small but competitive industry developed through government funding, too. But in contrast to Germany, governmental support was discontinued. According to CHLEBNA and SIMMIE (2018), this lack of funding and support for wind energy in Britain led to the failure of the evolution of the wind industry. CHLEBNA and SIMMIE (2018) also indicate, that the different character of the firms involved in path creation and their motivation – small companies and ideologically driven individual actors in Germany versus large engineering consortia with mainly commercial interest – affected path development.

Some studies show how environmental activists or social movements create enabling conditions for new wind technologies to emerge (DOBLINGER/SOPPE 2013; SINE/LEE 2009). For example, SINE and LEE (2009) revealed that social and environmental movements can change and create markets. In their study on the emergence of the US wind energy sector, they found that social movements shaped the institutional environment by creating and propagating norms, values and regulatory institutions that encouraged entrepreneurial activities. Environmental movement organizations successfully mobilized members and non-members activists and lobbied policy makers. According to the study, they had a greater effect on entrepreneurial activity than wind conditions and the availability of land. Although it is not the focus of the study, SINE and LEE (2009: 127) indicatedthat the influence of social movement organizations can account for the regional differences in entrepreneurial activity in the early phase of technological development.

Some other studies dealt in particular with the offshore wind energy industry and technology, which are not the focus of this dissertation. As SOMMER (2015) pointed out: onshore and offshore technologies have followed two different trajectories. However, some of these studies offer interesting insights into regional conditions and regional path creation. In a qualitative case study, FORNAHL ET AL. (2012) examined the relevance of region-specific conditions and capabilities and role of the declining shipbuilding industry for the emergence of the development path of the offshore wind energy industry in North Germany. They conclude that the shipbuilding industry only indirectly affected the emergence of the offshore wind energy industry in Northern Germany. They show that only a few offshore wind energy firms had their roots in shipbuilding. It were mainly onshore wind energy companies or firms of other industries that diversified into the new offshore wind energy. However, FORNAHL ET AL. (2012) argue that two shipbuilding-related local factors have positively affected the location of wind energy companies in Northern Germany. First, the infrastructure of the maritime industry like harbors, production halls and heavy lift terminals was a favorable location factor for offshore turbine manufacturers. Second, the crisis in the shipbuilding industry made companies and policy makers to look for new market areas. However, FORNAHL ET AL. (2012) admit that there has been a time lag of several years between the decline of the shipbuilding industry and the emergence of the offshore wind energy industry. Besides, the study points to the role of (regional) policy makers. In the case of the offshore wind energy, policy makers in the city-state of Bremen have attempted to change the framework conditions by formulating offshore wind energy support policies earlier than other federal states. In a recent paper, DAWLEY (2014) addressed the emergence and development of the offshore wind sector in North East England within the context of path creation activity by policy makers and economic actors on multiple scales. He argues that interplay between local entrepreneurial activities and national state-led strategic niche management created a regional "demonstration effect" through which the new path of offshore wind energy was created. Similar to the findings by FORNAHL ET AL. (2012) on the emergence of the offshore wind energy industry in Northern Germany, the case of the North East shows the relevance of diversification for new path creation.

Recently, BEDNARZ and BROEKEL (2020) emphasized the importance of local demand. In a quantitative study, they analyzed the impact of local supply-push and demand-pull mechanisms on the spatial evolution of the German wind industry. The authors found that the spatial diffusion was stronger shaped by local demand-pull factors (measured in future wind turbine installations) than by local supply-push effects. In line with FORNAHL ET AL. (2012), they showed that the first wind turbine manufacturers predominantly emerged in regions with related industries like the shipbuilding industry. Over time, local demand-pull factors became more relevant. New turbine manufacturers tend to emerge in proximity to existing local demand for wind turbines and near already existing manufacturers.

STEEN and HANSEN's (2018) study on the emergence of the offshore wind power industry in Norway since the early 2000s provide some insights on the processes and mechanisms of path creation. They found that path creation was mainly driven by diversification especially from the established Norwegian offshore oil and gas sector. This process was supported by several policy measures like funding the establishment of two cluster initiatives and a funding program for renewable energy.

The body of literature on wind energy indicates some industry- and technology-specific characteristics concerning the emergence and spatial evolution of wind energy technology. At least four aspects are important enough to be considered for the case study. First, inventions and innovations in wind energy technologies are derived from a broad range of scientific and technological knowledge bases. Secondly, the evolution of the industry has benefited from a strong entrepreneurial spirit. Third, various policies are seen as a central stimulus for technology and market development. Fourth, national and sub-national institutions have had a strong influence on the development of the market and the industry. Each of these factors is reflected by the theoretical predictions generated by the conceptual framework.

The development of the wind energy technology and wind turbines is based on knowledge generated by different industries including electronics, mechanics, materials science and aerodynamics (BERGEK/JACOBSSON 2003: 198; GARUD/KARNØE 2003: 282; MOLLY 2009: 15). The evolution of the modern wind energy technology is characterized by various innovations in wind turbine technology and design, power control, rotor blades, drivetrain technology and wind energy integration. Thus, knowledge creation is an interactive process involving actors from a set of more or less related knowledge fields.

Radical innovations and the emergence of the industry were mainly driven by entrepreneurial activity and innovative pioneers (BRUNS ET AL. 2008; GASCH/TWELE 2011; HAU 2014). Recent studies stress the role of individual inventors, innovators and entrepreneurs (CARPENTER ET AL. 2012; SIMMIE ET AL. 2014). Since the 1970s and early 1980s, new technological pathways have been created by experimentation and entrepreneurial activity.

Furthermore, several political strategies and changes have shaped the technological and market development path. Some fundamental formal and regulative institutions have had a substantial effect on the emergence of the wind industry. In Germany, governmental programs (FÖRDERGESELLSCHAFT WINDENERGIE E.V. 1995; HEYMANN 1995; SZARKA/BLÜHDORN 2006) and R&D funding (IBENHOLT 2002: 1183) have supported (niche) market creation and development at a national level. Additionally, demand-pull policies have been introduced in order to stimulate the market for the emerging energy technologies. In Germany, national and sub-national governments have set national and regional targets for renewable and wind energy. These energy concepts and expansion targets differ widely between the federal states *(Bundesländer*). Previous studies on the wind energy industry tend to focus on the national political and legal conditions (BERGEK/JACOBSSON 2003; BRUNS ET AL. 2008; CAMPOS

SILVA/KLAGGE 2011; MUSGROVE 2010) but have paid very little attention to place-specific institutions at different spatial scales.

Certainly, national policy has facilitated market development. However, considerable regional differences within Germany exist. Recent case studies on the social acceptance of the wind energy technology in southeast Germany (MUSALL/KUIK 2011) and Scotland (WARREN/MCFADYEN 2010) suggest that this kind of public attitude is largely determined at a regional or local level. According to these studies, there may be important, sub-national differences regarding normative and cognitive elements of the institutional environment. Furthermore, the findings of the two case studies indicate a positive impact of community ownership of wind farms on the regional acceptance of wind energy.

However, with few exceptions (such as DAWLEY 2014; SIMMIE 2012; SIMMIE ET AL. 2014; STEEN 2016) these studies mainly discuss the impact of national policies and incentives on the development and diffusion of renewable energy technologies in general and wind energy technologies in particular. Most studies tend to focus on the impact of either national institutions and policies or regional diversification processes without examining the interactions of various actors within a broader multi-scalar institutional environment. The emergence of wind energy is often reduced to regional branching and diversification. Other mechanisms of path creation have not been studied extensively. Exceptions are the studies by DAWLEY (2014) and DAWLEY ET AL. (2015), which illustrate how the interplay of policy interventions at multiple scales shaped a variety of path creation mechanisms. Moreover, empirical insights into the spatial evolution and diffusion of wind energy technology are still slight. Although several studies examine the development of the industry and technology over time, mechanisms and processes of technology and knowledge transfer are rarely mentioned.

# 4 Theoretical foundations

## 4.1 Evolutionary economic geography

In recent economic geography literature, an evolutionary perspective of economic development has gained increasing acceptance (BOSCHMA 2004; BOSCHMA/FRENKEN 2006; ESSLETZBICHLER/RIGBY 2007; FRENKEN/BOSCHMA 2007; HASSINK ET AL. 2014; HENNING ET AL. 2013; MARTIN 2010; MARTIN/SUNLEY 2006). Evolutionary economic geography refers to concepts of evolutionary economics and uses fundamental evolutionary metaphors and terminologies (BOSCHMA/FRENKEN 2006: 278; MACKINNON ET AL. 2009: 130; MARTIN/SUNLEY 2006: 396). Considered to be one of the most important principles in evolutionary economics, the idea of path dependency provides a theoretical foundation for the analysis of regional development paths (ESSLETZBICHLER 2002: 17; MACKINNON ET AL. 2009: 132; MARTIN/SUNLEY 2006: 397). As BOSCHMA and FRENKEN (2006) argue:

> “Thus, the current state of affairs cannot be derived from current conditions only, since the current state of affairs has emerged from and has been constrained by previous states of affairs. Evolutionary theory deals with *path dependent processes*, in which previous events affect the probability of future events to occur.” (BOSCHMA/FRENKEN 2006: 280, emphasis in original)

The concept of path dependency has received a great deal of attention resulting from the seminal studies by PAUL A. DAVID (1985) and BRIAN W. ARTHUR (1989, 1994) on evolutionary change of technologies and technical standards. In general, path dependency is characterized by a process of cumulative causation and self-reinforcing mechanisms. The concept is applied in different contexts by various scientific disciplines (MARTIN/SUNLEY 2006: 398).

The ideas of path creation and path dependency provide promising linkages between evolutionary and institutional approaches within economic geography. Therefore, evolutionary economic geography should pay special attention to the institutional context and its influence on the evolution and the regional development of new technologies and industries.

BOSCHMA and MARTIN (2007: 539, emphasis in original) state that "the basic concern of evolutionary economic geography is with *the processes by which the economic landscape —*

*the spatial organization of economic production, distribution and consumption — is transformed over time*". According to that, evolutionary economic geography aims to explore:

> "*the spatialities of economic novelty* (innovations, new firms, new industries), with how the *spatial structures of the economy emerge* from the micro-behaviours of economic agents (individuals, firms, institutions); with how, in the absence of central coordination or direction, the *economic landscape exhibits self-organization;* and with how the processes of *path creation* and *path dependence* interact to shape geographies of economic development and transformation, and why and how such processes are themselves place dependent". (BOSCHMA/MARTIN 2007: 540, emphasis in original)

The development of the wind energy technology can therefore be seen as an evolutionary process in which a variety of actors is involved. The emergence, formation and development of new industry or technology result directly from the micro-behavior of individual firms and other economic actors. From an evolutionary economic perspective, firm decisions and activities are influenced by their already acquired skills and experiences, which are generally described as routines (BOSCHMA/FRENKEN 2006: 277; BOSCHMA/LAMBOOY 1999: 416; SCHAMP 2002: 42). Such routines encompass the firm's knowledge basis, norms and patterns of action which manifest for example in specific production techniques, research and development or the company's business strategy and corporate philosophy (NELSON/WINTER 1982: 14). They bundle (tacit) knowledge and experiences of individual actors to form collective knowledge, for example from a firm or a subsidiary company (BECKER 2004: 661; COHEN/BACDAYAN 1994: 555).

## 4.2 Technological development, innovation and knowledge transfer

The OXFORD ENGLISH DICTIONARY (2019) defines technology as a "branch of knowledge dealing with the mechanical arts and applied sciences," "the application of scientific knowledge for practical purposes, especially in industry" and the "product of such application; technological knowledge or know-how". Thus, the term technology implies not only the knowledge needed to develop a new product or service but also the product or service itself. The thesis follows this understanding of technology. Technology is seen as applied in a particular product context and finds expression in a product (a like generator, drive train or a wind turbine).

In addition to this technical view, social science school of thoughts like technical sociology and science and technology studies (GEELS 2004; RAMMERT 1993; RIP/KEMP 1998) or the social construction of technology approach (SCOT) (PINCH T. J./BIJKER W. E. 1984) refer to technology as a socio-technical system. This sociological perspective on technology is based on the view of technology as a social construct (RAMMERT 1993; PINCH T. J./BIJKER W. E. 1984). According to RAMMERT (1993), technological development is a social process that results from the diverse interactions and interdependencies of technology, science, economy, politics, and society. Likewise, the social construction of technology (SCOT)[1] approach understands technological development as a social process (PINCH T. J./BIJKER W. E. 1984). This position argues that technology does not determine human action, but that rather, human action shapes technology. Technologies are seen to be characterized by ‘interpretive flexibility’, which means that each technological artifact has different meanings and interpretations for various groups. According to this, technological development is not an autonomous or exogenous process but shaped by the institutional environment.

Evolutionary models of technical change use a life cycle metaphor to describe technological progress in an industry over time. Technologies are assumed to develop – like living organisms – through a “life cycle” from birth (invention, innovation), growth, maturity (saturation), obsolescence (decline), and death (ABERNATHY/UTTERBACK 1978; KAPLAN/TRIPSAS 2008; TUSHMAN/ANDERSON 1986).

The literature on socio-technological transitions highlights the role of technological niches as an incubation room for path-breaking innovations and the emergence and diffusion of new technologies (GEELS 2002, 2004; SCHOT/GEELS 2007). Niches provide a protected space for experimenting with new technologies and learning processes. This way, a new technology can mature and the necessary social networks, such as supply chains and user–producer relationships, can be build up (FOXON ET AL. 2010).

The term "innovation" is a broad and commonly used term that has been defined differently in various contexts. According to the OECD Oslo Manual (OECD 2005: 46), "an innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace

---

[1] Social construction of technology (SCOT) is a theory within the field of science and technology studies that emerged in the 1980s.

organization or external relations". In this study, the focus is on product innovation and the actors involved and how they interact in the process of innovation.

For that purpose, an evolutionary perspective on innovation is adopted. The traditional linear model assumes that the innovation process follows a straight (linear) path from one phase to the next: basic research, development, production and introduction to the market. However, the model has been criticized as unrealistic as it overemphasizes the importance of research-based knowledge and neglects supplier and customer feedback (DOSI 1988; KLINE/ROSENBERG 1986; NELSON/WINTER 1982; RIP/KEMP 1998). In reality, innovation processes rarely follow a linear sequence starting with basic research. Based on evolutionary economics (e.g. DOSI 1982; NELSON/WINTER 1982), innovation processes are understood to be evolutionary, non-linear, and interactive. A seminal contribution to innovation research is the "chain-linked model" of innovation developed by KLINE and ROSENBERG (1986). They emphasize the importance of accumulated knowledge and multiple feedback loops within the whole innovation process. The model identifies five paths of innovation processes. The first path consists of the "central-chain-of-innovation" which extends from the identification of potential markets and an invention and/or production of analytic designs to more detailed designs and testing, to redesigns and production and finally to distribution and marketing. The second path is a series of feedback links between all stages of innovation as well as feedback from users of the innovation. The third path represents links between the central chain of innovation and science. Thus, science is understood as a stock of accumulated knowledge and as a link from science to innovation is not solely present at the beginning of the process but also along the entire development. The fourth path describes the rather rare situation when research generates new knowledge which leads to the creation of radical innovations, often accompanied by major changes and the emergence new industries. Finally, the fifth path indicates the feedback of innovation results to the scientific arena. The model highlights the diversity of potential sources of innovations. In addition to R&D activities, KLINE and ROSENBERG (1986) recognize various external knowledge sources such as customers, users, suppliers, and cooperation with other firms.

The interactive model of innovation (KLINE/ROSENBERG 1986) also stresses the importance of knowledge transfer and forms of interaction between firms and other actors. In order to understand the evolution of a technology, it is essential to examine knowledge and technology transfer processes. Knowledge transfer is defined as any process by which knowledge and expertise is exchanged from one individual, group or organization to another. In this thesis, the focus is on inter-organizational, or, more precisely, inter-firm knowledge transfer. Knowledge can be transferred between firms in various ways. Firms may gain new knowledge by monitoring, observing and imitating (co-located) competitors (MALMBERG/MASKELL 2002). Another important mechanism for knowledge transfer is labor mobility (ALMEIDA/KOGUT 1999). Knowledge flows between firms as workers change their employer during their career. A special type of this kind of knowledge transfer is the creation of new firms by employees (spin-off). Spin-off processes, where technologies, knowledge and routines a transferred from a parent company or university to a new firm, are considered to be a key mechanism for knowledge transfer (AGARWAL ET AL. 2004; KLEPPER 2002a, 2007; KLEPPER/SLEEPER 2005). Formal relationships, like joint ventures, licensing agreements, strategic alliances, and other forms of R&D collaboration, also often aim to acquire or transfer knowledge. In particular for an emerging technology, licensing agreements are an important channel of knowledge sourcing (KOLLMER/DOWLING 2004; MOWERY ET AL. 1996).

An important theoretical framework for analyzing the development and diffusion of new technologies is the concept of technological innovation system (TIS) (CARLSSON/STANKIEWICZ 1991). The TIS approach focuses on the role of actors, networks and institutions in the generation, development and diffusion of new technologies (MARKARD/TRUFFER 2008) and, thus, emphasizes the social and institutional dimension of innovation. In particular, TIS studies examine the processes and factors that influence the development, diffusion, and use of a new technology. These key processes, which have been derived from a number of different innovation system approaches, termed ‘functions’ (BERGEK ET AL. 2008). These functions include entrepreneurial activities, knowledge development, knowledge diffusion through networks, the guidance of the search, market formation, resource mobilization and the creation of legitimacy. (BERGEK ET AL. 2008; JACOBSSON/JOHNSON 2000; HEKKERT/NEGRO 2009). Entrepreneurial activities involve start-up activities and the diversification of incumbent companies into a new technology. Knowledge development refers to the creation of knowledge through processes of learning, such as learning by searching and learning by doing. Knowledge diffusion through networks includes activities that lead to the exchange of information and learning by interacting. Guidance of search refers to activities that affect expectations of the future of the technology and therefore how actors allocate their activities and investments between competing technologies. Market formation refers to the articulation of demand and the creation of niche markets. Resources mobilization refers to the process of mobilizing different types of resources, especially financial and human capital. Creation of legitimacy refers to the process of building legitimacy for the new technology, for example through the creation of advocacy coalitions (BERGEK ET AL. 2008; FOXON ET AL. 2010; HEKKERT/NEGRO 2009). By mapping and analyzing these key processes within a technological innovation system one can identify the drivers and barriers of the development, diffusion or implementation of a particular technology.

## 4.3 Institutions in evolutionary economic geography

In the context of the recent discourse on the distinction between evolutionary economic geography and institutional economic geography (see, e.g., BOSCHMA/FRENKEN 2006; MACKINNON ET AL. 2009) several scholars suggest to explicitly include institutions in the further development of evolutionary economic geography (BOSCHMA/FRENKEN 2009; ESSLETZBICHLER 2009; ESSLETZBICHLER/RIGBY 2007; RAFIQUI 2009; STRAMBACH 2010). For the purpose of this dissertation, some fundamental assumptions have been derived from institutional economic theory and literature in new institutional sociology. They provide a promising foundation to understand how institutions affect economic development and how economic actors – particularly inventors, entrepreneurs and firms – shape these institutions. These scholars emphasize the role of institutions in shaping the behavior of individuals, organizations and societies (NORTH 1990). As SCOTT (1995: 27) summarizes, “institutions construct actors and define their available modes of action; they constrain behavior, but they also empower it”. ESSLETZBICHLER (2009) emphasizes the relationship between structure and agency in economic relations and processes: "Institutions are the result of intentional action and unintended consequences of human behavior. They constrain and enable human action, structure human interaction, and are simultaneously shaped by these actions" (ESSLETZBICHLER 2009: 161).

It is essential to explicitly distinguish between institutions and organizations (NORTH 1990). Within institutional economics it is widely accepted to understand institutions as "the rules of the game in a society or [...] the humanly devised constraints that shape human interaction" (NORTH 1990: 3) whereas organizations, to stick with the metaphor, are the players of the game. These players are groups of individuals united by some common purpose to achieve specific objectives. Organizations include political bodies (political parties, governments, state entities and regulatory agencies at the national, regional and municipal level), economic bodies (firms, trade unions, cooperatives), social bodies (churches, clubs, associations) and educational bodies (schools, universities, research institutions, vocational training establishments) (NORTH 1990: 5).

In contrast to NORTH (1990), in economic geography institutions are often broadly conceptualized and encompass formal and informal regulations and norms as well as organizations (RAFIQUI 2009; SCHAMP 2002). However, this dissertation differentiates between institutions and organizations. In this thesis, institutions refer to informal and formal rules and norms shaping and constraining human behavior like environmental concerns, laws, and technical norms. Organizations are defined as groups of individuals bound by a common purpose of achieving certain objectives. Following NORTH (1990), organizations are understood as actors in the economy. Actors are individuals, groups or organizations that are capable of intentional action. They are embedded in an institutional context.

NORTH emphasizes that the purpose of institutions is “to reduce uncertainty by establishing a stable (but not necessarily efficient) structure to human interaction” (NORTH 1990: 6). Institutions "regulate the behavior of economic actors: firms, managers, investors, workers" (GERTLER 2004: 7) but do not determine their behavior (BOSCHMA/FRENKEN 2009; 2011b). SCOTT (1995: 33) defines institutions as “cognitive, normative, and regulative structures and activities that provide stability and meaning to social behaviour”. Regulative institutions, which closely correspond to NORTH'S (1990) definition of formal institutions, are formal rules and laws (SCOTT 1995: 35). Normative institutions such as norms, values and codes of conduct are less formal. They constitute both, constraints and incentives for social behavior (SCOTT 1995: 38). Cultural-cognitive conceptions are entrenched in the societies which shaped them.

A similar distinction is made between the "institutional environment" and "institutional arrangements" (NORTH 1990). The institutional environment consists of formal structures such as laws, constitutions, contracts, regulations, corporate governance and informal constraints and incentives like norms, conventions, routines, customs and codes of conduct which regulate interactions between agents. The institutional arrangements refer to institutions manifested in organizational forms such as firms, trade unions, public authorities or governmental institutions and governance structures (e.g. networks). The evolution of institutional arrangements in economic, political and social organizations is shaped by the institutional environments. At the same time institutional arrangements reproduce and alter the institutional environment (MARTIN 2000: 79; NORTH 1990).

Organizations act in an institutional environment but they can also alter existing institutions or constitute new ones. Enduring formal institutions like contracts or regulations are created by individuals or organizations. The emergence of informal institutions such as the environmental movement in the 1970’s in West Germany promoted a rethinking of energy policies and contributed to the formation of the Green Party, which reinforced environmental awareness. Hence, "it is the interaction between institutions and organizations that shapes the institutional evolution of an economy" (NORTH 1990: 7). Since organizations, like institutions, provide a structure to human interaction (NORTH 1990: 4), the distinction between institutions and organizations or the institutional environment and institutional arrangements is not always clear-cut. Organizations cannot be regarded as being separate from their role of adjusting specific social or economic behaviors and relations.

Economic Geography has developed a large body of theory and empirical research on the role of institutions in innovation processes and economic development. A considerable amount of this research focused on the regional level, for example concerning knowledge spillovers (AUDRETSCH/FELDMAN 2004) or local and regional innovation systems (ASHEIM/GERTLER 2005; BRACZYK ET AL. 1998). Institutional approaches to economic geography maintain that "the form and evolution of the economic landscape cannot be fully understood without giving due attention to the various social institutions on which economic activity depends and through which it is shaped" (MARTIN 2000: 77). Both evolutionary and institutional economic geography point out that innovation activity, knowledge creation and transfer are supported by regional institutions, socio- institutional structures and institutions. Economic activities and processes are constituted within and shaped by a social, political and institutional context. As MARTIN (2000: 79, emphasis in original) argues, "economic activity is *socially and institutionally situated*: it [...] has to be understood as enmeshed in wider *structures of social, economic, and political rules, procedures and conventions*".

Therefore, it is feasible to precisely work out the interaction between actors and institutions in the economic development. GERTLER (2010) claims that recent theoretical approaches still neglect the impact of institutions on the evolution of regional economies and proposes a "reconstituted institutional economic geography" (GERTLER 2010: 5) integrating four key features:

- a more agency-centered approach
- a dynamic approach stressing institutional evolution and change
- a more explicit spatial or even multi-scalar approach addressing the interaction between institutional structures at different spatial scales
- a greater methodological variety

The theoretical framework presented in this study aims to integrate the theoretical insights from the paradigm of evolutionary economic geography and institutional approaches.

## 4.4 Institutional change

The "institutions-as-rules" approach (NORTH 1990, 2005; RAFIQUI 2009) focuses on how the "rules of the game" influence the perceptions of players. According to NORTH (1990: 7), the continuous interaction between institutions and organizations is the key mechanism for institutional change. Institutions are constraints that influence preferences and behavior. Organizations are created by actors in response to the institutional environment and are, in turn, the promoters of institutional change. The state provides formal rules, laws and regulations, but cannot be treated as an exogenous entity. Policy decisions are the result of a process of negotiation between policy makers and other actors. NORTH claims that there are two major sources of institutional change: changes in relative prices as an exogenous source and changes in preferences or beliefs as an endogenous source of institutional change. Organizations try to adapt to and take advantages of the institutional environment or, over time, attempt to change certain rules in a certain direction. Hence, the direction of institutional change depends on the beliefs and perceptions of individuals and organizations, which makes institutional change an incremental and path-dependent process (NORTH 2005; RAFIQUI 2009). As specific (informal) institutions develop in different places, institutional change varies across space (MARTIN 2000: 80; RAFIQUI 2009: 341).

STRAMBACH (2010) discusses the idea of "path plasticity", emphasizing the "interpretative flexibility" (STRAMBACH 2010: 407) of institutions and institutional arrangements. Such plasticity results from the ability of actors to "recombine and convert or reinterpret institutions for their new objectives or transfer institutions to different contexts" (STRAMBACH 2010: 412).

Several scholars highlight the path-dependent nature of institutions in the context of the process of economic development (MARTIN 2000; NORTH 1990; RAFIQUI 2009; SETTERFIELD 1997). MARTIN (2000: 80), for example, argues that institutions "tend to evolve incrementally in a self-reproducing and continuity-preserving way". MARTIN and SUNLEY (2006: 402) have summarized the relationship between actors and institutions in the process of institutional change as follows:

> "Institutions are both the product of and a key factor shaping social agency: they provide the stability and predictability needed for social and economic actions and transactions, whilst incrementally responding to and incorporating the outcomes of those actions and transactions. This duality of institutions and social agency necessarily means that institutional evolution tends to exhibit path dependence. Like the economy, institutions thus tend to inherit the legacy of their past."

According to MARTIN (2000: 80), "It is at the regional and local levels that the effects of institutional path dependence are particularly significant". Hence, the evolutionary nature of institutions offers an explanation for the spatial patterns of economic evolution. This raises the question of how regional institutions shape region specific conditions for the actions of economic actors which leads to a particular development path (SCHAMP 2002).

Consequently, institutional change can lead to substantial subnational variation (GERTLER 2010). Firms operating in the same industry within the same national institutional framework may perform completely different due to regional institutions (e.g. SAXENIAN 1994). ANNALEE SAXENIAN's (1994) work on the evolution of the computer industry in Silicon Valley (California) and Boston's Route 128 area (Massachusetts) is a prominent example of how the institutional environment affects innovation processes. She emphasizes the role of regional institutions and argues that the competitiveness differs due to differences concerning regional (informal) institutions like business culture. The comparative analysis illustrates that the local institutional environment has an important impact on how regional actors (esp. firms) adapt to changing economic conditions (SAXENIAN 1994).

## 4.5 Co-Evolution

The concept of co-evolution, which originated in biology, refers to the – more or less – simultaneous evolution and mutual interference between two or more populations (SCHAMP 2010). MURMANN (2003) highlights the causal influences between the systems and claims that "two evolving populations co-evolve if and only if they both have a significant causal impact on each other's ability to persist" (MURMANN 2003: 22). The concept has been applied to different processes, e.g. evolutionary economics have focused on the co-evolution between technology, industry structures and policy institutions (MURMANN 2003; NELSON 1994, 1995). Other studies address the co-evolution of different sectors (JACOBIDES/WINTER 2005), the co-evolution of institutions and innovation (STRAMBACH 2010), or the co-evolutionary patterns of market structures, networks and clusters (BROEKEL 2015; TER WAL/BOSCHMA 2011).

Co-evolution refers to the evolution of two or more populations through interaction, reciprocal development and adaptation. MARTIN and SUNLEY (2006: 143) suggest the term of "path interdependence" to emphasize this mutually reinforcing interaction between path-dependent trajectories. In current economic geography, there are at least three different types of co-evolution (SCHAMP 2010). First, the process can refer to the co-evolution of two firm populations. This is the case when the evolution of an industry occurs in close association with the emergence of a supporting sector. Second, co-evolution can be understood as the dynamic interplay between institutions and organizations as mentioned by NORTH (1990, 2005). From this perspective, the focus is on the reciprocal dependence of an industry and certain institutional arrangements. For instance, MURMANN (2003: 23) examines the "bi-directional causality" between a population of firms and institutions. Third, co-evolution in the sense of co-location can involve the interaction between an industry and its local institutional environment. In this context, "co-evolution is a 'local' mechanism of self-reinforcement of an evolving (firm) population" (SCHAMP 2010: 436).

The concept of co-evolution provides a promising approach for the consideration of institutions in economic evolution. Evolutionary economic geography views institutions as both: an outcome of interaction between economic actors and a key factor shaping economic behavior. In contrast to institutional approaches, evolutionary economic geography expects institutions to play only a minor role in the spatial evolution of new industries (BOSCHMA/FRENKEN 2006; 2009). However, institutions are of considerable importance for the evolution of the economic landscape as they co-evolve with the emergence of a new industry. BOSCHMA and FRENKEN (2009: 155) argue that "What is crucial, though, is that such institutions are created deliberately to support and sustain the further growth of the industry in question. These supportive institutions often come into existence where the specific demand for them has emerged, that is, in those places where the new industry started to develop". Institutions co-evolve with technologies and industry structures at different spatial scales

(BOSCHMA/FRENKEN 2006; NELSON 1994; RIP/KEMP 1998; STRAMBACH 2010). BOSCHMA and FRENKEN (2009: 155) conclude that "if institutions play a role, it will be more often in an endogenous manner as entrepreneurial firms, consumers, and governmental officials engage in collective action to establish new institutions". With such a lens, institutions are not exogenously predetermined and static, but rather co-evolving with technological development and industrial dynamics. From an evolutionary perspective, co-evolution refers to a mutual relationship between firms, technologies and the institutional environment.

Recent research in the wider inter-disciplinary field of science and technology studies (STS) and the literature on socio-technological transitions adopt a systemic perspective on the innovation process and institutional change (GEELS 2002, 2004; KEMP ET AL. 1998; MARKARD/TRUFFER 2006; SCHOT/GEELS 2007). A socio-technical transition is conceptualized as a long-term process of transformative change from one system equilibrium to another one. This perspective highlights the co-evolution of technologies, markets and social systems, particularly with regards to co-evolving cognitive and normative institutions like common values, user practices or regulative institutions, organizations and policies.

This thesis is concerned with the co-evolution of technology, institutions and industrial structure as the core mechanism for the emergence of a new industry. A co-evolutionary process is understood as the dynamic interactions between technologies, economic actors and the institutional environment. Following MALERBA (2006: 18) "[t]he challenge for research here is to go to a much finer analysis at both empirical and theoretical levels, and to move from the statement that everything is coevolving with everything else to the identification of what is coevolving with what, how intense is this process and whether indeed there is a bi-direction of causality".

MURMANN (2003), for example, describes how an industry co-evolves with national institutions. In his seminal study on the emergence of the German synthetic dye industry in the 19th century, MURMANN (2003) analyzed the impact of the development of the dye industry on institutional changes in regard to patent practices, research and education systems and the creation of supporting organizations like research institutes and business associations. This co-evolutionary process took place through interaction and positive feedback. German dye companies shaped these emerging institutions, which facilitated the success of Germany as a worldwide leader.

Although the idea of co-evolution has become popular in various disciplines such as evolutionary economics, STS and innovation studies and increasingly in economic geography, it is often used as a fuzzy and abstract concept. Most empirical studies only consider co-evolution as a process of simultaneous development of two populations without questioning the mechanisms behind this process. It remains unclear whether co-evolution is a "natural", automatic process which occurs spontaneously during the evolution of a technology or industry (as it is implied in evolutionary economics). And if not, this raises the questions: How and under what circumstances does co-evolution occur? Or is co-evolution a necessary condition for the successful development of new technologies or industries? Similarly, the impact of strategic actions of economic actors, users, policy makers and other organizations and the interactions between actors and institutions have also largely been ignored.

The concept of co-evolution is used as a part of the conceptual framework to analyze the emergence of a new technology through the dynamic interactions between an institutional environment and institutional arrangements with technological development and industrial paths (see figure 2). Events and activities within one population enable changes in the other in a reciprocal manner.

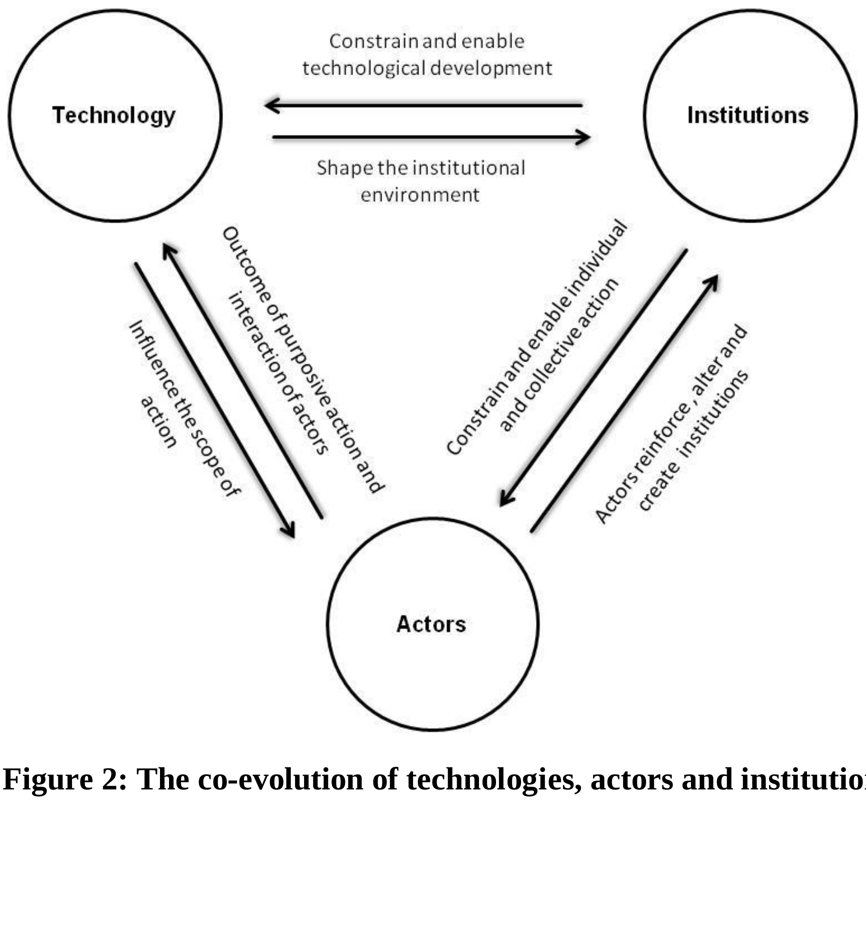


**Figure 2: The co-evolution of technologies, actors and institutions**

## 4.6 Path dependency

The idea of path dependency is considered to be one of the most important or even the core principle in evolutionary economics (e.g. MACKINNON ET AL. 2009: 132; MARTIN/SUNLEY 2006: 497) and provides a theoretical foundation for the analysis of regional development paths (ESSLETZBICHLER 2002: 17). The concept of path dependency received a great deal of attention resulting from the seminal studies by PAUL A. DAVID (1985) and BRIAN W. ARTHUR (1989, 1994) on evolutionary change of technologies and technical standards. In general, path dependency is characterized by the process of cumulative causation and self-reinforcing mechanisms. As DAVID (1985) states:

> "A path-dependent sequence of economic changes is one in which important influences upon the eventual outcome can be exerted by temporarily remote events, including happenings dominated by chance elements rather than systematic forces. Stochastic processes like that do not converge automatically to a fixed-point distribution of outcomes, and are called non-ergodic." (DAVID 1985: 332)

DAVID (1985) describes how a sequence of events and self-reinforcing processes influence subsequent technological development. He argues that individual decisions and actions – for example learning and knowledge accumulation, a firm's investments, decisions regarding a specific product design, or the development or adoption of a technology – shape and constrain the set of possible options (evolutionary paths) in the future. This is one of the key assumptions of evolutionary approaches for economic geography. More specifically, MARTIN and SUNLEY (2006: 402-3) define path dependence as a

> "probabilistic and contingent process: at each moment in historical time the suite of possible future evolutionary trajectories (paths) of a technology, institution, firm or industry is conditioned by (contingent on) both the past and the current states of the system in question, and some of these possible paths are more likely or probable than others. The past thus sets the possibilities, while the present controls what possibility is to be explored, which only becomes explained ex post". (MARTIN/SUNLEY 2006: 402)

The concept of path dependency has been adopted by a variety of different scientific fields in various contexts and can be applied at different levels of analysis. Besides economics, it has attracted a growing interest in social and organizational science, particularly in organizational and management studies (GARUD/KARNØE 2001b; GARUD ET AL. 2010; SYDOW ET AL. 2009;

VERGNE/DURAND 2010), and has become a frequently used concept in economic geography (BOSCHMA/FRENKEN 2011b; HENNING ET AL. 2013; MARTIN 2010; MARTIN/SUNLEY 2006).[2]

The concept of path dependency expresses the general acceptance of evolutionary economics that economic structures can be explained only by their own history (BOSCHMA/FRENKEN 2006: 280; DOSI 1997: 1531; MARTIN/SUNLEY 2006: 399). Path-dependent processes and systems are characterized by non-ergodicity (ARTHUR 1989; DAVID 1985; MARTIN/SUNLEY 2006). The idea is taken from the theory of stochastic systems and refers to "the inability to shake free of their history" (MARTIN/SUNLEY 2006: 399). A non-ergodic or path-dependent process or system is one whose outcome evolves as a consequence of the process's or system's own history (DAVID 1985: 332; MARTIN/SUNLEY 2006: 399). Both ARTHUR (1989) and DAVID (1985) emphasize that small variations in the sequence of events, caused by "historical accidents" (DAVID 1985: 335) or "small events" (ARTHUR 1989: 117) can have considerable consequences in the long-run as these initial events can trigger a self-reinforcing, cumulative process. According to path dependency theory, a pattern of action becomes locked-in to one path, like a single product or technology (ARTHUR 1989; DAVID 1985; VERGNE/DURAND 2010) or dominant technological trajectory (DOSI 1982).

The literature on evolutionary economics stresses the path dependency of technological development (ARTHUR 1989; DAVID 1985; DOSI 1982; NELSON/WINTER 1982). It is argued that technologies develop along distinct paths in a specific socio-technical context. The innovative and research activities of scientists and engineers are strongly influenced by cognitive heuristics. These shared routines and search heuristics, created by actors, develop in a path dependent manner and are themselves a carrier of path dependent behavior. To take this cognitive and behavioral framework into account, evolutionary economists put an emphasis on "technological regimes" (NELSON/WINTER 1982) and "technological paradigms" (DOSI 1982). A technological regime includes the technological and institutional environment in which economic actors operate and under which innovation occurs (NELSON/WINTER 1982). Similarly, DOSI (1982) proposes the concepts of "technological paradigm" and "technological trajectories". DOSI (1982: 152, emphasis in the original) defines a technological paradigm as a " 'model' and a 'pattern' of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material

[2] For an overview over the different steams of literature and topics see, for instance, MARTIN and SUNLEY (2006: 398).

technologies". A technological paradigm provides a set of opportunities and constraints for the direction of technological development and technological change. Once a new technological paradigm (DOSI 1982) or dominant design (TUSHMAN/ANDERSON 1986) has become established, technological progress follows a certain direction or trajectory set by this paradigm. A dominant design is a technical norm within a product category that gains general acceptance as the standard for technical features that other market players must follow if they want to acquire significant market share (UTTERBACK 1994). A dominant design for a technology (or a technological paradigm) comes into existence if one of the many technological alternatives wins the selection process. The emergence of a dominant design is the result of a path dependent process driven by increasing returns to scale. Basic technology or product features become established as a result of learning processes and continuous adaptation by producers and users (ABERNATHY/UTTERBACK 1978). MURMANN and FRENKEN (2006: 935) synthesize the causal mechanisms that explain why a particular design rather than other ones emerge as the dominant design into five categories: the selection of the best technological compromise, economies of scale, network externalities, superior firm strategy, and sociological, political and organizational dynamics. It is not always the best technological solution that becomes a dominant design. For example, JVC's Video Home System (VHS) became the dominant design for video tape recording although the technology was inferior to Sony's Betamax system. CUSUMANO ET AL. (1992) found that success mainly resulted from a better firm and marketing strategy. The company JVC was able to cooperate with their rivals and other electronic companies and formed strategic alliances through licensing agreements. Once a dominant design comes into existence, the basis of competition shifts from product innovation to process innovation and efficiency (ABERNATHY/UTTERBACK 1978). A dominant design or technology forms the selection environment for the new technology. As DOSI (1982: 153, emphasis in original) argues, "technological paradigms have a powerful *exclusion effect*: the efforts and the technological imagination of engineers and of the organisations they are in are focused in rather precise directions while they are, so to speak, 'blind' with respect to other technological possibilities". In other words, technological paradigms give rise to specific patterns in the direction of technical change, what DOSI (1982) calls a "technological trajectory". "A technological paradigm [...] embodies strong prescriptions on the *directions* of technical change to pursue and those to neglect.” (DOSI 1982: 152, emphasis in original)

Because of the cumulative nature of technological development, search heuristics become incrementally 'locked-in' to a particular technological trajectory. A technological trajectory can be seen as "the pattern of 'normal' problem solving activity (i.e. of 'progress') on the ground of a technological paradigm" (DOSI 1982: 152). This trajectory "can be represented by the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant. Progress can be defined as the improvement of these trade-offs" (DOSI 1982: 154). Thus, a technological trajectory may create substantial cognitive barriers.

Originally, the concept of technological path dependency has been used to describe continuity and cumulative patterns in the development of a technology (ARTHUR 1989, 1994; DAVID 1985). These formal models are generally referred to as the "canonical" models of path dependency (MARTIN 2010). Here, technological development is characterized by choices between competing paths of development like alternative technologies. Based on the studies on canonical model of path dependency by DAVID (1985) and ARTHUR (1989, 1994), SYDOW ET AL. (2009) suggest a three-stage model of organizational path dependency which can very well be applied to the evolution of a technology (figure 3). In the first, preformation phase, multiple opportunities for experimenting and developing a new technology, product, institution, or organization exist. Small events lead to a "critical juncture" and due to self-reinforcing mechanisms a particular opportunity, technology, product, or institution is preferred. The range of options or decision alternatives is narrowed down and a path begins to evolve (Phase II). Once a critical mass is reached and a dominant pattern becomes established, alternative options are no longer considered. Self-reinforcing mechanisms and positive feedback processes reinforce the path, which may lead to a lock-in (Phase III).

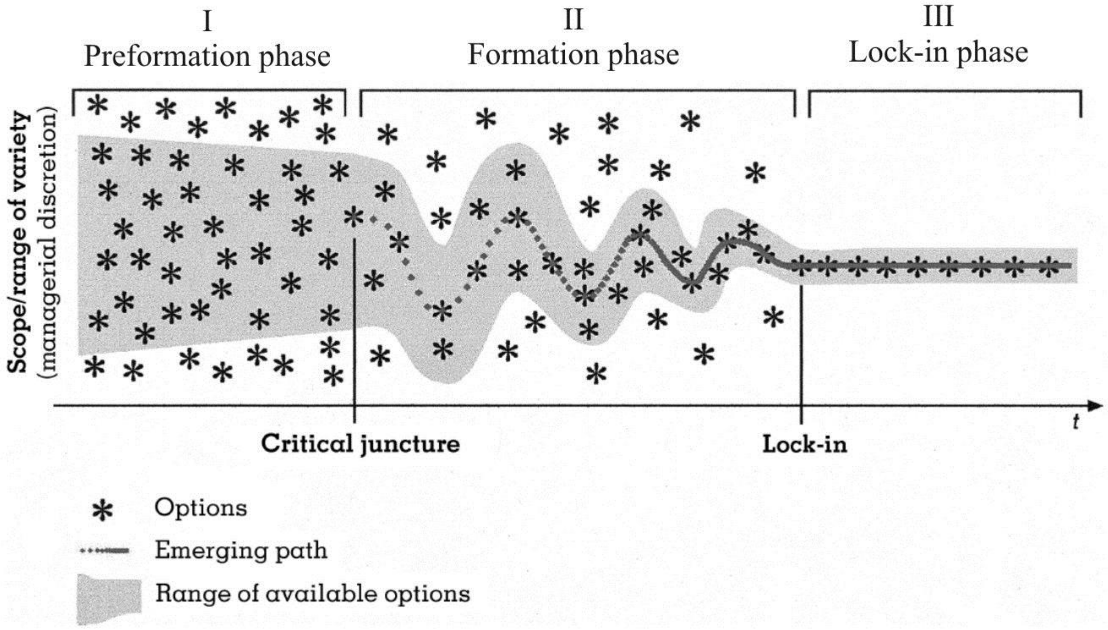


**Figure 3: The constitution of an organizational path**

Source: SYDOW ET AL. (2009: 692); supplemented by author

According to MARTIN and SUNLEY (2006: 400), three different views of path dependence can be distinguished in economics: technological lock-in, dynamic increasing returns and institutional hysteresis. The idea of path dependence as a technological lock-in is based on the work of DAVID (1985) and argues that a technology may become 'locked in' to a particular trajectory as a result of technical interrelatedness, economies of scale and a quasi-irreversibility of investments. Path dependence as a result of dynamic increasing returns, is based primarily on the work of ARTHUR (1989) and focuses on various forms of increasing returns and which produce positive feedback effects. This idea maintains that one technology is more likely to be adopted the more it is already used. ARTHUR (1989) suggests four self-reinforcing mechanisms which cause increasing returns: large fixed set up costs, learning effects, coordination effects and self-reinforcing expectations (ARTHUR 1989; MARTIN/SUNLEY 2006: 401). Path dependence as an institutional hysteresis suggests that institutions are "evolving, nonoptimal, path-dependent phenomena" (SETTERFIELD 1993: 769). Due to socio-economic actions and interactions, formal and informal institutions tend to reproduce themselves over time.

For economic geography, MARTIN and SUNLEY (2006) add a fourth perspective on path dependence: regional path dependence. Whereas institutional economists use the concept to explain the persistence of institutions through path-dependent self-reinforcing processes (NORTH 1990), evolutionary economists focus on self-reinforcing processes (ARTHUR 1989, 1994; DAVID 1985) and the role of organizational routines (NELSON/WINTER 1982). However, both streams of literature insufficiently explain uneven regional development. The institutional and evolutionary economic perspectives on path dependence do not take into account regional economic, technological and institutional structures that shape regional path-dependent economic development. Economic geographers emphasize the path dependence in regional economic development. Regional path dependence is mainly concerned with the persistence of regional industrial structures and regional lock-in (e.g. BATHELT/BOGGS 2003; GRABHER 1993; HASSINK 2005). HENNING ET AL. (2013: 1352) note that:

> "Most economic geographers employ the path dependence concept to explain why change takes a particular direction, focusing on the path-dependent development of regional economies. In particular, it is common to analyse how regional industrial structures change, or fail to change, as a consequence of path dependence in industrial, technological or institutional development." (HENNING ET AL. 2013: 1352)

MARTIN and SUNLEY (2006) argue that path dependence is a fundamental characteristic of the evolution of the regional economic landscape in a dual sense: The regional economic landscape, consisting of a set of economic actors, industries and institution, should be seen as "both an outcome of path-dependent processes of economic evolution, and a major determinant shaping many of those processes" (MARTIN/SUNLEY 2006: 410). From a regional perspective, path dependence can arise from a natural resource base, sunk costs associated with local assets and infrastructures, local external economies of industrial specialization, regional technologies, economies of agglomeration, region-specific formal and informal institutions, and interregional linkages (MARTIN/SUNLEY 2006: 412).

MARTIN (2010) summarizes the main assumptions of DAVID's (1985) and ARTHUR's (1989, 1994) formal models of path dependence with the focus on "lock-in" as a key concept as the canonical model of path dependence. According to this model, an initial event or early decisions trigger the emergence of a new path and over time, structures and actors become 'locked in' due to increasing returns. Thus, path dependency is concerned with the long-term historical development and continuity in regional, industrial, technological or institutional development and stresses self-reinforcing mechanisms and processes (HENNING ET AL. 2013; MARTIN/SIMMIE 2008; MARTIN/SUNLEY 2006). It provides a theoretical framework to explain why technologies, products, institutions and decisions follow specific trajectories in different regions. The key characteristics of the basic, canonical model of path dependency are depicted in figure 4.

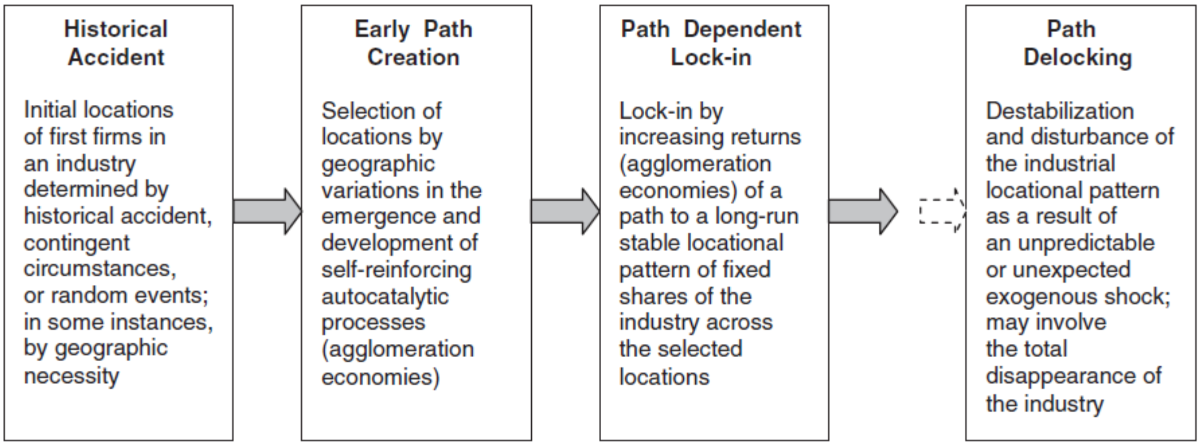


**Figure 4: The basic, canonical path dependence model of spatial industrial evolution**

Source: MARTIN (2010: 5)

The canonical model of path dependence has been applied in many empirical studies to explore the evolution of regional economic landscapes (BATHELT/BOGGS 2003; GRABHER 1993; HASSINK 2005). According to the model, the economic landscape evolves in a path-dependent manner. This will be included in the conceptual framework. The value, as well as the weaknesses, of this understanding of path dependence are pointed out in section 4.9.

## 4.7 Path creation

The discussion of the concept of path dependence in economic geography has resulted in some serious challenges and criticisms[3]. MARTIN (2010: 3), for instance, criticizes the classical canonical path dependence model for its deterministic perspective on lock-in as a too "limited and restricted way of thinking about path-dependent economic evolution". Furthermore, the classical path dependence theory is criticized for overemphasizing the role of small events, historical accidents, and random processes (GARUD/KARNØE 2001a; MARTIN 2010; MARTIN/SUNLEY 2006; SYDOW ET AL. 2009). This implies that a new path is created by pure chance and reduces the emergence of a new industrial and technological path to an accidental, serendipitous event. This interpretation of path dependence should be considered

[3] For a detailed review and critique of the canonical model of path dependence see MARTIN (2010).

to be too limited to explain the emergence of new industries or technologies (MARTIN/SUNLEY 2006: 428). Deviations from an established path and the development of new pathways are mainly associated with external shocks. MARTIN and SUNLEY (2006: 407) argue that a path dependent model of economic evolution needs to incorporate endogenous mechanisms that enable change and generate novelty. In a similar context, GARUD and KARNOE (2001a) criticize the concept of path dependency for its lack of attention to strategic agents. They argue that a path dependent perspective does not provide an explanation for how agents are able to shape their environment or even break out from an established path. By emphasizing continuity and stability, path dependency and the idea of lock-in may play a significant role in the development and the persistence of (possibly inefficient) institutions, technologies and regional industrial structures, but very little is said about how, where and why new paths are created (MARTIN/SUNLEY 2006: 407).

