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Mechanisms of energy transitions: National cases and the worldwide uptake of wind and solar power

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Author's declaration:

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Furthermore, this dissertation contains no materials previously written and/or published by another person, except where appropriate acknowledgment is made in the form of bibliographical reference, etc.

Vadim VINICHENKO

Statement of contribution

This thesis incorporates intellectual material from two published multi-author research papers co-authored by the candidate.

- Section 2.7.1 of the Literature Review (Chapter 2) and Section 3.1 of the Conceptual Framework (Chapter 3) are partially based on the following paper, where the candidate was the 2nd co-author:

  Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research and Social Science*, 37, pp.175–190.

- Sections 5.2 and 5.3 in the Comparative Analysis of Electricity Transitions in Germany and Japan (Chapter 5) are largely based on the following paper, where the candidate was the 2nd co-author particularly responsible for empirical data analysis; several illustrations in Chapter 5 are also sourced from this paper (these were primarily prepared by the candidate):

  Cherp, A., Vinichenko, V., Jewell, J., Suzuki, M. and Antal, M., 2017. Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan. *Energy Policy*, 101, pp.612–628.

Table of Contents

List of figures

List of tables

List of abbreviations

2FLC	Two-factor learning curve
ACF	Advocacy coalition framework
AIC	Akaike information criterion
BEP	Basic Energy Plan (Japan)
bln	billion
BMFT	Federal Ministry for Research and Technology (Germany)
BOO	Build-own-operate
BTSCS	Binary time-series cross-sectional [data]
CASE	Commission for Additional Sources of Energy (India)
CDM	Clean Development Mechanism
CME	Coordinated market economy
CR	Cox regression
DI	Discursive institutionalism
DME	Dependent market economy
DNES	Department of Non-Conventional Energy Sources (India)
EEC	European Economic Community
EEG	Renewable Energy Act (Germany)
EU	European Union
EU15	Fifteen EU member states prior to the enlargement in 2004
FIT	Feed-in tariff
GDP	Gross domestic product
GDP/ca	Gross domestic product per capita
GHG	Greenhouse gases
GNI	Gross national income
HI	Historical institutionalism
IAE	International Energy Agency
IAM	Integrated assessment model
IDAE	Institute for Energy Diversification and Saving (Spain)
INDC	Intended Nationally Determined Contributions
IREDA	Indian Renewable Energy Development Agency

IRENA	International Renewable Energy Agency
LCET	Low-carbon energy technologies
LCV	League of Conservation Voters
LDP	Liberal Democratic Party (Japan)
LME	Liberal market economy
LR	Logistic regression
MAP	National Environmental Action Plan (Netherlands)
METI	Ministry of Economy, Trade and Industry (Japan)
MLP	Multi-level perspective
MNES	Ministry of Non-Conventional Energy Sources (India)
MNRE	Ministry of New and Renewable Energy (India)
MP	Member of Parliament
NIS	National innovation system
Non-OECDHI/EU	Countries that are neither high-income OECD members nor EU member states
NREA	National Renewable Energy Agency (Egypt)
OECD	Organization for Economic Cooperation and Development
OECDHI	OECD members with high income per capita
OECDHI/EU	Countries that are high-income OECD members or EU member states
OLS	Ordinary least squares
p.p.	Percentage point
PPC	Public Power Corporation (Greece)
PPF	Production possibility frontier
PPML	Poisson pseudo maximum likelihood
PV	Photovoltaic
QCA	Qualitative comparative analysis
R&D	Research and development
RCP	Residential, commercial, and public services
RD&D	Research, development, and demonstration
RE	Renewable energy
RES-E	Renewable sources of electricity
RET	Renewable energy technology

ROI	Return on investment
RPS	Renewable portfolio standard
RSD	Relative standard deviation
SD	Standard deviation
SNM	Strategic niche management
SPD	Social Democratic Party (Germany)
StrEG	Feed-in Act (Germany)
STS	Science and technology studies
SW	Solar and wind power
TIC	Techno-institutional complex
TIS	Technological innovation system
UNIDO	United Nations Industrial Development Organization
USAID	US Agency for International Development
VoC	Varieties of capitalism

Abstract

An increase in the use of renewable energy is an important part of a global energy transition, essential for reducing the risk of climate change. The existing global scenarios of energy transitions poorly account for economic, social, and political circumstances of individual countries. Yet a global energy transition can only be achieved as sum of national energy transitions. This thesis contributes to understanding of energy transitions that is both nationally differentiated and globally relevant, empirically grounded, and integrates insights from relevant social science disciplines.

The conceptual contribution of this thesis is a conceptualization of national energy transitions as an outcome of recurring causal mechanisms within and across co-evolving systems of energy flows and markets, energy technologies, and energy policies. The thesis uses insights from techno-economic, socio-technical, and political perspectives on energy transitions to identify generic energy transition mechanisms and validates and refines these mechanisms, also demonstrating their explanatory power through a three-stage empirical research.