GARUD and KARNOE (2001a) offer an alternative perspective on path-dependent development which they call "path creation", illustrating the importance of a strategic agency in the emergence of new technologies. The concept has been developed in reaction to the limitations of viewing the emergence of a novelty as a historical accident or random event. The authors emphasize the active role of human agency in shaping technological paths. Apart from external shocks, actors can influence the creation and development of new technological paths. In this perspective, new paths are created by strategic choices and the deliberate action of powerful actors (GARUD/KARNØE 2001a; GARUD ET AL. 2010). They consider that "entrepreneurs attempt to shape paths, in real time, by setting processes in motion that actively shape emerging social practices and artifacts, only some of which may result in the creation of a new technological field" (GARUD/KARNØE 2001a: 2).

Path creation, however, does not reject the concept of institutional embeddedness. It does not mean that entrepreneurs have an unbounded strategic choice. Rather, path creation refers to the way actors may leave existing paths or structures in a process of "mindful deviation" (GARUD/KARNØE 2001a). Thus, an alternative path can be created by strategic action. This means that "entrepreneurs are embedded in the structures they jointly create and from which they mindfully depart" (GARUD/KARNØE 2001a: 9). Mindfulness implies that entrepreneurs are conscious of their embeddedness and are able to leave existing structures. These processes and the direction of change are characterized by path dependence. "[A]ctors frame issues about the future, coordinate their actions in the present and make sense of what may have transpired in the past" (KARNØE/GARUD 2012: 735). The accumulation of inputs from different actors generates a momentum of the emerging technological path that enables and constrains the activities of involved actors. (GARUD/KARNØE 2003: 278). GARUD and KARNØE (GARUD/KARNØE 2001a: 3) point out that a path creation perspective "assumes reciprocal interactions between economic, technical and institutional forces that constitute the technological artifacts and actors involved. Thus, social orders, institutional rules and artifacts are both medium and outcome of human endeavors".

Based on the Schumpeterian idea of "creative destruction", a new path can be created by entrepreneurs who deviate from existing structures and create new opportunities through the recombination and transformation of existing resources (GARUD/KARNØE 2001a: 6, 2003: 278). According to this view, "entrepreneurs are knowledgeable agents with a capacity to reflect and act in ways other than those prescribed by existing social rules and taken-for-granted technological artifacts" (GARUD/KARNØE 2001a: 2).

This understanding of path creation closely resembles the neo-institutional concept of the "institutional entrepreneur", highlighting the role of individual and collective actors in institutional change. The concept of "institutional entrepreneurs" integrates insights from entrepreneurship and institutional theory and is used to consider institutional changes as endogenous processes induced by strategic agents. Institutional entrepreneurs are actors who have an interest in modifying and transforming existing institutions and institutional arrangements or creating new ones (DIMAGGIO 1988; FLIGSTEIN 1997). These actors can be individuals or groups of individuals (FLIGSTEIN 1997) as well as organizations or groups of organizations (GARUD ET AL. 2002). Therefore, they need to mobilize others actors and organizations to generate a momentum for their initiative (GARUD/KARNØE 2001a: 15, 2003: 281). However, not all actors are equally capable of handling resistance and building capacities for collective action. Institutional entrepreneurship requires social and/or political skills that involve strategic actor power and the ability to mobilize minds and resources (DIMAGGIO 1988; FLIGSTEIN 1997; GARUD/KARNØE 2001a). In the context of the emergence of a new technology, institutional entrepreneurship involves the deliberate manipulation or creation of distinct institutional environments for a novel technology.

The main difference between the concepts of path dependency and path creation is that the latter emphasizes the role of human agency, in particular in terms of the ability of entrepreneurs to influence and shape paths in real time. From a path creation perspective, economic actors are seen as knowledgeable agents who are capable of reflecting the characteristics of a new trajectory and of mindful deviation from existing rules or routines and, therefore, from an established pathway. Table 2 gives an overview of the central differences between the two concepts[4]:

**Table 2: Path dependency vs. path creation**

| Dimensions | Path dependence | Path creation |
|---|---|---|
| **Initial conditions** | Given | Constructed |
| **Contingencies** | Exogenous and manifest as unpredictable, non-purposive and somewhat random events | Emergent and serving as embedded contexts for ongoing action |
| **Self-reinforcing mechanisms** | Given | Also strategically manipulated by actors |
| **Lock-in** | Stickiness to a path or outcome absent exogenous shocks to the system | Provisional stabilizations within a broader structurational process |

Source: Based on GARUD ET AL. (2010: 769)

## 4.8 The role of economic actors in institutional change and new path creation

This thesis is concerned with the role of human agency in the evolution of a new industry and technology. This raises the question about who exactly contributes to the creation and development of a new technological and industrial path.

Path creation theory focuses on the importance of human agency in shaping an existing development path or creating a new trajectory (GARUD/KARNØE 2001b, 2003). Adopting a path creation perspective may help to understand how new technological and industrial paths are created by the purposive behavior and intentional actions of economic actors. It is argued that multiple actors are able to shape an emerging technological path. Literature on path creation focuses on entrepreneurial activity as a key determinant of path creation. GARUD and

[4] For a detailed discussion on the different perspectives of path dependency and path creation see GARUD ET. AL (2010).

KARNØE (2001a, 2003) suggest that new technological paths are created by various kinds of entrepreneurs who mindfully deviate from existing paths. In this context, entrepreneurial activity encompass "distributed agency" (GARUD/KARNØE 2003: 279) in entrepreneurship. Agency is distributed over a variety of actors such as users, producers, evaluators and regulators who are all involved in the development of a new technology. In a similar vein, SIMMIE (2012: 769) argues that the emergence of a new technological path "require(s) social action by knowledgeable pioneering individuals, universities, companies and/or governments".

As GARUD and KARNØE (2003: 277) argue, "technology entrepreneurship is a larger process that builds upon the efforts of many". In this thesis, the term "industry actor" is defined more broadly and includes individuals such as inventors, innovators, entrepreneurs as well as a wide range of different types of firms (new entrants, incumbent companies and diversifying firms of different sizes), users and knowledge-producing and knowledge-diffusing organizations like universities and research institutes. The actors are involved at different phases of path development. In principle, they are engaged in the innovation process and the creation of novelty. Innovation is accomplished by entrepreneurs, firms or research institutes through knowledge creation or new combinations of existing resources. Users are also seen as an important source of innovation (VON HIPPEL 1986). In contrast to typical users, VON HIPPEL (1986: 791) emphasizes the particular importance of so-called “lead users”, who face needs that will be common in a marketplace months or years in the future. These users expect to benefit significantly from solutions to those needs. That is why they are highly motivated to engage in the innovation process to develop their own solutions to their problem. Consequently, a new technological path is created by the market introduction of a new product or technology. Apart from the generation of novelty, a crucial role is given to these industry actors in the formation and development of a new path. Developers as well as adopters of the new technology such as firms and research institutes contribute to the implementation and diffusion of new technologies and the ongoing technological development (GARUD/KARNØE 2001a, 2003).

It is also argued that these actors are able to actively shape the institutional environment and influence policy. Through their activities, they reinforce or change institutions or create new ones, for example by establishing specific design heuristics or new product standards. Thus, the role of the various types of industry actors is to mobilize resources for collective action. A powerful example of collaboration is the formation of national and regional industry and business associations and networks. Such organizations play an important role in shaping the institutional environment as they can serve as a collective agent for mediating business–government relations. They engage in lobbying, set industry norms and joint standards, collect data and share knowledge or promote the application of new technologies (FARLA ET AL. 2012; JACOBSSON/BERGEK 2004; MUSIOLIK/MARKARD 2011).

Similar to industry associations, civil society actors and social movements and can also act as strategic agents or institutional entrepreneurs and contribute to the creation of a new path. In particular for the evolution of renewable energy technologies, several studies provide empirical evidence on the relevance of social movements and other civil society actors and organizations (DOBLINGER/SOPPE 2013; GARUD/KARNØE 2003; JACOBSSON/LAUBER 2006; JACOBSSON/JOHNSON 2000; SINE/LEE 2009). Pressures from civil society may force the government to change policies. The political science literature (e.g. SABATIER 1998) highlights the role of advocacy coalitions, which indicates the ability to mobilize resources for collective action. Advocacy coalitions, covering various actors sharing similar values and beliefs, play a major role in influencing policy. According to JACOBSSON and BERGEK (2004: 821, emphasis in the original):

> "[…] for a new technology to gain ground, *technology specific coalitions* need to be formed and to engage themselves in wider political debates in order to gain influence over institutions and secure institutional alignment. As part of this process, advocates of a specific technology need to build support among broader advocacy coalitions, which have the strength to influence the policy agenda."

Similarly, JACOBSSON and LAUBER (2006) demonstrated how industry associations, networks policy makers successfully established an advocacy coalition supporting renewable policies and funding programs. SINE and LEE (2009), for instance, found that environmental and social movements (organizations) facilitated and increased entrepreneurial activities in the US wind energy sector by influencing norms and values and promoting favorable regulatory conditions. Similar to industry associations, these collective agents promote and build the legitimacy for new technologies.

Besides private actors such as entrepreneurs and firms, the importance of public organizations such as universities or research institutes in the creation of novelty has been widely acknowledged (e.g. NELSON 1993). As universities are considered to be a major source of knowledge creation and crucial for facilitating new technologies and innovation, they also thought to be agents or drivers of new path creation. In this context, LESTER (2007) suggests four main roles that universities can play in local or regional development:

(1) Indigenous creation of new industries through spin-offs;

(2) Transplantation from outside through the importation of new knowledge, firms, R&D-Institutes, or resources;

(3) Diversification of existing industries into related technological industries by establishing research and discussion forums for new applications of existing regional industries and technologies;

(4) Upgrading existing industries through the introduction of incremental innovations, contract research, consulting activities and education programs.

Thus, public research institutions and universities may shape path creation in various ways.

Whereas GARUD and KARNØE (2001a, 2003) focus on entrepreneurial activity as the key drivers of path creation, MARTIN and SUNLEY (2006: 426) suggest that: "It is not just strategic agency among entrepreneurs that is important in path creation. [...] we also have to examine the strategic decisions made by policy makers, including the nation-state, if we are to properly understand regional path creation". In this thesis, policy makers consist of all government and public agencies and officials who are responsible for developing and enacting policy. The key role of these actors is to set the legal and institutional environment. The state has an important role as a key decision maker and institution builder. As MARTIN (2000: 86) points out: "one of the key agents of institutional change […] is the state". Especially formal institutions are strongly influenced by governmental agencies. For example, the state plays a key role in establishing the regulatory framework in which economic actors are embedded and in which a technology develops. Policy makers can attempt to generate changes in the institutional environment by legislative reforms, the introduction of new laws and regulatory policies or shifts in policy programs (MARTIN 2000: 87). For example, energy or technology policies are crucial for the development and diffusion of technologies and for the behavior of industry actors. As argued above, state-led institutional change is embedded in a wider institutional context. Changes in environmental policies may be triggered by external events (like the Fukushima accident) or changes in informal or normative institutions that are concerned with the awareness of environmental risks, climate change or sustainability. Another important role of policy makers is that these policies attempt to promote a technology and contribute to the diffusion of innovations. Through subsidies, incentives and government regulations, the state may act as a facilitator of new technologies (KEMP ET AL. 1998). R&D policy usually seeks to promote technology and knowledge transfer. For example, policy makers and government agencies support research institutes or actively engage in research in a particular technological field. Apart from national policies, some studies highlight the role of regional policy in the process of path creation (COENEN ET AL. 2015; DAWLEY 2014; DAWLEY ET AL. 2015).

In this context, literature on "Strategic Niche Management" emphasizes the role of policy makers in the creation of niche conditions (GEELS 2004; KEMP ET AL. 1998). It is argued that niches provide a protected space for new technologies. Industry actors can uses these conditions to develop and test their inventions and technologies apart from mainstream markets. From this perspective the role of policy makers is to be an "enabling actor and catalyst rather than a regulator or technology sponsor" (KEMP ET AL. 1998: 191). DAWLEY (2014), for example, emphasizes the role of policy actors at multiple scales. At the national level, policy makers and regulatory institutions can stimulate path creation through R&D policy or environmental and energy policies. At the subnational level, local and regional organization, which are embedded in the existing, region specific institutional and industrial structure, shape the regional emergence of new industries and technologies (DAWLEY 2014). In contrast to promoting a new technology, policy may also (deliberately or inadvertently) create political, technological and institutional constraints and barriers (KEMP ET AL. 1998).

Starting from a broad understanding of the strategic agency, relevant actors for the emergence and development of a new technology thus include entrepreneurs, spin-offs and diversifying firms but also research institutes, policy makers, organizations and other civil society actors.

## 4.9 Utility of the concepts of path dependence and path creation

In this section, the value of the two concepts, path dependence and path creation, for explaining the emergence and evolution of new technologies is discussed. The path dependence perspective explains the emergence of novelty (development of a new technology or industry) as a result of a cumulative process of random events and historical accidents. It is argued that contingency and self-reinforcing mechanisms lead to the development of a certain path. Hence, the concept of path dependence provides a valuable starting point for understanding historical processes as potential constraints on future actions and decisions. In contrast to path dependent ideas, the concept of path creation focuses on how actors strategically influence and alter their environment. Path creation highlights the active role of entrepreneurs and firms in shaping new technological trajectories by interacting with the institutional environment.

By considering the idea of path creation not as a counter-concept (GARUD/KARNØE 2001a), but as a supplement or extension to the concept of path dependence, a more agency-oriented perspective on the evolution of the economic landscape is provided (MARTIN/SUNLEY 2006; SIMMIE 2012). This can lead to a better understanding of how particular individual and collective actors mobilize resources to introduce inventions and innovations or to shape the institutional environment in order to facilitate their own technology. New technological inventions and innovations may create new technological pathways that lead to the emergence of a new industry. In accordance with MARTIN and SUNLEY (2006), who argue for a more open and dynamic understanding of path, the process of economic evolution is understood as "an ongoing, never-ending interplay of path dependence, path creation and path destruction that occurs as actors in different arenas reproduce, mindfully deviate from, and transform existing socio-economic-technological structures, socio-economic practices and development paths" (MARTIN/SUNLEY 2006: 408).

In this context, MARTIN (2010) presents an alternative model of local industrial evolution (see figure 5). It categorizes industrial path dependence into four different phases: The first phase is a preformation phase, which is constituted by pre-existing economic and technological conditions and knowledge, resources and experiences inherited from previous local patterns of economic development. In the second phase, new regional paths are created. The third phase is a path development phase, which is based on local increasing returns and network externalities. In the fourth phase, the path may either follow towards ‘lock-in’ or continue to evolve dynamically.

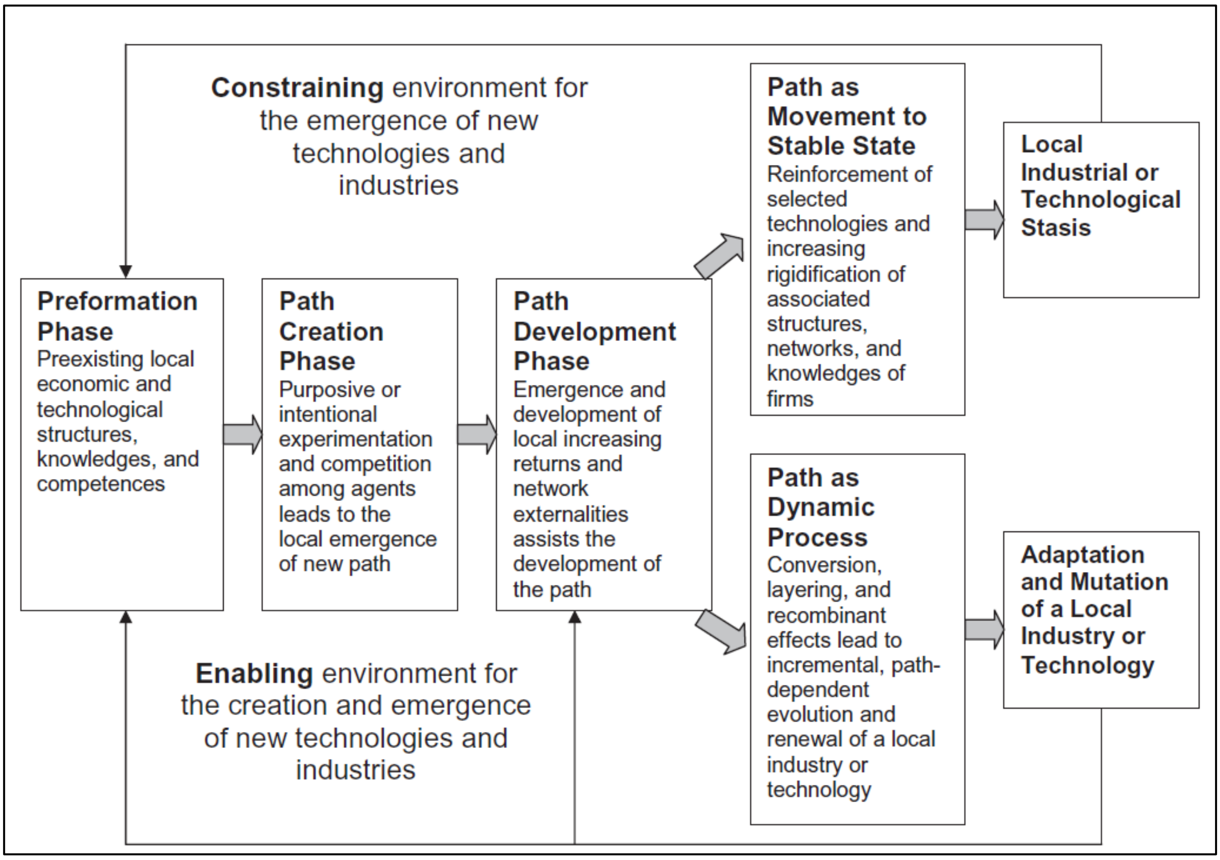


**Figure 5: Path dependence model of local industrial evolution**

Source: MARTIN (2010: 21)

By stressing that technological and economic development strongly depends on pre-existing economic, technological and institutional structures, path dependence theory offers an explanation for how and where a new path emerges. In other words, the creation of a new path is influenced by previously established trajectories. Here, at least two types of influence are possible. In the first scenario the established path constitutes barriers to new path creation (SIMMIE 2012). In the second scenario, an old path enables a new one. As the creation of a new technological path is built upon previously existing technologies, a new regional pathway can arise from previously existing ones which provide related technological competencies, knowledge or institutions. "Related industries could, for example, benefit from use of the same technologies or skills in the labour force" (HENNING ET AL. 2013: 1353). A recent stream of literature in evolutionary economic geography considers the emergence of a new regional path on the basis of a technologically related trajectory as an evolutionary branching process (BOSCHMA/FRENKEN 2011a; FRENKEN/BOSCHMA 2007; NEFFKE ET AL. 2011).

This conceptualization of local industrial evolution could be modified to develop a framework for analyzing the co-evolution of technologies, actors and institutions that are involved in the emergence of a new technology. For that purpose, some general aspects of MARTIN's (2010) stylized model are adopted and supplemented by additional approaches in order to explore the role of strategic agents and the interrelationship between technological development, institutional change and evolution of the economic landscape.

# 5 Revised theoretical and conceptual framework

Based on the theoretical arguments presented in the previous sections, a revised theoretical and conceptual framework is developed that explains the regional emergence and evolution of new technologies. Following MARTIN's (2010) model of local industrial evolution, the emergence and evolution of a new technology is divided into four phases:

(1) preformation phase

(2) path creation phase

(3) growth phase

(4) post-formation phase

The revised concept is illustrated in figure 6. The first three phases are grounded on MARTIN's (2010) model of local industrial evolution. The fourth phase represents a later stage of path development when the technology has matured and significant changes in the regional economic landscape have occurred. The actors and processes shaping the evolution of the economic landscape are at the heart of this conceptual framework. The term economic landscape refers to the spatial organization of a variety of actors, their activities and the interrelations between them. It encompasses the spatial structures of economic actors and of the emergence and diffusion of novelties (innovations, new technologies) and manifest themselves in the technological and industrial structure, in institutional and organizational forms and consequently in the formation and re-formation of the physical landscape. Drawing on an evolutionary perspective, the economic landscape is interpreted as both an outcome of the process of economic evolution and a major influence shaping that process (BOSCHMA/MARTIN 2007: 539; MARTIN/SUNLEY 2006: 410).

The process of economic evolution is regarded as a continuous process of creation, transformation and path dependent development. The phases illustrated in figure 6 repeat themselves in the form of a cycle as indicated by arrows at the bottom. The economic, technological and institutional structures of the post-formation phase set the conditions for subsequent actions and constitute the initial condition a new path. The double arrows indicate the co-evolution and feedback mechanisms between technological development and the institutional environment. The curved arrows illustrate the ongoing evolution of the economic landscape as a result of the continuous interaction between different actors and the institutional environment. The vertical triple arrows indicate the influence of strategic actions of economic actors, users, policy makers and other organizations on the evolution of a technology and the economic landscape.

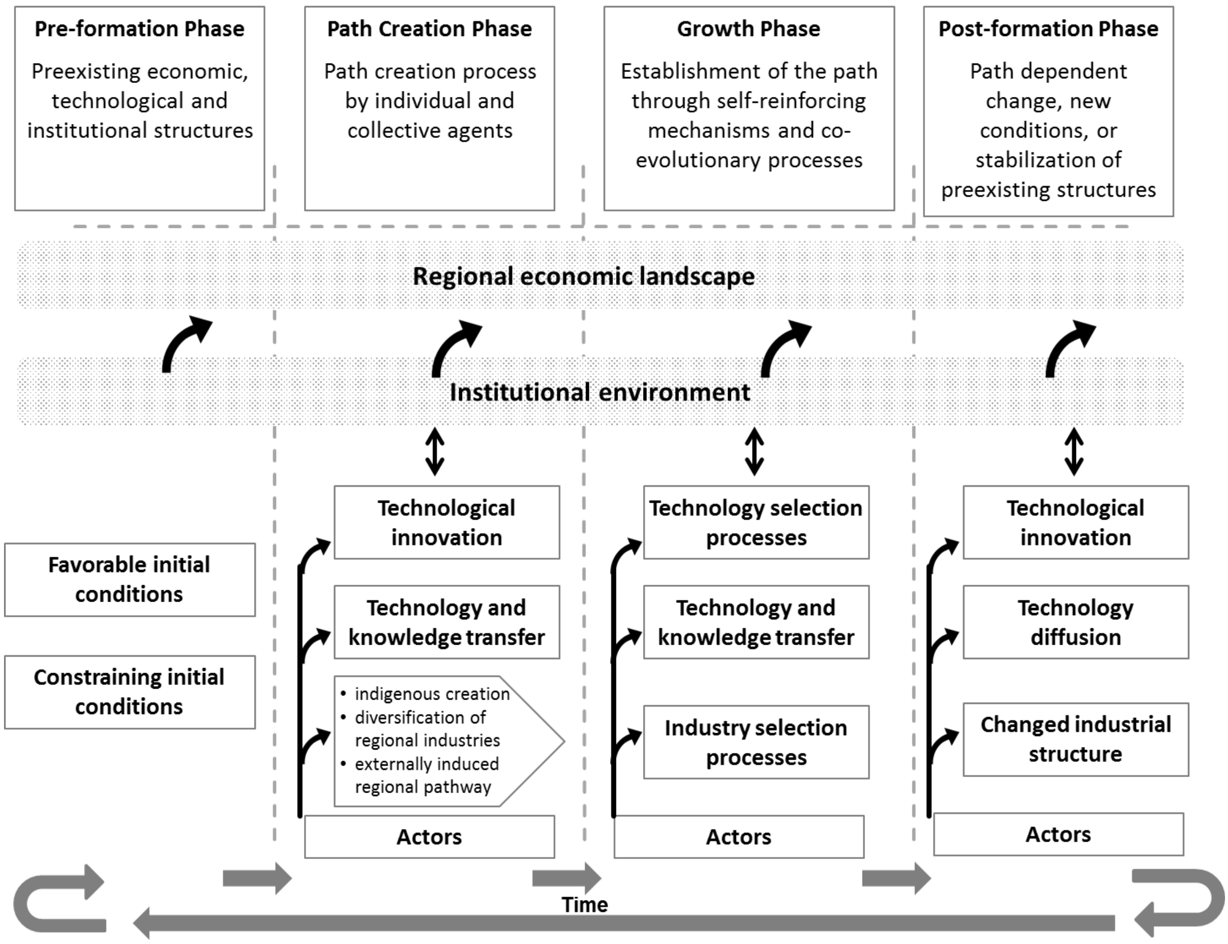


**Figure 6: Revised theoretical and conceptual framework**

**<u>Preformation phase</u>**

The 'preformation phase' stresses the pre-existing place-dependent factors and structures affecting the local emergence of a new industry or technology. It is argued that new industries emerge from technologically related activities in a region (BOSCHMA/FRENKEN 2011b; NEFFKE ET AL. 2011). MARTIN (2010) argues that the evolution of an industry in a certain region depends on regional resources related to the region's pre-existing industry structure:

> "The emergence of a new local industry may not be due to 'chance' or 'historical accident' but stimulated or enabled – at least in part – by the pre-existing resources,

> competences, skills and experiences inherited from previous local paths and patterns of economic development." (MARTIN 2010: 20)

The existing place-specific infrastructure, resources, industrial structure, knowledge and skills constitute the environment in which new economic activity emerges (MARTIN/SUNLEY 2006; MARTIN 2010). In sum, as MARTIN (2010: 19) points out, "the local inherited knowledge and skill base of an industry can form the basis of the rise of related new local paths of industrial and technological activity". These preexisting economic, technological and institutional structures/conditions can enable or constrain the regional emergence and development of a new industry or technology. For example, region-specific structures have an influence on the process of regional diversification. Recent empirical studies suggest that the emergence of a new industry in a region is more likely to occur if these activities are to some extent related to other already existing industries (BOSCHMA ET AL. 2013; FRENKEN ET AL. 2007; NEFFKE ET AL. 2011). Similarly, studies using patent data have shown that a new technology is more likely to become established in a region if it is related to the regional technological structure (BOSCHMA ET AL. 2015; RIGBY 2015). Thus, a new path may latently exist in an old one which means that structural change in regional economies is a gradual process.

In line with GARUD ET AL. (2010), initial conditions are not pre-given but constructed or strategically influenced by reflexive agents. Such conditions are a result of the path dependent industrial, technological and institutional structures. The industrial structure of a region is characterized by the actions and interactions of economic actors. The technological structure, as an outcome of previous technological trajectories, is manifested in the technological capabilities of firms and research institutes. The institutional structure is composed of the institutional environment, consisting of formal and informal norms, routines, rules, regulations and laws and their enforcement and institutional arrangements in terms of particular organizational forms like trade unions, associations, public authorities, or governmental institutions and governance structures. Together, these preexisting structures and conditions can enable or constrain the emergence of a new industry or technology.

At the pre-formation phase, there are hardly any changes of the economic landscape. Innovation and technological change is limited to individual action and experimentation in niches.

**Path creation phase**

Although path creation is an important issue for economic development, relatively little consideration has been given to the process of path creation and the active role of social agency in economic geography. Only a few empirical studies, however, have focused on how a new regional pathway has been created and how economic, state and civil society actors promote institutional change.

Path creation is seen as the process of a mindful deviation by individual or collective agents. It is argued that these agents deliberately shape a technological path by introducing new technologies and, therefore, escape lock-in situations. New path creation is characterized by (mainly small-scale) pioneering activities and the introduction of novelties. New knowledge is created through experimentation and learning. This involves trying out new ideas and solutions and sympathetically testing products and techniques. In this phase, technological development is characterized by several competing designs.

In the context of theorizing regional path creation, MARTIN and SUNLEY (2006: 420) suggest five ways for regions to escape lock-in situations and create a new pathway: indigenous creation, heterogeneity and diversity, transplantation from elsewhere, diversification into (technologically) related industries and the upgrading of existing industries (see table 3). All of these scenarios are based on technological development and imply that the regional development of new industries and technologies are co-evolving. In the context of the emergence of a new technology, it is of particular interest to distinguish between (a) indigenous creation, (b) diversification of regional industries and (c) externally induced regional pathways.

**Table 3: Mechanisms of new path creation**

| Sources of new path | Characteristics |
|---|---|
| **Indigenous creation** | Emergence of new technologies and industries from within the region that have no immediate predecessors or antecedents there |
| **Heterogeneity and diversity** | Diversity of local industries, technologies and organizations promotes constant innovation and economic reconfiguration, avoiding 'lock-in' to a fixed structure |
| **Transplantation from elsewhere** | Primary mechanism is the importation of a new industry or technology from elsewhere, which then forms basis of new pathway of regional growth |
| **Diversification into (technologically) related industries** | Transition where an existing industry goes into decline but its core technologies are redeployed and extended to provide the basis of related new industries in the region |
| **Upgrading of existing industries** | The revitalization and enhancement of a region's industrial base through the infusion of new technologies or introduction of new products and services |

Source: MARTIN/SUNLEY (2006: 420)

### (a) Indigenous creation

In the first case – the indigenous creation of a new technology and industry – a new regional pathway results from the behavior of interacting actors within the region. In a process of "mindful deviation" (GARUD/KARNØE 2001b), actor may deliberately shape their institutional environment and deviate from an established trajectory. "Entrepreneurs mobilize resources, ideas and people in the collective creation of new technological fields" (MARTIN/SUNLEY 2006: 426). Similarly, economic actors may deliberately convert or reinterpret pre-existing institutions (STRAMBACH 2010). Both imply an endogenous source of institutional change as stated by NORTH (2005) and his followers. In this way, institutional change facilitates new path creation. MARTIN and SUNLEY (2006) highlight two types of mindful deviation. The first type refers to path creation as an incremental process implying that "agents consistently cultivate and nurture experimentation in the search for new technologies, products, processes and the like" (MARTIN/SUNLEY 2006: 426). The other one involves "critical junctures and large-scale events or shocks" (MARTIN/SUNLEY 2006: 426) that cause agents to develop new strategies. In both cases strategic action is not restricted to entrepreneurs but also includes policy decisions, firm strategies and individual actions. Thus, in the process of path creation, multiple actors are involved (GARUD/KARNØE 2003). The enabling factors and mechanisms are especially entrepreneurial activity and human capital associated with actors such as entrepreneurs, inventors, companies and research institutes located within the region.

**(b) Diversification of regional industries**

A second type of a new regional path creation refers to the diversification of regional industries and technologies. As explained above, this process is shaped by the existing regional conditions such as place-specific infrastructure, resources and industrial structure and its local knowledge and skill base. The transformation and recombination of technological know-how, organizational routines and institutional conditions from the pre-existing industry structure into related or derived industries and technologies may give rise to a new trajectory (MARTIN 2010: 19; MARTIN/SUNLEY 2006: 423). Although this is, of course, also an endogenous mechanism as it builds on firms within the region, for theoretical and empirical reasons, both mechanisms – (a) and (b) – are regarded as different types because they both are based on different actors and processes of path creation.

From an evolutionary perspective, regional diversification is a path-dependent process (NEFFKE ET AL. 2011). As diversification into new and related industries may enable a new pathway, the emergence of a new regional industrial path can be conceptualized as an evolutionary branching process (BOSCHMA/FRENKEN 2011a; FRENKEN/BOSCHMA 2007; HENNING ET AL. 2013). Regional branching occurs in two ways: an industry may grow out of an existing one or it may result from the recombination of competences from different industries (BOSCHMA/FRENKEN 2011a: 69). The idea of regional branching is based on the existing literature on the role of localized knowledge spillovers for the regional concentration of economic activity (AUDRETSCH/FELDMAN 1996; e.g. JAFFE ET AL. 1993) and the concept of "related variety" (FRENKEN ET AL. 2007). Referring to the concept of "related variety", BOSCHMA and FRENKEN (2011a) argue that knowledge and organizational routines are more likely to spill over between agents and sectors that share technological capabilities or common knowledge bases. The idea of technological relatedness implies mechanisms of regional path dependence and new path creation. The industrial structure of a region enables or constrains regional diversification and branching (BOSCHMA/FRENKEN 2011a; NEFFKE ET AL. 2011). However, it remains unclear what precisely constitutes technological relatedness.

Often, the term is used to describe any kind of relationship between a preexisting and an emerging industry.

BOSCHMA and FRENKEN (2011a: 72) outline four mechanisms through which knowledge and routines can be transferred from existing industries to the emerging industry. These mechanisms are mostly localized at the regional level: spin-off activity, firm diversification, labor mobility and social networking (table 4).

**Table 4: Knowledge-transfer mechanisms and actors of regional branching**

| Mechanism | Actor | Definition |
|---|---|---|
| **Spin-off** | Individual | New entry arising from a corporate parent |
| **Firm diversification** | Firm | Existing firm diversifies into a new technology/ industry |
| **Labor mobility** | Individual | Inter-firm mobility of employees |
| **Social networking** | Individual + Firm | Inter-firm relationships |

However, not every mechanism is likely to be of equal importance for regional path development. From the industry life cycle perspective, entrepreneurship and spin-off activity are the key mechanisms in the early stage of industrial evolution (KLEPPER 1997, 2010; KLEPPER/SLEEPER 2005). Spin-off processes are considered to enhance regional diffusion of knowledge and routines because new firms, which exploit knowledge and organizational routines from a parent firm, tend to locate near their parent organizations (ESSLETZBICHLER/RIGBY 2007; KLEPPER 2007, 2010; MOSSIG 2000). Empirical research on industry evolution and firm capabilities highlights the relevance of pre-entry resources and capabilities of the entrant. These studies suggest that firms with prior experience and related knowledge are more likely to enter a market and that entrepreneurs with prior experience in a related industry have a higher survival rate than those without it (HELFAT/LIEBERMAN 2002; KLEPPER 2002b). Case studies about the British (BOSCHMA/WENTING 2007) and the U.S. automobile industry (KLEPPER 2007) have shown that branching through spin-off activity may lead to the spatial concentration of an emerging industry. These survival analyses also indicate that entrepreneurs are more successful if they had experience in the same or a technologically related industry. Whereas spin-offs and firm diversification from related industries may stimulate the emergence of a new industry in a certain region, labor mobility and social networking can be regarded as regional knowledge diffusion mechanisms at a subsequent phase of path development (TANNER 2014).

In addition, other feasible mechanisms can also be considered. The literature on the geography of innovation and knowledge flow emphasize the importance of local networking and inter-firm collaboration for transferring knowledge (ASHEIM/GERTLER 2005; BRACZYK ET AL. 1998; COOKE 2012). Furthermore, MALMBERG and MASKELL (2002: 442) argue that observation and comparison of competitors are important mechanisms for knowledge-transfer and regional learning. Spatial proximity facilitates this process of learning by observation and doing, as it allows co-located firms that undertake similar activities to observe activities of nearby firms, identify and take up new technological ideas, or even imitate products (MALMBERG/MASKELL 2002: 439; SAXENIAN 1994: 58).

As many of these mechanisms have a strong regional dimension, path creation has an important regional component, too.

**(c) Externally induced regional pathway**

Thirdly, a new regional path can also be created exogenously by the transplantation of an industry or technology into the region from elsewhere (MARTIN/SUNLEY 2006: 422). "This refers to the importation and diffusion of new organizational forms, radical new technologies, industries, firms or institutional arrangements, from outside" (MARTIN/SUNLEY 2006: 422). This type of path creation can be identified less clearly. In fact, this process should not be regarded separately from the sources of new path creation mentioned above. As changes in preferences or beliefs lead to changes in the institutional environment, regional actors (e.g. firms) adapt to these externally induced changes. Similarly, policy intervention and market development affect the regional economy and may promote the creation of new regional pathways.

Exogenous impulses are mainly associated with political initiatives and government incentives (COENEN ET AL. 2015; COOKE 2012; DAWLEY 2014; DAWLEY ET AL. 2015; ESSLETZBICHLER 2012; ISAKSEN/TRIPPL 2017) and, thereby, refer to attempts to change the institutional environment. COENEN ET AL. (2015), for instance, investigated the role of policy intervention in path renewal and new path creation. In a case study on the forest industry in Northern Sweden they show that regional innovation policies can facilitate the emergence of a new technology in a region through the implementation of a policy program to provide incentives for firms to diversify into new biorefinery technologies. DAWLEY (2014) highlights the interaction of various path creation mechanisms. He finds that the emergence of the offshore wind sector in North East England resulted from initial local entrepreneurial activities which were subsequently enhanced by strategic regional and technology policies and government interventions. Innovation policies can also seek to contribute to new path creation through the importation of new knowledge and technologies into a region, for example, by establishing new research institutes (ISAKSEN 2015).

Furthermore, new path creation can be triggered by the arrival of new actors from outside the region (CHEN/HASSINK 2020; TRIPPL ET AL. 2018). For example, the foundation or relocation of public research institutions (ISAKSEN/TRIPPL 2017) or the migration of scientists and highly skilled people (TRIPPL ET AL. 2018; SAXENIAN 2006) can transfer new knowledge into a region.

In all cases, the emergence of a new industry is characterized by the co-evolution of technology, institutions and industrial structure. Regions accumulate various institutional environments over time which affect the intensity and nature of interaction, knowledge creation and collective learning mechanisms between agents (BOSCHMA 2004: 1007).

The path creation phase is characterized by pioneering activities and a high rate of product variation. New technology development is mainly based on experimentation and learning. Entrepreneurs, inventors and firms attempt to introduce radical innovations to the market. Pioneers begin to recognize the potential of a new technology and start implementing this technology. Thereby, agents interact with the institutional environment. To introduce a new technology or a new product, they may shape their institutional environment or reinterpret existing institutions. Public policies and the creation of supportive institutions or niche conditions can improve the ability of firms and other economic actors to innovate and encourage technology implementation. Mechanisms of inter-organizational technology and knowledge transfer take place which are expected to positively affect the innovation process and to contribute to the diffusion of a new technology. A wide range of knowledge transfer mechanisms tends to occur at the regional level (spinoffs, firm diversification, labor mobility and social networking). These pioneering activities as well as institutional changes create new opportunities which enable the path development process.

**Growth phase**

During the growth phase, a path becomes stabilized and positive feedbacks arise. Once a critical mass is reached, technological development becomes locked in into a particular trajectory through self-reinforcing mechanisms and co-evolutionary processes. As a consequence, the scope of action becomes limited and patterns of action are manifested through increasing returns and positive feedback. A technological paradigm or dominant design is likely to become established and leads to a particular technological trajectory. Firms have to adapt to changing markets or environments. According to industry life cycle theory, there is a shift from product to process innovations. Firms tend to focus their activities on improvements of existing products and technologies. This reduces the product variety and innovations become less radical (ABERNATHY/UTTERBACK 1978; KLEPPER 1997).

The establishment of a certain technological paradigm or dominant design is usually reflected in documented knowledge in the form of product standards or engineering and construction design. As a consequence, knowledge becomes more standardized/codified and transferable across larger distances through R&D collaboration, licensing or mergers and acquisitions. At the same time, proven technologies associated with high profitability for firms are more valuable due to high market growth rates. Firms require sufficient resources and capabilities to invest in and get access to external knowledge.

According to the evolutionary perspective, the spatial evolution of new technologies or industries depends on the capacity of regions to upgrade or reshape specific institutions required for the evolution of new economic activities (BOSCHMA 2004: 1008). Because institutions tend to be path dependent, they may not only enable but also constrain subsequent path development. As the result of technological development, institutions may fall behind new technologies and fail to meet the changing needs of an industry. Thus, institutions, which previously facilitated the evolution of a new industry or technology, can become a barrier when a technology continues to evolve. Institutions need to be flexible and able to adapt relatively rapidly to context changes in order to avoid a regional lock-in. NELSON (1994: 55) points out that “various features of the institutional environment themselves tend to adapt and change in response to pushes and pulls exerted by the development of a new industry". These changes in the institutional environment do not include market processes but instead encompass complex processes such as the formation of collective bodies, or the formulation and implementation of policy decisions by government agencies and political actors. As a new industry emerges, institutions may adapt to the demands of this industry or new supportive institutions and organizations co-evolve with these demands (BOSCHMA/FRENKEN 2009: 155; MASKELL/MALMBERG 2007: 617). MASKELL and MALMBERG (2007: 617) argue, that "national, regional or local institutions gradually develop over time in response to the special requirements of the presently dominating industry and lead to further specialization by creating a favorable environment for similar and complementary economic activity".

A strict separation between the second and the third phase is not always clear and can be misleading. Many processes may even take place more or less simultaneously.

**Post-formation phase**

The canonical model of path dependence assumes that the path becomes increasingly rigid and tends toward a steady state or stable outcome. Due to self-reinforcing effects, technological, industrial and regional development and actors become "locked in" to a specific trajectory (ARTHUR 1989; DAVID 1985). MARTIN (2010: 21) calls this process "path as movement to stable state", created by the stabilization and reinforcement of existing technological and institutional structures. In such situation, there is very limited room for the generation of novelty and, therefore, for any kind of endogenous change or subsequent evolution. This refers to the stable "maturity stage" of an industry life cycle, characterized by a declining entry rate and slow growth (KLEPPER 1997). This may result in industry consolidation, accelerated by mergers and acquisitions.

The second scenario implies a more dynamic conception of path development and mechanisms of endogenous change. Industrial and technological development is characterized by ongoing change and evolution through layering, conversion and recombination (MARTIN 2010: 21). This requires a certain degree of "institutional plasticity" (STRAMBACH 2010) and the ability of institutions to adapt to changing conditions and needs of the emerging technology. In this case, the institutional environment and arrangements co-evolve with the technological and industrial development. However, it is unclear whether this is a random, automatic process.

**Co-evolution**

In contrast to the canonical path dependence theory, the framework of this thesis assumes that co-evolution and ongoing path development are driven by the strategic actions and interactions of multiple actors. From a co-evolutionary perspective, this change occurs as a result of the interaction and dynamic interplay between technological change, involved actors (e.g. firms and policy makers) and their institutional environment. If there are effective interactions and feedback mechanisms between actors, technologies and the institutional environment, institutions co-evolve with and adapt to changing conditions and the needs of an emerging technology and market changes. As a result of strategic action, institutions are shaped or altered in response to changing conditions. Thus, the institutional environment and arrangements co-evolve with technological and industrial development. Institutional flexibility and processes of adaptation and selection lead to incremental change and ongoing path renewal. Technological development and co-evolutionary processes may cause changes in the industrial structure. New firms enter the market while existing firms fail or are taken over by other firms. This ongoing selection process and the formation and reformation of the industrial structure shape the evolution of the industry. Firms make an effort to create new knowledge, to improve products or design new products and to gain access to new knowledge or technologies. They continuously shape the industrial and technological path through strategic action, such as investment decisions and R&D activities. The technology may reach a more mature stage, but will not necessarily become "locked-in". Ongoing technological development may result in innovations such as the introduction of new products, engineering designs or technologies.

The changing economic landscape is an outcome of path-dependent development and, at the same time, actively shaping that process. These changed economic, technological and institutional structures, in turn, provide the initial conditions for ongoing path development or new path creation.

As argued above, a theoretical model of the evolution of a new industry and technology should focus on the active role of multiple actors and the importance of purposive, strategic action. It is not just in the path creation phase that actors, such as firms, policy makers, organizations and other civil society actors, have the ability to proactively shape path development and construct their own environment by strategic action.

Evolutionary and co-evolutionary processes continue, which result in an ongoing evolution of the economic landscape. An industry develops through the actions and interactions of involved actors and selection processes. New firms enter the market, while other firms exit the market. This process of formation and reformation leads to an ongoing development or evolution of an industry. Firms seek to create and acquire new knowledge, to improve products and processes and to gain access to new products or technologies. They continue to shape the industrial and technological path through strategic action, such as new investments and R&D activities.

# 6 Empirical research design and methodology

## 6.1 Introduction

Empirical studies on the evolution of industries are predominantly quantitative in nature and mainly examine the evolution of populations of firms by means of indicators such as entry and exit rates within an industry (see e.g. the Dutch school of evolutionary economic geography). Furthermore, only a few empirical studies on the co-evolution of technology, institutions and industrial structure, especially in the case of the evolution of the wind industry, exist. It is, therefore, difficult to draw conclusions about how actors affect new path creation and how co-evolutionary processes shape a new trajectory. For example, MARTIN and SUNLEY (2007: 576) argue that a quantitative methodology based on statistical and econometric analysis has its limitations in evolutionary economic geography as "evolutionary processes in the social-economic sphere are not easily reduced to, nor rarely can be adequately represented by, formal models". As demonstrated by Dawley (2014) and Steen (2016) a qualitative approach is a fruitful way to investigate the processes and mechanisms of regional path creation.

For this study, an explanatory research design is utilized in order to obtain an in-depth understanding of the role of actors in the co-evolution of technology, institutions and industrial structure. Based on the conceptual framework, a qualitative case study approach is adopted to explain the mechanisms and processes of path creation and the emergence of a new technology and to reconstruct the co-evolution of technology, institutions and industrial structure. The case is defined by all actors, activities and processes that are involved in the wind energy technology (e.g. research, development, manufacturing, lobbing, shaping the regulatory and institutional environment) in Germany.
This chapter elucidates the research design and methodology for the empirical research of the study, including data collection and analysis.

## 6.2 Case study

As an exploratory method, case studies are particularly useful for investigating the motives and actions of economic actors and the interplay between actors and institutional environments in different spatial contexts. A case study can be considered as a comprehensive research strategy that provides an in-depth investigation of a complex process or phenomenon and its context (YIN 2014: 16). Typically, a case study aims at a "deep understanding of the actors, interactions, sentiments, and behaviors occurring for a specific process over time" (WOODSIDE/WILSON 2003: 497). As a flexible inquiry, case studies can combine different techniques of data collection and analysis (YIN 2014: 19).

In order to ensure validity of the results, the research design involves data triangulation of multiple sources of evidence (PATTON 1990; YIN 2014). The study draws on a mix of qualitative and quantitative data, including the analysis of documents, key figures and data concerning wind turbines and in-depth interviews. These different data sources may contain unique, overlapping, or complementary information, which enables the triangulation of multiple sources of evidence. According to YIN (2014: 120), the main advantage of data triangulation is "the development of converging lines of inquiry". The idea is to follow a similar convergence, so that any result or conclusion in a case study is more convincing and accurate as it is based on many different sources of information (YIN 2014: 120).

A case study method provides an appropriate research strategy for this study. It allows the study of a contemporary phenomenon, which cannot be easily separated from its context and, if it is necessary, to understand the relationship between a case and its context. Furthermore, a longitudinal case study allows observations and analyses of complex and interdependent processes that may change over time (YIN 2014; WOODSIDE/WILSON 2003).

## 6.3 Data collection and data analysis

### 6.3.1 Analysis of academic literature and document analysis

The document analysis is a widely used qualitative research technique in social science. The advantage of the document analysis lies in the fact that the data already exists and the collection of new data is not necessary. Document analysis is less costly than other techniques of data collection. To support data triangulation, data collected by document study constituted an additional source of evidence and was thereby used complementary to the interviews. Thus, the document analysis improves the validity and reliability of the results. This instrument is especially used to gain insights into past events, processes and factors (MAYRING 2002: 47).

The empirical survey focuses on the actors who have played a decisive role in shaping regional path creation and development. In the initial exploratory phase, the aim is to identify the relevant actors of the wind industry and to collect information on the national and subnational institutional environment. The first and crucial step in the analysis is the identification of all firms that have existed in the industry since 1980. This includes all firms that have produced at least one wind turbine in Germany.

For the document analysis, the major data source is the annual report of the Bundesverband WindEnergie e.V. (BWE, German Wind Energy Association). These reports, covering the years 1989 through 2014, provide longitudinal data on the firm level and on the technological development of wind turbines in Germany. Additionally, firm-specific information is gathered from literature (i.a. HEYMANN 1995; KAMMER 2011; MUSGROVE 2010; SZARKA 2007; SZARKA/BLÜHDORN 2006; OHLHORST 2009), industry magazines (*Windpower Monthly*, *Neue Energie*, *RENEWABLE ENERGY WORLD*), newspaper articles and company publications (magazines, newsletters, reports, press releases and websites). In this way, further firms, which have been active before 1989, were identified. Based on this survey of the literature and document analysis, a database of 120 wind turbine manufacturers was created containing firm-specific data (e.g. data on year of entry and exit, headquarter and production, ownership changes, license production, etc.).

According to KLEPPER (2002b, 2007), firms are classified into four types of entrants categories based on their background and mode of entry. The first type includes pre-existing firms that diversified into the wind industry from related industries. Following KLEPPER (2002b: 648, 2007: 621), these diversifiers are called experienced firms. The second type, called experienced entrepreneurs, includes de novo firms founded by individuals who previously headed or worked in a firm in another industry related to the wind industry. These are firms in which one of the founders has background or experience in related industries like mechanical engineering, shipbuilding or agricultural machinery industry. The third type, called corporate spin-offs, is defined as de novo firms with at least one founder who had previously worked for a wind industry firm. In this study, corporate spin-offs also include parent-company ventures (HELFAT/LIEBERMAN 2002) such as new subsidiaries of existing firms. In contrast to KLEPPER's classification, an additional category is added for the purpose of this thesis, namely university spin-offs. These are new companies that were founded by one or more university members, doctoral students or graduates who have experience and knowledge of wind energy technologies acquired at the university. The fifth category is residual and includes inexperienced firms and all other entrants (table 5). The entrant types are non-mutually exclusive and may overlap to some degree.

**Table 5: Entrant type and background**

| Type | Mode of entrant and background |
|---|---|
| **Experienced firm** | Diversifying entrant<br>Existing firm diversifies into the wind industry |
| **Experienced entrepreneur** | De novo entrant<br>Founder was previously employed in firm in related industry |
| **Corporate spin-off** | De novo entrant<br>Founder was previously employed in the wind industry |
| **University spin-off** | De novo entrant<br>Founder was a student or employee at a university and acquired knowledge on wind energy technologies from university research |
| **Inexperienced firm** | De novo entrant<br>Founder has no prior experience or contacts in the wind industry |

Source: Adapted from HELFAT and LIEBERMAN (2002: 730) and KLEPPER (2002b: 648) with own extension.

Furthermore, the annual reports of the BWE served as a fruitful source for long-term information on the technological development of wind turbines. Based on this information, a second database of all wind turbines which were commercially available in Germany from 1989 to 2014 was created, containing, among others, information on the rotor (position of rotor, diameter, hub height, number of blades), power control, type of generator, drive train design, power generation capacity and manufacturer. To determine when a wind turbine was introduced to the market and when it was taken from the market, dummy variables for each year were created. The resulting data set contains 750 wind turbines and provides a comprehensive overview of the German market of wind turbines between 1989 to 2014. This was supplemented by a literature study of the technological development to gain and validate information on specific wind turbines and R&D projects.

Additionally, data have been collected by studying various documents like laws and policy documents, newspaper articles, magazines and annual reports about the wind energy in

Germany. The document analysis provides information on the institutional environment, policy actors and their impact on the evolution of the wind industry. This is of crucial importance, as it addresses the central mechanisms and feedbacks in the co-evolutionary processes between the evolution of the wind energy technology and the institutional environment. By examining key events, activities and processes in the evolution of wind energy technology, this exploratory approach may give some qualitative insights into the reinforcing interaction between economic actors, technological development and the institutional environment.

### 6.3.2 In-depth interviews

While little data exists on the relevance of strategic actors in institutional change and path creation, this study will use qualitative methods of data collection. Qualitative methods are particularly suitable to examine how and why processes, phenomena and outcomes occur (GLÄSER/LAUDEL 2010; FLICK 2014; PATTON 1990; YIN 2014). As noted by YIN (2014: 110), interviews are one of the most important data sources for case study research. To obtain a more comprehensive picture concerning the emergence of a new technology, a qualitative approach using in-depth interviews is applied. This kind of data collection is particularly suitable to investigate individual motives, experiences and perceptions. Given the exploratory nature of this study, in-depth interviews serve as a crucial source of information on the roles of key actors in the evolution of the wind energy technology. In-depth interviews are used to identify the mechanisms and actors of regional path creation and to examine the forms and roles of strategic action. They enable deeper insights into relevant factors that influence the emergence of a new technology and into the institutional contexts. In combination with the findings of the literature and document analyses, the interview data provides a detailed characterization of the national and regional initial conditions under which the emergence of the wind industry has taken place.

The selection of the interview candidates is one of the key factors in qualitative research as it defines which empirical information can be gathered in general (GLÄSER/LAUDEL 2010: 97). This implies that identifying and getting access to interviewees with the right expertise is one of the main challenges in a data collection process. In contrast to quantitative studies, there is no random sample. Instead, in this study, a combination of a *purposive sampling* and a *theoretical sampling* method was used. In principal, the sample should be selected to enable the researcher to answer the research questions. Thus, the selection is based on theoretical models and on the objectives of the dissertation ("theoretical sampling") (GLÄSER/LAUDEL 2010: 97). Following a "purposive sampling" strategy (FLICK 2014: 95), cases were chosen because they were rich in information and because of their relevance for the study. The main criterion for selecting a case was the relevance of an actor for the evolution of wind energy technology (by inventions or innovations, through the development or production of wind turbines or by the shaping of the institutional environment). For example, inventors were identified and selected through patent data. Founders or managers of important former firms as well as representatives of organizations and other prominent persons were identified based on the document analysis. In particular, older industry magazines served as an important source of data for key actors of technological development. Additionally, the selection considered a variation of some important variables. On the one hand, this concerns different types of agents. The selection of interview partners should represent a wide spectrum of actors and minimize the influence of individual bias. Based on the current theoretical considerations and research on the wind industry, four central categories of actors were identified. The relevant stakeholders comprise key informants from research, associations and organizations, policy makers and experts from the industry including suppliers (see table 6). Most of the interview partners held (or had held) management positions (CEO, CTO, R&D manager, research director) in the wind industry or in relevant research and industry institutions or were government officials involved in the development of German wind energy or technology policies.

**Table 6: Types of interview respondents**

| Type | Actors and representatives | Example |
|---|---|---|
| **Industry players** | Inventors, entrepreneurs, firms | Current and former CEOs, CTOs, R&D managers of former and current turbine manufacturers and suppliers |
| **Organizations** | Industry associations, networks | WAB, BWE, IWB |
| **Research** | Universities, research institutes | IWES, DEWI, professors |
| **Political actors** | Policy makers at the regional, national government level, agents or witnesses of institutional change | Environment and research ministries |

In order to achieve the objective of the study it was important to acquire a sample covering the complete investigation period. The identification of respondents was carried out on the basis of the literature and document analysis and some personal contacts from within the industry. In addition, targeted enquiries and analysis of the business network "Xing.com", which provides biographical data and public profiles of many players of the German wind industry community, served as a useful tool to contact former professionals and executives or representatives of former existing companies. Furthermore, a snowballing technique was used to identify further relevant experts. Thereby initial contacts and gatekeepers provided the names of potential participants – either directly during the interview or afterwards by request. Hence, the selection of interview partners was characterized by an iterative process of data gathering based on purposive theoretical sampling, which should maximize the depth and quality of data collection.

In sum, 40 interviews were conducted during two survey phases between May and October 2015. After the first survey period, a preliminary evaluation of the interviews confirmed the assumption that suppliers could play a significant role in innovation processes in the wind energy technology. The second period, which was in October 2015 and involved three interviews, specifically intended to examine the role of suppliers. Table 7 provides an overview of all interviews conducted with the different groups of actors (F=Research, O=Organization, P=Political actor, U=Industry player). It also includes information on when and, if possible, how the person entered the wind energy industry (corresponding to the entrant types depicted in table 5).

**Table 7: Interviews conducted**

| Code | Date of Interview | Duration | Type* | First contact to wind energy | Entrant type** |
|---|---|---|---|---|---|
| **F1** | 29.05.15 | 01:01:32 | Research | 1997 | University spin-off |
| **F2** | 05.06.15 | 00:58:29 | Research | 1985 | University spin-off |
| **F3** | 08.06.15 | 01:07:13 | Research | 2003 | University spin-off |
| **F4** | 25.06.15 | 01:06:40 | Research | 1999 | University spin-off |
| **F5** | 29.06.15 | 01:25:09 | Research | 1977 | University spin-off |
| **F6** | 11.06.15 | 00:35:56 | Research | 1990 | University spin-off |
| **F7** | 01.07.15 | 00:46:22 | Research | 1961 | University spin-off |
| **F8** | 03.07.15 | 00:42:33 | Research | 1972 | University spin-off |
| **O1** | 20.05.15 | 01:26:34 | Organization | 1900 | - |
| **O2** | 21.05.15 | 00:28:09 | Organization | 2012 | - |
| **O3** | 15.06.15 | 00:40:03 | Organization | 1992 | - |
| **O4** | 16.06.15 | 00:37:08 | Organization | 1994 | - |
| **O5** | 19.06.15 | 01:03:31 | Organization | 1982 | - |
| **O6** | 30.06.15 | 01:03:31 | Organization | 2012 | - |
| **O7** | 14.07.15 | 00:29:37 | Organization | 1979 | - |
| **P1** | 08.07.15 | 01:12:35 | Political actor | 1989 | - |
| **P2** | 16.07.15 | 01:15:48 | Political actor | 1998 | - |
| **P3** | 28.07.15 | 01:16:11 | Political actor | 1993 | - |
| **P4** | 30.07.15 | 00:56:41 | Political actor | 1982 | - |
| **U1** | 09.06.15 | 00:59:20 | Industry player | 1982 | University spin-off |
| **U2** | 11.06.15 | 01:03:58 | Industry player | 1990 | Experienced firm |
| **U3** | 22.06.15 | 01:01:47 | Industry player | 1989 | University spin-off |
| **U4** | 29.06.15 | 01:00:56 | Industry player | 1986 | University spin-off |
| **U5** | 29.06.15 | 01:08:48 | Industry player | 1981 | University spin-off |
| **U6** | 01.07.15 | 01:00:05 | Industry player | 1987 | University spin-off |
| **U7** | 02.07.15 | 00:43:35 | Industry player | 1986 | Inexperienced firm |
| **U8** | 06.07.15 | 00:51:04 | Industry player | 1985 | University spin-off |
| **U9** | 07.07.15 | 01:08:44 | Industry player | 1998 | University spin-off |
| **U10** | 09.07.15 | 00:35:24 | Industry player | 2010 | Inexperienced firm |
| **U11** | 16.07.15 | 01:05:24 | Industry player | 2003 | University spin-off |
| **U12** | 21.07.15 | 01:07:30 | Industry player | 1995 | Experienced firm |
| **U13** | 23.07.15 | 00:30:52 | Industry player | 2000 | Experienced firm |
| **U14** | 29.07.15 | 00:52:53 | Industry player | 2003 | Experienced firm |
| **U15** | 26.08.15 | 00:47:18 | Industry player | 2000 | Experienced firm |
| **U16** | 05.10.15 | 01:39:54 | Industry player | 1983 | University spin-off |
| **U17** | 13.10.15 | 00:46:59 | Industry player | 1982 | Experienced firm |
| **U18** | 16.10.15 | 00:39:37 | Industry player | 2008 | Experienced firm |
| **U19** | 19.10.15 | 00:41:35 | Industry player | 1991 | Corporate spin-off |
| **U20** | 20.07.15 | 01:23:19 | Industry player | 1987 | University spin-off |
| **U21** | 24.07.15 | 01:24:46 | Industry player | 1991 | University spin-off |

* Type refers to the job and position at the time when the interviews were carried out.
** Entrant type refers to how the respondent entered the wind energy industry.

A clear assignment of the interview respondents into one of the four categories of actor is sometimes problematic. Often, a person had worked for more than one employer. Some of them switched from science to business or left an engineering firm to join a turbine manufacturer and vice versa. The intersections between two or more circles in figure 7 indicate that the interviewed actors had different functions during their individual employment history. In regard to the employment biographies of the interview partners, the interviews cover a period of over 35 years, approx. 20 turbine manufacturers, five engineering firms, five suppliers, ten research institutions, eight organizations and business associations and four policy actors.

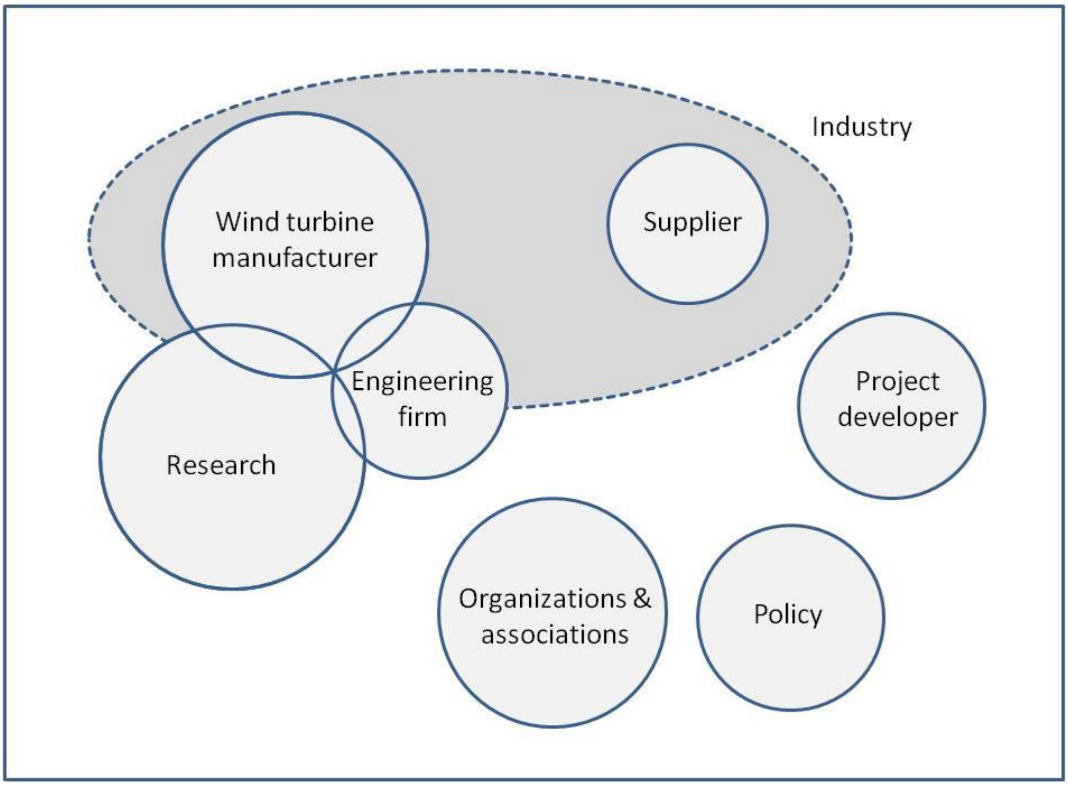


**Figure 7: Fields of work of the interviewees**

The potential interviewees were initially contacted by email, Xing or telephone and given a brief summary of the research objectives. Where necessary, follow-up phone calls with some interviewees were conducted to explain their importance for the study. Subsequently, if they agreed to participate in the study, they were contacted again by telephone or email to make an appointment for the interview. Interviews were recorded with the permission of the interview partner. The recorded interviews were then transcribed. During and immediately after each interview, the interviewer took field notes. The interviews lasted from 30 to 100 minutes, on average about 60 minutes.

All interviews were conducted as a semi-structured explorative interview instead of a structured interview, as this provided a flexible and more specialized instrument which ensured that different respondents could be approached differently while still investigating the same topics. This also allowed the researcher to adjust the sequence of questions that were asked in order to follow up on certain issues and to add further questions. For example, aspects or questions arising from previous interviews concerning specific inventions, innovations or institutions were included. The semi-structured interview guide covered the following issues:

- background information about the interviewee
- entry in and connection to the wind energy sector
- contribution to the development of wind energy technology
- evolution of the wind energy technology and estimation of the institutional environment
- influence on or shaping of the institutional environment
- outlook

Interviews were conducted with four different types of actors (industry players, organizations, research, political actors). The interview guidelines were adapted according to each respondent type so that all interview respondents of one type were interviewed using the same guideline. In case a respondent had worked in different fields or functions concerning wind energy during his career, two interview guidelines were combined to include all relevant questions. To validate the interview guidelines and the interview technique, two pilot interviews were conducted to test the application of the interview guidelines, to evaluate the relevance of the questions and to ensure the questions were easily understood.

### 6.3.3 Content analysis

Documents and transcribed interviews were analyzed using qualitative content analysis procedures, as this method allows a standardized analysis of non-standardized material (GLÄSER/LAUDEL 2010; MAYRING 2010). The content can be examined in a systematic manner. MAYRING (2010: 65) proposes three basic techniques for a qualitative content analysis: paraphrasing/summary (*Zusammenfassung*), explication (*Explikation*) and structuring (*Strukturierung*):

a) Paraphrasing/summary aims to reduce the material to its essential content. For this purpose, the material is paraphrased, generalized and reduced.

b) Explication refers to the explanation and clarification of ambiguous passages. The purpose is not to reduce the material, but rather to extend and enhance the data.

c) Structuring aims to filter out particular aspects and specific structures from the material.

In this study, the analytical method of structuring was used. According to MAYRING (2010: 92), this technique is one of the most important methods in qualitative data analysis. MAYRING (2010: 13) generally describes the content analysis as a "category-guided text analysis". A qualitative content analysis provides a systematic, replicable technique to evaluate data by using a coding scheme. The core process of content analysis is the development of a category system (GLÄSER/LAUDEL 2010: 198; MAYRING 2010: 49). In this way, it was ensured that the analysis of the documents and transcribed interviews was guided by a more structured process.

In line with other authors, MAYRING (2010) proposed two procedure of text interpretation: "deductive category application" and "inductive category development". In this dissertation a combination of both procedures was used. In a first step, categories were derived deductively based on the theoretical framework. Through the deductive category application, pre-defined theoretically grounded aspects of analysis were applied to the material (MAYRING 2010: 66). These categories were defined according to the research questions and the theoretical framework and relate, for example, to the different phases of path development, the mechanisms of path creation and the processes of technology and knowledge transfer. Using these theoretical pre-defined, deductively derived categories as a starting point, a basic structure of the material was created. In a second step, the category system was supplemented by inductive category development by which categories were derived directly from the text material. Following this approach, the data were analyzed independently from the previously formulated theoretical considerations (MAYRING 2010: 83). The process of inductive category development is shown in figure 8. The main idea was to establish selection criteria that can determine the aspects of the material taken into account for the category development. However, the basic direction and patterns of text interpretation were deduced from the theoretical framework and the research questions. Based on the selection criteria, the material was analyzed step by step to identify underlying themes and to revise, modify or specify existing (sub-)categories and deduce new (sub-)categories. It was neither feasible nor desirable to derive all categories through deductive category application. Because new and relevant insights could emerge from the data, but had not yet been included in the predefined category system, the category system was changed in this analysis step. This applied, for example, to information that had not been anticipated by or could not be categorized by the theoretical framework. Furthermore, relevant text passages were identified that could fit into existing categories but were more specific. In this case, a new subcategory was created.

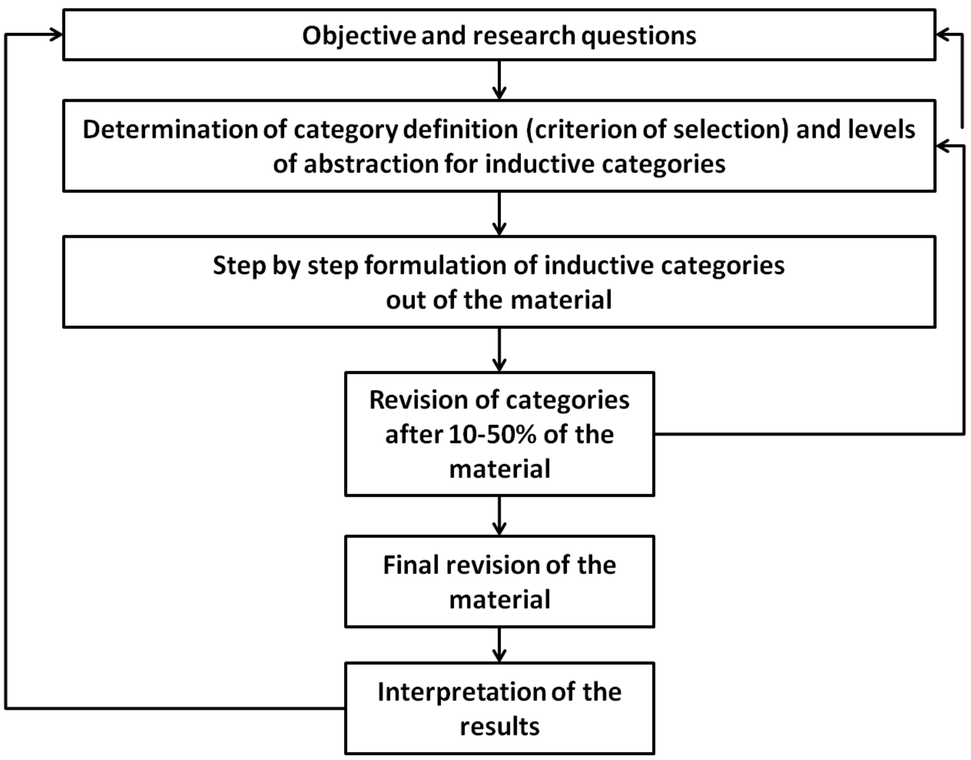


**Figure 8: Inductive content analysis procedures**

Source: Based on MAYRING (2010: 84)

The development of the category system involved multiple feedback loops in which the categories were revised within the process of analysis and checked with respect to their reliability. In this way content analysis remained an interactive and reflexive process. By means of the category system, it was possible to classify and summarize the material, so that its content could be analyzed. The content analysis was supported by the qualitative analysis software MAXQDA, which was used to organize and structure the data and to develop, define and redefine codes and categories.

# 7 The regional emergence and evolution of wind energy technology in Germany

The following two chapters present the results of the empirical analysis of the emergence and evolution of the wind energy technology in Germany. Chapter 7 focuses on the evolution of the wind energy technology. With reference to the theoretical and conceptual framework depicted in chapter 5, the analysis is divided into three sections, each with its own specific focus. In each phase – preformation phase, path creation phase, and growth phase – different factors and processes are prominent. The key factors and events of the emergence and growth of wind energy technologies in Germany are briefly summarized in figure 9. The initial conditions, the actors and mechanisms of path creation, and the underlying mechanisms of knowledge transfer and technology diffusion are presented in detail in the following sections.

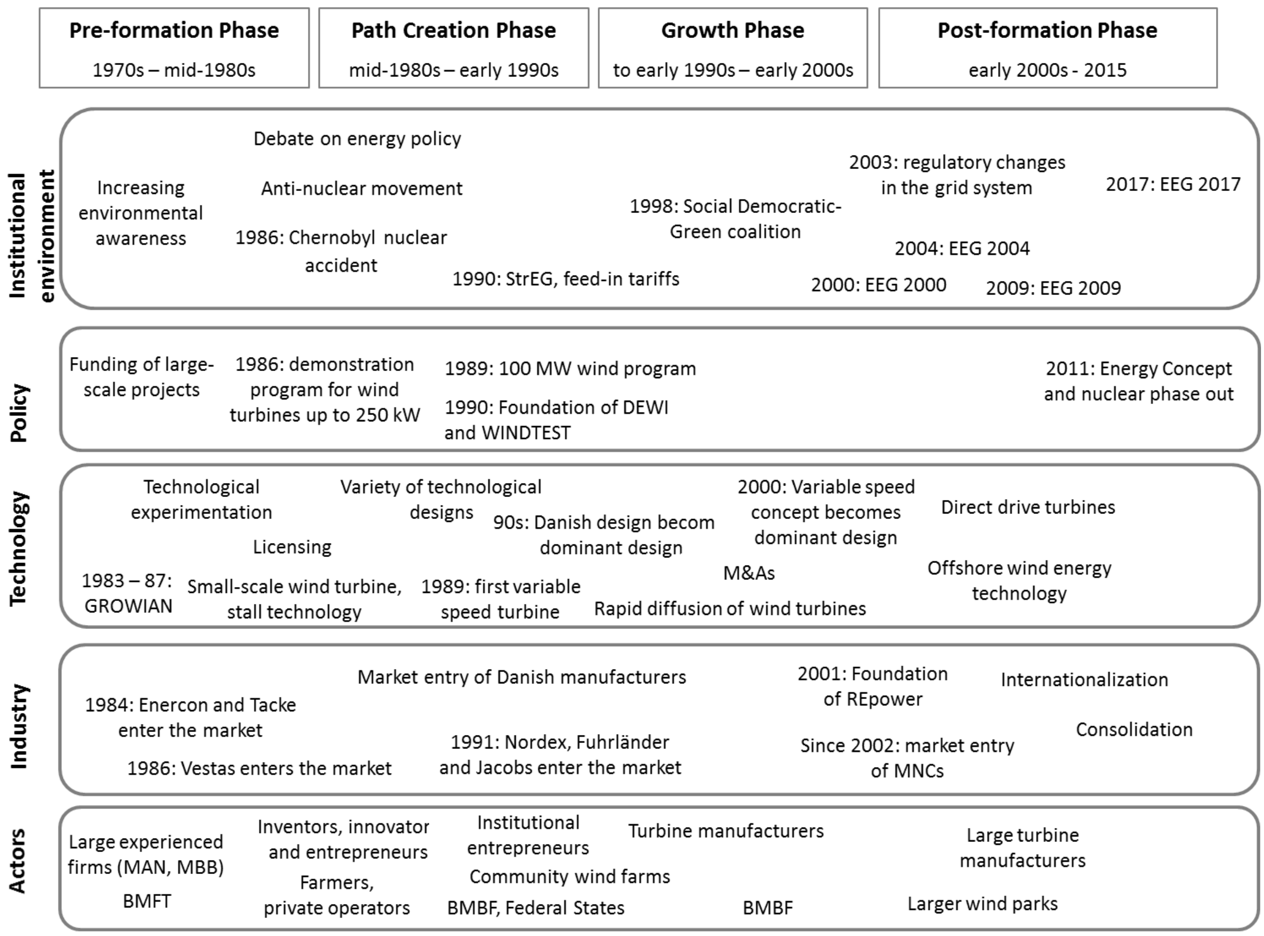


**Figure 9: Key actors, processes and events in the German wind energy industry and technology**

As argued above, the process of economic evolution is regarded as a continuous process of creation, transformation, and path-dependent development. The economic, technological and institutional structures evolving with the emergence and growth of a new technology and industry form the initial conditions for ongoing regional path-dependent development or new path creation. This is why there is no research question and accordingly no empirical analysis concerning the post-formation phase in this thesis.

The evolution of the wind energy technology is characterized by co-evolutionary processes and feedback mechanisms between technological development and the institutional environment. This concerns all phases of path development and is explored in detail in the next chapter.

## 7.1 Pre-formation phase: The initial conditions

First, this chapter provides a brief overview of the initial conditions under which the new wind energy technologies could emerge and evolve over time. It focuses on research question RQ 1: *What pre-existing conditions and changes in the institutional environment in Germany and what region-specific conditions (economic, technological and institutional conditions) are most important for the local emergence of wind energy technology?* In order to answer this central question, particular attention is paid to the institutional environment and changes at the national level followed by an investigation of the region-specific conditions in the three German regions with the first important innovative activities in wind technologies: Northwest Germany, Berlin and the region of Stuttgart in South Germany.

The emergence and evolution of the German wind energy technology and industry is closely associated with the changing political, social and institutional environment. Until the early 1970s, the utilization of wind energy was almost irrelevant in comparison to other energy sources. Instead, policy and government agencies as well as the domestic industries, electricity suppliers and research focused on fossil fuels and nuclear power. Competing technologies like wind energy technologies had hardly any opportunities for further development at that time (MUSGROVE 2010: 87; OHLHORST 2009: 90).

Since the beginning of the 1970s significant external shocks occurred which triggered a global debate on energy policy and environmental issues (BRUNS ET AL. 2008; HEYMANN 1995; JACOBSSON/LAUBER 2006; MUSGROVE 2010; OHLHORST 2009):

- The report "The Limits to Growth" published in 1972 by the Club of Rome (MEADOWS ET AL. 1972) raised considerable public interest and discussion about the relationship between natural resource availability and economic growth.
- The extreme oil price increases in 1973 and 1979 seemed to confirm the thesis about the limits of resource availability. Industrialized economies became increasingly aware of the strong dependence on foreign energy imports and the vulnerability to oil price changes.
- Nuclear energy was chosen as a solution strategy by many states and was massively intensified. At the same time, concerns about safety and sustainability of nuclear energy increased and the protests of the anti-nuclear movement caught wide public attention.
- Especially the accidents in the Three Mile Island nuclear power plant (Harrisburg, USA) in 1979 and in Chernobyl in 1986 profoundly shook the social trust and political confidence about the safety of nuclear power.
- A reinforced perception of the ecological effects of conventional energy sources and the discussion of a global ecological crisis (acid rain, "Waldsterben" (forest deaths), greenhouse effect, smog and ozone layer depletion) led to a rethinking of energy and environmental policies.

It was only after the oil crisis and the strong anti-nuclear movement that an interest in wind energy started to grow and institutional changes occurred. These changes created an environment for public support and funding of renewable energy and wind energy technologies. As the call for alternative energy sources grew louder in the course of the oil crisis, the Ministry for Research and Technology (BMFT) commissioned a study program on the use of wind power in 1974. The study was coordinated by Ulrich Huetter from the Institute for Aircraft Construction (IFB) at the University of Stuttgart and conducted in cooperation with the German Aerospace Research and Testing Establishment (DFVLR) (HEYMANN 1995: 366). For efficiency reasons, Huetter recommended the development of a large-capacity turbine with a rated power of oil price 1 MW and a diameter of 80 m, and mentioned that principally even a 3 MW wind turbine (with a rotor diameter of 113 m) could be realized. Following Huetter, the maxim of wind energy research was to achieve the maximum possible energy and efficiency. Based on these results, the BMFT formulated ambitious goals concerning the technical development of wind turbines (HEYMANN 1995: 369).

From the 1970s until the mid-1980s, German wind power technology policy and research funding was aimed at the development of large-scale wind turbines. The objectives of this funding strategy was to achieve a technological leap as proposed by Huetter. The research efforts were focused on the GROWIAN[5] project, which was initiated by the BMFT in 1978. Despite objections raised by some authors of the study program, the plans concerning the project's dimensions were enforced for political reasons. It was speculated that the aim of the project was not to realize a breakthrough in wind energy technology but rather to demonstrate that large scale utilization of wind energy is not feasible (HEYMANN 1995: 367; OHLHORST 2009: 95).

The intension of the demonstration project was to develop an enormous and powerful two-bladed wind turbine with a rotor diameter of about 100 m, a 100 m high tower, and a capacity of 3 MW. The turbine has been the world's largest wind turbine for a long time. GROWIAN began operation on July 6, 1983 in Kaiser-Wilhelm-Koog at the western coast of Schleswig-Holstein (HEYMANN 1995: 370). However, the technical implementation failed. The actors involved in the project, the large companies MAN and MBB, lacked experience and knowledge in wind technology. As stated by one of the interviewees, the project failed "simply because the basic technologies, the understanding of wind energy was not available" (Interview F2). Its scale, especially the rigid adherence to the rotor diameter, caused a lot of material and construction problems. Until then, many of the components, like rotor blades or the generator, had never been tested in a wind turbine of such a dimension. Due to numerous technical problems, the construction was finally terminated early in 1987. Altogether, the turbine operated only 420 hours (OELKER 2005: 53). The GROWIAN project turned out to be a financial disaster: Over 41% (90 million DM) of the total expenditures for wind energy technology in Germany until 1988 (218 million DM), were spent on GROWIAN alone (HEYMANN 1995: 382).

The actors that participated in the demonstration project were almost entirely big players, such as the mechanical engineering company MAN, the aircraft companies MBB (Messerschmid-Bölkow-Blohm) and Dornier, and the steel and engineering company Krupp. The BMFT aimed to establish a construction and operating company under the direction of the Hamburgische Electricitäts-Werke AG (HEW). It was a political decision to involve the energy suppliers, but these only showed very little interest in the project. Because of their low

[5] Abbreviation for "Großwindanlage" meaning "large wind power plant"

interest in wind energy and their willingness to drop the project, the energy suppliers became very powerful actors. They were able to successfully assert pressure on the BMFT to achieve favorable outcomes from negotiations (HEYMANN 1995: 372). Already before the start of the operation, some of the BMFT and the GROWIAN investment partners commented on the probability that the project will fail. For example, Guenther Klatte, Member of the Board of Directors of the energy supplier RWE stated: "We need GROWIAN to prove, that it doesn‘t work" (DIE WELT in February 1981, cited in HEYMANN 1995: 373). In a similar way, Matthoefer, the former Federal Minister of Research and Technology, said: "We know that it brings us nothing. But we do it to prove the proponents of wind energy, it will not work" (DIE WELT in December 1982, cited in HEYMANN 1995: 373).

With the fall of the oil prices in the 1980s, the interest in renewable energy had decreased. However, the nuclear reactor accident in Chernobyl again activated the debate on environmental matters and nuclear energy. The Chernobyl disaster triggered and strengthened an anti-nuclear movement and led to considerable public pressure that forced politicians to reconsider or alter their existing energy policies. Consequently, demand for the development of alternative energy sources has once again increased (Interviews O5, O7, P1, P2).

Figure 10 presents the public expenditures for wind energy (total and relative to GDP) in Germany between 1974 and 2017 compared to Denmark. R&D activities are an important source for generating new knowledge and are often described as main drivers of technological innovation output. In the 1970s and early 1980s, German policies towards wind power and public R&D expenditures have been focused on large-scale wind power technology and demonstration projects. The most prominent and expensive one was the GROWIAN project. As a consequence of this policy, public R&D funding first reached a peak in 1981. Until 1988, public R&D expenditure on wind energy research amounted to 218 million DM, of which about 90 million DM were attributable to the GROWIAN project. Apart from the research projects of the BMFT, the development of wind energy technologies was still in an experimental stage. The guiding principle of research was to achieve the maximum possible performance and efficiency. As HEYMANN (1995: 392) summarizes:

> "However, the BMFT did not feel responsible for the development of small wind turbines. The research policy was aimed at concepts that were particularly sophisticated and seemed too risky for industry to develop. Thus, the low public subsidies by international comparison related mainly to special technical developments such as Growian, Monopteros, Voith turbine, upward wind power

station, Darrieus rotor and concentrators (which together account for 162 million DM and 75% of subsidies for wind energy from the BMFT)."

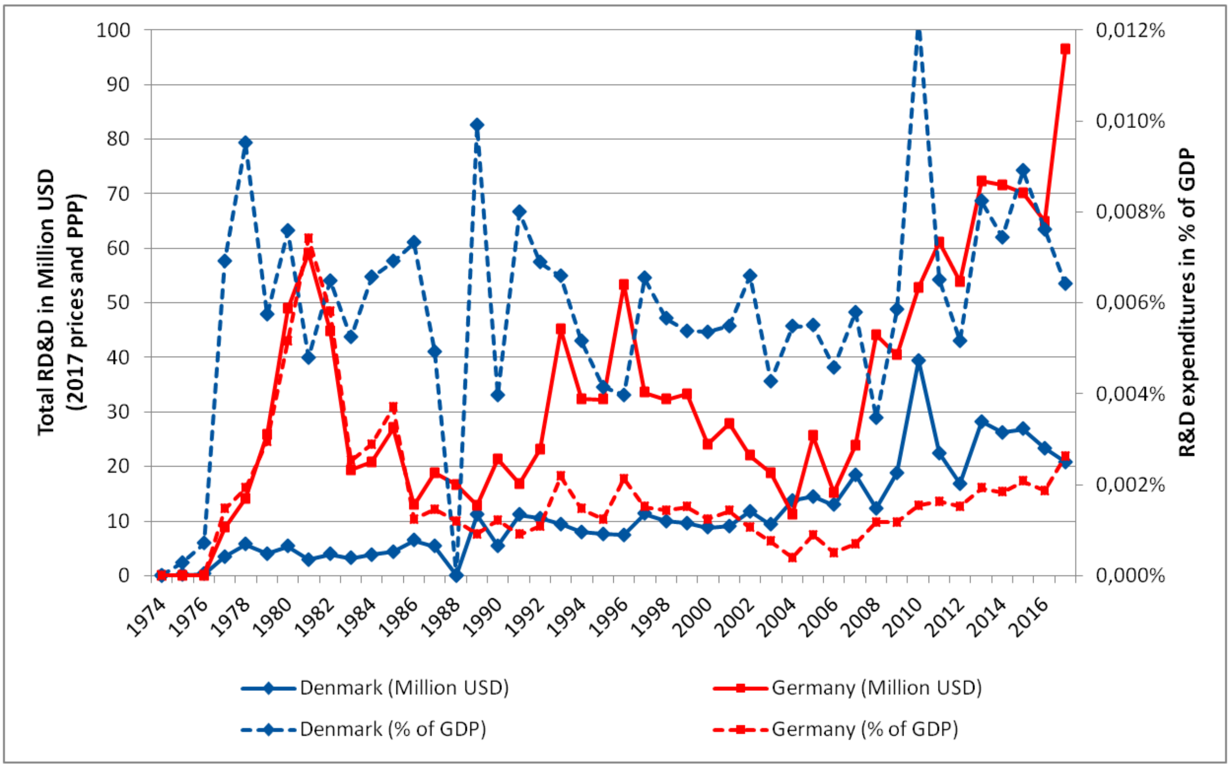


**Figure 10: Public energy R&D expenditures for wind energy in Germany and Denmark**

Source: Own illustration based on statistics from the IEA 2017b)

In comparison with Germany, the technology development had progressed considerably further in Denmark during the 1980s. Denmark is a pioneer in the development of modern wind energy. Danish manufacturers enjoyed a first-mover advantage based on technological leadership (GARUD/KARNØE 2003; GIPE 1995; KARNØE 1990). This success had been noticed in Germany as well. Many of the respondents especially underlined the importance of the Danish development. Germany was able to learn from the Danish wind boom in two ways: Firstly, in terms of the institutional regulatory environment, and secondly, concerning the technological path.

In Denmark in the late 1970s, a favorable environment for wind energy had already been created by the government who implemented a few research funding projects. Turbine manufacturers received significant government subsidies for R&D in the late 1970s and the 1980s. Furthermore, Denmark was a pioneer in the promotion of wind turbine operators and owners and in the regulation of grid connection. The Danish government introduced investment subsidies for individuals and cooperatives who wanted to install and operate a wind turbine (BUEN 2006: 3890). Additionally, wind turbine owners received partial energy tax refunds for each kWh of electricity generated by wind power (GARUD/KARNØE 2003: 293). Since 1984, agreements between the government and the utilities enabled grid connection of wind turbines and guaranteed a fixed feed-in payment for individual and cooperative turbines (BUEN 2006: 3890). Compared with Denmark, some interviewees mentioned a lack of policy support in Germany. One interviewee described the situation in the 1990s as follows:

> "Denmark has shown us how to do it. [...] In Germany, we said at the same time: Yes, wind energy, we want to do it. But they only took one step. They provided research funding. They simultaneously launched large projects. But they have done nothing for the operator. And so this has remained in the 1980's mainly on this research track, apart from a few visionary companies." (Interview U16)

The German government and the BMFT have learned from the technological successes in Denmark and the failures in the 1970s and 1980s. Germany turned away from demonstration project funding and the development of large-scale wind turbines and implemented the Danish turbine concept of focusing on less sophisticated, but robust and reliable small-scale wind turbines (Interviews F2, U4, U6, U9, U16, U20).

Since the mid-1980s, the direction of German energy and research policies were increasingly criticized. The unsatisfactory results of R&D policies since 1985 and the technical weaknesses and operational issues with wind turbines, which had particularly become obvious with the failure of GROWIAN, resulted in a paradigm shift in the German research policies towards a more market-oriented R&D policy. The BMFT turned away from its one-sided R&D policy of focusing on large-scale wind power technologies with large demonstration projects. Instead, it realized that it is not sufficient to create radically new, ambitious turbine concepts but that it is necessary to test and practically use the technology for gradual improvements in reliability and robustness. This included, in particular, supporting ongoing technological developments of smaller wind turbines and stimulating the deployment of wind power capacities (HEYMANN 1995: 427). Worth mentioning are: (1) the demonstration program for wind turbines up to 250 kW ("Sonderdemonstrationsprogramm für Windenergieanlagen bis 250 Kilowatt Nennleistung") over the period of 1986-1988 and (2) a project for the construction and operation of a wind farm with a capacity of 1 MW (1986-1987) ("Errichtung und Betrieb eines Windparks mit 1 MW Leistung"), which led to the erection of the first German onshore wind farm located in immediate proximity to the GROWIAN turbine (HOPPE-KILPPER 2003: 33; OELKER 2005: 364). Thus, not only the technical development, but also explicitly the use and operation of wind turbines was first promoted by the BMFT.

The Danish wind energy sector became a role model in regard to policy support (Interviews F1, F2, P2). In 1989, the BMFT launched a first market formation program, the "100 MW wind" program. This was a clear paradigm shift from R&D funding policy to market stimulation. It involved a combination of specific targets for the use of wind power, investment subsidies, and production incentives. With the adoption of the program, the government guaranteed a supplement to the negotiated feed-in tariff to the amount of 4 cents/kWh or an investment subsidy (up to 60% of the investment costs) (HEYMANN 1995: 429). The aim of the "100 MW wind" program was to install a capacity of 100 MW within five years and, thereby, test the use of wind energy on a large economic scale and gain experience over the long-term performance of wind turbines at various locations. This was quite ambitious considering the status of wind power in Germany at that time. However, the market creation program proved very successful: At the end of 1989, 126 turbines with a total capacity of 9.3 MW were installed in Germany. Within one year, the installed capacity increased by nearly 400% (46.2 MW, 353 turbines). At the end of 1993, a total capacity of 331 MW (1,721 turbines) had been installed (FÖRDERGESELLSCHAFT WINDENERGIE E.V. 1995: 4). The investment subsidy and the guaranteed price per kWh created a substantial incentive to invest in wind energy generation. Demand was mainly driven by private users. Especially local, individual farmers and private operators started to operate one or more wind turbines, primarily to cover their own energy needs (Interviews O1, O5, O6, P1, U4, U6, U11, U14).

Due to the unexpectedly high demand, the program was expanded in 1991 to the "250 MW wind" program, and the target was scaled up to a capacity of 250 MW over a period of five years (FÖRDERGESELLSCHAFT WINDENERGIE E.V. 1995: 44). The funding program of the BMFT was accompanied by the Scientific Measurement and Evaluation Program (WMEP) in which continuously all measurement and operating data of all funded wind turbines has been systematically gathered, evaluated and published. The WMEP has collected data on performance, operational experience, reliability of wind turbines as well as power generation costs transparent and documented the development of wind technology and commercial wind power generation in Germany (FÖRDERGESELLSCHAFT WINDENERGIE E.V. 1995: 45;

HEMMELSKAMP 1999: 177). The data and special reports have been published annually by the Institute for Solar Energy Supply Technology ISET in Kassel[6] (e.g. ISET /DEWI 1997).

The 100 MW and 250 MW wind programs created the preconditions for the emergence of the wind energy technology and of an industrial base. Most interviewees evaluated the market formation programs as a decisive success factor for the evolution of wind energy technologies. (Interviews F1, F2, O1, O5, O6, P1, P2, U1, U4, U5). The majority of funding went to operators in Northwest Germany. Lower Saxony (31.8%) and Schleswig Holstein (33.8%) accounted for about two thirds of the total public funding of the 100 and 250 MW programs (see figure 11).

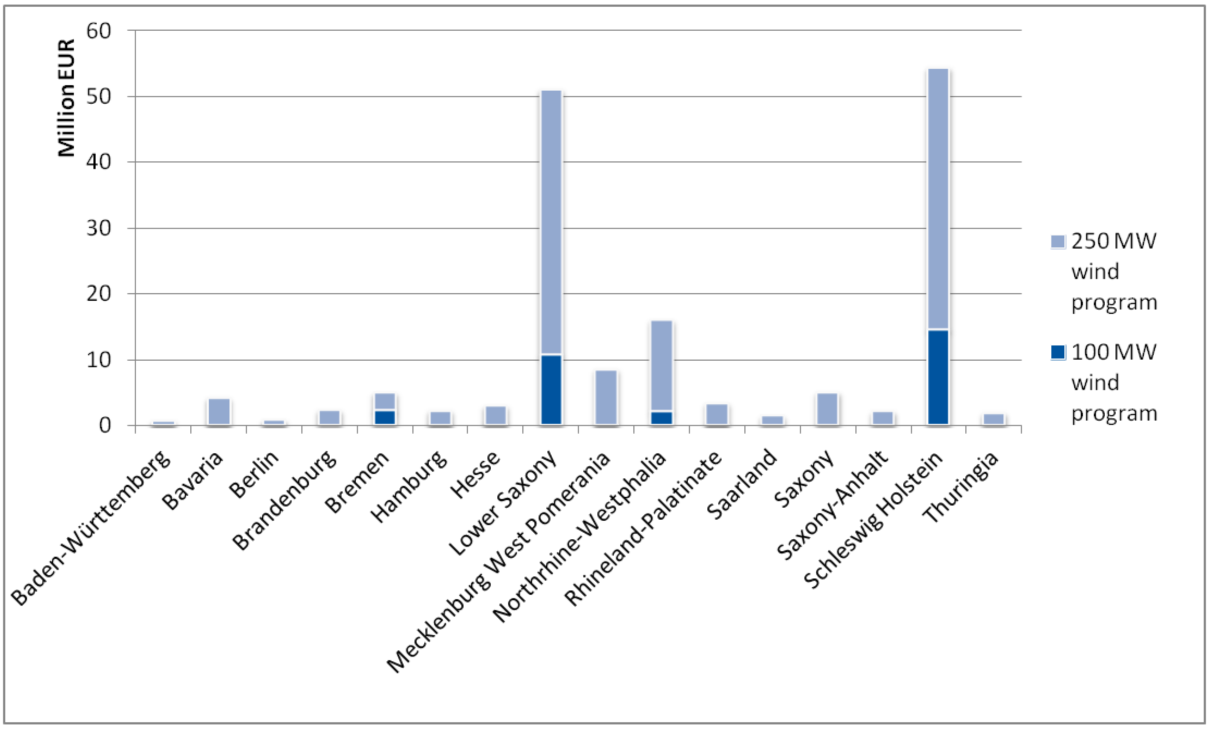


**Figure 11: Subsidies granted within the 100/250 MW program by federal states (1989-2008)**

Source: Own illustration based on the Foerderkatalog database (www.foerderkatalog.de)

As explained in chapter 5, evolutionary approaches in economic geography highlight the relevance of pre-existing regional factors and structures for the local emergence of a new

[6] In 2009, the ISET was transferred to the Fraunhofer Gesellschaft as Institute for Wind Energy and Energy System Technology, IWES (IWES 2014: 110).

industry or technology. Path creation is predominantly seen as a regional process. Thus, the study explicitly examines the region-specific conditions which may have affected the emergence of wind energy technology. Geographically, three nuclei of wind energy technology can be identified. A nucleus is understood as a geographical concentration of sustainable, economic activities with the aim of constructing a wind turbine. For that reason, crucial regional characteristics for the emergence of the wind energy technology in those three German regions, which brought major impulses for technology evolution, are outlined. These are: Northwest Germany (including the federal states of Schleswig-Holstein, Lower Saxony, and the city-states of Bremen and Hamburg), Berlin, and the region of Stuttgart in South Germany. Northwest Germany is selected, because it has today the highest concentrations of wind generating capacity and most of the domestic wind industry is located in the northern region. Berlin was selected because of the significant influence of Robert Gasch and his students and Stuttgart, because of early research and innovation activities and the work of wind pioneer Ulrich Huetter.

When looking at region-specific conditions for the emergence of wind energy technology, it seems sensible to take into account the local natural conditions. There are considerable differences within Germany concerning geographical and metrological onshore wind availability (see figure 12). Regions that present the most attractive potential (displayed in red) are located near coasts in Schleswig-Holstein and the northern parts of Lower Saxony. Wind availability decreases from north to south and most inland regions have limited wind resources. This means that regions in Northern Germany generally have better natural conditions for the utilization of wind power than southern regions. This is also reflected in the regional distribution of subsidies of the 100 MW and 250 MW wind programs. First of all, wind conditions influence the utilization of wind power, i.e. the installation of wind turbines, and do not provide information on the spatial evolution of the wind energy technology. However, several interviewees claimed that wind availability directly or indirectly affected the location of wind turbine manufacturers (Interviews F2, U6, U7, U8, U14, U20).

One interviewee summarized the requirements as follows: "Basically, you needed three factors: wind, money and the political will" (Interview F5). This view was confirmed by several interviewees in the same or similar terms (Interviews F2, F3, F4, O5, P1, P2, U1, U3, U5, U8, U16). This argument holds not only for the national level, but also at a regional and local level. In addition to wind conditions, the political will and interest to develop wind energy also differed strongly across Germany.

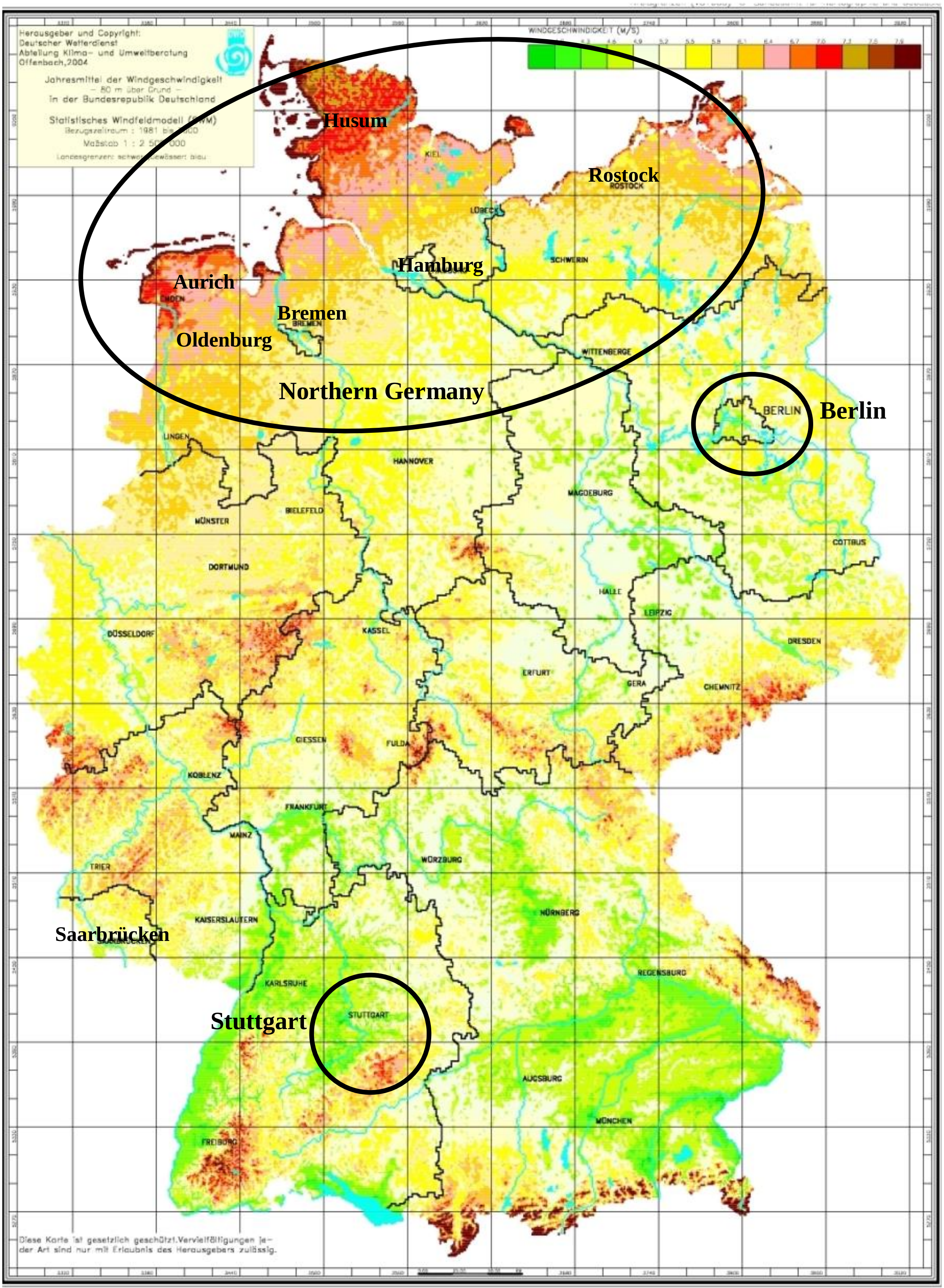


**Figure 12: Onshore wind energy resources in Germany (Annual mean wind speed 1981-2000 at 80 m height)**

Source: DWD 2018 (with own extension of place names)

**Northwest Germany**

The regional institutional environment was also an important driver for the emergence and the regional expansion of wind power utilization. In Northern Germany, wind energy gained much more popularity and political support than in other regions. Besides the impact on national R&D and energy policies, the Chernobyl nuclear accident also resulted in political response and institutional change at the level of the federal states. Since the end of the 1980s, discussions started about the future direction of environmental and energy policy, especially in the federal states of Northern Germany (Lower Saxony, Schleswig-Holstein) with the Social Democratic Party (SPD) in power and a large share of nuclear power. Activists in the anti-nuclear movement and engaged politicians and policy makers called for a reorientation of energy policy and therefore created a regional niche for the emergence of wind energy (Interviews O1, O5, P3). In the city-state of Hamburg, activists founded one of the first private association, whose aim was to operate a wind turbine (Interview U6).

The evolution of wind energy was promoted by additional wind support programs. In response to local protests against a nuclear power plant under construction in Hamburg, the federal state adopted a first funding program which included the of renewable energies (SUCK 2008: 106). In addition to Hamburg, especially the federal states of Lower Saxony and Schleswig-Holstein adopted important funding programs. In Lower Saxony, Economics Minister Walter Hirche[7] (FDP) proved to be a strong supporter and promoter of wind energy (Interviews O5, O7, P3). In the late 1980s, he prepared the establishment of the German Wind Energy Institute (DEWI) in Wilhelmshaven and thus sent a clear signal for the development of alternative forms of energy (CZYZ 2006). In 1987, a first funding program for wind power was established in Lower Saxony, again on the initiative of the Economics Minister Walter Hirche. Thereby the government granted a subsidy of 30% for each newly installed wind turbine (OHLHORST 2009: 114). Since 1991, wind turbines have been promoted by the investment subsidy of the "Directive on Energy" (Richtlinie Energie). Between 1987 and 1997, subsidies granted by the Ministry of Lower Saxony amounted to a total of 15.8 million EUR. About 84% of this amount (13.3 million EUR) were accounted for project funding, the remaining 16% were spent for R&D, especially for the benefit of firms located in Lower Saxony (HOPPE-KILPPER 2003: 78). With the foundation of the German Wind Energy Institute

[7] From 1986 to 1990, Walter Hirche was Minister of Economic Affairs, Labor and Transportation for Lower Saxony.

(DEWI) through by the federal state of Lower Saxony in 1990, the region finally acquired one of the most advanced research facilities in the emerging field of wind energy (Interviews F1, F8). In Mecklenburg-West Pomerania, the Institute for Energy and Transport Research (Rostock), which was responsible for research in the field of renewable energies and wind energy in the former German Democratic Republic (GDR), provided research infrastructure. With the German reunification in 1990, the institute was closed (Interview U20). In the early 1990s, some wind energy firms emerged in the region of Rostock. For example, the engineering company WIND-consult was found in 1990 as a spin-off of the Institute for Energy and Transport Research.

With the decline in the shipbuilding industry since the 1990s, especially policy makers in Bremen and Lower Saxony started to support new path development in the offshore wind energy industry (among other programs) (FORNAHL ET AL. 2012). Schleswig-Holstein has also played a pioneering role in promoting wind power. After the change in government in 1988, the social democratic government attempted to promote energy generation in order to enhance and maintain competition between Danish and German wind energy technologies. For this purpose, the state government started several energy policy initiatives. The key institutional actor was the Ministry of Energy in person of Klaus Rave[8] and Heinz Klinger (RAVE/RICHTER 2008: 60). The federal state engaged in project funding as part of the program "Renewable Energy". The program with a budget of approximately 22.2 million EUR started on 1 August 1989 and lasted until 30 June 1993. Since July 1993, it has been replaced by the incentive program "Renewable Energies - Wind" („Erneuerbare Energien - Wind“) (FÖRDERGESELLSCHAFT WINDENERGIE E.V. 1995: 62). In 1992, the government adopted an energy concept with the aim to increase the share of wind power to approximately 25% of the total energy consumption in 2010 (DER MINISTER FÜR ARBEIT UND SOZIALES, JUGEND, GESUNDHEIT UND ENERGIE DES LANDES SCHLESWIG-HOLSTEIN 1993: 16).

The different political tendencies in the federal states to develop wind energy is also revealed by the strategic action of policy makers and how they shape or create regulative institutions facilitating the utilization of wind energy. During the 1980s, the situation regarding planning processes of wind turbine installations was uncertain in Germany. Wind turbines were not

[8] Klaus Rave was head of Department of Energy at the Ministry for Social Affairs Health and Energy of Schleswig-Holstein from 1988 to 1995.

included in the Federal Building Code (BauGB). Most planning authorities decided on a case-by-case basis on turbine installations and showed only limited interest in stricter defined regulations and approval procedures. Whether administrative decisions concerning the authorization of new wind power developments were positive or negative mainly depended on the regional acceptance of wind energy. In the coastal areas of Northern Germany, wind energy projects were more often supported than in other regions. Authorizations were granted generously and many locations for wind turbines or wind farms were determined (Interviews P1, U14). With the concentration of demand in coastal areas, more spatial planning regulation became necessary. Schleswig-Holstein, as the first Federal State, released a "Guidelines for the layout, set-up and operation of wind turbines" (Richtlinie für die Auslegung, Aufstellung und das Betreiben von Windenergie-Anlagen) in 1984. Similarly, Mecklenburg-West Pomerania prepared regional plans to regulate the spatial requirements regarding wind energy project (MAB 1999: 4). In the German regions with defined binding guidelines, the approval process for wind turbines has clearly changed with less restrictive planning policies (BRUNS ET AL. 2008: 39; OHLHORST 2009: 118).

The growing popularity of wind energy can also be observed at a local level. Environmental activists and pioneering users, especially farmers, began to support wind energy. The first users of individual wind turbines were mainly farmers, for which the operation was also economically interesting as the agricultural land had considerable potential for wind power generation (DURSTEWITZ ET AL. 2003: 5; OHLHORST 2009: 115). This has led to the institutionalization of regional common interests and the creation of associations. In 1982, the German Society for Wind Energy (Deutsche Gesellschaft für Windenergie, DGW) was founded, mainly by farmers from Schleswig-Holstein and Lower Saxony, to promote wind energy and lobby for changes in the institutional environment (OHLHORST 2009: 144). They constituted a strong lobby group and promoted policy support and the creation of favorable conditions for wind power in specific federal states (mainly Lower Saxony, Schleswig-Holstein and North Rhine-Westphalia). Due to the regional member structures, other associations such as the Inland Wind Power Association (Interessenverband Windkraft Binnenland, IWB) were also characterized by a strong regional focus of lobbying.

Altogether, Northern Germany enjoyed relatively favorable market conditions. This refers, first, to the natural conditions for wind power generation, namely wind potential and landscape characteristics. The economic efficiency of wind turbines is highly dependent on local wind conditions, which vary greatly from the northern coastal areas to the southern inland areas. These favorable wind conditions facilitated technological development and innovation by pioneers and users. A wind turbine was primarily developed where it could be installed and operated (Interviews U14, U20). Second, the structurally weak rural regions in Lower Saxony (i.a. the region of East Frisia and the district of Emsland) and Schleswig-Holstein (i.a. the districts of Dithmarschen and North Frisia) provided a lot of large, flat areas that were appropriate and obtainable for the installation of individual wind turbines and large wind farms. These were either publicly owned (municipalities and cities) or, in most cases, owned by farmers. And third, a regional demand emerged. First of all, this was driven by farmers, for whom the installation and operation of wind turbines had become economically attractive through the funding programs of the federal state (Interviews O1, O5, O7, U6, U8).

Considering the size of the region and heterogeneity the industrial structure, Northwest Germany had a range of firms and research institutes in related industries and technologies (such as machinery and mechanical engineering). In order to assess whether this can explain the local emergence of the wind technology in Northwest Germany, it is necessary to examine the mechanisms of path creation in the next chapter.

**Stuttgart, Baden-Württemberg**

The federal state of Baden-Württemberg has a long tradition in wind energy research. Since the 1950s, the state capitol Stuttgart has benefiting from a strong research infrastructure. The capabilities and competences of research institutes in the field of aviation and aerospace provided opportunities for research and development of the utilization of wind power. The key actor in the region of Stuttgart was the wind energy pioneer Ulrich Huetter who is considered to be the founder of modern wind energy in Germany. The aircraft engineer was the head of the Institute for Aircraft Construction at the University of Stuttgart from 1965 until 1980 and also worked at the neighboring DFVLR[9]. Already in the 1950s, Huetter designed and developed small wind turbines based on aerospace know-how. Later he was decisively involved in the development of the GROWIAN project (Interviews F4, F6, U20). The DFVLR provided a wind energy test field near Stuttgart (Swabian Alb) with suitable conditions for the turbine size used at the time. The Institute of Aerodynamics and Gas

[9] The DFVLR (German Aerospace Research and Testing Establishment) was renamed DLR (German Aerospace Centre) in 1989.

Dynamics operated a laminar wind tunnel, and Franz Xaver Wortmann from this institute also researched wind energy applications (Interviews F4, F5). Thus, in the 1950s there was a large group of actors in Stuttgart, who were involved in wind energy. In addition, Huetter and Wortmann benefited from supportive research activities at other local institutes and supra-regional collaboration with further research institutes and departments (e.g. Institute for Aeroelastic in Goettingen) that were involved in specific engineering and technological issues (Interviews F6, F7).

**Berlin**

Basically, the regional conditions in Berlin were quite unfavorable. The major geographic disadvantage was caused by the inner-German border and the Berlin Wall. There was no domestic market and due to the isolated location, it was very difficult to open up a market from West Berlin. Hence, also the urban region fell away as a potential market area for the installation of wind turbines. Actors, who were concerned with wind energy technologies at this time in Berlin, thus complained about the lack of contact with customers and potential investors (Interviews U1, U4, U5). In addition, there was little political support for wind energy at Senate level. Due to the barriers and seemingly small prospect of success, financial support by federal state policy, as guarantees or concessionary loans, was not an issue at all (Interviews F5, U5).

In light of these constraining political and institutional conditions however, the region of Berlin reveals the central role of "strategic" agents. In connection with the initial conditions, all respondents pointed out the pivotal role of individual, dedicated key actors who were able to shape the institutional environment so that it favored the regional emergence of wind energy technology (Interviews F2, U1, U4, U5, U8, U16).

Robert Gasch proved to be particularly influential. Already in 1977, he founded the work group "wind energy converter" at the Institute for Aerospace Engineering of the Technical University Berlin (TU Berlin) and created thereby the origin of wind energy technology in Berlin (Interview F5). The following years, the work group made significant progress in the field of basic research. Besides, students were trained in large numbers in the field of wind energy technology at the TU Berlin for the first time. This was one of the essential conditions for achieving a critical mass of actors in wind energy and thus of central importance for the emergence and subsequent establishment of the development path. One respondent summarized the role of Robert Gasch as a pioneer in the following terms:

> "Someone took the initiative and started to deal with the subject in the 80s, the end of the 70s [...] because he was simply interested in it, because it motivated him, because he found it technically exciting. And he enthused people with the subject and has – he did not have to do it, it was his own initiative – has attracted research funds. Has set up lectures, which he did not have on the agenda. And everything of his own accord." (Interview U16)

Many of the respondents highlighted that Robert Gasch built up numerous close cooperations or a network within Berlin. Thus, he succeeded through personal contacts and his reputation to include professors from other mechanical and electrical engineering departments and to establish collaborations with other organizations, such as the "Interdisciplinary Project Group for Appropriate Technology" (IPAT) (Interviews F1, U1, U4, U5). Such personal contacts and the local network at the TU Berlin facilitated formal and informal collaboration as well the transfer of tacit knowledge and constituted an important foundation for the emergence of a local wind energy scene:

> "Berlin was characterized by the fact that Robert Gasch, a pioneer, a visionary, pushed things forward and understood them very intelligently. Establish the networking between these small spin-offs and the TU. [...] So it was an innovative, creative phase in Kreuzberg. [...] we have also tried to develop common strategies, that one develops companies from these small backyard workshops. And that was simply a feature of the Berlin situation that has been cooperated very closely and personally." (Interview U5)

Between 1978 and 1989, a number of university spin-offs emerged from the TU Berlin predominantly located in the former West-Berlin district of Kreuzberg: Wuseltronik, Südwind, ATLANTIS and Ammonit Measurement GmbH. These spin-off processes and especially the company Südwind will be studied in the following section (see section 7.2.2).

Most of the personal relationships, which resulted primarily from the joint education program at the TU Berlin, still exist today (Interviews F2, F5, U1, U4, U5, U8, U16). According to some respondents, this strengthened the emotional connection to the location of Berlin and created a regional spirit of shared values and interests:

> "It was some kind of Berlin school. We all were students of Robert Gasch, and finally he was the central person even if other profs have worked there. [...] there was a feeling of belonging together. [...] So it's a bit of Berlin clique then." (Interview U1)

Another aspect, related to the regional institutional environment that was viewed positively by many respondents, was the "collective thought" which was widespread in the 1970s and 1980s in Berlin (Interviews F5, U4, U5). This collective thought was based on common values as an alternative to capitalism. The basic values were based on low wages and a strong involvement of all employees in decision-making processes. This was an opportunity for start-ups and created space for technological experiments in small backyard workshops. Employees, mainly young mechanical or electrical engineers fresh from university, were not financially motivated, but passionate about renewable energy technologies and interested in doing "a meaningful job and activity, that you can stand behind and identify with" (Interview U5). Consequently, these collective enterprises were faced lower business and financial pressures in comparison to other organizational forms. This contributed to a favorable environment for start-ups and university spin-offs and enabled them to work and experiment with new wind energy technologies. In addition, these startups received some political support at the local level. In particular in the former district of Berlin-Kreuzberg, startups benefited from the provision of affordable premises by the district office (Interview U5).

After this section in which the initial conditions in Germany, respectively in the regions of Northwest Germany, Berlin and Stuttgart, were described, the next section will analyze the processes which led to the emergence of the wind energy technology.

## 7.2 Path creation phase: Actors and processes of path creation

This chapter addresses the mechanisms of path creation to provide a better understanding on how new regional paths emerge. If it is assumed that new paths do not emerge randomly or by accident, but are created by strategic action, the question that arises is: RQ 2: *Who are the actors engaged in path creation and what are the motives of the different actors to engage in a new technology? How do their motives influence path creation processes?*

Section 7.2.2 concentrates on the mechanisms and processes of path creation and deals with research question RQ 3: *How do new regional technological paths emerge? To what extent has the emergence and development of wind energy technology been influenced by diversifying from technologically related industries?*

### 7.2.1 Actors of path creation

The concept of "path creation" stresses the role of human agency and the active role of individual and collective strategic actors in emerging paths. Particularly various kinds of entrepreneurs should be able to create new pathways. In the case of the German wind energy, the findings show that crucial impulses were predominantly evoked by individual actors and entrepreneurs rather than by established companies. These actors had a wide range of technical backgrounds and experience including machinery and mechanical engineering, electrical engineering, aerospace and geography. To better understand the characteristics of these strategic agents, interviewees were asked about their motivation to engage in the emerging wind energy technology. The vast majority of these pioneering actors can be characterized as enthusiastic tinkerers, hobbyists, some kind of "freak" or visionaries. Indeed, "freak" is the term several interviewees used to describe themselves because they were very passionate about wind technology (Interviews F5, O5, U3, U5, U8). It was quite exotic to deal with renewable or wind energy at that time and economically it was rather unattractive. What the majority had in common was that they were primarily driven by the debate on energy and environmental policy in the 1980s. As one pioneer explains:

> "It was always about making something meaningful in the ecological field. And if you deal with energy technology and engineering in general as a mechanical engineer, the wind energy is an obvious solution for many ecological issues." (Interview U5)

These pioneers were actively seeking technical solutions for decentralized electricity production and called for the elimination of nuclear power. Several respondents mentioned explicitly the anti-nuclear movement and the Chernobyl nuclear accident:

> "This was, of course, a reaction to simply show that energy can be produced differently, for the Third World. So in the end as a consequence of the anti-nuclear movement. Because as an engineer, of course, you are not so politically shaped. But of course you are thinking: How can I do something different with my technology?" (Interview U1)

This environmental and political intrinsic motivation was a decisive factor for creativity and innovation during the initial phase of experimentation. In several cases, the innovators have also been the first users of the wind energy technology. Many "freaks" wanted to innovate for themselves. They were constructing and developing a wind turbine with their own values and needs in mind and for their own use. Prominent examples of these politically or environmentally motivated tinkerers are Robert Gasch, Sönke Siegfriedsen, and Aloys Wobben.

Not only industry actors like inventors and entrepreneurs, also users were among the most influential actors for new path creation. The emergence of a new technological path also involves the development of a demand for the new technology. In the early phase of development, initially private individual operators were interested in operating a wind turbine. Environmental and anti-nuclear activists considered wind energy to be a promising alternative energy source. In particular, local, individual farmers in Northern Germany installed wind turbines on their own land to generate their own electricity (Interviews P1, O1, O5). As they owned large areas with good wind conditions, famers had the most important resource for the utilization of the wind energy technology, the erection of wind turbines. Since the mid-1980s, local and regional citizen initiatives increasingly acted as operators (Interviews O1, O4). As a consequence of the increase in private demand, a new organizational form of operator emerged, the so-called "Bürgerwindparks" (community or citizen-owned wind farm). Driven by environmental concerns and the anti-nuclear power movement, the first local citizen-owned wind farm was founded immediately after the nuclear accident of Chernobyl. As stated by one of the interviewees:

> "Then I founded after Chernobyl with others together in Hamburg the first, today you would call it citizen-owned wind farm [...] Well, the Energiewende has been there since 2011. When I hear this I say my Energiewende was 1987, when I participated in this citizens wind park project after Chernobyl." (Interview U6)

These first users of wind energy technology are also among the pioneers. The large energy supply companies, however, seemed to underestimate the potential of wind energy. They continued to rely on conventional energy sources and nuclear energy for energy production, so that there was hardly any competition from the established market players (Interviews F2, F3, U7, U14). This created a (niche) market for wind energy technologies, primarily in Northern Germany. In 1995 almost half of the wind turbines installed in the 250 MW wind program were privately owned wind farms (mainly farmers), and an additional 11% were community wind farms and energy cooperatives, which also consisted of farmers to a large extent (see figure 13).

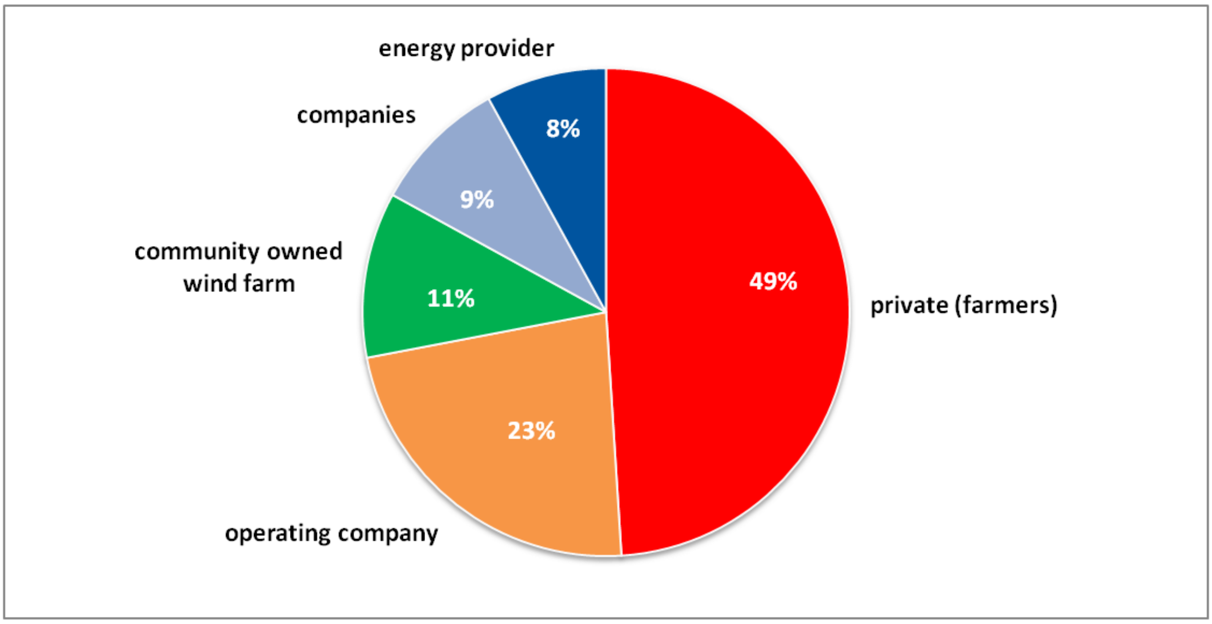


**Figure 13: Operator structure within the 250 MW wind program in 1995**

Source: DURSTEWITZ ET AL. (2003: 4)

### 7.2.2 Mechanisms and processes of path creation

As path creation refers to the generation of economic novelty, particular attention must be given to two partly interrelated processes as the key drivers of new path creation. The first one involves the creation of new knowledge and the introduction of new products, services or processes. In the case of wind energy, the emergence of the new technological path of wind energy required innovations in wind energy technology and was manifested in the development and production of wind turbines. The second process is the formation of new firms and the emergence of new participants in a regional economy. Both processes, the emergence of a new industry and a new technological path, appear to be interdependent and mutually reinforcing. An emerging technology provides new opportunities and is expected to attract other firms trying to imitate or adopt the new technology. Individuals who acquired relevant knowledge in related industries or at the university, may start a new firm. Likewise, existing firms seek to diversify into the new technology and market and enter the industry. New industry participants and the formation of new firms, in turn, can enhance technological development and innovation.

Since the end of the 1970s and the beginning of the 1980s, a first generation of actors entered into the wind energy business. However, emerging wind energy technologies were still at an experimental stage. The most important entrants into the wind industry between 1978 and 1995 are listed in table 8. These are firms that survived at least three years and which developed and sold at least two wind turbine models.

The largest group of the pioneering actors were participants without any relevant pre-entry experience. These de novo entrants were individual entrepreneurs, mainly do-it-yourself enthusiasts, dedicated engineers and inventors of wind energy technologies. Many of these entrepreneurs were motivated by environmental concerns. They mainly worked as farmers or in technical jobs and started to tinker with wind turbines as a sideline in their own garages. To finance their venture, the entrepreneurs drew on personal savings, small grants, and loans from friends and family members who supported their environmental and political motivation. Due to the experimental stage of wind energy technologies, new ventures could be started with relatively limited investments by visionaries, enthusiastic tinkerers and hobbyists. These were often very small or one-man companies such as Windkraftzentrale (WKZ), Wind Technik Nord, Ventis Energietechnik or Seewind.

Another important group of new participants was formed by incumbent firms that diversified into the emerging wind industry (experienced firms). In the course of the GROWIAN-project, a few new actors entered the market. In view of the lack of experience and an industry still at the experimental stage, the BMFT relied on large, established companies who had experience and knowledge in related industries. The contract for the project was awarded to experienced firms from the aviation and aerospace industry (MMB, Dornier) and mechanical engineering (MAN). These competencies in mechanical and electrical and their experience in large-scale projects were also in demand in wind energy technology.

Other wind turbine manufacturers emerged from established medium-sized companies in different related industries. As the company name indicates, Husumer Schiffswerft (HSW) (Husumer Shipyard) originated from the shipbuilding industry. Other companies had their roots in mechanical engineering (Tacke, Köster Maschinenfabrik, AN Maschinenbau und Umweltschutzanlagen) or in steel construction (Fuhrländer). These firms considered wind industry as an alternative business area and tried to enter the emerging industry.

University spin-off companies from related technological fields formed another group. Such companies were predominantly spin-offs from university departments of technology-oriented fields such as aviation and aerospace (Südwind, Berlin), physical engineering (aerodyn, Schleswig-Holstein) or mechanical engineering (Forschungsgruppe Windenergie, Saarland), which were mainly located in the same federal state or city as the universities. An exception was Enercon. After completing his studies in Braunschweig, Aloys Wobben moved to Aurich, about 300 km away, and founded the company there.

Not surprisingly, there were no corporate spin-offs at this early stage. This is understandable as corporate spin-offs originate from established firms. During the emergence of the wind energy industry there were no wind turbine manufacturers who could have served as a potential incubator or parent firm for a new spin-off venture. Hence, participants during the path creation phase were experienced firms (or entrepreneurs) and university spin-offs or had no prior experience or contacts in the wind industry. Only since the middle of the 1980s, Danish manufacturers began to enter into the German market by founding foreign subsidiaries or signing contracts for the distribution of their wind turbines. Since these new companies inherited knowledge from parent firms, they have already had pre-entry experience in wind energy technologies. The most important of these corporate spin-offs were Vestas Deutschland, Nordtank Windkraftanlagen and Nordex Energieanlagen.

**Table 8: Firms in the German wind energy industry 1978-1995 (selection*)**

| Year** | Company | Type of entry | Region |
|---|---|---|---|
| 1978 | MAN | Experienced firm | Munich, Bavaria |
| 1978 | Messerschmitt-Bölkow-Blohm (MBB) | Experienced firm | Ganderkesee, Lower Saxony / Ottobrunn, Bavaria |
| 1978 | Dornier | Experienced firm | Friedrichshafen, Baden-Württemberg |
| 1981 | Windkraftzentrale | Inexperienced firm | Brodersby, Schleswig-Holstein |
| 1982 | Südwind | University Spin-off | Berlin, Berlin |
| 1983 | aerodyn Energiesysteme | University Spin-off | Rendsburg, Schleswig-Holstein |
| 1984 | AN Maschinenbau und Umweltschutzanlagen | Experienced firm | Bremen, Bremen |
| 1984 | Enercon | University Spin-off | Aurich, Lower Saxony |
| 1984 | Tacke | Experienced firm | Rheine, North Rhine-Westphalia |
| 1989 | Heidelberg Motor | Experienced entrepreneur | Starnberg, Bavaria |
| 1985 | Husumer Schiffswerft (HSW) | Experienced firm | Husum, Schleswig-Holstein |
| 1986 | Köster Maschinenfabrik | Experienced firm | Heide, Schleswig-Holstein |
| 1986 | Wind Technik Nord | Inexperienced firm | Enge-Sande, Schleswig-Holstein |
| 1986 | Vestas Deutschland | Corporate spin-off | Husum, Schleswig-Holstein |
| 1989 | Ventis Energietechnik | Inexperienced firm | Braunschweig, Lower Saxony |
| 1989 | Seewind | Inexperienced firm | Walzbachtal, Baden-Württemberg |
| 1989 | Nordtank Windkraftanlagen | Corporate spin-off | Husum, Schleswig-Holstein |
| 1990 | Forschungsgruppe Windenergie | University Spin-off | Saarbrücken, Saarland |
| 1991 | Nordex Energieanlagen | Corporate spin-off | Melle, Lower Saxony |
| 1991 | Fuhrländer | Experienced firm | Waigandshain, Rheinland-Palatinate |
| 1991 | Jacobs Energie | Experienced firm | Heide, Schleswig-Holstein |
| 1995 | DeWind | Corporate spin-off | Lübeck, Schleswig-Holstein |

* Firms that firms that have existed for at least three years and that have commercially manufactured at least two wind turbine models.

** Year of market entry

The analysis of the types of entrants and their pre-entry experience indicates that the wind energy technology is rooted in related technological fields. The emergence of new industry participants, however, tells little about technological development and innovation. The firms differ substantially in size, experience and qualitative characteristics concerning their contribution to emergence and evolution of wind energy technologies. The first wave of participants included large established companies involved in the GROWIAN project (MAN, MBB, Dornier). After the GROWIAN experiment failed, they abandoned the wind business. On the other hand, very small innovative companies proved to be key actors.

To understand how new technological paths emerge, it is necessary to take a close look at the possible mechanisms – indigenous creation, diversification of regional industries, or externally induced regional pathways – and the roles of different actors in processes of path creation. What kind of knowledge and pre-entry experience mattered most? What kind of pioneering activities, products and innovations led to the creation of this new technological pathway? Therefore, how the strategies and pioneering activities of different entrepreneurs and firms as well as policy interventions contributed to the emergence of the wind energy technology is illustrated in the following.

#### 7.2.2.1 Indigenous creation

As explained in Chapter 7.2.1, the new pathway of wind energy technology was created primarily through pioneering local actors and entrepreneurial activities. In this process of path creation, the focus here is on actors like entrepreneurs, inventors and research institutes. From the 1980s some entrepreneurs in different regions were motivated by environmental concerns and independently began to enter the industry. These path creation processes can be observed, in particular, in Berlin and Southern Germany but there were also pioneers in other regions.

**Berlin**

Since the late 1980s, several university spin-offs from the TU Berlin in wind energy and related fields emerged in Berlin (i.a. Südwind, Wuseltronik, ATLANTIS and Ammonit Measurement GmbH). Due to its strong influence on the technological path of the wind energy technology, especially the company Südwind must be mentioned as a classical spin-off from the Technical University of Berlin. The company, which was founded in 1982 by wind pioneer Professor Robert Gasch and two colleagues, emerged from the interdisciplinary work group "wind energy converter" of the Institute for Aerospace Engineering (Interviews U4, U5) (cf. section 7.1). As with the creation of the company, the relations of and with Robert Gasch played a pivotal role for the further development of Südwind which continued to profit from his contacts and networks. In view of the limited personal and financial resources, this provided a more favorable environment for research and development. Furthermore, he also encouraged students and graduates to get more involved with wind energy technologies and/or to take part in a company internship. Consequently, many new employees, who were hired in the following years, were his former graduate students or research associates and entered the company via a research project, a thesis or an internship (Interviews F2, U1, U4, U8). For many actors, this was the first step into the emerging field of wind energy. Several former students worked for other German wind manufacturers later.

The structure and the working environment of Südwind resemble more an enthusiastic wind community with a weak financial situation than a professionally managed firm. What the employees shared was their enthusiasm for wind energy technology. The start-up allowed the interdisciplinary team of engineers and technicians to experiment with wind energy technology (Interview U4). Although staff salaries were extremely low, Gasch and his colleagues consistently found young, skilled, and highly motivated engineers who brought in new ideas, impulses and technical know-how to the firm. The findings from the interviews indicate that the main motivation was not to earn money, but to contribute to the construction of a wind turbine and to develop knowledge and acquire practical experience. This was expressed by several interviewees and was seen to be distinctive for the Berlin wind scene around Robert Gasch (Interviews F2, F5, U1, U4, U5, U8, U16).

Despite massive budget constraints, the company grew and was thus transformed from a civil law company (GBR) into a limited liability company in 1988 (Interview U5). The breakthrough and growth of the company occurred concurrently with market support policies of the "100 MW wind" program in 1989 and the introduction of the Electricity Feed-in Act (Stromeinspeisungsgesetz, StrEG) in 1990 (Interviews U1, U4, U5). The 100 MW wind program, which provided investment subsidies or guaranteed payment per kWh electricity produced, effectively reduced market uncertainty. As one respondent indicated, this institutional change was a significant driver for technological development and for the evolution of young spin-offs:

> "This was a huge boost for us, where we could simply set up a small wind turbine. And not always had to wait until a customer came around the corner and wanted to have something for his garden. [...] Without that, Südwind would never have started running." (Interview U1)

By providing incentives to investors, the "100 MW wind" program created a market niche for wind energy technologies. However, at that time, Südwind lagged behind market demand and the latest technological opportunities. The 30 kW turbine was becoming too small and the turbine design was not transferable to larger turbines. Therefore, Südwind had to bring a new turbine concept to the market. Due to the success of the robust and reliable Danish design, the company sought to adopt their technologies, but attempts to establish a cooperation or license agreement with a Danish partner were unsuccessful. Finally, the company came up with a 270 kW turbine based on the Danish design. Südwind was able to draw on the experience and technological know-how of the German gear manufacturer Flender, who had already developed a gearbox solution that met the new requirements. In 1993, the prototype was connected to the electricity grid (OELKER 2005: 116).

The analysis of the region-specific conditions in Berlin also shows that the regional presence of related technologies had a decisive influence on the emergence of wind energy technology: Modern wind energy technology resulted from the combination of the disciplines and industries engineering, mechanical engineering, electrical engineering and aerospace. The local concentration of university research institutes from different scientific fields provided an ideal platform for experimenting with wind energy technologies. At the TU Berlin, especially through Robert Gasch, but also through the initiative of individual students, structures were built up that allowed integrative and interdisciplinary research of the various disciplines. This was done primarily in application-oriented study projects, interdisciplinary work and research groups and joint research projects (Interviews F2, F5, U5, U8). The institutional environment of the TU Berlin and the existing regional technological structures contributed significantly to the emergence of wind energy technology:

> "And I think Berlin has offered a potential because it just brought together a lot of creative people [...] There was simply a certain scene. And certainly also driven by people like Gasch, there was also an anchorage in the universities." (Interview U4)

The local concentration and combination of various disciplines was very positively received in the university environment and had, according to many interviewees, a very positive effect on the perception of the research and teaching portfolio in the context of wind energy. One interviewee, for example, described the situation in Berlin in the early 1980s as follows:

> "And a study project was then the project of wind energy, which I conducted, where we have already worked on interdisciplinarity, namely electro technical issues, construction issues, machine building issues, aeronautical issues, all combined and

> coupled with practical work. And so, we actually built in '85 our own windmill, which we then put up in Berlin and tested." (Interview U2)

**Stuttgart, Baden-Württemberg**

Another nucleus of the German wind energy technology was Stuttgart in the federal state of Baden-Württemberg. In this case, path creation processes were closely connected to wind pioneer Ulrich Huetter who succeeded in mobilizing resources and actors. Researchers and engineers around Huetter played a pivotal role for early wind energy research and technological experimentation. In contrast to Northwest Germany and the region of Berlin, path creation activities started much earlier. In 1949, Huetter initiated – together with the regional energy utility – the association "Studiengesellschaft Windkraft e.V" (Society for the Study of Wind Power) which was engaged in exchange and networking among the various regional actors (political institutions, regional companies and researchers) as well as joint lobbying activities and research and development on wind energy. On behalf of a local mechanical engineering company (Allgaier Werkzeugbau GmbH), who was also a member of the association, Huetter designed a small wind turbine which proved to be quite reliable. Huetter adapted the fundamental idea of aircraft design on the construction of rotor blades. He attempted to develop and construct a new, technically sophisticated turbine concept introducing fiberglass composite blades and hydraulic pitch control. These were both important innovations which allowed a lightweight construction and a higher efficiency at relatively low wind speeds at inland sites. In 1958, a prototype of the two-bladed 100 kW turbine (StGW-34) was erected on a test field at the Swabian Alb near Stuttgart, which was operated by the DFVLR. The StGW-34 wind turbine developed by Huetter and his research group is widely considered to be an important milestone in the history of wind energy utilization (Interviews F6, F7).

However, due to low oil prices and the resulting change in energy policy in the 1960s, early path creation activities in Stuttgart came to a sudden end. Wind energy was found to be too expensive and political interest decreased strongly. Instead, the utilization of nuclear energy increased. This also had a significant influence on Stuttgart and its initial, favorable infrastructure, resources, and knowledge base. In 1961, the production and development of wind turbines at Allgaier was discontinued. In 1968, the first commercial nuclear power plant of Baden-Württemberg was started. With the retirement of Huetter from the university in

1980, wind energy research in Stuttgart lost much of its former importance. Finally, the DFVLR stopped its wind energy research programs and again concentrated on aerospace. This lead to the migration of several lead skilled workers and scientists. "Anyone who wanted to conduct further research in the field of wind energy had to go where the wind is" (Interview F8). Some of the DFVLR researchers moved to North Germany and were involved in the foundation of the German Wind Energy Institute (DEWI). Here, they found better wind conditions, a more favorable political and institutional environment, and other like-minded people. Another former employee relocated to Kassel and founded the Institute for Wind Energy and Energy System Technology (IWES), today Fraunhofer IWES. Because of their earlier research work, they enjoyed a high reputation in wind energy research (Interviews F6, U5, U6).

Analogous to developments in Germany in general, the Chernobyl nuclear accident led to a rediscovery of wind energy. In the following years, research activities focused mainly on Northern Germany (DEWI) and further locations of Fraunhofer Institutes (e.g. Kassel and Bremerhaven). While in Northern Germany the first commercial wind farms appeared, the expansion of wind energy barely played a role in Baden-Württemberg, which was reflected in regional planning. The federal state government focused on nuclear power and did not support wind power development[10]. Policy makers and planning authorities who authorized new wind power projects, decided case-by-case which mostly led to restrictive results (Interviews O2, O3). These restrictive policies lasted until the mid 2000s. Especially the Prime Minister of the State of Baden-Württemberg from 1991 to 2005, Erwin Teufel, was considered a strong opponent of wind energy (Interviews F7, O2, O3, P1). As stated by one of the interviewees: "It was politically intended. At the state level, the expansion of wind power was not wanted" (Interview O3). In the process existing prejudices were taken up and reinforced and the federal state government pursued an obstructionist policy (Interviews F7, O3). The "Landesplanungsgesetz" (state spatial planning act) in the version of July 10, 2003 (LplG, 2003) prescribed that regions with possible sites for regionally important wind turbines have to be determined in the regional planning process as priority areas and the other areas as exclusion areas. In the exclusion areas, the installation of wind turbines was not allowed. This resulted in precise region-wide plans for the installation of wind turbines, namely priority areas or exclusion areas, the so-called "black and white planning". This led to a situation in

[10] In 1990, nuclear energy still accounted for approx. 53% of total energy generation (MINISTERIUM FÜR UMWELT, KLIMA UND ENERGIEWIRTSCHAFT BADEN-WÜRTTEMBERG 2012: 5)

Baden-Württemberg in which very few areas were designated for the utilization of wind power. Proponents and advocates of wind energy such as the BWE were hardly involved in political discussions and decisions (Interview F7, O3).

Only 2004, wind energy research in Stuttgart has regained significance with the foundation of the first German Chair for Wind Energy. In 2011, six universities and research institutions from Baden-Württemberg and Bavaria[11] have launched the Windenergie Forschungsnetzwerk (WindForS –Wind Energy Research Alliance). To strengthen wind energy research in Southern Germany, the institutes attempt to pool their wind energy competence and cooperate in research as well as undergraduate and postgraduate education. Although the path creation process began about 30 years earlier than in other regions, the regional pathway has gained momentum and critical mass not until the 2000s.

As entrepreneurial activities and the creation of new knowledge in the region originated in research activities in the field of aviation and aerospace (Institute for Aircraft Construction, DFVLR) these path creation activities also imply that processes of regional diversification existed. Both, aerospace industry and wind industry are based on light materials and heavy loads and demanding conditions.

**Northwest Germany**

Also in Northern Germany, the emergence of the wind energy pathway has been stimulated and shaped by local entrepreneurs, inventors and indigenous business creation. One of the most influential actors shaping the emergence of wind energy technology was the inventor and entrepreneur Sönke Siegfriedsen. During a vacation at the west coast of Denmark in 1978, he visited the Tvind wind turbine, a milestone in the evolution of wind energy technology. From that point on he was passionate about wind energy. As a part of his diploma thesis at the Lübeck University of Applied Sciences (Lower Saxony), he constructed his first wind turbine. In 1983, he and two colleagues founded the engineering office aerodyn Energiesysteme GmbH in Rendsburg (Schleswig-Holstein) in northern Germany (AERODYN ENERGIESYSTEME GMBH 2013: 43; OELKER 2005: 117; RAVE/RICHTER 2008: 58). One year

[11] Aalen University, the Karlsruhe Institute of Technology (KIT), Stuttgart University, the University of Tübingen, the Technische Universität München (TUM) and the Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW – Centre for Solar Energy and Hydrogen Research Baden-Württemberg)

later, the company developed a compact 18 kW, two-bladed wind turbine (Aeolus 11). As a result of existing personal contacts, the company succeeded in installing and testing the prototype at a test field on the island of Pellworm. The data obtained from testing and monitoring ultimately provided an essential basis for the first guidelines for the construction of wind turbines in Germany developed by Germanischer Lloyd (GL) (AERODYN ENERGIESYSTEME GMBH 2013: 45; OELKER 2005: 120; RAVE/RICHTER 2008: 59).

The engineering company specialized in developing individual concepts for wind turbines. Thus, the company was dependent on the order situation and the general market situation in the industry. In the mid of the 1990s, two major customers, for which aerodyn developed a wind turbine, collapsed and had to declare bankruptcy (Interviews U8, U21). As a consequence, the company decided to change its business strategy:

> "And so we lost two big customers within a very short time. [...] As a result of this experience, the idea arose: can we with a license, a license product, get independent income. So that we have a basic financing. And based on the idea pro + pro emerged as a vehicle to develop this licensed product." (Interview U8)

Aerodyn saw an increasing market for wind turbines of the 1.5 - 2 MW class. They assumed that in-house development of such turbines was not feasible for many smaller companies that dominated the industry. For the implementation of the idea, aerodyn looked for a partner with sufficient capital and found the planning company Regenerative Energien Denker & Dr. Wulf KG, located near Rendsburg. The planning company had already beforehand invested in wind turbine manufacturer Jacobs Energie. Based on the collaboration with Denker & Wulf, the company pro + pro Energiesysteme GmbH & Co. KG was founded in 1997 with the aim of developing a 1.5 MW turbine until it was ready for serial production (AERODYN ENERGIESYSTEME GMBH 2013: 40). A close collaboration and division of labor was established, which was facilitated by geographical proximity, personal contacts and face-to-face interactions. Aerodyn served as the technical specialists, contributing its specialized knowledge and technological know-how, and Denker & Wulf was able to bring in its contacts and ensure the financial viability of the project (Interview U8). As a specialized engineering company, aerodyn worked for various wind turbine manufacturers. Besides the development of complete turbines, the company also designed and optimized single components (RAVE/RICHTER 2008: 59).

Another pioneer and key actor of path creation was the engineer and inventor Horst Frees. The entrepreneur who founded the company Windkraftzentrale in Schleswig-Holstein designed and developed some small-scale wind turbines in the 1980s. Besides, he constantly tried to influence and convince the government of the federal state Schleswig-Holstein and regional and local authorities to promote wind energy projects. Frees was also one of the founders of the "Verein für Windenergieforschung und -anwendung" (VWFA, Association for Wind Energy Research and Application), which was one of the first organizations in Germany that mobilized advocacy coalitions around the emerging wind energy technology (Interview P4).

**Other regions**

Mechanisms and dynamics of indigenous path creation can also be found in other regions. In particular, important activities and processes of path creation took place in the federal state Saarland in South-West Germany. This case demonstrates how local researchers, engineers and entrepreneurs contributed to the emergence of new wind energy technologies.

One of the first fundamental innovations in direct drive technology is closely connected to research activities in an academic environment. In 1990, the Forschungsgruppe Windenergie headed by the wind pioneer Professor Friedrich Klinger was founded at the Saarbrücken University of Applied Sciences (Saarbrücken Hochschule für Technik and Wirtschaft des Saarlandes) by a team of eight engineers and students. By introducing the idea of direct drive generators for wind turbines, the research group took a first step towards the development of a gearless wind turbine. After some years of basic research, they decided to develop and construct a new wind turbine. Instead of adapting the established Danish design, the research group worked on a project to develop a less fragile and more efficient turbine concept. In this process, they applied existing knowledge and technologies of the aerospace industry and in 1997 presented a prototype of a direct driven 600 kW wind turbine (GENESYS 600) with a multi-pole permanent magnet synchronous generator – a radical innovation at that time (VRIES 2007a). In this case, a new path was created by indigenous creation, namely the introduction of a radical innovation by indigenous researchers and entrepreneurs. The engineers and technicians involved in the project decided to adopt a technology which had been used in the aerospace industry. As highlighted by the former head of the research project:

> "We had seen something similar somewhere in an American aeronautical and military project. And they also had a small machine with permanent magnets. They sent to us a draught for $10,000 (laughing). And then we upscaled something like this to the 600 kW machine." (Interview U3)

The research group presented the prototype to representatives from leading wind turbine manufacturers, but their direct drive concept initially seemed to find little resonance in the wind industry. Plans to go into series production in 1998 failed because the research team was unable to find any potential investors (Interview U3).

They continued to follow the idea of direct drive turbines and remained on the chosen technological path. This resulted in more inventions and start-ups from the university research group. Particularly significant in this context are the creation of the INNOWIND Forschungsgesellschaft mbH in Saarbrücken, an independent research institute, and of the technology-based firm Vensys Energiesysteme GmbH & Co. KG (20 km from Saarbrücken) as an academic spin-off, both founded by research group members. Both organizations closely collaborated and used an interorganizational division of labor and expertise: INNOWIND focused on R&D whereas Vensys concentrated on the manufacturing of wind turbines (Interview U3). INNOWIND continued to develop a direct drive turbine with a permanent magnet type generator. Based on the innovative and proven turbine design of the GENESYS 600 and the operational experiences, a 1.2 MW direct drive turbine (Vensys 62) was developed. In 2003, a prototype was erected near Saarbrücken (Interview U3) (VRIES 2007a).

This illustrates how a small group of individuals contributed to the creation of a new technological pathway. Besides the creation of innovations and the development of new wind turbines, they set up a regional knowledge network over time. Many of the students and research group members have gone on to work for other German wind manufacturers or engineering companies and still keep in contact (Interview U3, U19).

#### 7.2.2.2 Diversification of regional industries

A key mechanism of new path creation in the German wind energy technology refers to regional industry diversification or regional branching as incumbent firms diversified into the new, related wind industry. Especially in northern Germany, small firms from the shipbuilding industry, agricultural machinery sector and mechanical engineering began to enter the industry. Faced with growing international competition, declining orders, or business and financial difficulties due to the crisis in the shipbuilding industry, these firms had to rethink business strategy (Interviews F1, O4, U2, U6). Inspired by the experience and the success of the early Danish pioneers, they searched for ways to diversify their product portfolio by constructing a wind turbine. Additionally, incentives such as government subsidies were provided for structurally weak regions in Northern Germany. By recombining existing knowledge and competencies to diversify into the new wind sector, new participants try to create new knowledge in order to develop new products and innovations. Thus, firm entry can create new knowledge. The local experimentation by some pioneering diversifying companies with different technological backgrounds was crucial for the emergence of new wind energy technologies – and for new path creation.

For example, Tacke, a mechanical engineering company that had a lot of experience with the development and construction of gearboxes for industrial and maritime application benefited from the performance requirements for marine gear units. In this sector, quality was mainly associated with sturdiness and durability. As a result, marine gear units were constructed with a relatively high share of steel materials, which made them extremely solid and stable (Interviews U2, U6). Similar technical requirements were needed for wind turbines (Interviews F1, F2, F3, F4, U4, U6). As explained by a former engineer:

> "In marine gear units the important thing is durability. [...] There you have benefited from and the first beginnings were also very helpful and the durability of gearboxes and components, which is also very important in the wind energy. Also the number of hours, if you have other transmissions, or in the car and so on, then this has no high operating hours. A wind turbine or a ship's gearbox runs continuously." (Interview U2)

Shipbuilding companies like Tacke tried to recombine this technological knowledge and transfer it to wind energy technology. The outcome was technically less sophisticated but led to a heavy and robust turbine design with solid components: the classic stall-regulated, three-bladed Danish design (TACKE 2004: 179).

> "And if you look at the old Tacke turbines, they have a lot of steel. [...] Very simple construction, with few failure possibilities, but also very robust with a lot of steel." (Interview U2)

In 1985, a 150 kW wind turbine (TW 150) developed by Tacke was installed on the island of Sylt in the North Sea. The firm retained the Danish design and its technological features.

Until 1990, the TW 150 was upscaled to 250 kW (TW 250) and two years later Tacke was the first manufacturer that introduced a 500 kW wind turbine (TW 500) produced in series to the market (OELKER 2005: 124).

Often there have been economic reasons that forced experienced firms to look for opportunities for diversification. As a response to the crisis in the shipbuilding industry, the Husumer Schiffswerft (HSW) began with the development of wind turbines in 1986. Besides national government support in the form of a BMFT demonstration program ("Sonderdemonstrationsprogramm für Windenergieanlagen bis 250 Kilowatt Nennleistung"), HSW received policy support from the federal state of Schleswig-Holstein for the preservation of the shipyard location in Husum and its workplaces (DER MINISTER FÜR ARBEIT UND SOZIALES, JUGEND, GESUNDHEIT UND ENERGIE DES LANDES SCHLESWIG-HOLSTEIN 1990: 6; OELKER 2005: 121). Therefore, the company was able to benefit from policy support for its diversification strategy and its innovative activities. In the final report of the demonstration project, the strategy was described as follows:

> "The continuing crisis in the shipbuilding industry has obliged Husumer Schiffswerft to embark on the frequently mentioned path of diversification, i.e. areas of engineering other than shipbuilding. [...] During planning and development the objective was to ensure that most of the components of the wind power installation could be produced in Husumer Schiffswerft's own workshops. The purpose of this was firstly to guarantee the closet possible link between design and fabrication and secondly to secure jobs, and perhaps create new ones, at Husumer Schiffswerft by undertaking the construction of wind power installations." (HUSUMER SCHIFFSWERFT 1994: 109)

This quote also reflects the importance of related resources, knowledge and competencies in dealing with huge machines and steel components for diversifying into the new wind industry. "Shipbuilding has also been individual manufacturing, it was about practical technical solutions for robust machines" (Interview F1). HSW also adopted the Danish design and with the support of the Flensburg University of Applied Sciences developed a 250 kW turbine: the HSW 250, a heavy, sturdy construction with three blades and stall control. In 1988, the turbine was tested within the BMFT demonstration program and successfully introduced to the market. Customers were primarily public companies, especially municipal utilities (so-called Stadtwerke). For private users, the purchase and operation of the HSW 250, the largest wind turbine at that time, initially were not worthwhile due to low feed-in tariffs (OELKER 2005: 121; RAVE/RICHTER 2008: 61).

This changed only with market stimulation policy of the German government, particularly with the introduction of the electricity feed-in act (StrEG) in 1990. The act provided guaranteed prices for fixed periods for wind power fed into the grid, and thus generated sufficient revenue for investors. Hence, the HSW 250 basically became interesting for private investors and customers. Nevertheless, these customers relied on the proven and more reliable turbines from the Danish manufacturer. Furthermore, at the beginning of the 1990s, the 250 kW turbine was already too small for the German market. For that reason, HSW began with the erection of a prototype of a more efficient 750 kW wind turbine (HSW 750) in 1993 (OELKER 2005: 122) (Interview U6).

However, HSW gained a lot of experience and knowledge about the Danish design through the HSW 250 project, much earlier than other German manufacturers. All components were tested in the field under different wind conditions. Due to technical problems, most components including generator and gearbox were modified, replaced and closely examined (RAVE/RICHTER 2008: 62). HWS focused on the technological trajectory of the Danish design and the HSW 750 was a further step in the learning process. However, the turbine remained a prototype. Instead of entering into series production of the 750 kW wind turbine, HSW decided in the same year to develop a 1 MW turbine (WINDPOWER MONTHLY 1994b).

In 1984, AN Maschinenbau und Umweltschutzanlagen GmbH (AN) was founded as a self-managed enterprise by 50 former employees of the Voith company and started to diversify in some environmental fields including wind energy. This example also highlights the importance of individual actors. Key entrepreneurs succeeded to mobilize collective action. In this way, they contributed to the creation of a new regional pathway by local experimentation and by introducing new technologies. The employees, mainly metal workers, electrical engineers, and technicians experimented with different small wind turbines for isolated operation. However, the successful entry and breakthrough only came when AN signed a cooperation agreement with the established Danish wind turbine manufacturer BONUS Energy AS in 1988. The agreement involved the production and distribution of AN Bonus wind turbines under license at the production location Bremen. In the following years, the company concentrated increasingly on the production and distribution of wind turbines and was finally renamed in 1997 into AN Windenergie GmbH (Interviews O4, U6).

Thus, the case of AN involves processes of regional industries diversification as well as entrepreneurship as a mindful deviation from one technological path to a new pathway by introducing new technologies (indigenous creation). In this way, the company was able to prevent a lock-in situation (Interviews O4, U6).

Although most of the experienced firms from related industries that diversified into the wind industry had already entered the market in the late 1970s and 1980s, there were also a few latecomers. For instance, Fuhrländer entered the market in 1991. Driven by the commitment of visionary and wind pioneer Joachim Fuhrländer, the company established a new additional segment, although the core business remained boiler and plant engineering (Interview U12). As a later entrant, Fuhrländer had to face some problems concerning market entry and entry strategies. Market access was further exacerbated by the location at Waigandshain in the state of Rhineland-Palatinate in south-west of Germany and the geographical distance to the market in northern Germany (Interview U12). Consequently, Fuhrländer had little interest in the coastal location of Northern Germany. Instead, they decided to focus on wind turbines specially designed for inland locations as a market niche (OELKER 2005: 186). This point was highlighted by a former engineer: "We have only made our experiences inland" (Interview U12). The company developed its own turbine which was especially adapted to the requirements of inland locations.

To diversify into the emerging wind industry, Fuhrländer adopted the technology and turbine design from Northern German entrepreneur Horst Frees and his firm Windkraftzentrale. A three-bladed 20 kW turbine developed by the wind pioneer Frees served as the basis for the first Fuhrländer turbine. The company further developed and advanced the turbine and constructed a 30 kW turbine (Interview U12). However, wind turbines with less than 100 kW of rated power had already become obsolete for the German market. Fuhrländer worked on the development of a 250 kW turbine. Due to the short product life cycle of wind energy technologies at that time and the developmental edge of competing manufacturers, the company sought to shorten product development cycles and manufactured wind turbines in very small quantities. A former engineer remembers:

> "The development then went much faster than today. At that time it was directly after the 250 kW, which had a running time of one to two years. That means no chance to get into a serial production somewhere. This means small quantities, although this is relative." (Interview U12).

What these companies had in common was that they could benefit from their experience, existing knowledge bases and competencies in related industries, particularly in mechanical and electrical engineering. The recombination of existing, related knowledge enabled new path creation. Furthermore, these experienced firms – or more specifically engineers and technicians at the firms – could build on practical experience, routines and tacit knowledge. Knowledge accumulated of wind energy technologies through practical experimentation and learning by doing. This was also a crucial precondition for the creation of the new technological pathway of wind energy.

#### 7.2.2.3 Externally induced regional pathways

The creation of the new pathway of wind energy was also supported by exogenous activities such as policy interventions, the foundation of public research institutions, the migration of entrepreneurs and scientists, and market entries of foreign manufacturers. In addition to federal political measures, this is particularly evident in northern Germany.

Policy interventions by regional or national governments were found to be an important endogenous driver of path creation. In particular, policy instruments introduced since the late 1980s created a niche for the development of wind energy technologies and facilitated market creation. When the BMFT began to stimulate market formation and offered significant financial incentives to potential investors with the 100/250 MW wind program and the Electricity Feed-in Act (StrEG), a market niche with great potential opened up (see section 7.1). The change in the institutional environment offered a possibility for firms in related industries to diversify into wind turbine manufacturing (Interviews O4, O5, P1, F2, F3, U4, U6, U8, U9, U11, U16). With the 100 MW wind program and its successor, the 250 MW wind program, the BMFT supported operators of wind turbines either with a 60% investment subsidy or a guaranteed payment of 4 euro cents/kWh in addition to the negotiated feed-in tariff. This was the first time that the German government promoted wind turbine operators.

According to the interviewees, "One of the most important success factors was the Electricity Feed-in Act" (Interview U8). The law obliged the energy suppliers to purchase and pay a tariff for the wind energy generated in their supply area. At the same time, the payment was stipulated to min. 90% of the average revenue per kilowatt earned by the network operators from sales to all final electricity consumers in the year before. The interviewed wind turbine manufacturers stated that the planning security with respect to the sales figures and the security for investors was significantly improved (Interviews U4, U6, U8, U9, U11, U16). As stated by one of the interviewees:

> "The biggest motor to drive the whole thing had definitely been the feed-in law. The ability to invest in such a technology and then to make a reasonable return on a relatively safe basis was so attractive that several people invested and, thus, the industry was built up." (Interview F3)

As a result, several companies invested in the wind energy sector. This triggered a boom in demand and led to a significant increase in wind energy utilization from 9.3 MW (126 installed turbines) in 1989 to 331 MW (1,721 turbines) in 1993.

Additionally, the Northern German federal states Schleswig-Holstein, Lower Saxony, and Hamburg started initial regional funding programs (see section 7.1). Since the 1990s, the investment and development banks of the states of Lower Saxony and Schleswig-Holstein granted subsidized loans to individuals or citizen initiatives for the installation of wind turbines (Interview P1, P4). This has considerably facilitated the development of a local market.

In Schleswig-Holstein and Lower Saxony, path creation processes were also supported by the establishment of public research institutions. The federal state of Lower Saxony founded the German Wind Energy Institute (DEWI) in Wilhelmshaven to support the still relatively young wind energy research field in 1990. The institute was to promote the establishment of wind energy companies and the development of a regional wind energy industry in Lower Saxony. DEWI was rapidly established as an influential research organization and business service provider and is now one of the internationally leading institutions in the field of wind energy. It offers a wide range of research and consulting services in the area of wind energy, such as measurements, forecasts, studies and trainings as well as technical, economic and political consultations for the industry, project developers, banks, politics and public administrations (Interviews F8, P3). Furthermore, DEWI provides workshops, trainings and courses for student engineers. Around the same time as DEWI was initiated, plans for the establishment of a research and test center for wind energy began in Schleswig-Holstein. In order to achieve the state's energy policy objectives and to have a neutral test field according to international agreements, which was not predominantly in private hands, the state of Schleswig-Holstein participated in the establishment of the company. In 1990, the WINDTEST Kaiser-Wilhelm-Koog GmbH was co-founded by the state of Schleswig-Holstein, the district of Dithmarschen, the municipality of Kaiser-Wilhelm-Koog, the energy utility Schleswag and the certification agency Germanischer Lloyd (GL). The chosen location was the rural community of Kaiser-Wilhelm-Koog at the North Sea Coast, where GROWIAN was built, installed and tested in the 1980s. Here also Germany's first commercial wind farm was established. According to a statement by the Parliament of Schleswig-Holstein, "the test field was built at Kaiser-Wilhelm-Koog, because the infrastructure of an already existing site with wind turbines of Germanischer Lloyd and the former GROWIAN plant could be used and expanded" (SCHLESWIG-HOLSTEINISCHER LANDTAG 2000: 69).

The federal state-funded research institutions were important steps towards enhancing and expanding wind energy research activities in Germany (Interviews O5, F8, U20). Besides, DEWI and WINDTEST promoted the spatial concentration of research activities in wind energy technologies in the northern federal states of Lower Saxony and Schleswig-Holstein. In both cases, the foundation of public research institutions attracted qualified scientists and engineers. For example, some researchers of the DFVLR in Stuttgart (Baden-Württemberg) moved to North Germany and joined DEWI. The migration of researchers and highly qualified workers from South to North Germany reinforced new path development in the Northern federal states (see section 7.3 Labor mobility and spin-offs).

New path creation in Aurich, Northern German, is another case of an external induced regional pathway. In Aurich, new path development originated from the relocation of Aloys Wobben the foundation of the company Enercon. After studying electrical engineering at the University of Applied Sciences of Osnabrück and the Technical University of Braunschweig (both Lower Saxony), Wobben returned to the East Frisian town of Aurich and founded Enercon in 1984 (BECKER 2006; RÜBEL 2012). During his studies and his work as a scientific assistant at the TU Braunschweig, he experimented with technical concepts and gained practical experience with the construction of small wind turbines (KOENEMANN 2009: 82; OELKER 2005: 130). Wobben, who is considered to be a "visionary and wind enthusiast" (Interview F8), started in a garage with two colleagues (ENERCON GMBH 2009: 8; RÜBEL 2012: 31). The entrepreneur mobilized political actors, industry associations, environmental groups and local farmers to develop local support networks of policy makers and civil society (Interview F8, U11, P1, P3).

In order to open up a market, Enercon or, more precisely Wobben, worked closely together with regional municipal utilities and energy suppliers in the field of product and technological development. The emergence of a market for the new wind energy technology was promoted by an increasing regional demand. In contrast to most other energy suppliers in Germany, the regional energy supplier (Energieversorgung Weser-Ems AG, EWE), showed a strong interest in wind energy in the 1980s (Interviews F3, P1, U14). The energy supplier negotiated with Enercon on the development of larger wind turbines. As explained by one of the interviewees:

> "Mr. Wobben had turbines and then contacted the EWE [...]. The CEO [...] then took the decisions and said: Okay. We'll do it. But your turbines are actually too small. We need something bigger. And for the development of these larger turbines Enercon didn't have the money. Then the EWE said: Okay. We'll give you the money, we'll finance that for you. Please develop the turbines." (Interview F3)

As a result, the first Enercon turbines were manufactured in and installed around Aurich. Concerning human resources policy, Enercon also pursued a regional strategy. Employees were mainly engineers from the regional university of applied sciences (Interview U11). The company's breakthrough came also with the 100 MW wind program in 1990. Demand increased significantly and Enercon went with the E-32 in series production (OELKER 2005: 132). The case of Enercon is therefore closely related to entrepreneurial activities.

Market entry of foreign manufacturers can also be considered as an exogenous source of path creation. In particular, the arrival of Danish wind turbine manufacturers in Germany promoted the inflow of external knowledge and technology. Denmark is a pioneer in the development of modern wind power technology. Danish manufacturers such as Vestas, Bonus, Micon and Nordtank have benefited from a first-mover advantage which resulted in an early dominance of the Danish wind industry and a leading role in the development of the technology (GARUD/KARNØE 2003; SIMMIE 2012; SZARKA 2007). From the middle of the 1980s, most major manufacturers from Denmark began to enter into the German market: Vestas Deutschland GmbH was founded in 1986, Nordtank Windkraftanlagen GmbH in 1989 and Nordex Energieanlagen GmbH in 1991. In the same year, Vestas set up their own production facility in Husum. They established branches in Germany or agreed to distribute their turbines through existing companies. Most of them were located in Schleswig-Holstein, partly because of geographical proximity, but also as a consequence of Schleswig-Holstein's institutional environment and funding policy (Interviews F2, U8, U16). Unlike the national "100 MW wind" program, which only subsidized turbines produced in Germany, there were generally no clauses in the early federal state funding programs that created barriers to market entry for foreign manufacturers (RAVE/RICHTER 2008: 60). The establishment of foreign subsidiaries and branches fostered knowledge and technology diffusion. Domestic firms (Tacke, HSW) decided to adopt the Danish design which enabled the emergence of a new technological trajectory.

This section explored how new technological path emerge. For that purpose, the relevance of different mechanisms of path creation – indigenous creation, diversification of regional industries and externally induced regional pathways – and the roles of different actors in processes of path creation were examined. The observations revealed that besides firms that diversified into the wind energy technology, individual actors, entrepreneurs and users affected new path creation. The different sources and mechanisms of path creation identified and described above are summarized in table 9.

The most important mechanism was indigenous creation through local entrepreneurial activities followed by regional industry diversification. Both mechanisms were later supported by various exogenous drivers of path creation, especially policy interventions, the mobility of entrepreneurs and scientists, and market entry of Danish manufacturers. In regional terms, there are some differences. In Northwest Germany, the dominating mechanism was the regional diversification of industries. These were predominantly small firms from the shipbuilding industry, the agricultural machinery sector, and mechanical engineering, which entered the emerging wind energy industry. Path creation processes in Berlin, Southern Germany, and Saarbrücken were driven by local pioneers, the concentration of various university research institutes, and the establishment of university spin-offs.

The mechanism of path creation and the technological background of the firm seem, among other factors (such as the regional institutional environment), to affect the strategy and technological concept of a firm and, thus, the technological path. Shipbuilding companies and manufacturers of agricultural machinery generally relied on the heavy and solid Danish design. Academic spin-offs with a specialized knowledge base generally followed a specific technological trajectory and tried to develop a "more sophisticated" technological design. Entrepreneurs and firms with competencies in electrical engineering tended to focus on power electronics and converters. These efforts were mainly aimed at developing alternative wind turbine designs, such as variable speed and direct drive wind turbine concepts.

**Table 9: Sources, mechanisms and actors of new path creation in the German wind energy technology**

| Source of new path | Mechanisms | Actors | Technological path | Region |
|---|---|---|---|---|
| **Indigenous creation** | University Spin-offs | Entrepreneurs, inventors, innovators | Danish design, direct drive | Berlin, South Germany, (Saarbrücken, Aurich) |
| **Diversification of regional industries** | Firm diversification and regional branching | Small firms from the shipbuilding industry, agricultural machinery and mechanical engineering | Danish design | Northern Germany |
| **Externally induced regional pathways** | Policy interventions, foundation of public research institutions, market entry of foreign manufacturers, labor mobility | State, foreign manufacturers, entrepreneurs, workers, scientists | - | Northern Germany |

However, in the path creation phase the evolution of wind energy technologies remained a patchwork of different technological approaches and technological experimentation of individual actors. How did the path became established? Which actors were involved in innovation processes? To answer these questions, the actors and processes that shaped the subsequent path development are studied in the next section.

## 7.3 Growth phase: Technological trajectories, knowledge transfer and the diffusion of wind energy technologies

This chapter focuses on the growth and spatial diffusion of wind energy technologies. The section begins a detailed explanation of the technological development of wind turbines over time (7.3.1). Afterwards, the section presents the main findings concerning key actors and drivers of innovation processes in order to answer the fourth research question RQ 4: *Which* *actors and processes have contributed to the establishment of the pathway of wind energy technology?*

Section 7.3.2 focuses on the influence and roles of different economic actors in innovation processes and how collaborations between different actors have shaped the pathway of wind energy technology (RQ 4a). Section 7.3.3 explores the relevance of mechanisms and processes of inter-firm technology and knowledge transfer for the evolution and spatial diffusion of wind energy technology (RQ 4b).

### 7.3.1 Technological development

The development of wind energy technology is based on knowledge generated by different industries including electronics, mechanics, materials science and aerodynamics. To study the technological trajectory, it is helpful to break down wind energy technologies and the product of a wind turbine into its core components and/or subsystems. The principle focus of this chapter is on drive train technology (generators) and power electronic technology (power converters). This enables an empirical investigation of individual innovation processes and provides a more detailed insight into the actors and factors contributing to the evolution of wind energy technologies and the emergence of a dominant design. Innovations in these sub-technologies have shaped the technological development path of the core technology.

The analysis of the data of wind turbines and interview data reveals that the evolution of wind energy technologies was shaped by different technological sub-trajectories and different strategies to create new knowledge and innovations. In the 1970s and 1980s, wind energy technologies were at an experimental stage. Technological development was mainly driven by creativity and experimentation. New participants focused on experimenting with practical knowledge and tried to transfer their experiences, skills and technological knowledge from related industries into the field of wind energy. Most actors relied on trial and error processes such as learning-by-doing and learning-by-using. Firms experimented with a variety of technical approaches and several competing designs of wind turbines emerged: horizontal (HAWT) and vertical axis wind turbines (VAWT), small- and large-scale wind turbines, turbines with a different number of rotor blades (from one to eight) and different positions of the rotor relative to the tower (upwind or downwind rotor).

During this period, German wind power technology policies and research funding were mainly aimed at the development of large-scale wind turbines. However, demonstration projects and efforts to develop multi-megawatt turbines resulted in less successful or failed technological trajectories. The most prominent project was the construction of the GROWIAN prototype (cf. section 7.1). The research project has been regarded as a failure since at least the turbine was shut down in 1987. GROWIAN is a striking example of the very ambitious, but unsuccessful rapid up-scaling development of wind turbines in Germany (Interviews F2, F5, U2, U6). Nevertheless, GROWIAN, afterwards, had also some positive effects and provided a considerable impetus for further development of wind energy technologies. This involved a process of experimentation, learning, and testing the technical boundaries. On the one hand, the project demonstrated that the rapid development of large-scale wind power to create a technological breakthrough was an inappropriate strategy. This experience led to a paradigm shift to a technology development process by gradually upscaling small-scale turbines (cf. section 7.1). Because of the failure of the GROWIAN project, Germany began to concentrate on the development of more practical and reliable turbines following the example of Denmark (Interviews F2, F3, F4, F5, O5). On the other hand, the demonstration project provided a platform for experimenting with materials, new technologies and technical solutions. The turbine design had some innovative features, in particular a variable speed drive train concept. From a present-day perspective, the radical innovation of GROWIAN was the adaptation and introduction of the doubly-fed-induction generator (DFIG) into a wind turbine (Interviews F4, U3, U5). Using a DFIG allows full control of active and reactive power to adjust the generator for optimal power generation. Stator and rotor are both connected to the grid: the stator directly whereas the rotor windings are connected to the grid through a power electronic converter which enables variable speed operation (HAU 2014: 439). Thereby, the turbine is capable of operating over a wide range of wind speeds. This was a complete novelty at the time. This point was highlighted by a wind pioneer:

> "The doubly-fed-induction generator was one of the very few outputs from the GROWIAN. GROWIAN has failed in many instances, but with the generator concept, there actually remained something, which then also found its way into further development. (Interview U5)

Furthermore, several respondents emphasized the learning effects that resulted from the prototype (Interviews F4, O5, U2). In particular, they reported that accompanying research and the data collected during test operations were a valuable source of insight about wind energy technology and provided new knowledge on electrical engineering, aerodynamics and mechanical engineering. From this point of view, GROWIAN was of great value for subsequent technological development (Interview F4). Another respondent claimed that the failure of GROWIAN was, among other factors, due to the lack of reliable measurement methods and models. Based on the measurement results, it was found that the load calculation methods used for wind turbines were incorrect and that the mechanical loads were much higher than assumed (Interview U2).

After GROWIAN, MAN was engaged in the development of a second large-scale wind turbine. The 1.2 MW turbine WKA-60, a demonstration project funded by the BMFT, was developed in 1984. MAN benefited from the experience and knowledge they gained from the prior GROWIAN project. In contrast to GROWIAN, the turbine design was much smaller and considerably more robust. Instead of a two-bladed downwind design, a three-bladed upwind design was chosen. The wind turbine was in operation from 1988 to 1995 on the island of Helgoland, but the results were unsatisfactory. Overall, the project was experimental and not for commercial purposes and never left the prototype stage (HAU 2014: 699; HEYMANN 1995: 426; OELKER 2005: 58).

Most of the large-scale projects, especially the GROWIAN project, more or less failed while in Denmark several technically reliable, small wind turbines were constructed. With a new focus on wind energy in the mid-1980s, the BMFT also funded the development of smaller wind turbines. In the 1980s some research projects were occasionally funded which, dealt with the improvement of the technical and engineering requirements for wind turbines (Interview P4). Other research projects addressed the development of small wind turbines. Under the scope of the demonstration program ("Sonderdemonstrationsprogramm für Windenergieanlagen bis 250 Kilowatt Nennleistung") a total of 48 wind turbines from thirteen manufacturers[12] were installed and tested (cf. section 7.1). The demonstration program was clearly experimental. Except for the focus on wind turbines up to 250 kW, there were no further technical funding conditions (HOPPE-KILPPER 2003: 33; OELKER 2005: 364). Considering the state of science and technology in the 1980s with several completely different

[12] The following companies participated in the program: Köster, aerodyn, Enercon, Südwind, Windkraftzentrale, Schönball Energietechnik, Renk Tacke, Wenus, Krogmann Mühlen- und Maschinenbau, Husumer Schiffswerft, Kähler Maschinenbau, Flender/Dornier and AN-Maschinenbau HOPPE-KILPPER 2003: 32.

technological designs, this can be seen as a suitable strategy to encourage technological experimentation and to stimulate the generation of new technologies and innovations.

The wide variety of designs also resulted from experimenting with the number of blades used in wind turbines. Individual attempts were made to develop and commercialize one- and two-bladed wind turbine designs. One noteworthy project is the Monopteros, a horizontal axis, single-bladed turbine constructed by MBB (Messerschmid-Bolkow-Blohm). However, the experimental turbine failed technically and economically (HEYMANN 1995: 386; TACKE 2004: 153). In addition, a considerable number of turbines with more than three blades from different manufacturers was available on the market. The multi-bladed turbines also included wind turbines for water pumping applications. For example, the company LUBING Maschinenfabrik developed and sold a four-bladed and several six-bladed wind pumps. Other experiments referred to the orientation of the axis of the rotor. Some vertical axis wind turbines (VAWT) were designed and constructed. One prominent example is the Darrieus rotor. The Darrieus concept technology was strongly promoted and applied in some research projects in the United States and Canada in the 1970s and 1980s. However, the design was not successful on the market (HAU 2014: 50; TACKE 2004: 154). In Germany, the aircraft company Dornier constructed a few Darrieus rotors of different sizes. In cooperation with the Flender Werft AG, Dornier developed and manufactured a 50 kW Darrieus VAWT. The project was also funded by the demonstration program (HOPPE-KILPPER 2003: 33). Like Huetter, Dornier preferred innovative concepts based on aerospace know-how, e.g. lightweight construction (Interview F7).

Another innovative project was the two-bladed wind turbine WEC-520 which was based on the concept of the W34 design by Ullrich Huetter. The turbine was constructed by the gear and water turbines manufacturer Voith in collaboration with Huetter (Interview F7). The prototype was tested from 1982 to 1985 on a test field of the German Aerospace Center (DLR) in the Swabian Alb, Baden-Württemberg. For the construction of the turbine, Voith received subsidies totaling 8.3 Mio. DM by the BMFT (HAU 2014: 325; HEYMANN 1995: 383; OELKER 2005: 25).

Some other companies tried to develop wind energy technologies for export and not for the domestic market. Many of these projects focused on the development of decentralized forms of generation for stand-alone operation, especially for export in developing countries. "That was a basic idea in Germany in the 1980s: electricity from renewable sources, decentralized, small, stand-alone operation and, if possible, outside Germany" (Interview U6). Several interviewees also reported that the decentralized use of wind energy for generating power from renewable sources was an obvious strategy for them to follow during this phase of technological experimentation. Often they received government grants or subsidies for research and development. Many of these visionaries and enthusiastic tinkerers, engineers and technicians thus succeeded in constructing their first wind turbine which they built in the 1980s. The results of these projects were mainly experimental, small wind turbines. These can be attractive options for off-grid sites but are not economically viable due to the high cost of energy. However, the involved wind pioneers gained valuable experience. Several respondents argued that "learning-by-doing" helped them to improve wind energy technologies (Interviews F6, U5, U6, U8). This also indicates that these pioneers were mainly driven by environmental or sustainability considerations and idealistic reasons and that these motives, in turn, shaped the technological path.

Beside theses attempts, the technological path of the wind energy technology in the 1980s was strongly influenced by the developments in Denmark and the USA. At this time, a first dominant design emerged in Denmark. The so-called Danish design was developed in the 1950s by the Danish engineer Johannes Juul who constructed a 200 kW turbine in 1957 (Gedser turbine). The turbine concept, a three-bladed upwind rotor with an asynchronous generator, stall regulation and constant rotor speed, was a pioneering design for modern wind turbines. Like Juul, most of the Danish key actors were inventors and entrepreneurs. Other engineers, craftsmen and tinkerers with small workshops and an interest in wind energy built on a practical knowledge base and copied the turbine design. Technological development was based on experimentation, practically testing and employing known components rather than through theoretical calculations and measurements. Due to the cheap and robust components and the reliable turbine design, the Danish design proved very successful and was implemented in the 1980s by some small Danish manufacturers of agricultural machinery (Vestas, Bonus, Nordtank, Windworld, etc.) (GASCH/TWELE 2011: 35; HAU 2014: 40).

Despite the wide range of manufacturers and variety of wind turbine designs, a selection process and consolidation of designs occurred during the 1980s. Certain technological characteristics prevailed and defined the technological development path. Concerning the axis design, a tendency toward horizontal axis wind turbine (HAWT) increasingly emerged. German manufacturers, individual inventors and entrepreneurs copied major features of the

Danish design: upwind rotor, three-bladed horizontal axis turbine with fixed speed and stall control. Among the different technological concepts, the Danish design evolved through a path dependent process as the most robust turbine and emerged as the dominant design or technological paradigm. The path dependence had mainly two reasons. First, the Danish design was established and has already proven to be extremely reliable and, thus, successful in Denmark. As the Danish design was technologically less sophisticated, it was more easy to adopt. As a consequence, the wind energy technology diffused rapidly across Denmark. A respondent described the situation in the 1980s in the following terms:

> "We had more than 30 manufacturers in Denmark in the 1980s since almost every agricultural machinery manufacturer was able to buy engineering drawings. Here in Germany, the real wind energy history, apart from the piecework and pure prototypes, actually started with the feed-in law on 01.01.1991" (Interview U6).

The few German manufacturers were able to learn from and imitate Danish firms. One respondent stated that he had important contacts with the Risø National Laboratory for Sustainable Energy in Roskilde, Denmark (Interview U20). The Department of Meteorology and Wind Energy was one of pioneering and most influential wind research institute. One interviewee reported: "They also conducted basic research in wind energy at the time and we worked very closely together with them." (Interview U20)

Second, self-reinforcing mechanisms and positive feedback processes had been identified that fostered the adoption of the technology already available. According to path dependence theory, previous decisions and events influence future decisions and the behavior of a firm. In particular, established relationships with component suppliers who had experience with fixed speed turbines influenced the choices of actors for further projects. Finding and establishing a relationship with a new supplier was usually associated with high switching costs which reinforced existing supplier-manufacturer relations. In this way, relationships and the technological path of a firm may become locked in (Interviews F2, F5, U1, U4, U6, U12, U13). Furthermore, the adoption of the technology was accompanied by learning effects. Based on the Danish design, these manufacturers aimed to improve their turbine and increase the capacity. At this stage of path development, most new turbine development efforts focused on incremental innovations (Interviews U1, U2, U5, U6, U8, U12).

Most companies, which entered the market in the 1980s in Germany, adopted the Danish technology, for example Enercon, Tacke, HSW and AN Maschinenbau. Until the late 1990s, the design has been adopted and imitated by most manufacturers. Other development paths or technological sub-trajectories of wind energy technologies, like the VAWT or the two-blade design, came to an end.

Figure 14 shows the development of the market share of the four main turbine designs in terms of the share of total turbines on the German market since 1990. In 1990, the Danish design accounted for around 45% of total turbines. Another 16% were turbines with an advanced Danish design. Direct drive turbines, which had been on the market at the time, were exclusively small-scale turbines with two to six blades for stand-alone operations. VAWT and other two-bladed and multi-bladed turbines with a gearbox are summarized in the category "others". In total, these different designs made up around 22% of all turbines in 1990.

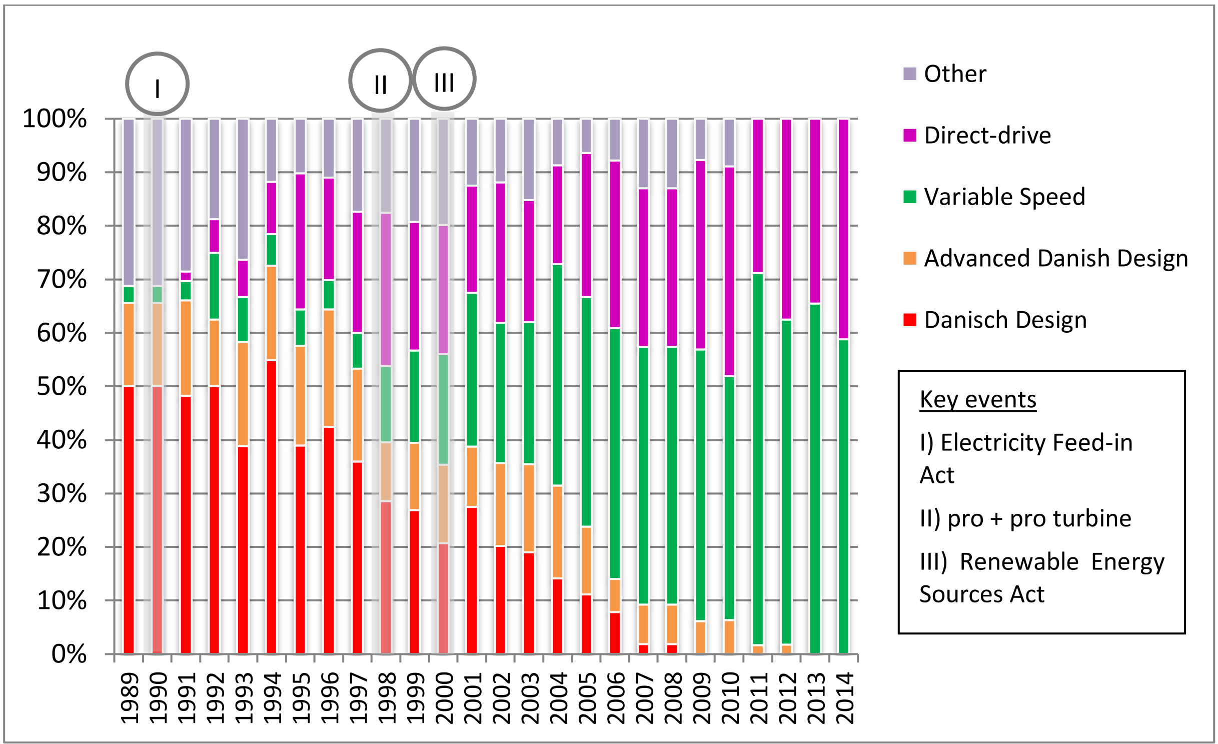


**Figure 14: Development of market shares of wind turbine designs**

Source: Own calculations based on BWE annual reports 1989-2014.

Until the late 1990s, most turbine manufacturers developed and sold fixed speed stall regulated turbines. The Danish design dominated the market for turbines up to 1.5 MW. Whereas the fixed speed Danish concept has already reached its peak, a new sub-trajectory began to emerge in the 1990s. The first commercial variable speed wind turbines were introduced by the German wind pioneer Enercon in 1989 (E-17, E-32) (see figure 15). However, Enercon turned away from this technology and dedicated itself to the development and construction of direct drive turbines. Three years later, Wistra GmbH, distribution partner of the Dutch manufacturer Lagerwey, began to sell Lagerwey variable speed wind turbines. The turbines had been developed independently of each other, not involving any technology or knowledge transfer (Interview O7). Also some technological characteristics of the Lagerwey and the Enercon turbine were fundamentally different. During the early 1990s, the small companies Südwind and DeWind introduced variable speed turbines to the market. Both turbines were developed independently of each other, but based on the same technology and the same suppliers (Interviews U1, U13). However, there were only a few variable speed turbines on the market. The dominant concept was still the fixed speed Danish design. The real breakthrough came in 1998, when pro + pro Energiesysteme GmbH developed a variable speed turbine (1.5 MW) with a doubly-fed induction generator (DFIG). This introduction can be considered as a milestone. Pro + pro sold licenses to four wind turbine manufacturers which then changed to a variable speed system: Jacobs Energie GmbH, BWU, Fuhrländer AG and Südwind Energy GmbH. One year later, a total of ten wind turbine manufacturers had developed variable speed turbines. Especially for wind turbines rated above 1 MW, the trend was to use a pitch controlled machine with variable speed and DFIG. Most turbine manufacturers changed to variable speed technology and, thus, a new dominant design was established. In 2000, the variable speed concept was adopted by most manufacturers with a total of 24 variable speed turbines on the market.

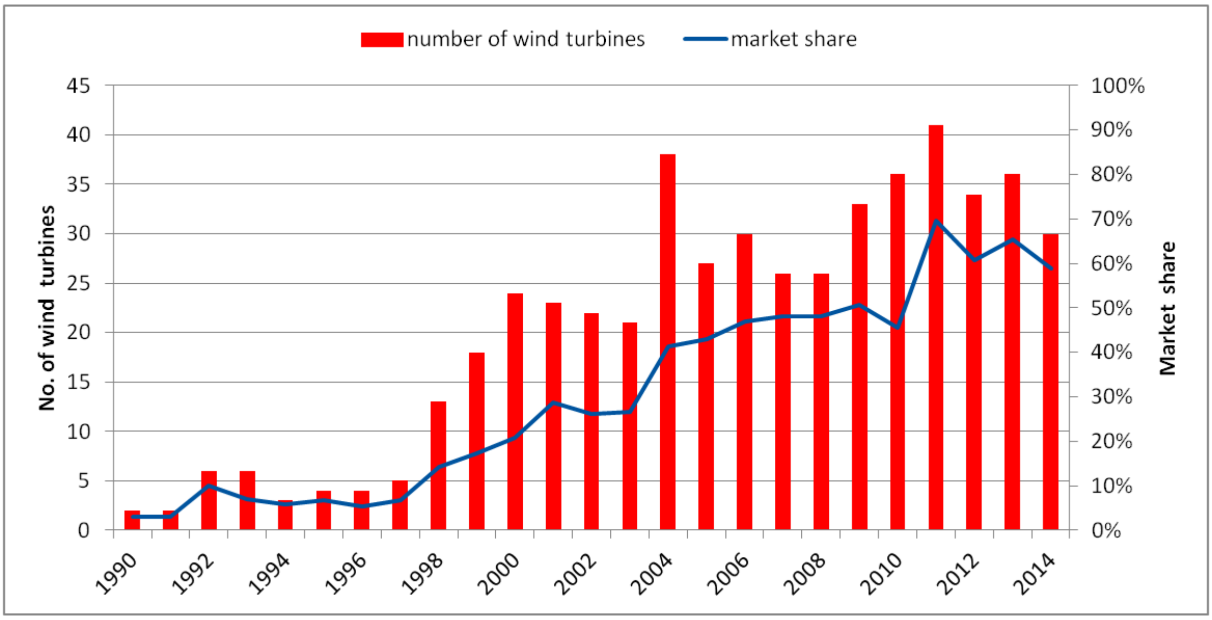


**Figure 15: Development of variable speed technology**

Source: Own calculations based on BWE annual reports 1989-2014.

Some of the firms (Tacke, Nordex) kept the technological trajectory of the Danish design for a long time. For instance, Nordex developed the N 60 and the N 62, two 1.3 MW turbines with stall regulation, and launched them to the market in the year 2000. Tacke introduced a variable speed turbine only in 2000 for the first time (TZ 750i). Since then, the technology has been used in all other subsequent turbine models. Although some manufacturers still offered stall controlled wind turbines, the vast majority of newly installed wind turbines in Germany were pitch controlled variable speed turbines. Stall turbines were only produced for the export in counties with other infrastructural conditions and energy systems (GASCH/TWELE 2011: 119). Since 2005, no new wind turbines of the Danish design were established in Germany.

Whereas firms previously followed a practice-oriented and experience-based strategy (learning-by-doing, learning-by-using) to develop new wind turbines and generate innovations, in the 1990s they began to apply scientific methods. Most of the interviewees pointed out that the biggest challenge was to build up system expertise (Interviews F2, U4, U5, U6, U8, U9). As wind energy technology is a combination of various individual technologies, innovation processes and ongoing path development were based on the creation and recombination of knowledge. In particular, new methods for load calculations and simulation tests enabled the development of more technically sophisticated turbines (Interviews U1, U2, U4).

Almost all interviewees stressed that the introduction of the doubly-fed-induction generator (DFIG) and variable pitch technology was one of the most important innovations in wind energy technology (Interviews U1, U2, U4, U6, U9, U12, U13, U15, U16). The technology, which enabled the changeover from traditional fixed blades and fixed speed to adjustable blades and variable speed operation, was fundamental for technological development and the establishment of the pathway of wind energy, as this interviewee described:

> "This was simply a huge leap, because you could massively reduce the loads on wind turbines. […]. This is the reason why it has actually only been possible to build 1 or 1.5 MW turbines. Otherwise there would be a technological limit. That was the main leap." (Interview U1)

The stall technology was increasingly being questioned. Technological development and up-scaling of the turbines made it necessary to create new solutions (Interview U 1, U5, U9). In order to reduce mechanical stress in the drive train, wind turbines above 1.0 MW were almost exclusively equipped with pitch regulation incorporating a power electronic converter for variable speed generators. As this allowed the turbine to rotate at the optimal rotational speed for each wind speed, it improved the dynamic behavior of the turbine and increased energy output in comparison with conventional constant speed systems. In addition, audible noise was reduced despite larger turbines (Interviews F4, U1, U2, U4, U12, U16).

A key characteristic of the development path of the German wind energy technology is the direct drive technology. After the introduction of variable speed wind systems, the development of direct drive turbines is considered by the interviewees to be a fundamental path shaping technological innovation. The key driver of this development were innovations in power electronic technology, especially full-power converters (Interviews F3, F4, U1, U2, U4, U5, U11, U12, U15, U16). The pioneer of this gearless technology was again Enercon's Aloys Wobben, who developed and introduced the first direct drive turbine in 1991, the E-40 (500 kW). The design involved a wound rotor ring generator which was directly connected to the hub. Enercon has been using this turbine concept since the introduction of the E-40 in all turbines. Through incremental improvements and modifications, Enercon succeeded in advancing the technology and continuing upscaling of the rotor diameter and capacity of wind turbines. In 2003, the first 4.5 MW direct drive turbine (E-112) was sold which was later upscaled to 6 MW. In 2010, Enercon introduced the E-126 as the further development of the E-112 with an output power of 7.5 MW which still is the world's biggest onshore turbine (ENERCON GMBH 2016).

For a long time, Enercon has been the only major supplier of direct drive wind turbines and has dominated the direct drive wind turbine market. Other wind turbine manufacturers continued to rely on gear-driven turbines. However, some small start-up companies have specialized in wind turbines designs without gearboxes. Pioneer Friedrich Klinger was the first who adopted the permanent magnet generator (PMG) technology to develop a direct drive turbine concept. The initial steps were taken at the Forschungsgruppe Windenergie (Saarbrücken). Klinger and his team started to develop a prototype. By introducing a direct-driven 600 kW wind turbine with PMG onto the market, a fundamental product innovation was created. As a result, a new technological path emerged. Through his company Vensys, Klinger further developed the technology and went into series production. Vensys, which started as a pioneer and niche player, has become one of the leading turbine manufacturers and designers in direct drive PMG technology (HAU 2014: 334) (see also 7.2.2).

However, path breaking activities like those from Vensys were the exception. The implementation and diffusion of direct drive technology were mainly hindered by high cost of permanent magnet generators and power electronics. In the 1990s, PMG concepts were thus considerably more expensive than turbine designs with gearbox (Interviews U1, U2, U9). Furthermore, most manufacturers lacked the relevant knowledge and experience in direct drive technology. With the exception of Enercon with Aloys Wobben, who originated from electrical engineering, most manufacturers had been too small to invest in and were not able to develop more competencies in the areas of power electronics and electrical converters (Interviews F1, U4, U5, U6, U6, U11, U16). As a result of path dependence on strategies and routines, most manufacturers maintained their technological concept (variable speed concept with pitch control): "a technology, which we already knew [...] which was available" (Interview U12). Moreover, like in the case of the Danish design, existing business relationships with suppliers reinforced continuity and path dependent development**.** If a manufacturer wanted to adopt a new turbine design, he usually had to switch suppliers and build up new relationships (Interviews U1, U4, U6, U12).

When the cost of permanent magnets and power electronics began to decrease, the interest in PMG increased. Recently, more manufacturers have introduced direct drive wind turbine models. Siemens Wind Power and GE Wind Energy changed from gearbox turbines to direct drive turbines using PMG (WINDPOWER MONTHLY 2008). Since the mid-2000s, direct drive systems have become increasingly popular in new turbine designs. In 2011, they accounted for 39% of total turbines on the German market. Currently, both direct drive technologies co-exist. The majority of the manufacturers of direct drive turbines developed a turbine design based on PMG which is offered by Siemens Wind Power, GE Wind Energy and Vensys. In contrast, Enercon uses wound rotor ring generators with electrical excitation and full converters.

The different technological sub-trajectories of wind energy technologies are depicted in figure 16. Each dot represents a wind turbine model, the color shows the corresponding turbine manufacturer and the size illustrates the capacity of wind turbines. The figure shows that early technological designs such as VAWT and the two-bladed design, have not prevailed. The Danish design emerged as a first dominant design, which was later replaced by the variable speed and the direct drive design, which in turn developed along two different sub-trajectories. Because of their technological capabilities, learning effects, and existing supplier relations, most companies pursued an upgrading strategy and followed their chosen technological trajectory. An exception is Enercon, which switched from variable speed to direct drive technology very early on. Some other companies managed to switch through an acquisition (Nordex, REpower).

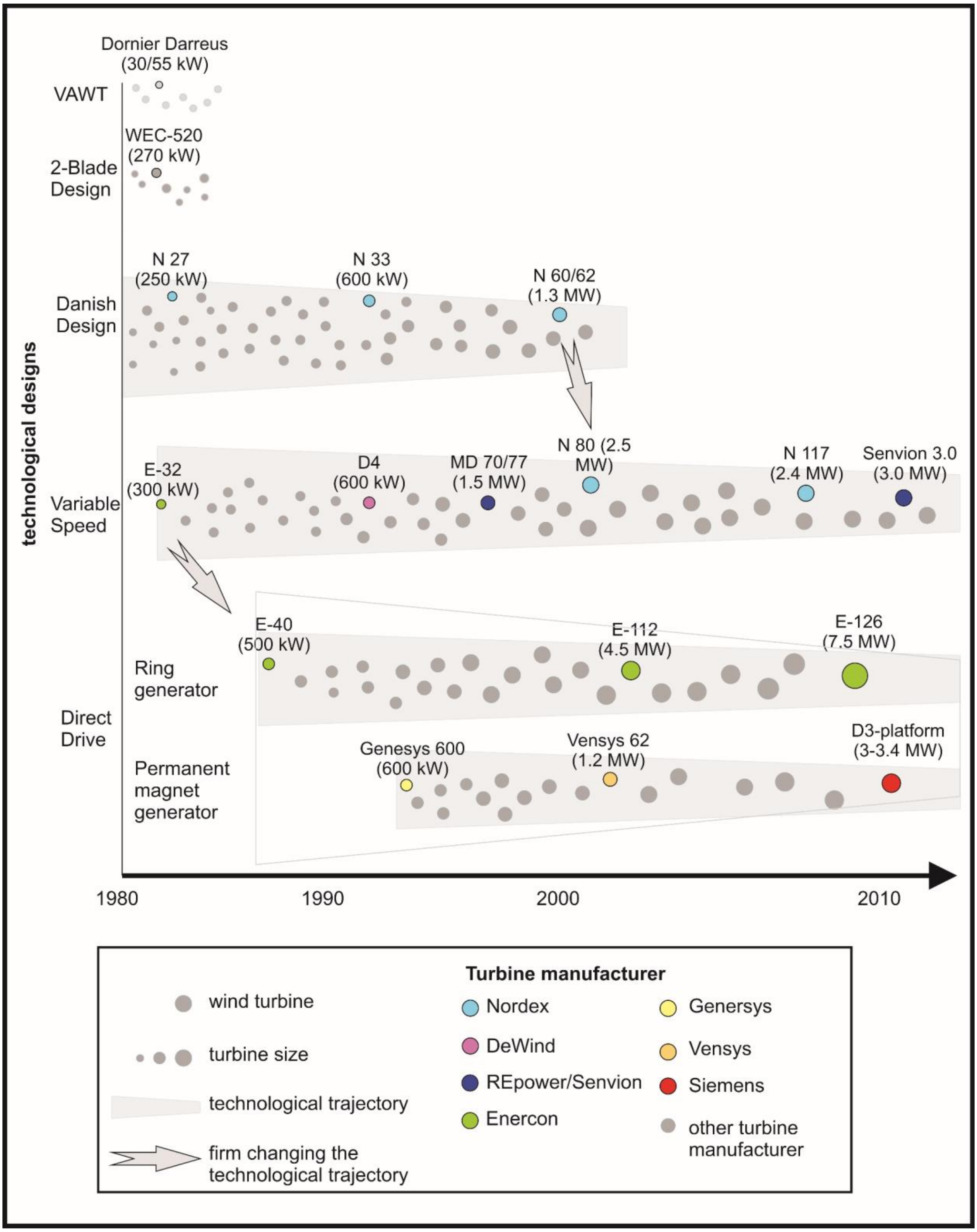


**Figure 16: Technological trajectories within German wind energy technologies**

### 7.3.2 Actors of innovation activities and collaboration

The evolution of wind energy technology is based on knowledge creation and innovations by various industry players. Besides turbine manufacturers, component suppliers and engineering companies have played pivotal roles in creating and establishing the pathway of wind energy technology. Turbine manufacturers are mostly system integrators which bring together different subsystems or components to create a wind turbine system. With the evolution of wind energy technology, external sources of knowledge have become increasingly relevant. In their efforts to generate innovations and to develop new wind turbine products, firms mostly had to rely on external knowledge.

**Suppliers of wind turbine components**

In particular, key components suppliers have played a central role for the development of wind energy technologies. This was reported by most of the interviewed turbine manufacturers (Interviews U1, U2, U3, U4, U6, U8, U9, U12, U13). Taking a closer look at innovation processes also reveals that suppliers of wind turbine components and manufacturer-supplier collaborations were key drivers in the innovation process.

If and to what extent wind turbine manufacturers collaborated with suppliers for the development and manufacturing of a new product depends on the company's strategy, culture and internal structure. Most wind turbine manufacturers had, and still have, a low degree of vertical integration, which means that the majority of components was produced by the suppliers. One exception is the turbine manufacturer Enercon with an extremely high degree of vertical integration (approximately 80%). Enercon produces nearly all key components of its wind turbines in-house, such as ring generators, inverters, rotor blades, cast components, towers and machine houses.

Moreover, the role of suppliers differs with respect to the components and sub-technologies. The relationship between manufacturer and suppliers and the suppliers' role varies from "build-to-print" contracts to collaborative relationships and strategic partnerships. If a large part of the know-how belongs to the supplier, the wind turbine manufacturer aims for a close and intensive collaboration. Suppliers are seen as valuable external sources of knowledge and innovation. This leads to the establishment of strategic relationships or partnerships with certain preferred suppliers (Interviews U1, U2, U4, U5, U6, U8, U9, U12, U17, U20). This is especially the case for "components that make a decision about whether or not a platform will be a success" (Interview U13). These are primarily the generator, gearbox, drivetrain, rotor blades and converter systems. Such solutions are often customized to a specific turbine. "For this reason, gearbox manufacturers are, of course, much more involved in research and development than it is the case with other components" (Interview U13). Here, manufacturers attempt to integrate key supplies in idea generation, concept development and product design during the early phases of the innovation process. At that stage, component suppliers can contribute their expertise and competencies which are related to core components of wind turbines. In particular for the new development of a wind turbine or a platform, suppliers are integrated early into the development process (Interviews U2, U6, U12, U15, U16, U17). For example, one interviewee described the introduction of a new turbine design where initial tests were carried out jointly with suppliers to develop technical specifications. Then a prototype was constructed and core technology and components, in particular doubly-fed induction generator and converter systems, were tested and modified in close collaboration with key suppliers (Interview U16). Several interviewees stressed the importance of generator, gearbox and drive manufacturers for the introduction and further development of variable speed technology. The development of the first variable speed turbines from different manufacturers "was massively driven by the suppliers because they had this technology already in mind from completely different areas" (Interview U1). Likewise, another turbine manufacturer reported that first electric pitch systems and a variable speed system with frequency converter were developed together with supply partners (Interview U2).

An important supplier in the German wind industry also stressed that long-term collaborations or strategic partnerships played a crucial role for the development of an entire new wind turbine. If they are involved in the production of an already existing wind turbine with fixed specifications, for example as a second source supplier, they have hardly any influence on the turbine design. In case of new developments of wind turbines and generators, however, the supplier can be responsible for the complete development, design and engineering of the component (Interview U15).

The respondents especially underlined the need for mutual trust and reputation as crucial requirements for an effective collaborative partnership (Interviews U11, U13, U17). Such strategic partnerships are predominantly based on a long-term relationship between the manufacturer and a specific supplier. For example, the collaboration can emerge from former market based interactions or existing contracts. One interviewee described the process in the following terms:

> "They are quasi partners. You simply talk to them somehow. You have already had a long-term cooperation, with the former technology. Already at [turbine a], [firm X] had always been a supplier of gearboxes. Afterwards also [firm X]." (Interview U12)

There is, thus, a certain continuity in collaborative relationships between wind turbines manufacturers and the suppliers of specific components. Another manufacturer reported that the development and construction of a novel pitch-regulated variable speed turbine could only be achieved through intensive involvement of selected suppliers. In this way, individual components were adapted and optimized for the entire wind turbine system. The turbine manufacturer described the development of a new wind turbine as a collaborative effort between the manufacturer and selected suppliers and emphasized the importance of integrating the specific competencies and experiences:

> "We were a very small company and could not do everything ourselves. And we also knew that the generator supplier, the transmission manufacturer and so on have more competencies about their field than we did. These are the specialists, of course." (U19)

The company acted as a system integrator. The development of components like the generator and aspects concerning control technology and simulations were transferred to suppliers and engineering companies. As stated by another interviewee:

> "And what we have done is, especially at the beginning, was that […] a lot more development packages were outsourced to the suppliers. We started with a very small team. We could not do everything ourselves. So we have load calculations for example, those simulations, we have not done this ourselves. They have commissioned engineering firms to do this. Only in later years, five years later, we began to build up a team, in-house, that hat could do this." (Interview U16)

For moderately complex and more standardized components such as cast components, like the rotor hub or machine frame, or electrical components the turbine manufacturer generally relies on subcontractor or "build-to-print" relationships to suppliers. Here, the turbine manufacturer defines all features, designs the specifications and gives detailed blueprints which the supplier then executes (Interviews U9, U13, U16). In some cases, they can just purchase standard products through catalogues. Moreover, several interviewees saw an increasing trend towards standardization in the supplier industry in recent years. Major suppliers like Bosch Rexroth, Winergy or Eickhoff have a leading position in the market and are key suppliers for many turbine manufacturers. As a result, sometimes identical components can be found in turbines of different manufacturers (Interviews U8, U9, U13).

Overall, it must be stated that key components suppliers are crucial for the evolution of wind energy technology. On the one hand, suppliers are integrated in innovation processes through collaborations and strategic partnerships. On the other hand, suppliers often have the role as technical innovator. They continuously need to improve their products and design new components and thereby drive innovation (Interviews U15, U17, U18). The larger suppliers also conduct their own R&D**.** For example, gearbox manufacturer Winergy AG has proactively developed a new drivetrain concept called "HybridDrive". By combining a two-stage planetary gearbox and a permanent-magnet generator, the company developed a significantly shorter system compared to conventional geared transmission system designs. It was developed in close cooperation with the engineering company W2E and the turbine manufacturer Fuhrländer (Interviews U12, U17). In this case, an innovation created by the supplier industry provided a significant impetus for the evolution of wind energy technology and even resulted in the emergence of a new technological sub-trajectory.

**Collaboration with service providers and engineering offices**

As wind energy technologies evolve and mature, they become more complex. At the same time, the development and construction of a wind turbine has become increasingly project- and location-specific. Considerable more research and development is needed to improve existing technologies and create new innovations. Search processes tend to become more complicated, more difficult, and more expensive for a firm. In view of the increased competition, turbine manufacturers additionally find themselves under serious time constraints. Especially smaller companies, which made up the vast majority in the 1990s and early 2000s, were hardly able to develop new turbines in a short period of time. They often lacked the necessary human, financial or technical resources to cope with the more complex requirements specifications.

In this context, the interviewed turbine manufacturers highlighted the role of R&D collaborations with specialized engineering offices. Although today all German turbine manufacturers have their own R&D departments, almost all interviewed companies cooperate or have cooperated with external service providers for technology consulting and engineering services (Interviews F1, U1, U3, U6, U8, U9, U10, U12, U16). An important reason why R&D-activities are outsourced and transferred to specialized engineering service providers is a shortage of qualified personnel. All turbine manufacturers, who are still on the market, have grown significantly over the last ten years. In addition, the development of wind turbines has also become increasingly complicated, with the result that research and development requirements have increased. Several manufacturers reported that it has become increasingly difficult to find sufficiently skilled workers for their mostly peripheral locations. A strategic, long-term cooperation with engineering firms can tackle this problem and at the same time provides access to external skills and expertise (Interviews F2, F3, U8, U9, U12, U16).

Through the interviews, two strategies or types of engineering firms were identified. First, there were many engineering companies which have acted as a service provider. These small, specialized engineering firms provided, for example, calculations, simulations or modeling of individual parts and components. It was a simple division of labor: Many wind turbine manufacturers only had a small development department, or none at all, and handed of specific service packages, to service providers and engineering offices (Interview U8). These engineering offices usually did not have any long-term relationships with manufacturers. "You just make what the customer wants [...] and it is only little strategic" (Interview U9). Collaborations were mainly project-specific and as a consequence, the engineering companies were heavily dependent on orders by turbine manufacturers. The second type or strategy refers to engineering firms which conduct their own product development. These firms design and develop key components or an entire wind turbine and subsequently sell their product or technology through licensing. As in the case of strategic partnerships between manufacturers and suppliers, the turbine manufacturer, as the buyer, is usually integrated in the development activities. Most of the interviewed firms were able to build up competencies and system expertise in wind energy technologies over time and succeeded to move from being a pure service provider to becoming an engineering company specialized in the development of new wind turbines (Interview U15, U17, U18).

In several cases, a project-based collaboration turned into a strategic and long-term relationship which resulted in new product development and innovation. Based on a close collaboration with engineering company W2E Wind to Energy GmbH, which was founded by former Nordex engineers, Fuhrländer was been able to develop a new 2.5 MW wind turbine.

For the development of a 3 MW turbine, which for the first time was to utilize a permanent magnet synchronous generator (PMSG), Fuhrländer also commissioned W2E. Because Fuhrländer was forced to declare insolvency in the meantime, W2E continued the project on its own. Today, W2E distributes this wind turbine under license (SONNE, WIND & WÄRME 2012) (Interview U12).

Thus, engineering firms have contributed decisively to the development of wind energy technologies in Germany and are among the most influential players in this development process.

#### Collaboration with other turbine manufacturers

Looking at the relationships between German turbine manufacturers, it seems that R&D-collaborations among competing firms have played only a minor role for path development until now. There has been hardly any collaboration or joint technology development between turbine manufacturers. Overall, the protection of products, internal processes and know-how is considered important which hinders collaboration among wind turbine manufacturers. The interviews indicated that the main barrier for collaboration and sharing knowledge is a lack of trust among manufacturers (Interviews F2, F3, U1, U6, U8, U9, U11, U13, U15, U16).

Due to lack in networking and collaborations between turbine manufacturers, other forms of knowledge transfer may have affected the evolution of wind energy technologies.

### 7.3.3 Technology and knowledge transfer

In order to understand the evolution and spatial diffusion of wind energy technology, it is necessary to understand the relevance of different forms of knowledge and technology transfer mechanisms in the German wind energy industry.

#### Licensing

Especially in the early phase of path development, licensing was an important channel of knowledge and technology transfer. Purchasing a technology often went faster than in-house development. Several firms entered the business through license agreements with Danish manufacturers or German engineering firms. For example, AN Maschinenbau und Umweltschutzanlagen GmbH signed a licensing agreement with the Danish manufacturer BONUS Energy AS which permitted the German company to build and distribute the wind turbines of the Danish partner. Since 1988, the company from Bremen has taken over service, maintenance, and sales of Bonus wind turbines in Germany and has also developed and produced turbines under license in its own facilities (WINDPOWER MONTHLY 1994a, 1994b) (Interview U6). Similarly, Wind Technik Nord, a pioneering company founded 1986 in Schleswig-Holstein, began to specialize in the production of wind turbines through the cooperation with the Danish turbine manufacturer Wincon. Since 1989, the small company produced a 200 kW turbine of the proven Danish concept (3-bladed, asynchronous generator, stall-regulated), the WTN 200/26, under license. The license agreement was not only a source for accessing a new technology, it also involved effective knowledge transfer which led to the successful creation and recombination of new knowledge. Based on the Danish technology, Wind Technik Nord was able to develop its own 300 kW turbine and later on a 600 kW turbine by in-house development (OELKER 2005: 101).

As mentioned above, engineering firms played an important role in innovation processes and the transfer of wind technologies. They have taken crucial research and development activities and developed wind energy technologies and wind turbines in close collaboration with a manufacturer. In some cases, they even developed a turbine on their own and then marketed it via licensing agreements. Several interviewees stated that the turbine developed by the engineering firm pro + pro Energiesysteme was a key innovation (Interviews F2, F4, U2, U4, U8, U12, U21) (see 7.2.2.1). In 1998, the small company designed a modern variable speed 1.5 MW turbine (gear-driven, pitch-controlled, DFIG). Afterwards, the wind turbine was licensed to four German turbine manufacturers: Jacobs Energie GmbH (distributed as Jacobs MD 70), BWU (bwu MD 70/ bwu MD 77), Fuhrländer AG (Fuhrländer FL MD 70) and to Südwind Energy GmbH (Südwind S 70/77). For the four companies, this was a significant technological leap. A former engineer of Fuhrländer explained the importance of the technology transfer:

> "So far we had only constructed stall turbines. [...] And we were totally new in that technology. Well, then we got to know the engineering office pro + pro and they had developed a 1.5 MW turbine, the MD 70 / 77. With that turbine, we entered into this technology." (Interview U12)

The MD 70/77 is one of the most successful turbines in its class. At the time, it was the largest wind turbine that was built in serial production (Interview U8).

Licensing had another effect on the evolution of wind energy technologies. Different turbine manufacturers developed almost identical wind turbines:

> "The suppliers then supplied the three companies so that some components were in principle equal to the GE turbine. So a generator of the 1.5 MW turbine, which then fits into a REpower, which fits into a Südwind, which fits into a GE, which fits into each turbine." (Interview U2)

The formal transfer of technology via licensing was and is not spatially bounded. Some German manufacturers used license agreements with Danish manufacturers to access their technology. Moreover, German engineering companies and small manufacturers (Südwind, Vensys) granted licenses for the Indian or Chinese market.

**Mergers and acquisitions**

Another knowledge transfer mechanism that has contributed to the evolution and diffusion of wind energy technology is mergers and acquisitions (M&A). M&As provide an opportunity for strategic expansion and to acquire external knowledge and technologies.

Since 2000, the wind turbine industry in Germany (and other European countries) has experienced a consolidation process through M&As and through diversification and market entry by multinational corporations (MNCs). Most of these firms had no or only little prior experience in wind energy technology and engaged in external technology sourcing. Mergers and acquisitions have become the preferred strategy for achieving growth and have considerably shaped the economic landscape. MNCs, such as General Electric, Siemens, Areva and Suzlon entered the industry while smaller firms came under considerable pressure. In May 2002, General Electric (GE) purchased the Enron wind division, which had acquired the assets of German wind turbine manufacturer Tacke Windtechnik GmbH in 1997, and formed GE Wind Energy. In 2004, Siemens entered the market by taking over the Danish turbine manufacturer Bonus Energy A/S (AN Bonus), a major player in the offshore sector. In this way, Siemens also acquired direct drive technology:

> "Without the acquisition, this new development would not have been possible. So these so-called synergies, which are always read in acquisitions, have actually been released in that case by bringing people together who know the wind generators, people who know electrical machines, with people who know turbines and the wind power which first made it possible to develop this turbine." (Interview U15)

In 2004, Fuhrländer took over the onshore activities of Pfleiderer Wind Energy including customer relationships, patents, licenses, and trademark rights. In this way, the company acquired the wind turbines in the 600 kW and 1.5 MW power classes that Pfleiderer has developed and launched on the market in recent years (ENERGIE & MANAGEMENT 2004). In 2007, the French energy group AREVA also tried to expand in wind energy, but failed in its attempt to acquire the German turbine manufacturer REpower. After a long takeover battle, REpower was acquired by Suzlon Energy (VRIES 2007b). Instead, AREVA purchased 51% of Multibrid, a German wind turbine manufacture and, in 2010, acquired the remaining 49% of Multibrid's share capital (AREVA 2010).

One of the most important processes in the evolution of the German wind industry is the formation of REpower Systems (today Senvion SE). In 2001, the two German manufacturers Jacobs Energie GmbH, which had acquired the wind energy division of HSW shortly before, and BWU (Brandenburgische Wind- und Umwelttechnologien GmbH) merged with the German engineering consultancy pro + pro Energiesysteme GmbH & Co to form the REpower Systems Group (REPOWER SYSTEMS AG 2002: 4). The core of the merger was pro + pro's wind turbine, the 1.5 MW MD70 (Interviews U4, U8). The turbine was one of the most advanced, efficient and reliable wind turbines at that time and soon became REpower's core product (Interview U8). REpower benefited from the experience, competencies and resources of the turbine manufacturers Jacobs (resp. HSW) and BWU: "And they have brought along the production site and, of course, the experience, the employees" (Interview U8).

In order to accelerate innovation, the turbine manufacturer Nordex chose to acquire the necessary technological knowledge from external sources rather than develop it in-house. Nordex only had experience with Danish design stall turbines and was especially interested in Südwind's development department and its variable speed turbine with doubly-fed asynchronous generator (S46, 750 kW) (NORDEX SE 2010: 43; WINDPOWER MONTHLY 1999). One interviewee explained this knowledge acquisition strategy as follows:

> "But for Nordex, the problem was that they have already seen: variable speed operation could become an issue and they did not have the infrastructure, the people. And then came to the conclusion: A simple possibility would be to buy a company that already had the technology." (Interview U4)

Due to the lack of resources and technological capabilities, Nordex explicitly aimed to acquire human capital in the form of (tacit) knowledge, skills, and competences carried by engineers, technicians and project managers. This was confirmed by a former engineer of Südwind and Nordex Energy: "So the Südwind people have already introduced the whole concepts for variable speed operation. [...] So above all, people were bought" (Interview U4). When Südwind was taken over by the Nordex Group in 1999, Südwind's variable speed technology was transferred to wind turbine manufacturer Nordex (Interviews U4, U20).

GE Wind Energy GmbH, which originated from the turbine manufacturers Tacke (Germany) and the Zond (US) used a similar strategy. In 2009, GE attempted to reenter the offshore wind market by acquiring Norway's ScanWind, a developer of direct-drive turbines. Victor Abate, vice president of renewable energy at GE, explained the investment:

> "This acquisition will give GE the ability to provide a direct drive, offshore wind turbine offering as an option to our customers. Scanwind represents the next strategic fit for our wind turbine line and we look forward to further developing their proven technology." (VRIES 2009)

The major technical advantage was the directly driven wind turbine with permanent magnet synchronous generators (PMSG) with its higher reliability and efficiency, specifically developed for coastal onshore and offshore deployment. For GE Wind Energy, access to Scanwind's direct drive wind technology provided an opportunity to combine Scanwind's proven state-of-the-art 3.5-MW class (with PMSG) with their own technology to develop an optimized 4.X MW offshore turbine (VRIES 2009). However, only a prototype was created. Only a short time later, GE Wind Energy again dropped the offshore market and concentrated on the onshore segment. Also the direct drive PMSG technology was not pursued any further. Instead, the company continued its well-established DFIG technology (Interview U13). Most recently, at the end of 2015, GE made a further attempt: with the takeover of the Alstom Energy business, GE also acquired Alstom's innovative 6 MW direct drive permanent magnet generator offshore turbine Haliade (VRIES 2015).

In the global wind industry, the development of Suzlon and its emergence as a key global player serves as another example of the importance of acquisitions to gain access to external knowledge and implement new technologies. The R&D department of the Indian wind company is situated in Rostock and was built around leading engineers of wind turbine manufacturer Südwind (Interview U16). Thus, the company also shaped the evolution of the wind energy technology in Germany. Suzlon was able to successfully takeover selected companies to accelerate the implementation of new technologies, to extend its vertical integration and to gain access to newly emerging markets. Since the takeover of the Dutch AE-Rotor in 1999, their facilities are used as a major R&D center for rotor blades (KAMMER 2011: 157). By acquiring the Belgian company Hansen Transmission International NV, the world's second largest wind turbine gearbox designer, manufacturer and supplier, Suzlon increased the degree of vertical integration and expanded its access to gearbox technology. With this strategic acquisition, Suzlon planned to enhance its research and engineering capabilities (Interview U16). Suzlon Group Chairman and Managing Director Tulsi Tanti said: "The acquisition of Hansen gives us technological leadership and will make Suzlon a leading integrated wind turbine manufacturer in the world. [...] [It] will allow us to integrate gearbox technology into the total turbine solution enabling a more reliable and competitive product in the marketplace" (apax Partners 2006).

Of course, the acquisition of REpower Systems enabled the access to new technologies and additional knowledge as well. In May of 2007, Suzlon Energy acquired the majority shareholding of the German wind turbine manufacturer Repower Systems AG. A joint statement by the Management Board and Supervisory Board on the takeover reads as follows:

> "The acquisition of REpower by Suzlon enabled Suzlon to accelerate its growth plans in Europe and thereby achieving a significant presence in all key wind markets around the world. Suzlon Energy is also convinced that REpower Systems AG has special expertise in research and development. [...] The strategy of Suzlon Energy is therefore to achieve the leading position not only through internal growth, but also through acquisitions and strategic partnerships." (REPOWER SYSTEMS AG 2007: 4)

Suzlon was especially interested in REpower's multi-megawatt class wind technology (1.5-5 MW). Apparently the key asset for Suzlon was the immediate access to the 5 MW class offshore wind technology, an expertise it lacked. Furthermore, Suzlon benefited from REpower's strong presence in the European market, particularly Germany and the emerging wind power markets in Portugal and France (VRIES 2007b).

The access to new knowledge and the accumulation of knowledge plays a central role also for the suppliers, who have very specific know-how. In order to design new, competitive products and innovation, they seek to enhance their knowledge base and to extend their skills and resources. As one respondent summarized:

> "The supply industry wants to build up much more system expertise. They have no interest in becoming a wind turbine manufacturer. But they want to gain a better understanding of the overall system and develop more appropriate components and actually start to develop more systems. So not only to supply a pitch gearbox, but also, ideally, the control drive and control system." (Interview U9)

**Labor mobility and spin-offs**

Another important mechanism of knowledge transfer is inter-firm mobility of human resources. In regard to the technological path of wind energy technology, labor mobility served as an important channel for transferring knowledge, especially tacit knowledge. Although some knowledge on wind turbines can be codified, a considerable amount of important technological knowledge is tacit, based on personal experiences. Consequently, it cannot be effectively transferred in codified form, but only through direct or face-to-face contact. Especially in the early phase of technology evolution, wind energy technologies were largely based on practical skills and personalized, tacit knowledge. The employment biographies of the interviewees indicate a high labor mobility. Employees moved strongly between companies within the wind industry. The high fluctuation between turbine manufacturers is perceived as a "kind of substitute for cooperation" (Interview O2).

The result was a lively exchange of knowledge and experience among different turbine manufacturers. Workers moved because they saw better opportunities elsewhere or because their company abandoned the wind business segment or even had to declare bankruptcy. When a company went bankrupt, executives, senior engineers and project managers were mostly hired by other companies, so the knowledge remained in the industry. Several interviewed executives stated that the recruitment of skilled developers, technicians and engineers from other manufacturers was an important strategy for acquiring external knowledge (learning-by-hiring) (Interviews U2, U3, U4, U5, U8, U9, U12, U16).

Learning effects and transfer of experience and know-how also resulted from the GROWIAN project. Many of the involved engineers and technicians who very early acquired valuable specific know-how and tacit knowledge through the project remained in the wind industry. Many of them were lured away by other wind turbine manufacturers and were able to bring in their experience from the GROWIAN project (Interviews O7, U3, U4). Because most of the valuable knowledge, which individuals acquired at the project, was tacit, labor mobility was an important mechanism for knowledge transfer. This point was highlighted by a wind pioneer, and later founder and managing director:

> "We then also had an employee, who previously worked at MAN in Munich and who was project manager of GROWIAN. [...] He already knew very well, what has worked and got things moving. And that was the greatest source of experience." (Interview U3)

The geography of knowledge transfer through labor mobility reveals some surprising results. Mobility of skilled and experienced workers was not just a regional matter. Engineers and researchers involved in the GROWIAN project were partially hired by turbine manufacturers in Northern Germany (Interviews U3, U4). Several former engineers and technicians of Südwind (Berlin) and Tacke (Rheine) also went to manufacturers throughout Germany (Interviews U2, U4, U5, U8, U13, U16). Thus, inter-firm labor mobility also facilitated and supported inter-regional knowledge transfer.

Figure 17 depicts the career trajectories of ten interview partners. It shows that both employees and founders were highly mobile. While labor mobility between research institutions and firms and between firms was often a regional process, it also reflects the spatial evolution of the wind industry. Many persons went from Berlin – in particular from the TU Berlin University – and South Germany to Northern Germany over time.

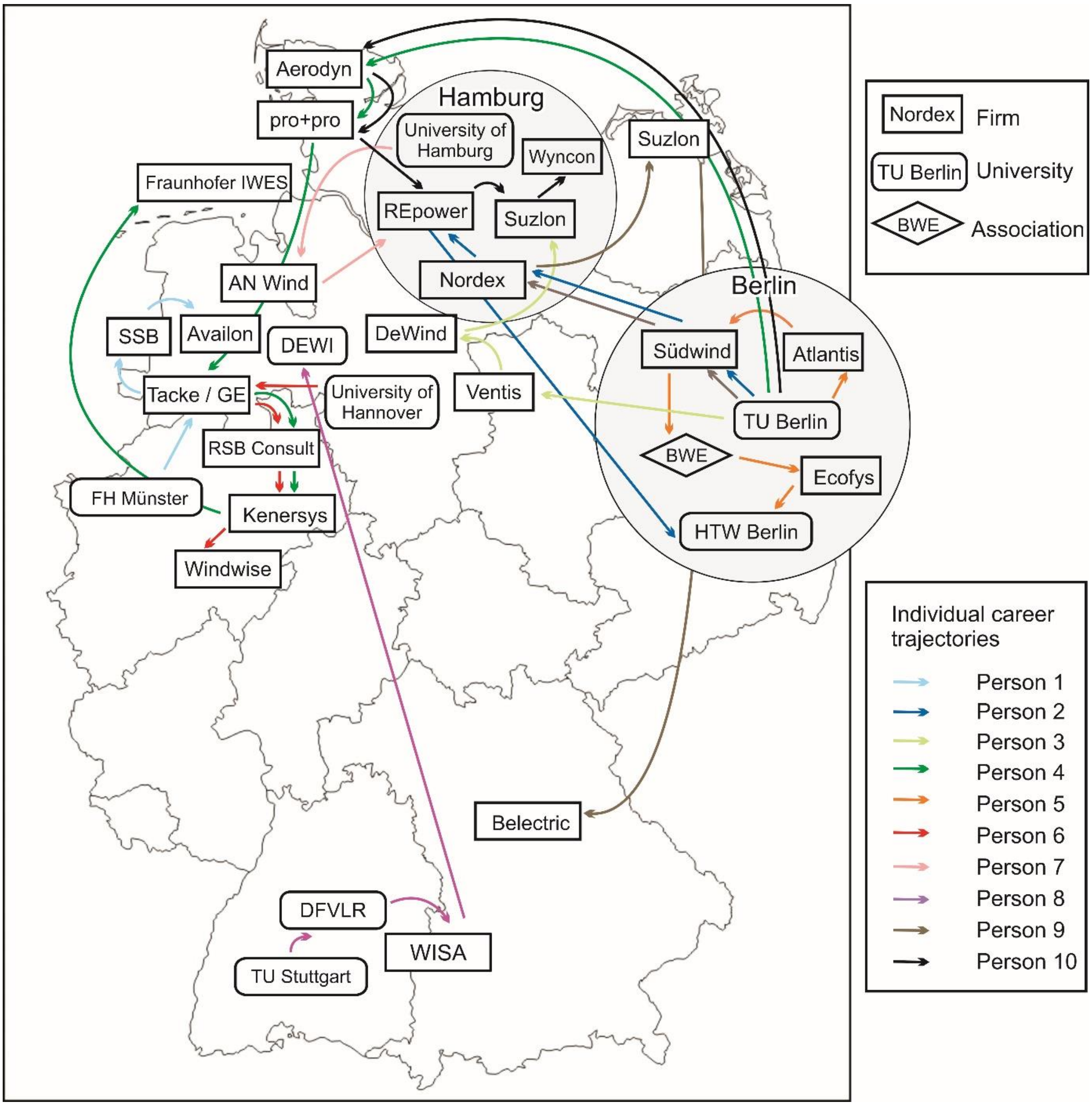


**Figure 17: Labor mobility 1980-2015**

Spin-off dynamics, which can be understood as a particular form of labor mobility, played only a minor role in wind energy technology. However, the spin-off firms, which have emerged during all phases of the development path, have been a significant mechanism of knowledge transfer and diffusion. As explained in chapter 7.2.1, university spin-offs have contributed to path creation. The most important spin-off firms were located in Berlin (Südwind), Saarland (INNOWIND, Vensys), Schleswig-Holstein (aerodyn) and Lower-Saxony (Enercon). Later, a few spin-offs from turbine manufacturers were founded, predominantly engineering and project planning firms or specialized supplier firms. For example, the engineering company W2E Wind to Energy was set up by former Nordex engineers, RSB Consult was established by former GE Energy employees, and former Kenersys employees founded the engineering firm Windwise. All employees from Windwise were former employees of Kenersys, nearly half of them had previously worked for GE Wind Energy. One of the few exceptions was the turbine manufacturer DeWind, which originated as a corporate spin-off from Ventis Energietechnik. Nearly all corporate spin-off firms located near their parent firm. In many cases, the spin-off firms collaborated with their parent firms or the parent was their main customer to whom they offered design and engineering services. When leaving an existing firm and founding a new one, engineers and technicians took important knowledge, competences and routines from their former employer. This was one reason why many spin-offs were subsequently purchased by turbine manufacturers or component suppliers. As the creation of spin-offs was a largely localized processes of knowledge transfer, the spatial concentration of wind energy technology was favored (Interviews U3, U5, U8, U9, U16, U21).

Altogether, licensing has been the most important source of external technology for German manufacturers. Especially in the early phase of path development, knowledge transfer between firms occurred primarily through licensing and knowledge spillovers from Denmark. With the evolution of the wind energy technology, mergers and acquisitions have gained in importance. Besides, the findings indicate a relatively high degree of labor mobility throughout the evolution of the wind technology and industry. Many workers changed jobs repeatedly which contributed to knowledge transfer. Spin-off dynamics had, apart from early university spin-offs in the path creation phase (see section 7.2), a rather subordinate role and were mainly concentrated to a few service providers and specialized suppliers.

### 7.3.4 Diffusion of wind energy technologies

The different mechanisms of knowledge and technology transfer explained above strongly influenced the spatial diffusion of wind energy technologies. The mechanisms which have shaped the evolution of wind technologies until 1996, 2000 and 2015 are summarized and depicted in figure 18–20. The interval of the three periods of time was chosen because of significant events concerning technology evolution and transfer. The arrows show the direction of technology transfer, the different types of arrows represent different mechanisms of technology transfer, and its color shows the basic technology in terms of the turbine design: Danish design, variable speed, and direct drive technology. In most cases, also the firms could be attributed to their dominant technology. The three figures build on each other in chronological order. Whereas the first figure depicts the few technology transfers until 1995, the last of the three figures summarizes all transfers until 2015.

In the early phase of path development, licensing was the most important channel of knowledge and technology transfer. Figure 18 shows that the diffusion of the Danish design occurred primarily through license agreements between Danish and German manufacturers and within the emerging German wind industry. In this way, both, experienced firms that diversified into the wind industry like AN Maschinenbau und Umweltschutzanlagen (since 1997 AN Windenergie GmbH) as well as inexperienced firms like Wind Technik Nord (WNT) or BWU, which was only founded in 1996, entered development collaborations and license agreements to get access to the successful Danish design technology.

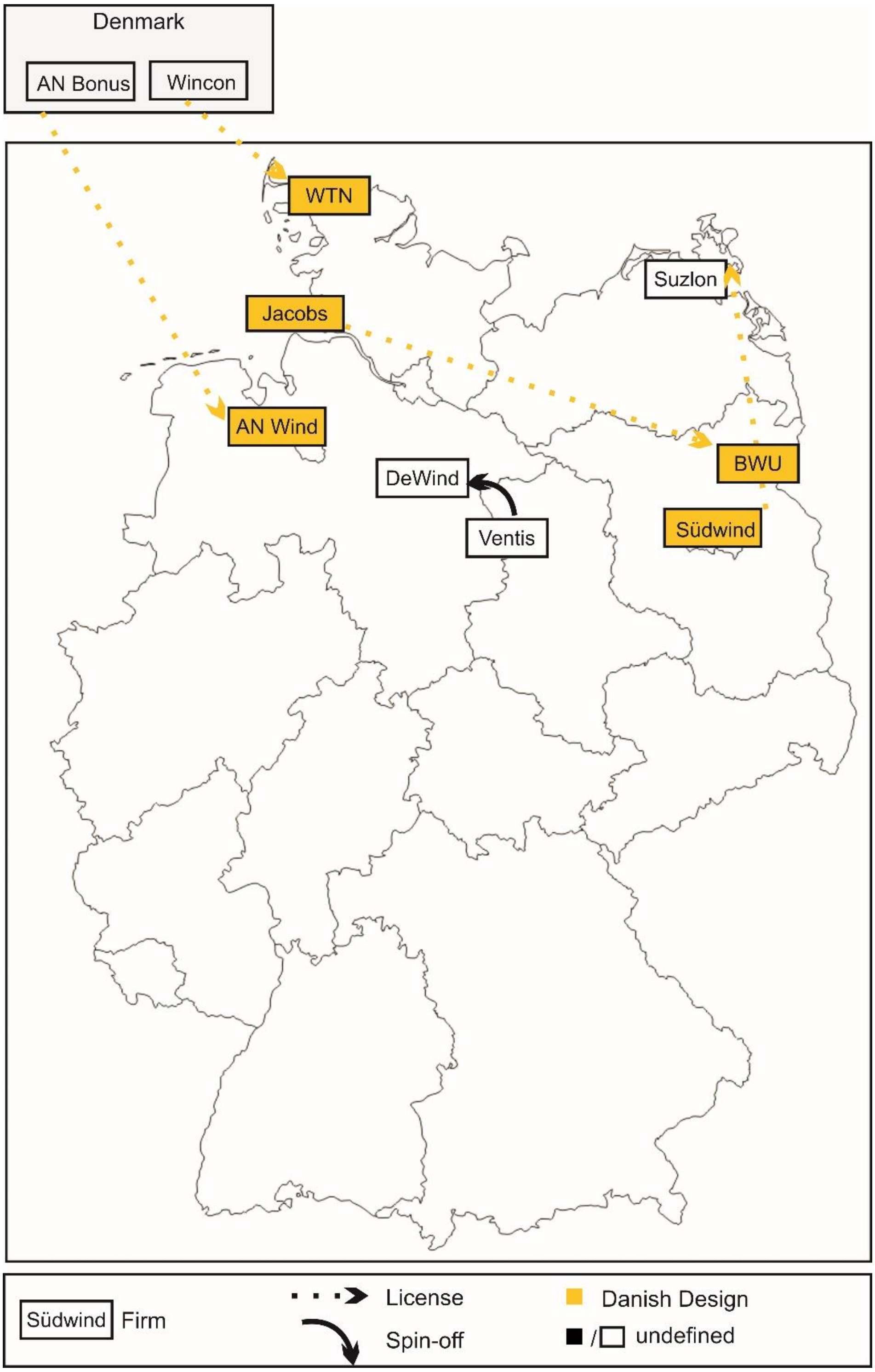


**Figure 18: Wind energy technology transfers until 1995**

Until 2000, significant contributions to knowledge and technology transfer (variable speed and Danish design technology) resulted from licensing and, in a few cases, from takeovers (see figure 19). Technology transfer now took place primarily within Germany between German companies. As pointed out above, a crucial impulse for the evolution and diffusion of variable speed technology was the development of a 1.5 MW variable speed turbine through the engineering company pro + pro Energiesysteme GmbH. The company sold licenses to four wind turbine manufacturers (Jacobs Energie, BWU, Fuhrländer and Südwind). In addition, mergers and acquisitions caused knowledge and technology transfer. Tacke's variable speed technology was first acquired by Enron and afterwards by General Electric (GE). Nordex took over Südwind to get access to the new technology and Fuhrländer acquired the onshore activities of Pfleiderer Wind Energy. With Jacobs, the first German manufacturer sold a license to Chinese manufacturer Goldwind.

In contrast to that, the diffusion of direct drive technology was a local process at that time. Vensys was founded as an academic spin-off by former employees of the Forschungsgruppe Windenergie (FGW). Based on a prototype developed by FGW and the experience of the engineers, Vensys was able to construct and market a 1.2 MW direct drive turbine.

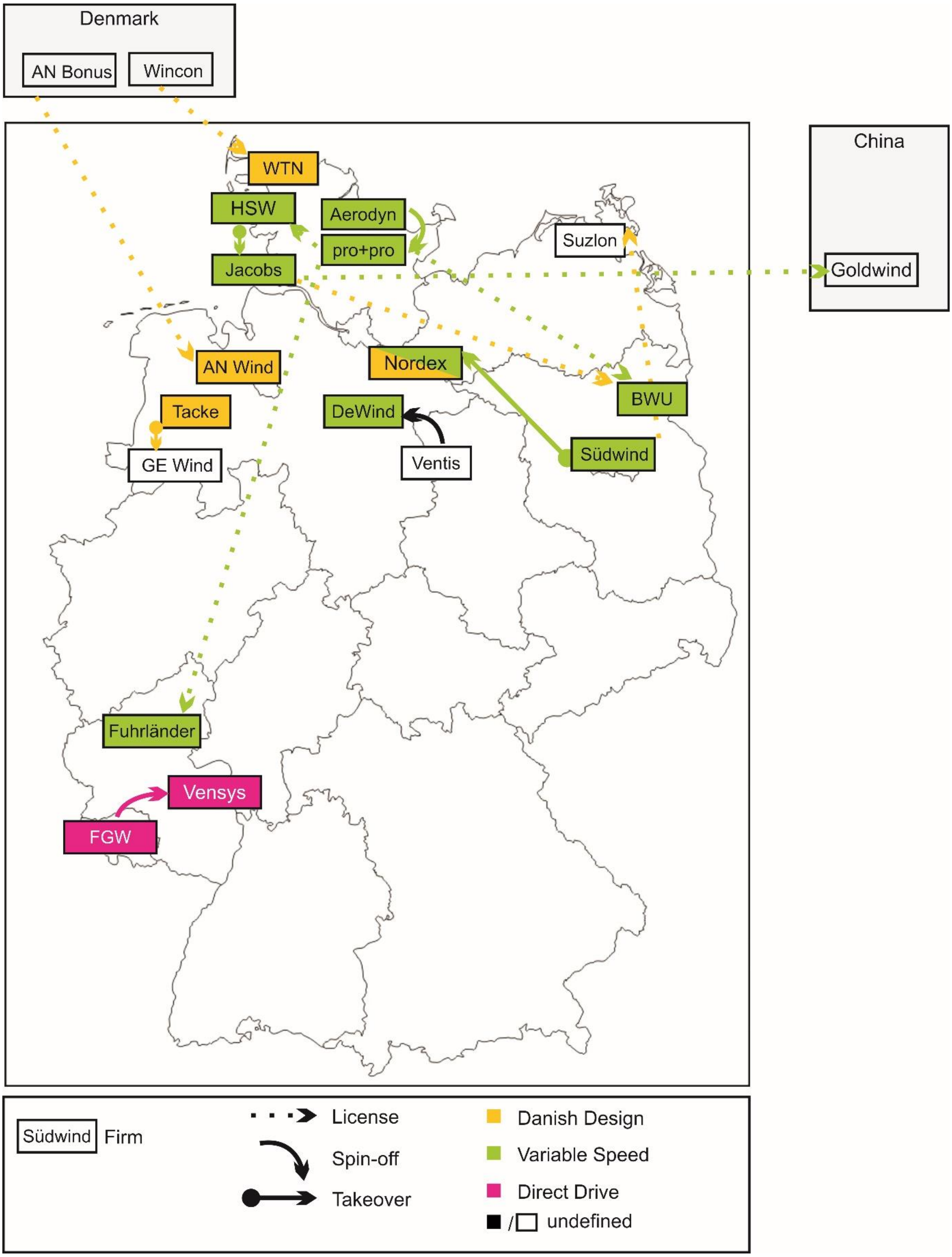


**Figure 19: Wind energy technology transfers until 2000**

On a later, more mature stage of wind energy technology, knowledge and technology transfer occurred predominantly via M&As and licensing (see figure 20). In addition, some engineering firms were established as spin-offs from larger companies. For example, Idaswind and W2E Wind to Energy emerged from Nordex, RSB Consult from GE Wind Energy and Windwise from Kenersys. The findings indicate that the new ventures exploited knowledge and skills that their founders and former employees had gained at the parent firm. For example, W2E further developed and advanced variable speed technology and constructed a prototype of 2.5 MW turbine. Shortly afterwards, these small, specialized engineering companies and other small firms (AN Windenergie, Jacobs) became important targets for acquisitions. A major technology transfer was realized with the fusion of Jacobs, BWU and pro + pro into REpower centered on the innovative 1.5 MW MD technology. Likewise, in order to become involved with the new promising direct drive wind technology, M&As became more important. Siemens acquired direct drive technology by taking over AN Bonus. GE Wind Energy followed a similar strategy. To access direct drive technology, GE first acquired Scanwind (Norway) and later Alstom (France).

Moreover, licensing contributed significantly to international knowledge transfer and technology export. In particular, Vensys licensed its direct drive technology to Goldwind (China), ReGen Powertech (India), Impsa (Brasilia), Eozen (Spain) and to the Arab Organization for Industrialization (AOI, Egypt). Fuhrländer and REpower sold their 1.5 MW variable speed platform (MD70 / MD77), which they had previously obtained through a licensing agreement with the engineering company pro + pro, to Chinese companies Dongfang and Sinovel.

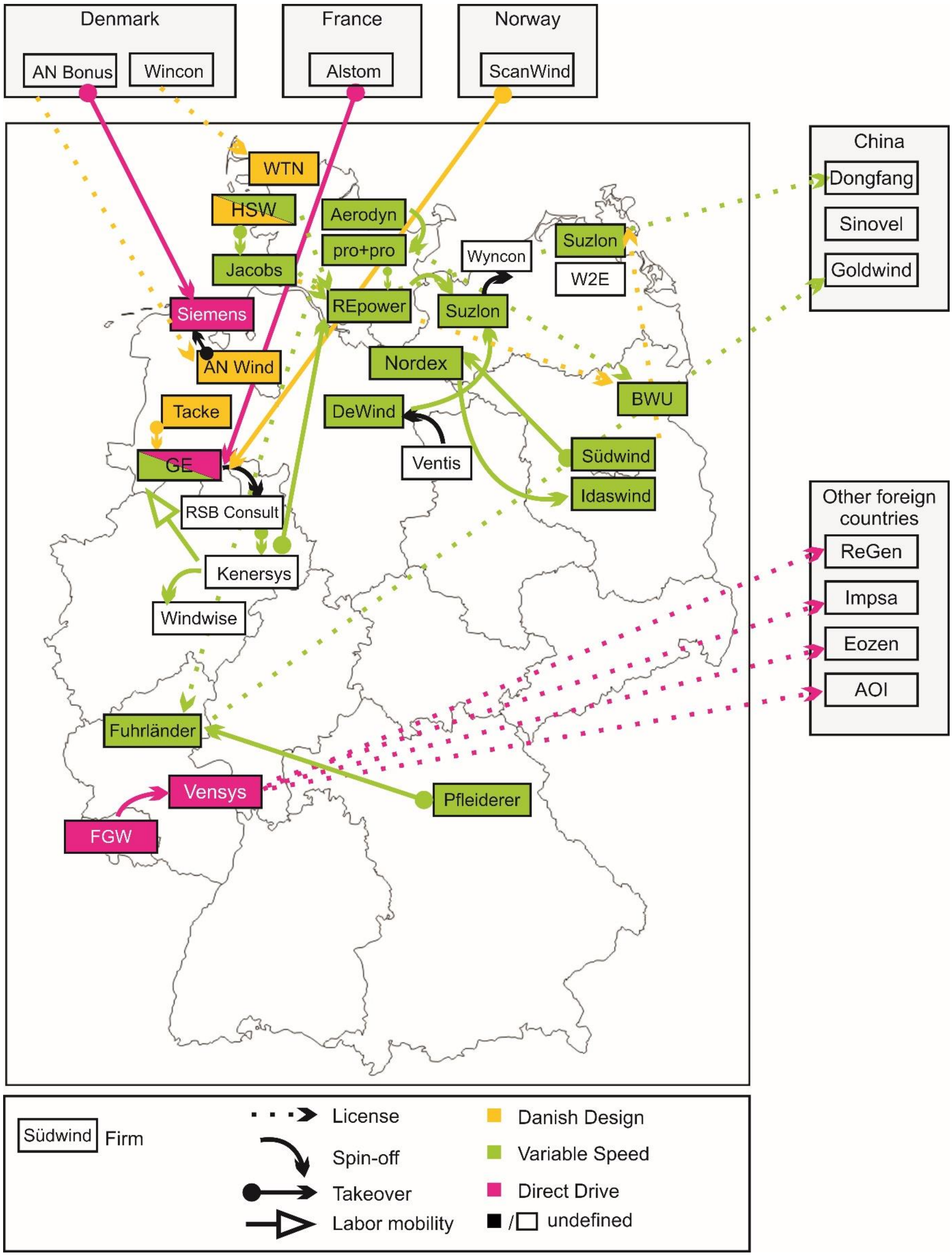


**Figure 20: Wind energy technology transfers until 2015**

The above section has illustrated that the evolution of wind energy technologies is characterized by different technological sub-trajectories and new product development and innovations from various industry players. Besides in-house R&D activities of turbine manufacturers, collaborations with suppliers and engineering companies shaped the pathway of wind energy technology. The diffusion of the variable speed technology is partly characterized by market entry of firms, by various R&D activities and by inter-firm knowledge transfers through license agreements, mergers and acquisitions as well as spin-offs and labor mobility.

# 8 Co-evolution of wind energy technologies and the institutional environment

This chapter is concerned with the co-evolution of the institutional environment and institutional arrangements with technological development. As argued in chapter 4.5, institutions are assumed to co-evolve with technology in a path dependent way. Evolutionary approaches emphasize the interrelations between technologies, industrial structures and the institutional environment. Context and technology mutually influence each other. In this section, an analysis of specific patterns and processes of co-evolution is presented in order to answer the fifth research question RQ 5: *How and under what circumstances does co-evolution arise? To what extent does co-evolution result from strategic actions of economic actors, users, policy makers and other organizations and how large is the impact of strategic actions on the institutional environment?*

At first, an overview on co-evolutionary processes and mechanisms during the evolution of the wind energy technology is presented, describing how institutions co-evolve with the emergence of a new technology and industry (section 8.1). Subsequently, three examples of co-evolution will be investigated and explained in more detail. The three cases were formative for the evolution of the wind energy technology and refer to different types of institutions. The first example illustrates the co-evolution of organizational structures such as businesses and industry associations (section 8.2). The second example of a co-evolutionary process relates to the technical and institutional design of the grid system (section 8.3). The third example is concerned with the co-evolution of formal, regulative institutions and of public policies with wind energy technologies and the industrial structure, namely the Electricity Feed-in Act (StrEG) and Renewable Energy Sources Act (EEG) (8.4). This raises the question whether co-evolution results from strategic action. For that purpose, section 8.5 investigates how actors affect co-evolution.

## 8.1 Co-evolutionary processes and mechanisms

The analysis of co-evolutionary processes in the emergence of the wind energy technology reveals interactions and feedback mechanisms between technology, institutions and economic actors during all phases of path development (see figure 21).

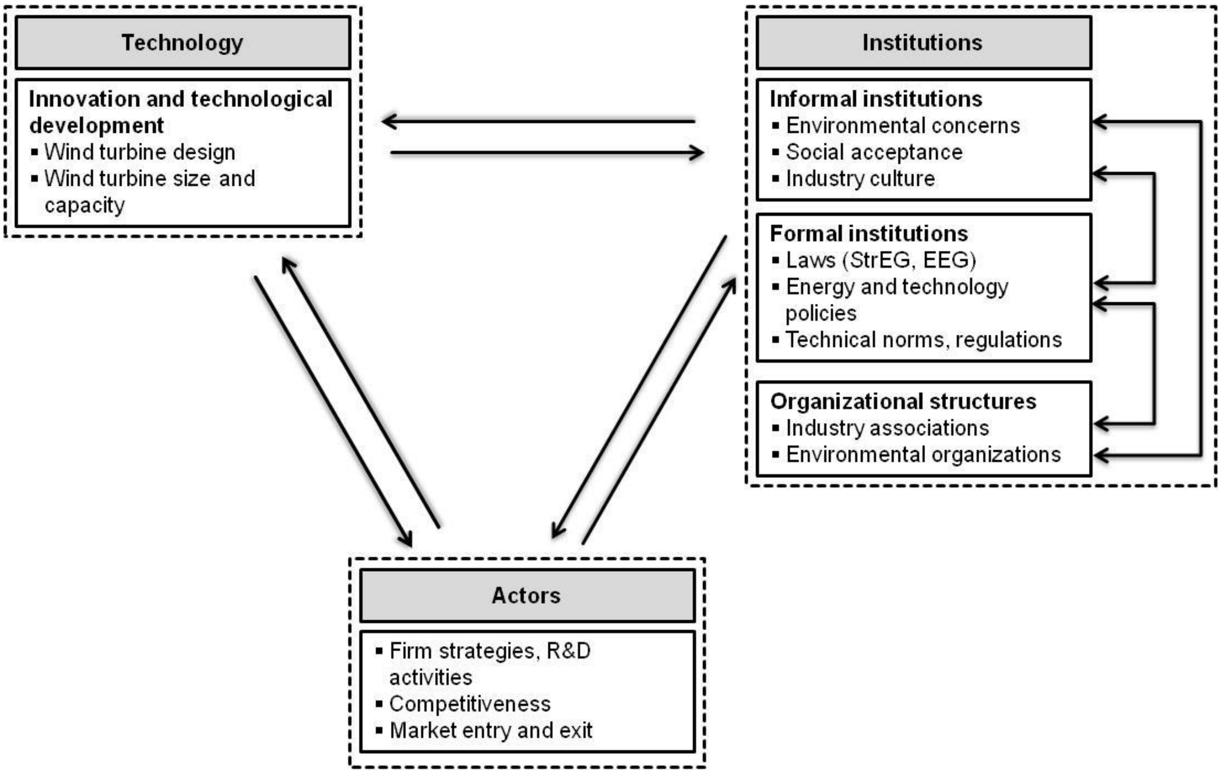


**Figure 21: The co-evolution of wind energy technology, institutions and economic actors**

A key mechanism of co-evolution concerns the interrelationship and interaction between formal and informal institutions which have fostered the evolution of wind energy technologies. Growing environmental concerns and anti-nuclear movements provided a fundamental precondition for new path creation. As described in chapter 7.1, the change of cognitive and normative frames created an institutional environment for the recognition and promotion of renewable energy and wind energy technologies. The environmental and energy policy discussion formed the foundation for all entrepreneurial activity and experimentation. In this context, new companies emerged and firms from related industries experimented with wind technologies.

As explained in section 7.1 and 7.2, support policies and laws that provided financial incentives (100 MW wind program, StrEG) created a market niche and encouraged local involvement in wind energy projects. This was a crucial factor because the emergence of the German wind industry was based on a domestic wind market. As a consequence of the growing private demand, the innovative operator model of community and local citizen-owned wind farms (so-called "Bürgerwindparks) expanded. While in 1989 there were 221 community owned wind turbines, in 1992 there were 1,149 and in 1995 this number increased to 3,625 community owned wind turbines in Germany (OHLHORST 2009: 139). Wind energy associations and interest groups such as the IWB or later the BWE heavily promoted the concept (Interviews O6, O7, P4). Participation of individual private operators, especially farmers, in the form of locally owned wind projects and the diffusion of citizen-owned wind farms had, in turn, a lasting positive effect on the local acceptance of wind projects. The growing demand for wind turbines has prompted turbine manufacturers to rapidly develop marketable and competitive solutions. Most firms focused on the robust and reliable Danish design which shaped the technological trajectory. At the same time, the market niche created an opportunity for firms in related industries to diversify into the wind turbine industry or for founding new companies. The increase in demand also led to more public R&D activities in various areas (materials science, measurement and control technology, aerodynamics, etc.). For example, in 1990, the German Wind Energy Institute (DEWI) was founded by the state of Lower Saxony.

With the increasing demand for suitable sites for wind turbines or wind farms as well as the increasing size of turbines, legally required aspects gained in importance. In the 1980s, there was no legal basis in the form national regulations for the installation of wind turbines. Wind turbines were treated as small auxiliary constructions which were usually installed by farmers on their own land to generate electricity. The Federal Building Code (BauGB) was no longer adequate for the development of this particular technology and market. Often, operators and developers depended on arbitrary case-by-case decisions of local authorities. This was changed with the amendment of the BauGB in 1997. Wind turbines were granted a privileged status meaning that local planning authorities could define priority areas for wind turbine installation excluding other uses in this area and concentration zones in their local development plan (BauGB, 2004). Thereby, the construction of wind turbines was permitted in these specified locations. This enabled municipalities to control and concentrate the spatial development of wind turbine installations and also reduced the uncertainty concerning the planning processes of wind turbine installations. The modification of the Federal Building Code was considered by many interviewees to be an important policy initiative and regulation for the evolution and diffusion of wind energy technology (Interviews P1, P3, O1, O5, O6, O7, U7, U8, U14, U16).

During the development and growth of the industry, the firm population underwent a selection process. Most firms developed from very small or one-man companies to medium-sized enterprises and multinational companies. However, the business sizes of firms still vary from small, specialized engineering offices to large, vertically integrated multinational enterprises. With the development of the industry, norms and routines were changing. Many interviewees reported that a change of industry culture has occurred. An example, as mentioned by several of the respondents, is the HUSUM Wind trade fair. Over the last two decades, the HUSUM Wind has become increasingly professionalized and internationalized (Interviews F2, O4, O6, U4, U6, U8). The first fair in 1989 took place in a small livestock auction hall with 20 exhibitors. In 1997, as the number of exhibitors exceeded 100, a new exhibition hall was built. The HUSUM Wind developed from a provincial meeting to a leading exhibition of international importance. The 2015 trade fair attracted about 650 exhibitors and 17,000 visitors, two years ago there were over 1,100 exhibitors and about 30,000 visitors (MESSE HUSUM & CONGRESS GMBH & CO. KG 2017). Many interviewees considered the exhibition to be an important platform for presentation, interaction and learning through communication, observation and information exchange. Thus, the Husum Wind fair served as a form of knowledge network for wind energy technologies: "This is where the whole scene meets" (Interview U19). Here, all relevant actors and stakeholders of the wind industry come together: representatives of wind turbine manufacturers, component suppliers, operators, project planners and developers, energy utilities, financial services, scientists, national, regional and local policy makers, public authorities, associations and societies.

The growth of the industry and the trade fair resulted in a change of industry culture which is reflected in routines and the appearance of the actors. For example, in the early years actors were often very casually dressed in T-shirts, jeans and even rubber boots. Later, there was a clear trend to dress formally with most actors appearing in suit and tie, pants suits or dresses (Interviews F2, O4, O6, U4, U6, U8). After a longer and controversial discussion about the internationalization and professionalization of the wind trade fair within the industry and between the two exhibition companies, in 2014 the trade fair took place in the city of Hamburg for the first time. Compared to the small town of Husum, Hamburg provided a more appropriate, urban infrastructure and had already hosted numerous trade fairs and exhibitions. Now, the WindEnergy Hamburg and the HUSUM Wind trade fair alternate every year. Interviewees, however, who have only been active in the wind industry since some years and who have experience from other industries, stated that the industry culture has still its pioneering spirit and the wind industry community is still relatively familiar (Interviews U10, U15, U17, U18).

## 8.2 Co-evolution of organizational structures

Alongside the development and growth of the industry, the institutional environment also changed from informal routines and environmental concerns to the institutionalization of interest groups and the establishment of organizational structures. Since the mid-1980s, path development of wind energy technologies was supported and stabilized by the co-evolution of institutional arrangements. In order to bundle and represent their interests, operators of wind turbines, therefore, organized themselves in organizations and associations (see table 10). Analogously to the emergence of the wind energy technology, these were primarily concentrated in Northern Germany and Berlin. In addition to smaller, local wind associations, the first influential supra-regional industry associations were established in northern Germany in the mid-1980s. In 1982, the German Society for Wind Energy (Deutsche Gesellschaft für Windenergie) was founded, mainly from farmers from Schleswig-Holstein and Lower Saxony. Three years later, the Inland Wind Power Association (Interessenverband Windkraft Binnenland, IWB) was founded by private operators in Lower Saxony. In 1996, both wind associations joined together to form the Bundesverband Windenergie (German Wind Energy Association, BWE), in order to create a powerful advocacy group for the entire German wind sector (Interviews O1, O7).

**Table 10: Wind energy-specific organizations and institutes**

| Year | Organization | Location |
|---|---|---|
| 1974 | Foundation of the Association for Wind Energy Research and Application (VWFA) | Eckernförde, Schleswig-Holstein |
| 1980 | German Electricity Association (DWEV) became successor to the VWFA | Eckernförde, Schleswig-Holstein |
| 1982 | German Society for Wind Energy (DGW) became successor to the DWEV | Eckernförde, Schleswig-Holstein |
| 1985 | Foundation of the Inland Wind Power Association (IWB) | Osnabrück, Lower Saxony |
| 1985 | Foundation of the Federation of German Wind Power (FGW) | Berlin |
| 1990 | Foundation of the German Wind Energy Institute (DEWI) | Wilhelmshaven, Lower Saxony |
| 1991 | Foundation of the German Renewable Energy Federation (BEE) as umbrella organization for German renewable energy associations | Berlin |
| 1993 | Foundation of an wind energy group within the German Mechanical Engineering Industry Association (VDMA) | Berlin |
| 1996 | Merger of the IWB and DGW to the German Wind Energy Association (BWE) | Osnabrück, Lower Saxony; since 2009 Berlin |
| 1996 | Foundation of the Wind Power Plants Trade Association (WVW) | Hamburg |
| 2002 | Foundation of the Wind Energy Agency Bremerhaven/Bremen (WAB) | Bremerhaven, Bremen |
| 2002 | Foundation of the WindEnergy Network e.V. | Rostock, Mecklenburg-West Pomerania |
| 2007 | Merger of four individual energy associations to the German Energy and Water Association (BDEW) | Berlin |

Source: Based on OHLHORST (2009: 145); supplemented by author

Another important association is the WAB, the former Wind Energy Agency Bremerhaven/Bremen. The WAB was founded in 2002, originally with a regional focus on the cities of Bremen and Bremerhaven. Meanwhile the geographic scope goes beyond northwest Germany and the association has established a nationwide network for the offshore wind industry. It represents more than 250 companies and institutes (WAB 2020). The WAB focuses on two areas of activity. First, it represents a network or cluster organization with the aim of increasing the competitiveness of the member companies. For this purpose, the WAB offers its members support with regard to cooperation projects, internationalization issues (for example through joint marketing and trade fair presence), application for funding (through the subsidiary company Germanwind GmbH) and also offers trainings and qualifications (for example through workshops, seminars and the participation in continuing studies programs[13]). Second, the WAB regards itself as a lobby or association for wind energy in general. WAB's central issues promote the social acceptance of wind energy and encourage favorable legal and political conditions for the whole industry (Interview O4). Another influential network for wind energy in the Northeast of Germany is the WindEnergy Network e.V., located in Rostock (Mecklenburg-West Pomerania). The association sees itself as a platform for the entire wind energy value chain and supports the companies through networking, active lobbying work, the promotion of positive awareness of the wind energy industry, the pooling of information and know-how and the representation of the network at trade-fairs (WINDENERGY NETWORK E.V. 2020).

The establishment of organizational structures spatially overlaps with the evolution of the industry and technology. The first associations were located in Northwest Germany (Schleswig-Holstein, Lower Saxony) and, after the reunification, in the capital city of Berlin as the political center of Germany. Especially the BWE had a significant influence on the institutional environment. This concerns in particular the adoption of the Electricity Feed-in Act (StrEG) and the Renewable Energy Sources Act (EEG) as well as the association's impact on the acceptance for wind energy in the population. Both will be explained in detail in section 8.4 and 8.5.

## 8.3 Co-evolution of technical standards

Another type of co-evolution relates to the interrelationship between formal, regulative elements of the institutional environment and technology. Particularly significant in this context is the revision of the national grid codes (E.ON Netzanschlussregeln), which was described by several interviewees as a critical factor for the evolution of wind energy technologies (Interviews U4, U6, U10, U11, U12, U13, U15, U16). The Netzanschlussregeln

[13] ForWind, a joint center for wind energy research of the Universities of Oldenburg, Hannover and Bremen, the WAB and the city of Oldenburg, has recently developed two continuing studies programs, one explicitly for offshore wind energy and one for onshore (FORWIND 2017).

defined technical requirements for wind turbines and, therefore, conclusively affected the technological development path.

Technical grid standards evolved in the 1980s and were based on the prevalent technological development at that time, when wind power has only been installed on a very small scale. Although there were some studies in the mid 1990s providing first indications of possible effects of wind turbine on grid compatibility in Germany (DEWI 1994: 41), the grid codes remained unchanged. Until 2000, decentralized energy supply was still assumed to play only a minor role. Given the relatively low proportion of decentralized and renewable energy generation, wind energy was found to be of subordinate importance for grid stability of the German interconnected grid system and the European transmission grid (UCTE).

As a result of technological development, the increase in wind turbine dimensions and the increasing number of wind turbines led to the continuing growth of wind capacity. Since the beginning of the 1990s, the share of wind power in electricity generation has been rapidly increasing. Although in 1999, wind power still accounted for only about 1% of German power supply, in the E.ON Energie grid zone, the share of wind power was significantly above national average (BMWI 2017). Due to the increasing use and distribution of wind energy technology, the institutional requirements and economic conditions changed significantly. As a consequence, the integration of wind power into the electric grid required new regulations for grid connection; technical standards needed to co-evolve with technological development. In other words, the co-evolution of institutions was a precondition, or at least a major accelerator, for the evolution of wind energy technology.

This co-evolutionary process was driven by purposive actions of individual economic actors. The trigger was an initiative by the transmission system operators, in particular E.ON Netz GmbH (Interviews U4, U6). In a study commissioned by the German Energy Agency (DENA) on the integration of wind power into the national grid, it was shown that the existing integrated grid system would reach its technological limits in case more wind energy was produced (DEWI ET AL. 2005). The DENA grid study resulted in substantial changes in the grid connection of wind turbines. At that time, in case of grid disturbances, a wind turbine immediately had to be disconnected from the grid, causing large voltage fluctuations in regions with a high penetration of wind power. Consequently, the DENA grid study developed and suggested new grid codes for wind energy systems which would improve system security by 2015. The new regulations for the grid connection of wind turbines of

E.ON Netz GmbH came into effect on August 1, 2003 (E.ON NETZ GMBH 2001). With these regulations, wind turbines could be used to support the grid, especially during disturbances (SANTJER/KLOSSE 2003: 28).

This set in motion a co-evolutionary process of adaptation and positive feedbacks between technological selection and the institutional environment. The new grid codes had significant effects on the development of wind energy technologies, especially on generator technology and power control systems in wind turbines. Firms were forced to adapt to the changing technical standards. Not all wind turbines could fulfill these requirements. In particular, stall-controlled wind turbines with asynchronous generators (Danish design) which are directly connected to the grid are not able to provide active power during severe grid disturbances. A former R&D manager explained:

> "The requirements for grid support, which then came, were actually the decisive knockout criterion, because then stall control systems could simply no longer exist in the market." (Interview U4)

The new grid codes had a notable impact on the strategies and decisions of firms and in this way reinforced the co-evolution of a new dominant design (cf. section 7.3.1). According to several respondents, the new technical standards posed a huge challenge for many wind turbine manufacturers, as shown in the following quotation: "Companies had to adapt themselves very quickly to new technologies. Some of them simply did not get it fast enough" (Interview U4). In addition to the already prevailing cost pressure, a considerable technological pressure was created for the wind industry. At that time, some turbine manufacturers had no experience with the new turbine design (Interviews U4, U6, U12, U15, U16).

The radical change in technological requirements supported and accelerated the selection process of technologies which, at the same time, favored firms that had already introduced variable speed concepts or direct drive concepts with full-scale frequency converters. For turbine manufacturer Enercon, for example, only minor adaptations were necessary. As the company had been developing wind turbines with full-scale frequency converters since the early 1990s, the new grid codes provided a technologically competitive advantage. With its technology, Enercon was able to deliver electricity which conformed to energy supplier requirements (KOENEMANN 2009: 83) (Interview U11).

## 8.4 Electricity Feed-in Act (StrEG) and Renewable Energy Sources Act (EEG)

The creation and development of the German Electricity Feed-in Act (StrEG) (see section 7.2.2.3) and its successor, the Renewable Energy Sources Act (EEG), the most important driver for the emergence and evolution of wind energy, is an important example of how co-evolution of formal institutions and public policies affected the evolution of wind energy technologies. The example also illustrates the influence of institutional entrepreneurs in the evolution of the German wind energy technology. The adoption of the StrEG was enabled through the creation of an advocacy coalition supporting renewable energy, especially hydropower. This advocacy coalition was comprised of a small group of influential policy makers of different parties (CDU/CSU, SPD and the Greens, in particular Social Democrat and leading advocate for solar energy Hermann Scheer[14]), hydropower plant owners from the southern part of Germany (Bavaria and Baden-Württemberg) and some representatives of wind energy from North Germany (Interview P1). The joint initiative successfully advocated and lobbied for a higher, secure remuneration of renewable energies and developed a draft law. Due to the great support of all parties, the law was passed by the German Parliament (Bundestag) in 1990 with the consensus of all parliamentary groups. Initially, the StrEG did not receive much attention. Several interviewees expressed the view that many politicians and especially the energy suppliers initially underestimated the consequences of the law (Interviews P1, P2, P3, U11).

However, with the rapid diffusion of wind turbines in the following years, the large energy suppliers and network operators recognized the far-reaching implications of the StrEG and they began to fight the law in the early 1990s. The strongest opposition came from the energy utility companies organized in the German Electricity Association (Verband der Elektrizitätswirtschaft, VDEW). In particular, the energy suppliers criticized the supposedly

---

[14] Hermann Scheer has been member of the German Parliament (Bundestag) since 1980. He is regarded as a key initiator and advocate of several laws and programs to promote renewable energies, e.g. the StrEG, the 100,000 Roofs Programme for solar energy and the EEG. He was also founder and president of the European Association for Renewable Energy (EUROSOLAR) and co-founder of the International Renewable Energy Agency (IRENA). Scheer was honored with the Right Livelihood Award in 1999 for his dedication for renewable energies. The magazine Renewable Energy World called him "father of the feed-in tariff" and Time Magazine declared him "Hero for the Green Century" (EUROSOLAR E.V. 2017; JONES 2010).

high financial burden. They lobbied to change or overturn the law, and temporally it seemed that the utility companies would be successful (Interviews O5, P1).

On the other hand, a larger supporter base for the Electricity Feed-in Act emerged. The increasing number of individual wind turbine operators and the emergence of a national wind industry considerably enhanced the influence of the wind turbine lobby. Industry and operator associations such as the German Society for Wind Energy (DGW), the Inland Wind Power Association (IWB) and the newly founded German Renewable Energy Federation (BEE) strengthened their influence on policy. Through networking and lobbying activities, these and other associations were able to mobilize a lot of support for the StrEG in the 1990s. Especially the BEE, which was founded as an umbrella organization for German renewable energy associations to represent and protect the interests of (mainly individual) operators, proved to be a powerful lobbying force and played a vital role in advocating and promoting the Electricity Feed-in Act. Worth mentioning is also an advocacy coalition initiated by the BWE in 1997, when a compensation reduction of renewable energies was discussed by the German Parliament ("Aktion Rückenwind"). Together with several renewable energy organizations, environmental associations, manufacturers and operators, the BWE organized a national campaign to support renewable energy and to protect the StrEG (Interviews O1, O6). According to the BWE, over 3,000 people demonstrated against the proposed cuts (BWE 2012: 12). From the wind lobby's point of view, the initiative was a great success and helped ensure that compensation was not reduced (Interviews O1, O6).

Despite the resistance of the energy suppliers, advocates of renewable energy succeed in the political struggle. Facilitated by a change of government in 1998 and the formation of the government coalition between the Social Democrats and Green Party, the StrEG was replaced by the EEG in 2000 (EEG, 2000). Again, Hermann Scheer played a decisive role in the conception, design and realization of the EEG. Like the StrEG, the EEG was a strongly parliamentary initiative and the relatively fast adoption of the law was strongly influenced by an advocacy coalition (Interviews F3, P1, U5).

The technological development and diffusion of wind energy technology triggered a lively debate about the future of the StrEG. At the same time, various actors had an interest in modifying the existing feed-in law. Important reasons for the new regulation of the framework conditions were controversies about high burdens of individual energy suppliers. In addition, as a result of the liberalization of the electricity market in 1998, the prices for electricity decreased which also led to lower feed-in prices. Moreover, electricity from renewable energy sources (RES) threatened to reach the cap of 5%[15]. Redesigning the Electricity Feed-in Act thus provided an opportunity to solve a number of weaknesses and shortcomings of the former StrEG, which harmed the development and diffusion of RES technologies, and to adapt the law to the developments in wind energy technology (and other renewable energy technologies) and the market.

First, whereas the StrEG consisted on a remuneration system based on the average utility revenue per kWh sold, the EEG replaced this by fixed feed-in tariffs. The tariffs varied in relation to different RES technologies. In addition, the cap on the share of electricity from RES was removed. Second, a degression mechanism was introduced: a reduction of the feed-in tariff rate each year for newly installed RES systems. This was supposed to stimulate innovation and technological development in order to reduce energy costs and achieve greater efficiencies. Third, wind turbine operators were generally granted a guaranteed payment for their electricity for a period of time, typically for 20 years. Previously, under the StrEG, the duration of payments was not specified. In addition, the EEG significantly increased the feed-in tariff rates in comparison to the StrEG and introduced a purchase obligation for the local grid operator. Due to the priority purchase obligation for utilities and guaranteed feed-in tariffs, the EEG offered investors a high degree of planning security and also economic incentives for investors to set up and operate wind turbines. Fourth, a nationwide equalization scheme for RES electricity – purchased and paid for – was introduced. This regulation was designed to solve a shortcoming of the former StrEG and to eliminate regional disadvantages. As RES plants, especially wind turbines, were distributed unevenly among regions, regional energy utilities, and ultimately end consumers, were burdened differently. This equalization scheme thus relieved some North German energy suppliers from areas with high wind energy inputs, such as EWE (Lower Saxony) and SCHLESWAG (Schleswig-Holstein) (Interviews O1, O5, P1, P2).

With the development of wind energy technology and the expansion of wind power, the EEG has been continuously revised and adapted to changed conditions (EEG, 2004; EEG, 2009; EEG, 2012; EEG, 2014; EEG, 2017). Since its introduction, report and audit processes were

[15] The feed-in tariffs paid under the StrEG were capped at 5% of a utility's generation.

implemented in the EEG which help to ensure that the law can be adapted to the dynamic development of renewable energies.

The first amendment of the EEG (EEG 2004) committed Germany to a national target for the expansion of renewable energy of 12.5% total energy consumption by 2010 and to at least 20% by 2020. Furthermore, the feed-in tariffs for the different technologies were adjusted to cost and market developments and the law was harmonized to the requirements of the EU directive on renewable energies. Another new feature of the EEG 2004 was the introduction of a financial incentive for repowering which means replacing existing wind turbines with new higher-performance wind turbines. This was to promote new product development and innovation. The dynamic development of wind energy (and other RES) technologies and increased market penetration of renewable energies resulted in two more substantial amendments in 2009 (EEG 2009) and 2012 (EEG 2012).

With the amendment of the EEG in 2009, technical requirements for wind turbines were stated in the law to ensure a better integration of renewable energies into the national grid. Thereby, the EEG responded to the results and demands of the DENA grid study. For that purpose, a system service bonus (SDL bonus) was established. This is a bonus for wind turbines that meet minimal technical requirements concerning grid compliance. It is paid as a supplement to the remuneration. Several wind turbine manufacturers stated that the SDL bonus had an important impact on their R&D and product development activities. Turbine concepts with full-scale frequency converters became more attractive because they received the SDL bonus. Two manufacturers even developed a new turbine design (Interviews U1, U4, U8, U10, U11, U12).

With the amendment of the EEG in 2012 (EEG 2012), the targets determined in the German Energy Concept (BMWI/BMU 2010) were anchored in the law and the EEG now had clear quantitative objectives. According to these goals, the share of renewable energy in the total electricity consumption is to increase to at least 35% by 2020, 50% by 2030, 65% by 2040 and 80% by 2050. Furthermore, the EEG is to provide a basis for better integration of renewable energies into grid, market and energy systems.

The EEG 2014 introduced a paradigm change. The aim of the revision was to facilitate the integration of renewable energies into the market and, simultaneously, reduce the economic costs of expanding renewable energy supplies. With the EEG amendment in 2014 (EEG 2014), direct marketing became mandatory for all new wind turbines. In order to better integrate renewable energy into the market, operators of RES plants received a market premium when selling their generated electricity directly, either independently or through a direct marketer (EEG2014). This is an important step from subsidies to more competition and to test the marketability of wind energy technologies. Instead of the previous minimum targets, an annual expansion corridor for onshore wind energy of 2,400 to 2,600 MW per year was defined. Depending on how much the newly installed capacity exceeds the target, the feed-in tariffs are reduced (so-called “breathing cap”) (EEG 2014).

The latest amendment of the EEG (EEG 2017), which came into effect in 2017, introduced several new key features. Policy makers argued that wind energy technology (and other RES technologies) had matured and were able to compete on the market (BMWI 2016). The major reform of the Renewable Energy Sources Act was the decision to introduce market-based elements and switch from the guaranteed feed-in tariffs to an auction system. Instead of fixed electricity prices, the price for renewable electricity is determined in competitive bidding processes. By setting up annual capacity volumes for onshore wind installations and other RES, the expansion of onshore wind would be limited and regionally controlled. Local citizen-owned wind companies could take part in the auctions for onshore wind energy projects under easier conditions. Therefore, the diversity of stakeholders should be maintained (EEG, 2017).

The EEG 2017 has considerable effects on technological development. The introduction of an auction system leads to more intense competition between turbine manufacturers which increases innovation incentives for cost reduction and more efficient turbines. At the same time, smaller turbine manufacturers may face difficulties when they want to reduce their costs. As a consequence, the EEG 2017 could accelerate the concentration process in the wind industry. Apart from cost reductions, manufacturers need to seek new market niches such as developing cost-efficient weak wind turbines or entering new export markets. At the same time, the annual targets and the auction system set in the EEG 2014 and 2017 affect the expansion of onshore wind energy. With the cessation of fixed feed-in tariffs, new installations are only economically viable in the best locations such as hillside locations. And this is precisely where are often local conflicts concerning nature protection or the impact on the landscape character. In addition to technological development, the political and planning framework conditions as well as the acceptance within the population are decisive factors for the further development of wind energy.

In the case of the EEG, the co-evolutionary process of wind energy technology was characterized by continuous changes and adjustments of the relevant laws. Whereas the EEG has originally been designed as an initial funding program for a niche technology to support market introduction, it was continually adapted to the dynamic development and diffusion of the technology to an industrial and technology policy instrument which aims to promote competition between operators and to improve cost efficiency of the energy transition (BMWI 2016: 5). The introduction of a degression mechanism in the EEG and transformation of the remuneration system from guaranteed feed-in tariffs to an auction system are good examples for how politics react to technological development and for how formal institutions co-evolve with technology and changing circumstances.

## 8.5 How do actors affect co-evolution? The influence of strategic actions on the institutional environment

The processes, interactions and feedback mechanisms described above show that co-evolution is not a random process. Co-evolution of the institutional environment and institutional arrangements is a result of the actions of users, firms, policy makers and other organizations. The analysis of path creation processes in Berlin shows how a few researchers and entrepreneurs shaped the regional institutional environment. Local actors built up research infrastructure, established a local network and created a regional spirit of shared values and interests leading to the establishment of a local wind energy scene. The development and adoption of the StrEG also points to the influence of institutional entrepreneurs in the evolution of wind energy technology. This section summarizes the findings regarding the impact of different actors on the development of the institutional environment.

Several interviewees emphasized the influence of members of the German Parliament and institutional entrepreneurs like Hermann Scheer who initiated the adoption of the StrEG and the EEG (Interviews F3, O7, P1, U5, U14). In fact, Hermann Scheer was a particularly influential actor and a remarkable personality who played a decisive role in the introduction of the two most important legislative instruments to promote electricity that is generated from renewable energy sources (see 8.4). Furthermore, most interviewees especially underlined the role of stakeholder groups such as associations and organizations. Organizations and associations continuously attempted to exert influence on institutions and political framework conditions. Here, the BWE and the VDMA were perceived to be the most important actors (Interviews O3, U1, U2, U5, U6, U11, U10, U13, U14, U15, U17). The VDMA, a large and powerful industry association, represents the interests of the turbine manufacturers. The association concentrates on public relations and political lobbying in favor of the wind industry and strongly advocated the StrEG (Interviews U1, U11, U13, U17). The BWE proved to have had a considerable influence on the institutional environment and public policies. The wind energy association claimed to represent the whole wind energy sector (Interview O6). The focus was, however, on the interests of operators and owners with the majority of its members being wind turbine operators. With its headquarters in Berlin, the work of the association is mainly directed at the federal level. Through its 13 state and 43 regional associations, however, the BWE was also represented at the regional level, and thus maintained contact with local and regional policy (BWE 2017). Through various advocacy and lobbying initiatives and close contacts in politics, the BWE shaped energy policies and programs (Interviews O3, U1, U2, U5, U10, U11, U14, U15). This is also evident in the case of the StrEG and the EEG. The development of the EEG was not an automatic process but the result of continuous influence and lobbying of different interest groups. In particular, an advocacy coalition of BEE, BWE and individual wind activists pushed forward the creation of a favorable regulatory environment and support for wind energy.

Moreover, policy makers are dependent on the expertise and experience of the industry (Interviews P2, P3). The associations were involved and exerted influence through statements and position papers on draft laws and, for example, on technology-specific or legally required issues. In the BWE, various committees and work groups for specific issues provided expertise and know-how (Interview O3). This was confirmed by many interviewees. The association enjoyed a high status and reputation among the public and politicians.

Many firms tried independently to represent and defend their individual interests against the EEG policy. Enercon, for example, had an office in Berlin which mainly focused on committee work and lobbying. However, most companies see their influence as limited as long as they act as an individual player:

> "The direct influence that we have compared to other small manufacturers, if we only refer to Germany, is low. However, that changes in the moment you go over the joint association, the VDMA in our case." (Interview U13)

Some interview partners from R&D departments and/or institutions reported that they are perceived by policy makers to be experts to a certain extent (Interviews F2, F3, F4, F8). Research institutes played a consultative role on technological questions and wind energy research. For example, two interviewees indicated that they had an influence on the fundamental orientation of research funding of the BMWi within the Federal Government's Energy Research Program (Interviews F2, F4). Two respondents who had worked for a turbine manufacturer and also at a research institute confirmed the influence on political issues concerning funding programs (Interviews U3, U5). Especially in research, these activities are flanked by membership and involvement of individual persons in relevant associations and organizations at different special scales. One respondent described his functions as follows:

> "In addition, I am active in several organizations in the EU, at the national and regional level, all kinds of advisory boards. I have also been board member of the European Wind Energy Association, a really powerful industry partner". (Interview F3)

Thereby, these actors participate actively in the relevant discussions and political decision-making on different political levels.

The fact that institutions do not automatically co-evolve with technology becomes apparent also when looking at elements of the institutional environment where co-evolution has not occurred yet. This is the case, for example, with restrictive national and federal planning law. According to several interviewees, one challenge in this respect is repowering activities. Technological development and the increased size of wind turbines require adjustments to the regulations concerning repowering activities. One interviewee remarked: "We need a clear legal regulation for repowering" (Interview U15). Another respondent described the situation in similar terms: "We have difficulties, from our point of view, in the political framework, the designation of locations for wind turbine installation" (Interview U17). Existing height limitations and distance regulations for wind turbines hamper the replacement of old turbines with newer, larger high-performance wind turbines. This indicates that co-evolution of the institutional environment is initiated and effected by the actions of various actors.

# 9 Reconsideration of the theoretical framework

In chapter 5, a revised theoretical framework was constructed by synthesizing the strengths of other conceptual frameworks and theoretical insights. It serves to answer research question RQ 6: *How can evolutionary economic geography and the inclusion of institutions and institutional changes contribute to analyzing and understanding the interrelationship between strategic actors and the institutional environment and its influence on the evolution of a new industry and technology?*

The proposed framework is based on work in evolutionary economic geography (e.g. MARTIN 2010; MARTIN/SUNLEY 2006), institutional economic geography (e.g. GERTLER 2010; MARTIN 2000) and social and organizational science (e.g. GARUD ET AL. 2010). A basic assumption is the path dependency perceptive, which implies that the regional evolution of economic activities strongly depends on the technological, institutional and industrial structure actually present in a region.

Compared to MARTIN's (2010) model of local industrial evolution, the framework allows a stronger focus on how economic actors shape the emergence and evolution of a new technological path. The concept of coevolution offers a more complete framework for understanding the interactions and interrelations between economic actors, technology and the institutional environment. The framework also offers a more comprehensive perspective on the existing place-specific conditions going beyond technological relatedness and the mechanisms of path creation. Whereas MARTIN (2010) mainly focusses on firm-actors and conceptualizes path creation as a process, where firms create new options, the suggested framework incorporates the interplay of a variety of actors and mechanisms.

The first phase focuses on the role of initial conditions on the actions of economic actors and for new path creation. The initial conditions refer to exiting resources, factors and structures established in the past, specific to a country or a particular region, which can have a major impact on when and where a new technology or industry emerges.

The second phase is the process of path creation. It begins with the introduction of novelties (technological invention or innovation) through mindful deviation of strategic agents. The conceptual framework proposes that there are three basic mechanisms through which a new path is created in a region: through indigenous creation with the regional creation of an entirely new technology or industry, through diversification of regional industries and/or through external activities and events.

The third phase is the growth phase where a path becomes stabilized and positive feedbacks arise. Self-reinforcing mechanisms and co-evolutionary processes and effects lead to subsequent path-dependent development and the establishment of a pathway. The scope of action narrows down and activities become more specific. Technology selection processes lead to the stabilization of technological development. With the emergence of a dominant design, technological change becomes incremental.

As the result of technological development, institutions which once facilitated the evolution of a new industry or technology can become less efficient or even act as a barrier over time. Thus, institutions need to be flexible and capable of adapting to changing conditions and needs of a new technology to support the emerging technology. Co-evolutionary effects lead to changes of the institutional environment and arrangements. Existing institutions may adapt to or new supportive institutions and organizations co-evolve with the demands of an emerging industry. This includes subsequent policies and programs, policy responses to certain barriers, or (regulatory) institutions which more specifically address the needs of a new technology. Co-evolution also refers to the establishment of organizations such as business and industry associations or lobby groups. This leads to the fourth phase, the post-formation phase, which represents the changed economic landscape.

In chapter 7 and 8, the revised theoretical framework was applied to a case study on the evolution of the wind energy technology in Germany. This pointed out some advantages of the theoretical framework. In respect of MARTIN's (2010) model of local industrial evolution, the empirical analysis revealed three important complements.

First, the actor-centered perspective focusing on both firm and non-firm actors contributes to a deeper understanding of the regional evolution of new technologies. It allows to examine how economic actors like inventors, entrepreneurs, firms, and policy-actors create new opportunities for new technological development and shed some additional light on the motives of the different actors to engage in a new technology. The focus goes beyond diversification and regional branching and considers multiple mechanisms such as indigenous path creation or external impulses and transplantation processes. The findings suggest a closer look at the mechanisms of path creation as well as how actors shape the institutional environment.

Second, the findings highlight the need for a more in-depth investigation of institutions and institutional change on multiple scales as an important factor of the enabling and constraining environment. The path dependency perspective implies that the analysis focuses on the effect of key events of institutional change at different spatial scales on subsequent development. These key events were the Chernobyl accident and the oil crisis on the national (or even global) level, and the emergence of environmental and anti-nuclear movements, local energy cooperatives and regional lobby groups at the regional level. As explained in chapter 7, these institutional changes encouraged pioneers to build and run small wind turbines. The focus on the regional institutional structures also proved to be a sensible approach. For example, it has been shown how the institutional environment in Berlin with a specific regional sprit and shared values facilitated the emergence of several university spin-offs and a local network of wind energy enthusiasts. This also highlights that both informal and formal institutions play an important role.

Third, the empirical findings on the co-evolution of wind energy technologies and the institutional environment offer important empirical and conceptual insights into the evolution of new technologies. In chapter 8, it has been shown that the institutional environment and institutional arrangements needs to co-evolve with technological development. The passing and development of the StrEG and the EEG highlighted the role of powerful actors, so-called institutional entrepreneurs, in institutional change. The legal and regulatory framework, infrastructures (like the electrical grid) and social dimensions of the institutional environment need to co-evolve with changes in technologies. This calls for a stronger consideration of the interplay between technologies, economic actors and the institutional environment in a new development path. In this way, the revised conceptual and theoretical framework is helpful to shed some light on the "black-box" of co-evolution in economic geography (GONG/HASSINK 2019).

Based on this case study, it seems fruitful to combine an evolutionary economic geography perspective on the regional development of new technologies with a more actor-based perspective and a stronger focus on institutions and institutional change.

# 10 Conclusions and implications

## 10.1 Major results

This dissertation has focused on understanding the emergence and evolution of new technologies. The key question of the study was: Where, how, by whom and under which conditions do new technologies emerge? This has been examined by an explanatory case study on the emergence and evolution of the onshore wind energy technology in Germany. A qualitative research design was chosen, that provided an in-depth investigation of the processes, mechanisms and actors. The study was guided by six research questions (s. section 1.2).

Based on a revised theoretical and conceptual framework, the thesis examined the multifaceted nature and interrelationships of the conditions, regional environment, actors and mechanisms that shaped the mechanisms of path creation and development. The empirical findings suggest that the emergence and evolution of new technologies is a path- and place-dependent process. In the case of wind energy technology in Germany, a variety of factors were found which created enabling conditions for the emergence of the new technology and industry: favorable wind conditions, external shocks which triggered a debate on energy policy and gave rise to an anti-nuclear movement and policy interventions, soft factors of the regional institutional environment such as social capital, local networks and a regional spirit, and the formation of a domestic market. The new pathway was primarily created by pioneering inventors and entrepreneurs and through regional industry diversification in Northwest Germany, Berlin and the region of Stuttgart in South Germany. Afterward, different technological sub-trajectories developed and technological development was driven mainly by turbine manufacturers, component suppliers, and engineering companies. By three cases of co-evolutionary processes, it has been illustrated how the co-evolution of formal institutions and public policies affected the evolution of wind energy technologies.

## 10.2 Contribution to the literature

The dissertation contributes to the emerging body of literature in economic geography, especially in evolutionary economic geography, which focusses on how new path are created. First, the study contributes to the conceptual and theoretical understanding of new regional path development in economic geography. It has been criticized that the role of institutions and institutional change and their impact on the evolution of new technologies or industries have received little attention in evolutionary economic geography so far (GERTLER 2010; MACKINNON ET AL. 2009; PIKE ET AL. 2016; SCHAMP 2010). The first aim of the dissertation was to address the shortcomings in the evolutionary economic literature and to advance theory development by combining and modifying existing theoretical concepts. Building upon a dynamic understanding of regional industrial evolution and a path creation perspective offered by MARTIN (2010) and SIMMIE (2012) a theoretical and conceptual framework was developed that helps to explain the emergence and evolution of new technologies and therefore takes into account the interactions and interrelationships between technology, institutions and industrial structure.

The refined theoretical framework presented in chapter 5 illustrates the emergence and regional development of new technologies. The evolution is divided into four phases of path development: (1) a pre-formation phase; (2) a path creation phase; (3) a growth phase; and (4) a post-formation phase. The framework highlights the influence of strategic actions of economic actors, users, policy makers and other organizations on the evolution of a technology and the economic landscape. This provides a more comprehensive and theoretically grounded framework for analyzing and explaining the emergence of new technological and industrial paths. The refined framework offers a broader analytical perspective to the pre-existing, place-specific conditions, which advances the understanding of path creation (DAWLEY 2014; HASSINK ET AL. 2019; MACKINNON ET AL. 2019). Most empirical studies in evolutionary economic geography on the evolution of new industries or technologies assume that it is primarily the existing regional industrial structures which enable or constrain the regional emergence and development of a new pathway (BOSCHMA/FRENKEN 2011a; HENNING ET AL. 2013; NEFFKE ET AL. 2011). Broadly speaking, it is often argued that new industries emerge from technologically related industries. Although the argument is reasonable and holds true for some specific cases, these approaches tend to overemphasize regional diversification and branching processes. This dissertation not only takes into account the industrial structure, but also the regional technological resources and institutional conditions. Together they constitute the environment in which new economic activities emerge. In contrast to various previous studies, the framework suggests that these initial conditions are assumed to be not predetermined but created or strategically influenced by actors.

The empirical findings on the **pre-formation phase** show that the emergence and evolution of the German wind energy technology and industry was primarily due to some external shocks and radical changes in the institutional environment, especially rapid oil price increases and the nuclear reactor accidents in Harrisburg and Chernobyl. The findings in **chapter 7.1** confirm evidence in earlier studies on the political and institutional context (JACOBSSON/LAUBER 2006; OHLHORST 2009). In particular, the rise of an anti-nuclear movement was a main trigger for the emergence of wind energy technologies in Germany. Only then, the debate about utilization of wind power and thus its promotion was initiated. These economic and social conditions created the preconditions for structural changes in energy policy. With the 100 MW wind program and the Electricity Feed-in Act (StrEG), a market niche for wind energy technologies was created. The market stimulation policy of the German government provided the basis for first experiences in producing and using wind turbines on a larger scale. Therewith, the findings confirm the conclusions drawn by SIMMIE (2012: 770) that new technological pathways are created in niches. Besides institutional change and policy intervention at the national level, the findings also indicate that pre-existing regional conditions affected the local emergence of a new industry or technology. Especially in Northwest Germany, environmental activists and engaged policy makers espoused for concrete wind energy projects. This confirms the observation made by SINE and LEE (2009) that the extent and influence of social and environmental movements vary regionally. There were strong inter-state differences with regard to the political will and interest to develop wind energy across Germany which led to different institutional conditions. In particular, the funding policies of the federal states, especially in Lower Saxony and Schleswig-Holstein, made an important contribution to the expansion of wind power utilization and the emergence of wind power technology in Germany. Moreover, planning requirements were also designed differently either to support or oppose wind turbine installations and still vary between the federal states in Germany. The case of Berlin highlights a regional institutional environment which was characterized by local networks and a regional spirit of shared values and interests. In addition, natural conditions for wind power generation and the emergence of a regional demand in Northern Germany affected the location of emerging wind energy technologies. This supports the demand for a multi-scalar perspective for studying the emergence of new regional pathways (BINZ ET AL. 2016; ESSLETZBICHLER 2012; HASSINK ET AL. 2019; MACKINNON ET AL. 2019; TRIPPL ET AL. 2018).

Second, this dissertation contributes to the ongoing theoretical debate in evolutionary economic geography on path creation. Although the concept has been discussed from a theoretical point of view (MARTIN 2010; MARTIN/SIMMIE 2008; MARTIN/SUNLEY 2006) and in different empirical contexts (BINZ ET AL. 2016; DAWLEY 2014; DAWLEY ET AL. 2015; SIMMIE 2012; SIMMIE ET AL. 2014; STEEN 2016), surprisingly little attention has been paid to the role of actors and the mechanisms of regional path creation. One of the shortcomings in the literature on path creation is a lack of research and empirical evidence on how new paths are created (BINZ ET AL. 2016; DAWLEY 2014). By taking an actor-centered, dynamic perspective, this dissertation provides new insights on the actors, mechanisms and processes of path creation. The case study and its focus on the **path creation phase** reveal that the emergence of wind energy technologies in Germany was characterized by a variety of partly overlapping and simultaneous processes. Overall, the findings confirm one of the basic assumptions in evolutionary economic geography, namely that new paths do not emerge randomly, but are created by strategic action (ESSLETZBICHLER 2012; MARTIN 2010; MARTIN/SUNLEY 2006; SIMMIE 2012; SIMMIE ET AL. 2014). The findings in **chapter 7.2** show that entrepreneurs were able to recombine existing knowledge, to mobilize more actors and resources, and to shape regional environments. Concerning the actors of path creation, the German case shows some similarities with the insights already obtained for Denmark (GARUD/KARNØE 2003; SIMMIE 2012) and confirms the proposition that "new technological pathways are created by pioneering inventors and innovators" (SIMMIE ET AL. 2014: 898). In particular, dedicated engineers and inventors, driven by the debate on energy and environmental policies in the 1980s and a strong anti-nuclear movement, have played a decisive role in new path creation. Pioneering inventors, innovators and entrepreneurs made a substantial contribution to technological development in form of research, inventions, prototypes or innovations. Moreover, the findings reveal that in the early phase of technological development, strategic efforts of some pioneers who shaped the institutional environment facilitated path creation. The presented path creation processes in Berlin and Saarbrücken highlight the role of strategic agents and pioneers. These pioneers were able to inspire other people for their ideas and also transfer their enthusiasm for wind energy to others. In this way, such actors encouraged students, graduates or young researchers to become more intensively involved with wind energy technologies. For many actors, this influence was a significant factor for entering the emerging field of wind energy. This becomes also clear by the investigation of the entrance motives.

The findings also offer additional insights into the influence of wind turbine manufacturers on local demand (BEDNARZ/BROEKEL 2020). Through close contacts and collaboration with regional municipal utilities and energy suppliers, Enercon has succeeded in creating a local demand for the emerging wind energy technology.

In the early phase of path creation, interest in wind power came initially predominantly from private users. Especially local, individual farmers and private operators started to operate a wind turbine to cover their own energy needs. In several cases, individuals developed and constructed a wind turbine in accordance to their own ideas and visions for their own use. Hence, these pioneers were both: first developers and users of wind turbines. Thus, path creation was partly a user-driven (innovation) process. The finding on early experimental activities and pioneering actors such as tinkerers, hobbyists and visionaries support the concept of user innovation (VON HIPPEL 1986). This strand of literature was only marginally discussed in this thesis, but it could be a promising theoretical lens to shed new light on the emergence of new technologies. Universities and research institutes shaped path creation as direct sources of new technological knowledge for wind energy technologies and through the creation of new firms through spin-offs. These university spin-off companies, in turn, contributed to both – the process of knowledge creation as well as the diffusion or transfer of knowledge. This also supports the need to look beyond firms as actors of path creation and draw attention non-firm actors such as private inventors, users and universities, as recently suggested by HASSINK ET AL. (2019) and MACKINNON ET AL. (2019).

Concerning the mechanisms of path creation, the study provides empirical support for the demand that "future research should look beyond diversification to consider other causal mechanisms, particularly transplantation and indigenous path creation" (MACKINNON ET AL. 2019: 131). The findings show that the new pathway of wind energy technology was primarily driven by indigenous activities in form of local entrepreneurial activities and regional industry diversification. The relevance of the processes differs between the regions. The study provides evidence for two mechanisms of new path creation: types of indigenous creation through strategic action of individual entrepreneurs and stakeholders in Berlin and South Germany and technological diversification of the pre-existing regional industry in Northwest Germany. These were later supported by various exogenous drivers of path creation, especially policy interventions. A comparison of path creation mechanisms in Berlin, Stuttgart, Saarbrücken and Northern Germany highlights, that actors and their activities are strongly influenced by the spatial setting. This not only applies to different countries, as shown by SIMMIE ET AL. (2014) and CLEBNA and SIMMIE (2018), who found significant national differences between Germany and UK which shaped new path creation in the wind energy industry, but also at the regional level. The findings also suggest that a strict separation between the three mechanisms is not always possible. In some cases, the mechanisms and processes of path creation overlap and reinforce each other. Path creation of the (onshore) wind energy in Germany, therefore, differs from the emergence of the offshore wind energy in other European countries. For example, STEEN and HANSEN (2018) identified branching and diversification from related industries as the main path creation mechanisms in the offshore wind power industry in Norway. DAWLEY ET AL. (2015) found that the transplantation of new knowledge from outside the region has been a key mechanism of path creation in the Scottish offshore wind sector.

Earlier studies on the offshore wind energy in Northern Germany (FORNAHL ET AL. 2012) and North East England (DAWLEY 2014; DAWLEY ET AL. 2015) confirm the relevance of diversification as a endogenous source of new path creation. However, regional diversification has not been restricted to the shipbuilding industry. In addition to the Husumer Schiffswerft, which initially produced onshore wind turbines, this case study also showed firm diversification from other industries such as mechanical engineering (Tacke, Köster Maschinenfabrik, AN Maschinenbau und Umweltschutzanlagen) and steel construction (Fuhrländer). Besides, FORNAHL ET. AL (2012) reveal an indirect relationship between the declining shipbuilding industry and the emerging offshore wind energy in Northern Germany. Policy makers in the Federal States, that have been particularly hard hit by the crisis (Bremen, Lower Saxony, and Schleswig-Holstein), started to support new path creation in the wind energy industry. The findings in chapter 7 support this view. Experienced firms, that diversified into the wind energy technology, as wells as entrepreneurs have benefited from this.

In this context, the dissertation also contributes to the conceptual and empirical understanding of the emergence of a new regional path as an evolutionary branching process (BOSCHMA/FRENKEN 2011a; FRENKEN/BOSCHMA 2007; HENNING ET AL. 2013; NEFFKE ET AL. 2011). By recombining existing knowledge and competencies, small companies from the shipbuilding industry, agricultural machinery sector and mechanical engineering diversified into the new, related wind industry. These firms benefited from their practical experience, routines and existing knowledge bases in related industries, particularly their knowledge of mechanical and electrical engineering. The results also suggest that technological diversification is not restricted to experienced firms who entered the new industry. Similarly, university spin-offs which were mostly based on related knowledge that was acquired at the university and entrepreneurs coming from related industries diversified into the wind industry. Such a proposal goes beyond the common understanding of regional branching (BOSCHMA/FRENKEN 2011a; BOSCHMA ET AL. 2013; NEFFKE ET AL. 2011). For example, in the case of regional path creation in Stuttgart, know-how from aerospace technology was successfully transferred to wind energy. In Berlin, wind energy technologies emerged from the local concentration of related research activities like aerospace engineering, electrical engineering and mechanical engineering. Hence, it seems more accurate to discuss related skills, competences and knowledge (which are found in existing industries or research fields) than about an aggregation of related industries.

Moreover, the findings indicate that the technological background, the type of entrant (academic spin-off, diversifier) and the regional institutional environment affected the strategy and technological concept of a firm. Shipbuilding companies and manufacturers of agricultural machinery tended to apply and exploit their technological knowledge on durable and sturdy gearboxes and generally relied on the heavy and solid Danish design. Academic spin-offs generally had a specialized knowledge base. They followed a specific technological trajectory and tried to develop a "more sophisticated" technological design. Entrepreneurs and firms with competencies in electrical engineering tended to focus on power electronics and converters. These efforts were mainly aimed at developing alternative wind turbine designs, such as variable speed and direct drive wind turbine concepts.

Third, by using a qualitative case study research design and taking an actor-centered perspective, this dissertation contributes to a deeper understanding of the evolution and spatial diffusion of new technologies. The analysis of the data of wind turbines and interview data presented in **chapter 7.3** reveals that the evolution of wind energy technologies is characterized by different technological sub-trajectories and different strategies to create new knowledge and innovations. This is depicted in the **growth phase**. In the 1980s, a technology selection process occurred. The Danish design evolved in a path dependent process as the most reliable and successful turbine concept, and a dominant design or technological paradigm emerged. While the fixed speed Danish concept reached its peak, a new technological sub-trajectory began to emerge in the 1990s. Technological development and up-scaling of wind turbines made it necessary to develop new solutions. The first variable speed wind turbines with pitch control were introduced and the design became the favored option for wind turbines larger than 1.5 MW. By the year 2000, the Danish design was superseded by the variable speed concept. Technological change was driven by new firms as well as by established firms who changed to variable speed technology. Besides, innovation in direct drive technology led to a new technological path or sub-trajectory. These two sub-trajectories continue to coexist, there is no evidence for a technological lock-in to a single path so far. These findings are in line with a study by BERGEK and ONUFREY (2014) who also argued that multiple technological paths can co-exist within an industry. Offshore technology is a further trajectory. Although some turbine manufacturers have produced both onshore and offshore turbines, there are considerable differences in technical characteristics, involved actors, the institutional environment (e.g. regarding the promotion of wind energy technologies or planning, implementation and financing of wind parks) and the time of path creation (FORNAHL ET AL. 2012; SOMMER 2015; STEEN/HANSEN 2018).

Whereas path creation was primarily driven by individual actors and entrepreneurs, the main agents in subsequent path development of wind energy technologies and the innovation processes were turbine manufacturers, component suppliers and engineering companies. The findings also indicate that collaborations with component suppliers and engineering companies have played pivotal roles in the evolution of wind energy technologies. Suppliers were involved at different phases of new product development. The relationship between manufacturer and supplier differed with respect to the components and sub-technologies from simple "build-to-print" contracts to collaborative relationships and strategic partnerships. In several cases, specialized engineering companies served as collaborative partners for new product development. By analyzing micro-level processes of technology and knowledge transfer, the dissertation provides a contribution to theorizing the evolution and diffusion of new technologies. The case study provides a deeper and more comprehensive perspective to understand how technologies are transferred between firms, namely through licensing, mergers and acquisitions, labor mobility, and spin-offs. At the early stage, technological development was mainly driven by creativity and experimentation of various actors (such as researchers, engineers, technicians and users). This is consistent with the existing literature on the emergence of the wind energy technology in Denmark (GARUD/KARNØE 2003; SIMMIE 2012). Knowledge transfer between firms occurred primarily through licensing and knowledge spillovers from Denmark. As a wind turbine had a short product life cycle, for small firms, licensing was often a quicker and more efficient way for introducing a new turbine than internal development. As technologies have matured, they became more complex, and collaborative relationships or strategic partnerships with suppliers and collaboration with engineering firms have increasingly gained importance. Besides, mergers and acquisitions were found to be the preferred strategy to gain access to new knowledge or technologies. Especially for firms with no experience in new turbine technology, M&As or license agreements provided a valuable opportunity to acquire external knowledge and technologies. In addition, labor mobility and spin-offs provided another important mechanism of knowledge transfer, especially concerning tacit knowledge. Employees who left a firm and established a new venture can be regarded as carriers of knowledge, skills and routines. During the evolution of the wind energy technology, a number of engineering firms was founded as spin-offs from turbine manufacturers following their parents' technological path. Due to their specialized knowledge, many spin-offs were subsequently acquired by turbine manufacturers. Hence, the study demonstrates that labor mobility between firms and spin-off processes should not only be reflected in the context of path creation and regional branching (BOSCHMA/FRENKEN 2011a) but also are also relevant for the diffusion of a technology at a later stage of path development.

The findings on policy instruments and technological trajectories are consistent with other case studies on the evolution of wind energy technologies. In particular, the presented German case shows some similarities with the emergence and evolution of the wind turbine industry in the United States and Denmark, as described by GARUD and KARNØE (2003). Initially, German technology policy and research funding was aimed to create a technological breakthrough in form of radically new, ambitious turbine concepts for large-scale, multi-megawatt turbines. The focus was on large R&D programs and demonstration projects such as the GROWIAN turbine. As in the US case, this strategy was characterized by a top-down approach and the programs were also largely unsuccessful. Large established companies, which participated in demonstration projects, have proved to be less innovative. Later, Germany relied on more market oriented R&D policies and funding programs which promoted technological experimentation. Similar to the Danish strategy, research projects were designed to test and apply practical knowledge in order to develop smaller and simpler turbine designs. The actors were mostly individual inventors or small companies with different technical backgrounds that led to a variety of technological designs. Technological development was based on the recombination of existing knowledge and practical know-how, as well as on continuous improvements of proven technological solutions through learning-by-doing and learning-by-using. As a consequence, several German firms and adopted the

Danish turbine concept and focused on less sophisticated, but robust and reliable small-scale wind turbines.

Fourth, the dissertation contributes to the understanding of the concept of **co-evolution**. Although the idea of co-evolution is being increasingly applied in economic geography, it remains an abstract and fuzzy concept. The conceptual framework and the empirical investigation of this dissertation show that a co-evolutionary perspective on the emergence and spatial evolution of new technologies and industries contributes to a more comprehensive basis for understanding the mechanisms, processes and roles of agency in path creation and development. According to MURMANN (2003) co-evolutionary processes take place through interaction and positive feedback. The findings in **chapter 8** reveal multiple interrelations and feedback mechanisms between technological development and the institutional environment. Concerning the suggestion formulated by MALERBA (2006), the example of the Netzanschlussregeln revealed a bi-directional causality between wind technology and institutions: technical standards co-evolved with technological development and vice versa, which significantly influenced the technological trajectories. It has also been shown, that the co-evolution of supporting formal and informal institutions is a precondition or at least a major accelerator for the successful development of new technologies. The co-evolution of technologies and institutions is not just an outcome of the evolution of the economic landscape in the post-formation phase. Co-evolutionary processes occur during all phases of path development. Moreover, co-evolution is not a random process. It needs to be driven by actors who play an active role in shaping and adjusting institutions with technological development and changing circumstances. This emphasizes that co-evolution relies on strategic action of powerful actors (GARUD/KARNØE 2001a; GARUD ET AL. 2010).

This dissertation also contributes to the recent and growing empirical literature in economic geography on energy transitions, renewable energy technologies and eco-innovation (COOKE 2012; ESSLETZBICHLER 2012; HANSEN/COENEN 2015). In the context of other case studies, the results provide additional insights into the evolution of renewable energy technologies and lead to some important policy implications, which are discussed in section 10.4. But first, the limitations of the study are discussed in the next section.

## 10.3 Limitations and implications for further research

As with any research, this thesis has a number of limitations and raises new questions that should be addressed by future research. First of all, there may be limitations related to the research design. In order to answer the research questions, a case study on the emergence and evolution of the wind energy technology in Germany was conducted. This was found to be an appropriate strategy to investigate how and under which conditions new technologies emerge. A central aim of a case study approach is to assess the complexity of a single case (YIN 2014). However, this raises questions about the generalizability of the results. As with most qualitative research, this exploratory case study does not claim to be representative of a larger population or to be generalizable in any empirical-statistical sense (FLICK 2014; MAYRING 2002). The results are understood to be analytically generalizable (YIN 2014). This means that the theoretical and conceptual framework can be transferred and applied to other case studies investigating the evolution of new technologies or industries in order to further validate and refine the framework. In addition, there is also a content-related reason why the results are not necessarily transferable to other countries. As the literature as well as the empirical results of the dissertation indicate, the national and regional institutional environment affect the evolution of new technologies. For example, it has been shown, that an anti-nuclear sentiment and social movements were the main driver of the evolution of the wind energy in Germany. Compared with this, we know from other countries with a strong anti-nuclear sentiment such as Sweden, Switzerland, New Zeeland and to some extend France (in the 1970s and 80s) where wind energy did not exist, as well as from countries with a considerable wind energy sector where anti-nuclear movements only played a minor role like in Spain (for a long time) or China. Hence, further research of the evolution of wind energy technology in different geographical and institutional contexts or comparative case studies on other technologies or industries is recommended to develop a more comprehensive understanding of the interplay between technologies, economic actors and the institutional environment in a new development path.

Moreover, it is also important to underline that this dissertation has only analyzed one specific technological path. In regard to the findings on the mechanisms and actors in path creation and on how processes of knowledge transfer contribute to the diffusion of new technologies, there is still a need for further research. Additional research on path creation in other technologies will be needed to provide a more comprehensive picture of the role of actors in the emergence and evolution of new technological pathways and the relative importance of indigenous creation, diversification of regional industries and externally induced regional pathways. In particular, future research should examine the role of ideologically driven people, such as inventors and entrepreneurs as well as users, in new path creation. Qualitative studies can provide additional insights into why (or why not) and how actors engage in a new technology. Another key question for future research is how different types of innovators and industry participants, such as academic spin-offs or diversifiers, affect the technological trajectory.

In addition, there may also be limitations due to sampling. This study used a combination of a purposive sampling and a theoretical sampling method to obtain a representative sample of interviewees covering different actors of over 30 years of German wind energy technology. However, the possibility of selection bias cannot be excluded. Another problem could result from face-to-face interview situations which can influence the answers of the respondents – apart from all advantages such as high response rates, in-depth interactions, more in-depth answers and a higher possibility of controlling the interview (adding and explaining questions, clarifying misunderstandings). Although the interviewer tried to create a relaxed and confidential atmosphere and encouraged free expression, the possibility of strategic or socially desirable answers cannot entirely be ruled out.

In addition to the limitations that are specific to the research design, there are at least three limitations, which point to some future avenues of research. One limitation concerns the role of institutions at different special scales in the development of new growth paths. The results of the case study suggest that the multi-scalar institutional environments have a significant influence on the regional emergence of new industries. However, systematic evidence of what kind of institutions (national, regional, formal, informal) matter most, is missing. Further studies are needed to gain a more complete understanding of which institutional environments facilitate or constrain the emergence and evolution of a new regional path. In his context, insight from the regional innovation system (RIS) approach could provide a deeper understanding of how regional institutions affect path creation (ISAKSEN/TRIPPL 2017; TRIPPL ET AL. 2018). A promising future agenda of research, which has been broached in the revised framework and the case study but not in detail, is a multi-scalar and multi-actor approach which has recently been suggested as a helpful perspective for studying new path development (BINZ ET AL. 2016; CHEN/HASSINK 2020; HASSINK ET AL. 2019; MACKINNON ET AL. 2019).

A further limitation addresses the empirical evidence on how technological paths and institutions co-evolve and influence one another. The dissertation has analyzed some particular co-evolutionary processes in the emergence of the wind energy technology. However, it is generally difficult to empirically prove causality concerning interrelations and reciprocal development. To cope with MALERBA's (2016) challenge for co-evolutionary research, a more specific theoretical framework a needed to provide satisfying explanations of reciprocal causality and bidirectional relationships between the evolution of two populations like institutions and technologies or industries. The dissertation thus suggests that future research should explore how to operationalize and measure causality and interrelationship in the context of economic development. Additionally, future case studies from other countries or technologies, utilizing a variety of methods, could investigate similar processes in more detail to better understand how institutions co-evolve with the emergence of a new technology and industry.

Another limitation refers to the question “Why do new growth paths fail?”. The case of early path creation mechanisms in the region of Stuttgart indicates how local and regional institutional change hinders the emergence and development of new economic activities. Indeed, there is room for deeper investigations of new path development, which did not gain momentum. Such case studies would enhance our understanding of the characteristics of a favorable institutional environment and the role of actors of new path creation and would help to formulate more effective policy recommendations.

## 10.4 Policy implications

In addition to the theoretical and empirical contributions, this research study also provides insights for policy makers. Basically, the following question arises: what can be learned from the emergence and evolution of wind energy technology for the emergence and distribution of future new renewable energy or sustainable technologies. The mechanisms of new path creation discussed above have several implications for the design and implementation of policy instruments.

First, policy makers can facilitate path creation through the development and fortification of protected market niches in which new sustainable technologies can mature. In particular, for technologies in areas of public interest, this can stimulate product development and market introduction. In the case of wind energy, financial and tax incentives, R&D funding and, especially, feed-in tariffs turned out to be a successful support scheme for the emerging technology. Niches and fields of experimentation can also be spatially limited – at the federal state, as well as at the local level (e.g. model region, zero-carbon district or housing area).

Second, the findings suggest that the creation of a new pathway can be facilitated by supporting technological experimentation to develop different technological solutions instead of hasty determining the technological approach beforehand. This way, novel designs can be introduced by engineers and scientists. In the 1980s and early 1990s, inventors and firms experimented with a variety of technical approaches and several competing designs of wind turbines emerged. Such "open" R&D programs in an early stage of technological development can also attract various different actors with different technological backgrounds, skills and knowledge. This variety of actors, in turn, increases the level of technological experimentation and the generation of novelties. Thus, protected niches and technological experimentation create conditions for interactive learning and learning-by-doing.

Third, effective technology and innovation policy should ensure that policy measures and incentives support potentially innovative actors and users based on their motivation. In the case of wind energy technology, large demonstration projects (e.g. GROWIAN) funded relatively unsuitable actors with different interests and who only had limited economic and technological benefits for the evolution of the wind energy technology. Only the paradigm shift in the German research policy led the focus away from demonstration project funding which was aimed at creating a technological breakthrough and addressing unsuitable, large companies towards a more market oriented R&D policy and the development of small-scale wind turbines which in turn advanced the development of wind energy technology. The same holds true for the first users of new technologies. The demand for wind energy emerged from local, grassroots actions by individual farmers and private operators. These private users who operated small-scale wind turbines for self-provision and decentralized energy generation had a major influence on the evolution and diffusion of wind energy technology. The idealistic thinking and environmental motivation that created energy cooperatives and the model of citizen-owned wind parks was an important social innovation for path development. Market formation programs for the utilization of new (energy) technologies should, therefore, recognize and focus on potential users. Policy measures should stimulate demand for these technologies and, in this way, increase incentives to improve these technologies. Such instruments might include incentives, subsidies, emission taxes, or tax advantages to encourage potential users to apply this technology or stimulate other firms to adapt to it, or direct public-sector investments.

Fourth, in order to create a favorable institutional environment and facilitate the co-evolution of supporting institutions, policy makers can support the institutionalization of interest groups and the establishment of organizational structures such as business and industry associations and support advocacy coalitions which favor the development of the emerging technology. As illustrated by the example of the adoption of the StrEG and the EEG, an advocacy coalition with regional politicians and associations initiated institutional change. The associations took over important functions as intermediaries through lobbying and networking, public relations at the federal level and regional level, the publication of information material and magazines, presentations, conferences and congresses. They succeeded to mobilize the activities of other actors and to shape local attitudes concerning the acceptance of wind energy technologies. The case study indicates that the effects of innovation policy also depend on the wider context and the timing of funding programs. The emergence and evolution of the German wind energy technology illustrate the importance of the wider social, economic and environmental context and external shocks. Especially the rapid oil price increases and the nuclear reactor accident in Chernobyl led to institutional changes, which created an environment for public support and funding of renewable energy and wind energy technologies. Whereas such external shocks can hardly be influenced, the task for policy makers is to use such external events as an opportunity for promoting technological change to adopt technology support programs at the right time. In fact, this happened in Germany after the Fukushima nuclear disaster. The accident led to a fundamental shift in public perception of nuclear energy and of social and political acceptance and support of renewable energies. As a consequence, the German government reversed course on nuclear energy and decided on a gradual phasing out of nuclear energy.

Fifth, by offering new insights on the emergence of new regional paths, this dissertation provides policy implications for facilitating path creation processes. The emergence of the wind energy technology was primarily driven by local entrepreneurial activities and regional industry diversification. In both cases, pioneering activities were based on related knowledge, competences (e.g. shipbuilding industry, mechanical engineering), or research activities (e.g. aerospace engineering, electrical engineering). The results suggest that policy makers who intend to promote new path creation should take into account regional skills, competences and knowledge when designing regional innovation policies to support regional diversification.

This regional knowledge base contains firms, universities and research institutes as well as potential inventors and entrepreneurs. For example, regional policies should support the diversification of firms in declining industries into new industries. As individual inventors, innovators and entrepreneurs are found to be another key mechanism, this should be supplemented with initiatives to encourage local entrepreneurial activities in these technologies. A strategy could be the identification and involvement of technology enthusiasts and users and the promotion of experimental activities during the early stages of the innovation processes. The state or regional or local authorities can create or support innovative environments and physical spaces containing technical equipment such as a FabLab, Makerspace or Hackerspace to bring together those enthusiasts and inventors and to increase learning-by-doing and learning-by-using. Additionally, digital technologies and 3D printing provide new technological opportunities that support experimental activities during innovation processes. Furthermore, it is important that not only enterprises but also individual persons have access to funding programs. In addition to financial support, which can give a boost to implement an idea and bring a product onto the market, support can also involve consulting, coaching, mentoring and the promotion of networks.

Sixth, the practical relevance of a new technology seems to play a crucial role in the emergence and development of new technological pathways. A large number of first inventors invested in the development of wind turbines in order to install and use them themselves. A local market and the applicability of the technology facilitate path creation. At the same time, the direct participation possibilities increase the acceptance of new technologies. The task of the policy is, in this case, to create the legal and economic framework conditions to strengthen this (local) market. Besides support programs, laws, and regulations this also includes the provision of an enabling infrastructure (depending on the technology e.g. grid expansion and smart grids, charging infrastructure, digital infrastructure), financing instruments, technical standards, as well as training and qualification of personnel.

Seventh, the theoretical arguments and the empirical findings indicate that the emergence and diffusion of a new technology is dependent on the co-evolution and further development of complementary technologies and products and as well as institutional and organizational changes. In the case of wind energy technology, but also for other energy technologies, special research and development programs are needed in key technologies such as energy storage and smart grid technologies. The task of technology and innovation policy would be to identify innovative potentials and needs in supporting technologies, to stimulate innovation and to promote the diffusion and adoption of these technologies. For this, players from industry and research should be close involved. For many technologies, there is also a need for new technology-specific infrastructure. In the case of wind energy, this was the grid system. Electric mobility, for example, needs a widespread charging infrastructure. Public support for infrastructure development is a central policy instrument for the emergence and especially the diffusion of new technologies.

The example of the Renewable Energy Sources Act (EEG) also highlights that the legal framework and funding mechanisms need to be flexible and continuously develop and adjust to the development of the technology and industry. Whereas at the early stage of experimentation (pre-formation and path creation phase) open R&D programs are useful to increase variety until dominant designs are established, on a later stage (growth and post-formation phase) policy instruments with market-based approaches are helpful to promote technology selection and diffusion processes and improve cost efficiency. The theoretical arguments on ongoing path development and empirical evidence from the case study suggest that also at a more mature stage of technology development, R&D funding and innovation policies should target technological experimentation. That allows, for example, to consider new fields of applications, to address new economic actors and to look ahead to future technology. This helps to avoid a lock-in situation with a specific technology.

Another aspect of co-evolution concerns the emergence of vocational education, training programs, new scientific disciplines, and research alliances. The policy should identify and evaluate technology trends early on and purposefully promote and support education and research in these fields. In the case of the onshore wind energy, this took a long time[16].

[16] According to ALLNOCH ET AL. (2008), in 2008 only five of the more than 170 university education programs in Germany that relate to renewable energies and environmental technologies are specifically geared towards wind energy.

## References

ABERNATHY, W. J. and UTTERBACK, J. M. (1978): Patterns of industrial innovation. *Technology review* 64(7): 254.

AERODYN ENERGIESYSTEME GMBH (2013): 30 Jahre aerodyn. Entwicklung von Windenergieanlagen seit 1983. (30 years of aerodyn. Development of wind turbines since 1983). Rendsburg.

AGARWAL, R.; ECHAMBADI, R.; FRANCO, A. M. and SARKAR, M. (2004): Knowledge Transfer Through Inheritance: Spin-Out Generation, Development, and Survival. *Academy of Management Journal* 47(4): 501–522. DOI: 10.2307/20159599.

ALLNOCH, N.; KLEINMANNS, B.; POCHERT, O. and SCHLUSEMANN, R. (2008): Zur Struktur der Windenergieforschung in Deutschland. *Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit (BMU)*.

ALMEIDA, P. and KOGUT, B. (1999): Localization of Knowledge and the Mobility of Engineers in Regional Networks. *Management Science* 45(7): 905–917. DOI: 10.1287/mnsc.45.7.905.

APAX PARTNERS (2006): Suzlon Energy signs definitive agreement for strategic acquisition of Hansen Transmissions. Press release 17 March 2006. London. Retrieved from: https://www.apax.com/news/press-releases/2006/march/suzlon-energy-signs-definitive-agreement-for-strategic-acquisition-of-hansen-transmissions/, 10/20/2020.

AREVA (2010): AREVA confirms its commitment to the offshore wind industry. Press release 21.05.2010. Paris.

ARTHUR, W. B. (1989): Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal* 99(394): 116–131.

ARTHUR, W. B. (1994): Increasing Returns and Path Dependence in the Economy. Ann Arbor: The University of Michigan Press.

ASHEIM, B. T. and GERTLER, M. S. (2005): The Geography of Innovation. Regional Innovation Systems. In: Fagerberg, J., Mowery, D. C. and Nelson, R. R. (ed.): The Oxford handbook of innovation. Oxford, New York: Oxford University Press: 291–317.

AUDRETSCH, D. B. and FELDMAN, M. P. (1996): R&D Spillovers and the Geography of Innovation and Production. *The American Economic Review* 86(3): 630–640. DOI: 10.2307/2118216.

AUDRETSCH, D. B. and FELDMAN, M. P. (2004): Knowledge spillovers and the geography of innovation. In: Henderson, J. V. and Thisse, J.-F. (ed.): Handbook of Regional and Urban Economics: Cities and Geography, Volume 4: Elsevier: 2713–2739.

BATHELT, H. and BOGGS, J. S. (2003): Toward a Reconceptualization of Regional Development Paths: Is Leipzig's Media Cluster a Continuation of or a Rupture with the Past? *Economic Geography* 79(3): 265–293. DOI: 10.1111/j.1944-8287.2003.tb00212.x.

BauGB (2004): Baugesetzbuch in der Fassung der Bekanntmachung vom 23.09.2004 (BGBl. I S.2414), zuletzt geändert durch Artikel 1 des Gesetzes vom 21. Dezember 2006 In: BGBl. I, S.3316.

BECKER, M. C. (2004): Organizational routines: a review of the literature. *Industrial and Corporate Change* 13(4): 643–678. DOI: 10.1093/icc/dth026.

BECKER, T. (2006): Der schweigsame Pionier aus dem Norden. *Handelsblatt*, 5/25/2006.

BEDNARZ, M. and BROEKEL, T. (2020): Pulled or pushed? The spatial diffusion of wind energy between local demand and supply. *Industrial and Corporate Change* 29(4): 893–916. DOI: 10.1093/icc/dtaa012.

BERGEK, A. and JACOBSSON, S. (2003): The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries. In: Metcalfe, J. and Cantner, U. (ed.): Change, Transformation and Development. Heidelberg: Physica: 197–227.

BERGEK, A.; JACOBSSON, S.; CARLSSON, B.; LINDMARK, S. and RICKNE, A. (2008): Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy* 37(3): 407–429. DOI: 10.1016/j.respol.2007.12.003.

BERGEK, A. and ONUFREY, K. (2014): Is one path enough? Multiple paths and path interaction as an extension of path dependency theory. *Industrial and Corporate Change* 23(5): 1261–1297. DOI: 10.1093/icc/dtt040.

BINZ, C.; TRUFFER, B. and COENEN, L. (2016): Path Creation as a Process of Resource Alignment and Anchoring: Industry Formation for On-Site Water Recycling in Beijing. *Economic Geography* 92(2): 172–200. DOI: 10.1080/00130095.2015.1103177.

BMWI (2018): The Energy of the Future. Sixth “Energy Transition” Monitoring Report. Berlin.

BOSCHMA, R. (2004): Competitiveness of Regions from an Evolutionary Perspective. *Regional Studies* 38(9): 1001–1014. DOI: 10.1080/0034340042000292601.

BOSCHMA, R.; BALLAND, P.-A. and KOGLER, D. F. (2015): Relatedness and technological change in cities: the rise and fall of technological knowledge in US metropolitan areas from 1981 to 2010. *Industrial and Corporate Change* 24(1): 223–250. DOI: 10.1093/icc/dtu012.

BOSCHMA, R. and FRENKEN, K. (2006): Why is economic geography not an evolutionary science? Towards an evolutionary economic geography. *Journal of Economic Geography* 6(3): 273–302. DOI: 10.1093/jeg/lbi022.

BOSCHMA, R. and FRENKEN, K. (2009): Some Notes on Institutions in Evolutionary Economic Geography. *Economic Geography* 85(2): 151–158. DOI: 10.1111/j.1944-8287.2009.01018.x.

BOSCHMA, R. and FRENKEN, K. (2011a): Technological relatedness and regional branching. In: Bathelt, H., Feldman, M. P. and Kogler, D. F. (ed.): Beyond territory. Dynamic geographies of knowledge creation, diffusion, and innovation. New York: Routledge (Regions and cities): 64–81.

BOSCHMA, R. and FRENKEN, K. (2011b): The emerging empirics of evolutionary economic geography. *Journal of Economic Geography* 11(2): 295–307. DOI: 10.1093/jeg/lbq053.

BOSCHMA, R. and MARTIN, R. (2007): Editorial: Constructing an evolutionary economic geography. *Journal of Economic Geography* 7(5): 537–548. DOI: 10.1093/jeg/lbm021.

BOSCHMA, R.; MINONDO, A. and NAVARRO, M. (2013): The Emergence of New Industries at the Regional Level in Spain: A Proximity Approach Based on Product Relatedness. *Economic Geography* 89(1): 29–51. DOI: 10.1111/j.1944-8287.2012.01170.x.

BOSCHMA, R. A. and LAMBOOY, J. G. (1999): Evolutionary economics and economic geography. *Journal of Evolutionary Economics* 9(4): 411–429. DOI: 10.1007/s001910050089.

BOSCHMA, R. A. and WENTING, R. (2007): The spatial evolution of the British automobile industry: Does location matter? *Industrial and Corporate Change* 16(2): 213–238. DOI: 10.1093/icc/dtm004.

BRACZYK, H.-J.; COOKE, P. and HEIDENREICH, M. (ed.) (1998): Regional Innovation Systems: The Role of Governance in a Globalized World. London: ULC.

BROEKEL, T. (2015): The Co-evolution of Proximities – A Network Level Study. *Regional Studies* 49(6): 921–935. DOI: 10.1080/00343404.2014.1001732.

BRUNS, E.; KÖPPEL, J.; OHLHORST, D. and SCHÖN, S. (2008): Die Innovationsbiographie der Windenergie. Absichten und Wirkungen von Steuerungsimpulsen. Berlin: Lit-Verl (Innovationsforschung, 2).

BUEN, J. (2006): Danish and Norwegian wind industry: The relationship between policy instruments, innovation and diffusion. *Energy Policy* 34(18): 3887–3897. DOI: 10.1016/j.enpol.2005.09.003.

BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE (BMWI) (2016): Die erneuerbaren Energien. Fit für den Strommarkt. Fit für die Zukunft. Alle wichtigen Fakten zum neuen EEG 2017. Berlin.

BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE (BMWI) (2017): Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland. Stand: Februar 2017. Retrieved from: http://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2016-excel.xlsx?__blob=publicationFile&v=10.

BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE (BMWI) and BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT (BMU) (2010): Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply. Berlin. Retrieved from: http://www.germany.info/contentblob/3043402/Daten/3903429/BMUBMWi_Energy_Concept_DD.pdf.

BUNDESREGIERUNG (ed.) (2010): Energiekonzept. für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Beschluss des Bundeskabinetts vom 28. September 2010. Retrieved from: http://www.bundesregierung.de/Content/DE/_Anlagen/2012/02/energiekonzept-final.pdf?__blob=publicationFile&v=5.

BUNDESVERBAND WINDENERGIE E.V. (BWE) (various years): Windenergie. BWE-Marktübersicht. Bonn, Berlin.

BUNDESVERBAND WINDENERGIE E.V. (BWE) (2012): Eine starke Stimme für den Wind. Der Bundesverband WindEnergie stellt sich vor. Retrieved from: https://www.wind-energie.de/

sites/default/files/download/publication/eine-starke-stimme-fuer-den-wind/bwe_imagebroschuere_2012_web.pdf.

BUNDESVERBAND WINDENERGIE E.V. (BWE) (2017): Landes- und Regionalverbände. Retrieved from: https://www.wind-energie.de/verband/landes-und-regionalverbaende.

CAMPOS SILVA, P. and KLAGGE, B. (2011): Branchen- und Standortentwicklung der Windindustrie in globaler Perspektive: kontinuierliche Pfadentwicklung und die Rolle der Politik. *Geographica Helvetica* 66(4): 233–242.

CAMPOS SILVA, P. and KLAGGE, B. (2013): The Evolution of the Wind Industry and the Rise of Chinese Firms: From Industrial Policies to Global Innovation Networks. *European Planning Studies* 21(9): 1341–1356. DOI: 10.1080/09654313.2012.756203.

CARLSSON, B. and STANKIEWICZ, R. (1991): On the nature, function and composition of technological systems. *Journal of Evolutionary Economics* 1(2): 93–118. DOI: 10.1007/BF01224915.

CARPENTER, J.; SIMME, J.; CONTI, E.; POVINELLI, F. and KIPSHAGEN, J. M. (2012): Innovation and New Path Creation: The Role of Niche Environments in the Development of the Wind Power Industry in Germany and the UK. *European Spatial Research and Policy* 19(2). DOI: 10.2478/v10105-012-0016-5.

CHEN, Y. and HASSINK, R. (2020): Multi-scalar knowledge bases for new regional industrial path development: toward a typology. *European Planning Studies*: 1–19. DOI: 10.1080/09654313.2020.1724265.

CHLEBNA, C. and SIMMIE, J. (2018): New technological path creation and the role of institutions in different geo-political spaces. *European Planning Studies* 26(5): 969–987. DOI: 10.1080/09654313.2018.1441380.

COENEN, L.; MOODYSSON, J. and MARTIN, H. (2015): Path Renewal in Old Industrial Regions: Possibilities and Limitations for Regional Innovation Policy. *Regional Studies* 49(5): 850–865. DOI: 10.1080/00343404.2014.979321.

COHEN, M. D. and BACDAYAN, P. (1994): Organizational Routines Are Stored as Procedural Memory: Evidence from a Laboratory Study. *Organization Science* 5(4): 554–568. DOI: 10.1287/orsc.5.4.554.

COOKE, P. (2012): Transversality and Transition: Green Innovation and New Regional Path Creation. *European Planning Studies* 20(5): 817–834. DOI: 10.1080/09654313.2012.667927.

CUSUMANO, M. A.; MYLONADIS, Y. and ROSENBLOOM, R. S. (1992): Strategic Maneuvering and Mass-Market Dynamics: The Triumph of VHS over Beta. *Business History Review* 66(1): 51–94. DOI: 10.2307/3117053.

CZYZ, N. (2006): Windenergie ist ein Wirtschaftsfaktor. *NWZ*, 3/17/2006. Retrieved from: http://www.nwzonline.de/wilhelmshaven/windenergie-ist-ein-wirtschaftsfaktor_a_6,1,2300142777.html.

DAVID, P. A. (1985): Clio and the Economics of QWERTY. *The American Economic Review* 75(2): 332–337.

DAWLEY, S. (2014): Creating New Paths? Offshore Wind, Policy Activism, and Peripheral Region Development. *Economic Geography* 90(1): 91–112. DOI: 10.1111/ecge.12028.

DAWLEY, S.; MACKINNON, D.; CUMBERS, A. and PIKE, A. (2015): Policy activism and regional path creation: the promotion of offshore wind in North East England and Scotland. *Cambridge Journal of Regions, Economy and Society* 8(2): 257–272. DOI: 10.1093/cjres/rsu036.

DER MINISTER FÜR ARBEIT UND SOZIALES, JUGEND, GESUNDHEIT UND ENERGIE DES LANDES SCHLESWIG-HOLSTEIN (1990): Windkraft. 2. überarbeitete Aufl. Kiel (Die neue Energiepolitik, 1).

DER MINISTER FÜR ARBEIT UND SOZIALES, JUGEND, GESUNDHEIT UND ENERGIE DES LANDES SCHLESWIG-HOLSTEIN (1993): Energiekonzept Schleswig-Holstein. 3. Aufl. Kiel (Die neue Energiepolitik).

DEUTSCHE WINDGUARD GMBH (2020): Status des Windenergieausbaus an Land in Deutschland - Jahr 2019. Varel. Retrieved from: https://www.wind-energie.de/fileadmin/redaktion/dokumente/pressemitteilungen/2020/Status_des_Windenergieausbaus_an_Land_-_Jahr_2019.pdf.

DEUTSCHER WETTERDIENST (DWD) (2018): Windkarten zur mittleren Windgeschwindigkeit. Retrieved from: https://www.dwd.de/DE/leistungen/windkarten/deutschland_und_bundeslaender.html.

DEWI (various years): Windenergienutzung in der Bundesrepublik Deutschland. IN: DEWI MAGAZIN. Wilhelmshaven.

DEWI (1994): Netzrückwirkungen, verursacht durch den Betrieb von Windkraftanlagen am Netz (DEWI Magazin, Nr. 5).

DEWI; E.ON NETZ; EWI; RWE TRANSPORT GRID and VE TRANSMISSION (2005): Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020 (DENA Grid study). German Energy Agency (dena). Cologne.

DIMAGGIO, P. J. (1988): Interest and agency in institutional theory. In: Zucker, L. G. (ed.): Institutional patterns and organizations: Culture and environment. Cambridge, MA: Ballinger: 3–22.

DOBLINGER, C. and SOPPE, B. (2013): Change-actors in the U.S. electric energy system: The role of environmental groups in utility adoption and diffusion of wind power. *Energy Policy* 61(0): 274–284. DOI: 10.1016/j.enpol.2013.07.028.

DOSI, G. (1982): Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy* 11(3): 147–162. DOI: 10.1016/0048-7333(82)90016-6.

DOSI, G. (1988): Sources, Procedures, and Microeconomic Effects of Innovation. *Journal of Economic Literature* 26(3): 1120–1171.

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

DURSTEWITZ, M.; HOPPE-KILPPER, M. and VON SCHWERIN. CATARINA (2003): Nutzung von Windkraft durch die Landwirtschaft. Schlussbericht. Forschungsprojekt 01HS053 im Auftrag der Bundesanstalt für Landwirtschaft und Ernährung (BLE) Laufzeit: 01.09.2002 – 28.02.2003. Institut für Solare Energieversorgungstechnik e. V. (ISET). Kassel.

E.ON NETZ GMBH (2001): Netzanschlussregeln - allgemein. Technische und organisatorische Regeln für den Netzanschluss innerhalb der Regelzone der E.ON Netz GmbH im Bereich der ehemaligen Preussen Elektra Netz GmbH Co. KG.

ENERCON GMBH (2009): Windblatt. Enercon Magazin für die Windenergie. 03/2009. Aurich.

ENERCON GMBH (2016): ENERCON wind energy converters. Technology & Service. Image brochure. Retrieved from: http://www.enercon.de/fileadmin/Redakteur/Medien-Portal/broschueren/pdf/EC_TuS_en_092016_web.pdf.

ENERGIE & MANAGEMENT (2004): Pfleiderer gibt Windkraft-Geschäft ab. Retrieved from: https://www.energie-und-management.de/nachrichten/detail/pfleiderer-gibt-windkraft-geschaeft-ab-47897.

ESSLETZBICHLER, J. (2002): Evolutionäre Wirtschaftsgeographie: Neues Forschungsparadigma oder Sackgasse? *Geographischer Jahresbericht aus Österreich* 2002(59): 11–30.

ESSLETZBICHLER, J. (2009): Evolutionary Economic Geography, Institutions, and Political Economy. *Economic Geography* 85(2): 159–165. DOI: 10.1111/j.1944-8287.2009.01019.x.

ESSLETZBICHLER, J. (2012): Renewable Energy Technology and Path Creation: A Multi-scalar Approach to Energy Transition in the UK. *European Planning Studies* 20(5): 791–816. DOI: 10.1080/09654313.2012.667926.

ESSLETZBICHLER, J. and RIGBY, D. L. (2007): Exploring evolutionary economic geographies. *Journal of Economic Geography* 7(5): 549–571. DOI: 10.1093/jeg/lbm022.

EUROPEAN WIND ENERGY ASSOCIATION (EWEA) (2009): Wind Energy - The Facts. A guide to the technology, economics and future of wind power. London: Earthscan.

EUROSOLAR E.V. (2017): The European Association for Renewable Energy. Retrieved from: http://www.eurosolar.de/.

FARLA, J.C.M.; MARKARD, J.; RAVEN, R. and COENEN, L. (2012): Sustainability transitions in the making: A closer look at actors, strategies and resources. *Technological Forecasting and Social Change* 79(6): 991–998. DOI: 10.1016/j.techfore.2012.02.001.

FLICK, U. (2014): An introduction to qualitative research. Edition 5. Los Angeles: SAGE.

FLIGSTEIN, N. (1997): Social Skill and Institutional Theory. *American Behavioral Scientist* 40(4): 397–405. DOI: 10.1177/0002764297040004003.

FÖRDERGESELLSCHAFT WINDENERGIE E.V. (1995): Untersuchung zur Förderung und Weiterentwicklung von WKA in Deutschland und Europa. Brunsbüttel.

FORNAHL, D.; HASSINK, R.; KLAERDING, C.; MOSSIG, I. and SCHRÖDER, H. (2012): From the Old Path of Shipbuilding onto the New Path of Offshore Wind Energy? The Case of Northern Germany. *European Planning Studies* 20(5): 835–855. DOI: 10.1080/09654313.2012.667928.

FORWIND (2017): Zentrum für Windenergieforschung. Aus- und Weiterbildung. Retrieved from: http://www.forwind.de/forwind/index.php?article_id=27&clang=0.

FOXON, T. J.; HAMMOND, G. P. and PEARSON, P. J. G. (2010): Developing transition pathways for a low carbon electricity system in the UK. *Technological Forecasting and Social Change* 77(8): 1203–1213. DOI: 10.1016/j.techfore.2010.04.002.

FRAUNHOFER INSTITUT FÜR WINDENERGIE UND ENERGIESYSTEMTECHNIK (IWES) (2012): Windenergie Report Deutschland 2011. Kassel.

FRAUNHOFER-INSTITUT FÜR WINDENERGIE UND ENERGIESYSTEMTECHNIK (IWES) (2014): Windenergie Report Deutschland 2013. Stuttgart.

FRENKEN, K. and BOSCHMA, R. A. (2007): A theoretical framework for evolutionary economic geography: industrial dynamics and urban growth as a branching process. *Journal of Economic Geography* 7(5): 635–649. DOI: 10.1093/jeg/lbm018.

FRENKEN, K.; VAN OORT, F. and VERBURG, T. (2007): Related Variety, Unrelated Variety and Regional Economic Growth. *Regional Studies* 41(5): 685–697. DOI: 10.1080/00343400601120296.

GARUD, R.; JAIN, S. and KUMARASWAMY, A. (2002): Institutional Entrepreneurship in the Sponsorship of Common Technological Standards: The Case of Sun Microsystems and Java. *The Academy of Management Journal* 45(1): 196–214.

GARUD, R. and KARNØE, P. (2001a): Path Creation as a Process of Mindful Deviation. In: Garud, R. and Karnøe, P. (ed.): Path dependence and creation. Mahwah, N.J: Erlbaum: 1–38.

GARUD, R. and KARNØE, P. (ed.) (2001b): Path dependence and creation. Mahwah, N.J: Erlbaum.

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

GARUD, R.; KUMARASWAMY, A. and KARNØE, P. (2010): Path Dependence or Path Creation? *Journal of Management Studies* 47(4): 760–774. DOI: 10.1111/j.1467-6486.2009.00914.x.

GASCH, R. and TWELE, J. (2011): Windkraftanlagen. Grundlagen, Entwurf, Planung und Betrieb. 7. Aufl. Wiesbaden: Vieweg + Teubner.

GEELS, F. W. (2002): Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* 31(8-9): 1257–1274. DOI: 10.1016/S0048-7333(02)00062-8.

GEELS, F. W. (2004): From sectoral systems of innovation to socio-technical systems. *Research Policy* 33(6-7): 897–920. DOI: 10.1016/j.respol.2004.01.015.

GERTLER, M. S. (2010): Rules of the Game: The Place of Institutions in Regional Economic Change. *Regional Studies* 44(1): 1–15. DOI: 10.1080/00343400903389979.

EEG (2014): Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 21.07.2014. In: BGBl. I, S. 1066.

EEG (2017): Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 21.07.2014. In: BGBl. I, S. 1066. Zuletzt geändert durch Art. 2 G v. 22.12.2016 BGBl. I, S. 3106.

EEG (2004): Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 21.07.2004. In: BGBl. I, S. 1918.

EEG (2009): Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 25.10.2008. In: BGBl. I, S. 2074.

EEG (2000): Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 29.03.2000. In: BGBl. I, S. 305.

EEG (2012): Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 30.06.2011. In: BGBl. I, S. 2730.

GIPE, P. (1995): Wind energy comes of age. New York: Wiley (Wiley series in sustainable design).

GLÄSER, J. and LAUDEL, G. (2010): Experteninterviews und qualitative Inhaltsanalyse. Als Instrumente rekonstruierender Untersuchungen. 4. Aufl. Wiesbaden: VS Verlag für Sozialwissenschaften.

GONG, H. and HASSINK, R. (2019): Co-evolution in contemporary economic geography: towards a theoretical framework. *Regional Studies* 53(9): 1344–1355. DOI: 10.1080/00343404.2018.1494824.

GRABHER, G. (1993): The weakness of strong ties. The lock-in of regional development in Ruhr area. In: Grabher, G. (ed.): The Embedded Firm. On the Socioeconomics of Industrial Networks. London: Routledge: 255–277.

HANSEN, A. D. and HANSEN, L. H. (2007): Wind turbine concept market penetration over 10 years (1995–2004). *Wind Energy* 10(1): 81–97. DOI: 10.1002/we.210.

HANSEN, T. and COENEN, L. (2015): The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environmental Innovation and Societal Transitions* 17: 92–109. DOI: 10.1016/j.eist.2014.11.001.

HASSINK, R. (2005): How to unlock regional economies from path dependency? From learning region to learning cluster. *European Planning Studies* 13(4): 521–535. DOI: 10.1080/09654310500107134.

HASSINK, R.; ISAKSEN, A. and TRIPPL, M. (2019): Towards a comprehensive understanding of new regional industrial path development. *Regional Studies* 53(11): 1636–1645. DOI: 10.1080/00343404.2019.1566704.

HASSINK, R.; KLAERDING, C. and MARQUES, P. (2014): Advancing Evolutionary Economic Geography by Engaged Pluralism. *Regional Studies* 48(7): 1295–1307. DOI: 10.1080/00343404.2014.889815.

HAU, E. (2014): Windkraftanlagen. Grundlagen, Technik, Einsatz, Wirtschaftlichkeit. 5., neu bearb. Aufl. 2014. Berlin, Heidelberg: Springer.

HEKKERT, M. P. and NEGRO, S. O. (2009): Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technological Forecasting and Social Change* 76(4): 584–594. DOI: 10.1016/j.techfore.2008.04.013.

HELFAT, C. E. and LIEBERMAN, M. B. (2002): The birth of capabilities: market entry and the importance of pre-history. *Industrial and Corporate Change* 11(4): 725–760. DOI: 10.1093/icc/11.4.725.

HEMMELSKAMP, J. (1999): Umweltpolitik und technischer Fortschritt. Eine theoretische und empirische Untersuchung der Determinanten von Umweltinnovationen. Berlin, Heidelberg: Springer (Umwelt- und Ressourcenökonomie).

HENNING, M.; STAM, E. and WENTING, R. (2013): Path Dependence Research in Regional Economic Development: Cacophony or Knowledge Accumulation? *Regional Studies* 47(8): 1348–1362. DOI: 10.1080/00343404.2012.750422.

HEYMANN, M. (1995): Die Geschichte der Windenergienutzung, 1890-1990. Frankfurt, New York: Campus.

HOPPE-KILPPER, M. (2003): Entwicklung der Windenergietechnik in Deutschland und der Einfluss staatlicher Förderpolitik. Technikentwicklung in den 90er Jahren zwischen Markt und Forschungsförderung. Dissertation. Kassel.

HUSUMER SCHIFFSWERFT (1994): Wind-energy converter HSW 250. Final report. EUR 14920 DE/EN. EUROPEAN COMMISSION. Luxembourg.

IBENHOLT, K. (2002): Explaining learning curves for wind power. *Energy Policy* 30(13): 1181–1189. DOI: 10.1016/S0301-4215(02)00014-9.

INTERNATIONAL ENERGY AGENCY (IEA) (2017a): Renewables 2017. Analysis and Forecasts to 2022.

INTERNATIONAL ENERGY AGENCY (IEA) (2017b): Statistics. Retrieved from: https://www.iea.org/statistics/.

ISAKSEN, A. (2015): Industrial development in thin regions: trapped in path extension? *Journal of Economic Geography* 15(3): 585–600. DOI: 10.1093/jeg/lbu026.

ISAKSEN, A. and TRIPPL, M. (2017): Exogenously Led and Policy-Supported New Path Development in Peripheral Regions: Analytical and Synthetic Routes. *Economic Geography* 93(5): 436–457. DOI: 10.1080/00130095.2016.1154443.

ISET /DEWI (1997): Allgemeine Entwicklung der Kosten der Windstromerzeugung in Deutschland. Studie im Auftrag des Bundesverband Windenergie e.V. Kassel, Wilhelmshaven.

JACOBIDES, M. G. and WINTER, S. G. (2005): The co-evolution of capabilities and transaction costs: explaining the institutional structure of production. *Strategic Management Journal* 26(5): 395–413. DOI: 10.1002/smj.460.

JACOBSSON, S. and BERGEK, A. (2004): Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and Corporate Change* 13(5): 815–849. DOI: 10.1093/icc/dth032.

JACOBSSON, S. and JOHNSON, A. (2000): The diffusion of renewable energy technology: an analytical framework and key issues for research. *Energy Policy* 28(9): 625–640. DOI: 10.1016/S0301-4215(00)00041-0.

JACOBSSON, S. and LAUBER, V. (2006): The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy Policy* 34(3): 256–276. DOI: 10.1016/j.enpol.2004.08.029.

JAFFE, A. B.; TRAJTENBERG, M. and HENDERSON, R. (1993): Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations. *The Quarterly Journal of Economics* 108(3): 577–598. DOI: 10.2307/2118401.

JONES, J. (2010): Solar Hero Dr. Hermann Scheer Dies. October 15. Retrieved from: http://www.renewableenergyworld.com/articles/2010/10/dr-hermann-scheer-dies.html.

KAMMER, J. (2011): Die Windenergieindustrie. Evolution von Akteuren und Unternehmensstrukturen in einer Wachstumsindustrie mit räumlicher Perspektive. Stuttgart: Steiner [u.a.] (Mitteilungen der Geographischen Gesellschaft in Hamburg, 103).

KAPLAN, S. and TRIPSAS, M. (2008): Thinking about technology: Applying a cognitive lens to technical change. *Research Policy* 37(5): 790–805. DOI: 10.1016/j.respol.2008.02.002.

KARNØE, P. (1990): Technological innovation and industrial organization in the Danish wind industry. *Entrepreneurship & Regional Development* 2(2): 105–124. DOI: 10.1080/08985629000000008.

KARNØE, P. and GARUD, R. (2012): Path Creation: Co-creation of Heterogeneous Resources in the Emergence of the Danish Wind Turbine Cluster. *European Planning Studies* 20(5): 733–752. DOI: 10.1080/09654313.2012.667923.

KEMP, R.; SCHOT, J. and HOOGMA, R. (1998): Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management* 10(2): 175–198. DOI: 10.1080/09537329808524310.

KLEPPER, S. (1997): Industry Life Cycles. *Industrial and Corporate Change* 6(1): 145–182. DOI: 10.1093/icc/6.1.145.

KLEPPER, S. (2002a): Firm Survival and the Evolution of Oligopoly. *The RAND Journal of Economics* 33(1): 37–61. DOI: 10.2307/2696374.

KLEPPER, S. (2002b): The capabilities of new firms and the evolution of the US automobile industry. *Industrial and Corporate Change* 11(4): 645–666. DOI: 10.1093/icc/11.4.645.

KLEPPER, S. (2007): Disagreements, Spinoffs, and the Evolution of Detroit as the Capital of the U.S. Automobile Industry. *Management Science* 53(4): 616–631. DOI: 10.1287/mnsc.1060.0683.

KLEPPER, S. (2010): The origin and growth of industry clusters: The making of Silicon Valley and Detroit. *Special Issue: Cities and Entrepreneurship* 67(1): 15–32. DOI: 10.1016/j.jue.2009.09.004.

KLEPPER, S. and SLEEPER, S. (2005): Entry by Spinoffs. *Management Science* 51(8): 1291–1306. DOI: 10.1287/mnsc.1050.0411.

KLINE, S. J. and ROSENBERG, N. (1986): An overview of innovation. In: Landau, R. and Rosenberg, N. (ed.): The Positive Sum Strategy: Harnessing Technology for Economic Growth, Bd. 14. Washington, DC: 275–305.

KOENEMANN, D. (2009): Erfolg durch Technik. *Sonne, Wind & Wärme*(11): 82–84.

KOLLMER, H. and DOWLING, M. (2004): Licensing as a commercialisation strategy for new technology-based firms. *Research Policy* 33(8): 1141–1151. DOI: 10.1016/j.respol.2004.04.005.

LplG (2003): Landesplanungsgesetz (LplG) vom 10. Juli 2003 (GBl. 2003, Nr. 10, S. 385).

LESTER, R. K. (2007): Universities, Innovation and the Competitiveness of Local Economies: An Overview. In: Lester, R. K. and Sotarauta, M. (ed.): Innovation, Universities, and the Competitiveness of Regions. Helsinki (Technology review, 214): 9–30.

MACKINNON, D.; CUMBERS, A.; PIKE, A.; BIRCH, K. and MCMASTER, R. (2009): Evolution in Economic Geography: Institutions, Political Economy, and Adaptation. *Economic Geography* 85(2): 129–150. DOI: 10.1111/j.1944-8287.2009.01017.x.

MACKINNON, D.; DAWLEY, S.; PIKE, A. and CUMBERS, A. (2019): Rethinking Path Creation: A Geographical Political Economy Approach. *Economic Geography* 95(2): 113–135. DOI: 10.1080/00130095.2018.1498294.

MALERBA, F. (2006): Innovation and the evolution of industries. *Journal of Evolutionary Economics* 16(1-2): 3–23. DOI: 10.1007/s00191-005-0005-1.

MALMBERG, A. and MASKELL, P. (2002): The elusive concept of localization economies: towards a knowledge-based theory of spatial clustering. *Environment and Planning A* 34(3): 429–449. DOI: 10.1068/a3457.

MARKARD, J. and TRUFFER, B. (2006): Innovation processes in large technical systems: Market liberalization as a driver for radical change? *Research Policy* 35(5): 609–625. DOI: 10.1016/j.respol.2006.02.008.

MARKARD, J. and TRUFFER, B. (2008): Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy* 37(4): 596–615. DOI: 10.1016/j.respol.2008.01.004.

MARTIN, R. (2000): Institutional Approaches in Economic Geography. In: Sheppard, E. and Barnes, T. J. (ed.): A Companion to Economic Geography. Oxford, UK: Blackwell Publishing Ltd: 77–94.

MARTIN, R. (2010): Roepke Lecture in Economic Geography-Rethinking Regional Path Dependence: Beyond Lock-in to Evolution. *Economic Geography* 86(1): 1–27. DOI: 10.1111/j.1944-8287.2009.01056.x.

MARTIN, R. and SIMMIE, J. (2008): Path dependence and local innovation systems in city-regions. *Innovation: Management, Policy & Practice* 10(2-3): 183–196. DOI: 10.5172/impp.453.10.2-3.183.

MARTIN, R. and SUNLEY, P. (2006): Path dependence and regional economic evolution. *Journal of Economic Geography* 6(4): 395–437. DOI: 10.1093/jeg/lbl012.

MARTIN, R. and SUNLEY, P. (2007): Complexity thinking and evolutionary economic geography. *Journal of Economic Geography* 7(5): 573–601. DOI: 10.1093/jeg/lbm019.

MASKELL, P. and MALMBERG, A. (2007): Myopia, knowledge development and cluster evolution. *Journal of Economic Geography* 7(5): 603–618. DOI: 10.1093/jeg/lbm020.

MAYRING, P. (2002): Einführung in die qualitative Sozialforschung. Eine Anleitung zu qualitativem Denken. 5., überarb. und neu ausgestattete Aufl. Weinheim [u.a.]: Beltz (Beltz-Studium).

MAYRING, P. (2010): Qualitative Inhaltsanalyse. Grundlagen und Techniken. 11., aktual., überarb. Aufl. Weinheim: Beltz (Beltz Pädagogik).

MEADOWS, D. H.; MEADOWS, D.; RANDERS, J. and BEHRENS III, W. W. (1972): The limits to growth: a report to the club of Rome. New York: Universe Books.

MENZEL, M.-P. and KAMMER, J. (2011): Unterschiede der Evolution von Industrien in *Varieties of Capitalism* – eine Überlebensanalyse der Windanlagenhersteller in Dänemark und den USA. *Geographica Helvetica* 66(4): 243–253. DOI: 10.5194/gh-66-243-2011.

MESSE HUSUM & CONGRESS GMBH & CO. KG (2017): History HUSUM Wind – from the first Husum Wind Energy days to now. Retrieved from: http://www.husumwind.com/husumwind/en/messe/messedaten/geschichte_entwicklung.php.

MINISTERIUM FÜR ARBEIT UND BAU MECKLENBURG-VORPOMMERN (MAB) (1999): Windenergienutzung im Spannungsfeld zwischen Klimaschutz, Naturschutz, Wohnen und Tourismus. Raumentwicklung in Mecklenburg-Vorpommern. Informationsreihe der Obersten Landesplanungsbehörde Nr. 1/1999. Schwerin. Retrieved from: http://databases.eucc-d.de/files/documents/00000108_MV_Windenergie.pdf.

MINISTERIUM FÜR UMWELT, KLIMA UND ENERGIEWIRTSCHAFT BADEN-WÜRTTEMBERG (2012): Auf gutem Kurs. Bilanz und Ausblick. Ein Jahr grün-rote Energiepolitik für Baden-Württemberg. Stuttgart. Retrieved from: https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/5_Energie/Energiewende/Auf_gutem_Kurs_-_Ein_Jahr_gruen-rote_Energiepolitik_fuer_BW.pdf.

MIÖRNER, J. and TRIPPL, M. (2017): Paving the way for new regional industrial paths: actors and modes of change in Scania's games industry. *European Planning Studies* 25(3): 481–497. DOI: 10.1080/09654313.2016.1212815.

MOLLY, J. P. (2009): Wind Energy – Quo Vadis? *DEWI Magazin*(34): 6–15.

MOSSIG, I. (2000): Lokale Spin-off-Gründungen als Ursache räumlicher Branchencluster. Das Beispiel der deutschen Verpackungsmaschinenbau-Industrie. *Geographische Zeitschrift* 88(3/4): 220–233.

MOWERY, D. C.; OXLEY, J. E. and SILVERMAN, B. S. (1996): Strategic alliances and interfirm knowledge transfer. *Strategic Management Journal* 17(S2): 77–91. DOI: 10.1002/smj.4250171108.

MURMANN, J. P. (2003): Knowledge and competitive advantage. The coevolution of firms, technology, and national institutions. Cambridge, New York: Cambridge University Press (Cambridge studies in the emergence of global enterprise).

MURMANN, J. P. and FRENKEN, K. (2006): Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy* 35(7): 925–952. DOI: 10.1016/j.respol.2006.04.011.

MUSALL, F. D. and KUIK, O. (2011): Local acceptance of renewable energy—A case study from southeast Germany. *Energy Policy* 39(6): 3252–3260. DOI: 10.1016/j.enpol.2011.03.017.

MUSGROVE, P. (2010): Wind power. Cambridge: Cambridge Univ. Press.

MUSIOLIK, J. and MARKARD, J. (2011): Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany. *Energy Policy* 39(4): 1909–1922. DOI: 10.1016/j.enpol.2010.12.052.

NEFFKE, F.; HENNING, M. and BOSCHMA, R. (2011): How Do Regions Diversify over Time? Industry Relatedness and the Development of New Growth Paths in Regions. *Economic Geography* 87(3): 237–265. DOI: 10.1111/j.1944-8287.2011.01121.x.

NELSON, R. and WINTER, S. G. (1982): An evolutionary theory of economic change. Cambridge: Belknap Press.

NELSON, R. R. (1993): National innovation systems. A comparative analysis. New York: Oxford University Press.

NELSON, R. R. (1994): The Co-evolution of Technology, Industrial Structure, and Supporting Institutions. *Industrial and Corporate Change* 3(1): 47–63. DOI: 10.1093/icc/3.1.47.

NELSON, R. R. (1995): Co–evolution of Industry Structure, Technology and Supporting Institutions, and the Making of Comparative Advantage. *International Journal of the Economics of Business* 2(2): 171–184. DOI: 10.1080/758519306.

NORDEX SE (2010): 25 Jahre Nordex. Pionier und Wegbereiter der Windindustrie. Norderstedt.

NORTH, D. C. (1990): Institutions, institutional change, and economic performance. Cambridge, New York: Cambridge University Press (The Political economy of institutions and decisions).

NORTH, D. C. (2005): Understanding the process of economic change. Princeton, N.J: Princeton University Press (The Princeton economic history of the Western world).

OECD (2005): Oslo Manual. Proposed Guidelines for Collecting and Interpreting Technological Innovation Data. 3rd Edition. Paris: OECD Publishing. DOI: 10.1787/19900414.

OELKER, J. (2005): Windgesichter. Aufbruch der Windenergie in Deutschland. 1. Ausg. Dresden: Sonnenbuch-Verl.

OHLHORST, D. (2009): Windenergie in Deutschland. Konstellationen, Dynamiken und Regulierungspotenziale im Innovationsprozess. 1. Aufl. Wiesbaden: VS Verlag für Sozialwissenschaften (VS research : Energiepolitik und Klimaschutz).

OXFORD ENGLISH DICTIONARY (2019): "technology, n.". Retrieved from: https://www.oed.com/view/Entry/198469?redirectedFrom=technology&.

PATTON, M. Q. (1990): Qualitative evaluation and research methods: SAGE Publications, inc.

PIKE, A.; MACKINNON, D.; CUMBERS, A.; DAWLEY, S. and MCMASTER, R. (2016): Doing Evolution in Economic Geography. *Economic Geography* 92(2): 123–144. DOI: 10.1080/00130095.2015.1108830.

PINCH T. J. and BIJKER W. E. (1984): The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other. *Social Studies of Science* 14(3): 399–441. DOI: 10.1177/030631284014003004.

PROGNOS AG (2019): Beschäftigung und Wertschöpfung in der deutschen Onshore-Windindustrie. Szenarien zum künftigen Ausbau der Onshore-Windenergie und Effekte auf Wertschöpfung und Beschäftigung in den Kernbereichen der Branche in den Kernbereichen der Branche.

RAFIQUI, P. S. (2009): Evolving economic landscapes: why new institutional economics matters for economic geography. *Journal of Economic Geography* 9(3): 329–353. DOI: 10.1093/jeg/lbn050.

RAMMERT, W. (1993): Technik aus soziologischer Perspektive. Opladen: Westdeutscher Verlag.

RAVE, K. and RICHTER, B. (2008): Im Aufwind. Schleswig-Holsteins Beitrag zur Entwicklung der Windenergie. Neumünstert: Wachholtz.

REN21 (2017): Renewables 2017 Global Status Report. Paris.

REPOWER SYSTEMS AG (2002): Geschäftsbericht 2001. Hamburg.

REPOWER SYSTEMS AG (2007): Gemeinsame Stellungnahme des Vorstands und des Aufsichtsrats der REpower Systems AG.

RIGBY, D. L. (2015): Technological Relatedness and Knowledge Space: Entry and Exit of US Cities from Patent Classes. *Regional Studies* 49(11): 1922–1937. DOI: 10.1080/00343404.2013.854878.

RIP, A. and KEMP, R. (1998): Technological change. In: Rayner, S. and Malone, E. L. (ed.): Human choice and climate change. Columbus, Ohio: Battelle Press: 327–399.

RÜBEL, J. (2012): Aurich, aber wahr. *brand eins*(04/12): 28–34.

SABATIER, P. A. (1998): The advocacy coalition framework: revisions and relevance for Europe. *Journal of European Public Policy* 5(1): 98–130. DOI: 10.1080/13501768880000051.

SANTJER, F. and KLOSSE, R. (2003): Die neuen ergänzenden Netzanschlussregeln von E.ON Netz GmbH – New Supplementary Regulations for Grid Connection by E.ON Netz GmbH. *DEWI Magazin*(22): 28–34.

SAXENIAN, A. (1994): Regional advantage. Culture and competition in Silicon Valley and Route 128. Cambridge, MA, London: Harvard university press.

SAXENIAN, A. (2006): The new argonauts: Regional advantage in a global economy. Cambridge, London: Harvard university press.

SCHAMP, E. W. (2002): Evolution und Institution als Grundlagen einer dynamischen Wirtschaftsgeographie: Die Bedeutung von externen Skalenerträgen für geographische Konzentration. *Geographische Zeitschrift* 90(1): 40–51.

SCHAMP, E. W. (2010): On the Notion of Co-evolution in Economic Geography. In: Boschma, R. and Martin, R. (ed.): The Handbook of Evolutionary Economic Geography. Cheltenham: Edward Elgar Publishing: 432–449.

SCHLESWIG-HOLSTEINISCHER LANDTAG (2000): Kleine Anfrage der Abg. Heinold (BÜNDNIS 90/DIE GRÜNEN) und Neugebauer (SPD) und Antwort der Landesregierung. Drucksache 15/ 675. Kiel.

SCHOT, J. and GEELS, F. W. (2007): Niches in evolutionary theories of technical change. *Journal of Evolutionary Economics* 17(5): 605–622. DOI: 10.1007/s00191-007-0057-5.

SCOTT, W. R. (1995): Institutions and organizations. Thousand Oaks: SAGE (Foundations for organizational science).

SETTERFIELD, M. (1993): A Model of Institutional Hysteresis. *Journal of Economic Issues* 27(3): 755–774. DOI: 10.2307/4226717.

SETTERFIELD, M. (1997): Should Economists Dispense with the Notion of Equilibrium? *Journal of Post Keynesian Economics* 20(1): 47–76. DOI: 10.1080/01603477.1997.11490138.

SIMMIE, J. (2012): Path Dependence and New Technological Path Creation in the Danish Wind Power Industry. *European Planning Studies* 20(5): 753–772. DOI: 10.1080/09654313.2012.667924.

SIMMIE, J.; STERNBERG, R. and CARPENTER, J. (2014): New technological path creation: evidence from the British and German wind energy industries. *Journal of Evolutionary Economics* 24(4): 875–904. DOI: 10.1007/s00191-014-0354-8.

SINE, W. D. and LEE, B. H. (2009): Tilting at Windmills? The Environmental Movement and the Emergence of the U.S. Wind Energy Sector. *Administrative Science Quarterly* 54(1): 123–155. DOI: 10.2189/asqu.2009.54.1.123.

SOMMER, P. (2015): Die Entwicklung der Windenergie: Onshore versus Offshore. Industrieräumlicher Wandel in Europa zwischen inkrementeller und radikaler Innovation. Stuttgart: Franz Steiner Verlag (Mitteilungen der Geographischen Gesellschaft in Hamburg, 107).

SONNE, WIND & WÄRME (2012): Fuhrländer übernimmt W2E Wind to Energy. Retrieved from: http://www.sonnewindwaerme.de/windenergie/fuhrlaender-uebernimmt-w2e-wind-energy.

STEEN, M. (2016): Reconsidering path creation in economic geography: aspects of agency, temporality and methods. *European Planning Studies* 24(9): 1605–1622. DOI: 10.1080/09654313.2016.1204427.

STEEN, M. and HANSEN, G. H. (2018): Barriers to Path Creation: The Case of Offshore Wind Power in Norway. *Economic Geography* 94(2): 188–210. DOI: 10.1080/00130095.2017.1416953.

STRAMBACH, S. (2010): Path Dependence and Path Plasticity: The Co-evolution of Institutions and Innovation – the German Customized Business Software Industry. In:

Boschma, R. and Martin, R. (ed.): The Handbook of Evolutionary Economic Geography. Cheltenham: Edward Elgar Publishing: 406–429.

SUCK, A. (2008): Erneuerbare Energien und Wettbewerb in der Elektrizitätswirtschaft. Wiesbaden: VS Verlag für Sozialwissenschaften.

SYDOW, J.; SCHREYÖGG, G. and KOCH, J. (2009): Organizational Path Dependence: Opening the Black Box. *Academy of Management Review* 34(4): 689–709. DOI: 10.5465/AMR.2009.44885978.

SZARKA, J. (2007): Wind power in Europe. Politics, business and society. Houndmills, Basingstoke, Hampshire, New York, N.Y: Palgrave MaCmillan (Energy, climate, and the environment series).

SZARKA, J. and BLÜHDORN, I. (2006): Wind power in Britain and Germany. Explaining contrasting development paths. London: Anglo-German Foundation for the Study of Industrial Society.

TACKE, F. (2004): Windenergie. Die Herausforderung. Gestern, Heute, Morgen. Frankfurt am Main: VDMA-Verl.

TANNER, A. N. (2014): Regional Branching Reconsidered: Emergence of the Fuel Cell Industry in European Regions. *Economic Geography* 90(4): 403-427. DOI: 10.1111/ecge.12055.

TER WAL, A. L. J. and BOSCHMA, R. (2011): Co-evolution of Firms, Industries and Networks in Space. *Regional Studies* 45(7): 919–933. DOI: 10.1080/00343400802662658.

TRIPPL, M.; BAUMGARTINGER-SEIRINGER, S.; FRANGENHEIM, A.; ISAKSEN, A. and RYPESTØL, J. O. (2020): Unravelling green regional industrial path development: Regional preconditions, asset modification and agency. *Geoforum*(111): 189–197.

TRIPPL, M.; GRILLITSCH, M. and ISAKSEN, A. (2018): Exogenous sources of regional industrial change: Attraction and absorption of non-local knowledge for new path development. *Progress in Human Geography* 42(5): 687-705. DOI: 10.1177/0309132517700982.

TUSHMAN, M. L. and ANDERSON, P. (1986): Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly* 31(3): 439. DOI: 10.2307/2392832.

UTTERBACK, J. (1994): Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change. Boston: Harvard Business School Press.

VERGNE, J.-P. and DURAND, R. (2010): The Missing Link Between the Theory and Empirics of Path Dependence: Conceptual Clarification, Testability Issue, and Methodological Implications. *Journal of Management Studies* 47(4): 736–759. DOI: 10.1111/j.1467-6486.2009.00913.x.

VON HIPPEL, E. (1986): Lead users: a source of novel product concepts. *Management Science* 32(7): 791–805.

VRIES, E. de (2007a): Innovation: The ingenious is always simple. *RENEWABLE ENERGY WORLD* 10(6): 68.

VRIES, E. de (2007b): REpower-Suzlon wins takeover battle. *RENEWABLE ENERGY WORLD* 10(4): 195.

VRIES, E. de (2009): GE Energy to Acquire Offshore Wind Turbine Supplier ScanWind of Norway. RENEWABLE ENERGY WORLD. 24 August 2009. Retrieved from: http://www.renewableenergyworld.com/rea/news/article/2009/08/ge-energy-to-acquire-offshore-wind-turbine-supplier-scanwind-of-norway.

VRIES, E. de (2015): Turbines of the year: Offshore turbines. WINDPOWER MONTHLY. 28 December 2015. Retrieved from: http://www.windpowermonthly.com/article/1377329/turbines-year-offshore-turbines.

WAB (2020): The WAB. The network for wind energy. Retrieved from: https://www.wab.net/en/wab/about-us/wab/.

WARREN, C. R. and MCFADYEN, M. (2010): Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. *Land Use Policy* 27(2): 204–213. DOI: 10.1016/j.landusepol.2008.12.010.

WINDENERGY NETWORK E.V. (2020): Turning power into business. Retrieved from: https://www.wind-energy-network.de/.

WINDPOWER MONTHLY (1994a): AN Maschinenbau und Umweltschutzanlagen celebrates its first decade. Retrieved from: http://www.windpowermonthly.com/article/958893/maschinenbau-und-umweltshutzanlagen-celebrates-its-first-decade.

WINDPOWER MONTHLY (1994b): HSW develops a 1 MW turbine. 06/1994. Retrieved from: http://www.windpowermonthly.com/article/960073/hsw-develops-1-mw-turbine.

WINDPOWER MONTHLY (1999): Nordex takes over Südwind. 02/1999. Retrieved from: http://www.windpowermonthly.com/article/951891/nordex-takes-s-uumldwind.

WINDPOWER MONTHLY (2008): A potential game changing move - Siemens' direct drive experiment. 09/2008. Retrieved from: http://www.windpowermonthly.com/article/952925/potential-game-changing-move---siemens-direct-drive-experiment.

WOODSIDE, A. G. and WILSON, E. J. (2003): Case study research methods for theory building. *Journal of Business & Industrial Marketing* 18(6/7): 493–508.

YIN, R. K. (2014): Case study research. Design and methods. Fifth edition: SAGE.

# Curriculum vitae

| | |
|---|---|
| Name: | Jasper Wellbrock (né Ammermann) |
| Born: | 01 February 1985 in Bremen, Germany |

**Career**

| | |
|---|---|
| 2017 – 2021 | Business Promotion Service, City of Minden |
| 2013 – 2017 | Research Associate at the Institute of Economic and Cultural Geography, Leibniz University Hannover |
| 2012 – 2013 | Research Associate at the Department of Geography, University of Bayreuth |
| 2011 – 2012 | Research assistant at Prognos AG, Bremen |

**Academic education**

| | |
|---|---|
| 2013 – 2020 | PhD student, Institute of Economic and Cultural Geography, Leibniz University Hannover |
| 2006 – 2011 | Studies of Geography (diploma) at the University of Münster |
| 2005 – 2006 | Studies of Geography (diploma) at the Leibniz University Hannover |

**Education**

| | |
|---|---|
| 1997 – 2004: | Gymnasium Osterholz-Scharmbeck |
| 1995 – 1997 | OS Am Wällenberg, Hambergen |