The first stage is a comparative case study of energy transitions in Germany and Japan. It explains why Germany has become a leader in renewables while phasing out nuclear energy, whereas Japan has deployed less renewables while becoming a leader in nuclear power. The thesis identifies such explanatory mechanisms as the faster growth of electricity demand in Japan, the easier diffusion of onshore wind power technology, and the weakening of the nuclear power regime induced by stagnation and competition from coal and renewables in Germany. This explanation contrasts and improves on the majority of the single-factor explanations of this difference in the existing literature.

At the second stage, the thesis analyses early phases of wind and solar power adoption in 12 countries with diverse socio-economic circumstances. It identifies the “formative phase” mechanisms with particular focus on the formation of state goals, international diffusion, and local technology deployment systems.

At the third stage, the thesis analyses the introduction of wind and solar power in 60 largest electricity producers worldwide. Methodological contributions of this thesis include using the “takeoff year” when the combined share of solar and wind power first exceeds 1% of electricity supply as the dependent variable and using event history analysis for the analysis of this variable. As a novel application of the mechanisms-based approach, it compares the strengths of different mechanisms across countries in terms of capacities, motivations, and interactions of state and non-state actors involved in energy transition mechanisms.

The empirical contribution of the thesis is clarifying socio-political and economic factors which influence the position of a country in the core or periphery of technology diffusion. This highlights an exceptional role of the European Union, effective governance associated with the OECD membership, high-income status, and large size of economies in low- and middle-income countries. It observes that major energy exports in non-OECD countries hinder their capacity to introduce renewables. The thesis does not find any evidence that the level of democracy or climate impacts of energy systems affect the timing of renewable energy introduction within either developed or developing countries.

The thesis outlines a research agenda of extending its analytical approach and empirical findings beyond the formative phase and beyond wind and solar power. In addition to explaining national differences, it identifies a regular global pattern of renewable energy adoption, something that can be used in constructing more informative and realistic decarbonization pathways and scenarios.

Keywords: energy transitions, renewable electricity, causal mechanisms, event history analysis.

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1 Introduction

Rapid deployment of renewable energy (RE) on the global scale is essential for curbing carbon emissions and mitigating dangerous climate change (GEA 2012). What is required is a true energy transition – "a change in the state of an energy system as opposed to a change in an individual energy technology or fuel source" (Grübler et al. 2016, p.18). Is such a transition possible? Can it be done sufficiently fast to reduce climate change risks?

Global energy scenarios seek to answer this question by identifying plausible transition pathways (GEA 2012). These scenarios underpin major international assessments and policy recommendations. However, being based primarily on Integrated Assessment Models (IAMs), they almost entirely rely on stylized assumptions from energy engineering and neoclassical economics and do not account for diverse political and socio-technical factors that are critical for the deployment of renewables (Holtz et al. 2015). The question the models are best poised to answer is what is plausible from the economic and technical standpoint, not whether it is likely to be achieved under given social and political circumstances.

Furthermore, the models deal mostly with the global level or, at best, use a few large macro-regions differentiated by their resource endowments and energy demand, and not by their social and political characteristics. But the global transition is going to happen in a world that consists of individual countries and therefore can succeed only as a sum total of national transitions calling for a national-level analysis.[1] Analytical focus on the national level is important for three reasons. First, energy systems, especially in the electricity sector which is at the center of my thesis, are usually nationally delineated, governed and monitored. Second, the national level remains central in policy-making and thus determining policy-driven changes in energy systems. Third, many conditions that influence deployment of renewable energy (such as geography, demography and economy) are more similar *within* than *across* countries. Focusing on the national level immediately gives rise to a number of questions important to the pace and outcome of the global transition. Why do individual countries adopt renewables? Why some countries introduce renewables earlier than others? Are government policies the key driver of renewable energy deployment? How fast can a given country deploy renewable energy on a nationally significant scale? Conceptually rigorous and empirically validated answers to such questions are essential for constructing global pathways that reflect nationally differentiated long-term regularities in energy transitions.

[1] This does not exclude international factors, but considers them by and large in light of their ability to affect national-level developments.

There are two large bodies of literature focused on national energy transitions, which are potentially able to provide relevant empirical and conceptual knowledge. One is centered at national case studies.[2] These studies explore in detail the evolution of socio-technical systems embedding renewable energy technologies within specific geographic, economic and political circumstances of individual nations. The in-depth case studies demonstrate complexity and contingency involved in energy transition processes. However so far, it has been difficult to generalize their findings in the global perspective. They are well-positioned to explain transitions in an individual country or several similar countries, but have less to say about whether a particular factor is significant for a broader set of diverse countries, especially in a longer-term perspective.[3] This is especially the case because these studies typically focus on frontrunner countries[4] (mainly wealthy industrial democracies), while technology adoption in "periphery" countries, often more significant from the global standpoint, receives less attention.

Another body of literature is cross-country quantitative studies of renewable energy deployment.[5] In contrast to in-depth case studies, this literature looks into large samples comprising dozens or even over a hundred countries. It seeks to produce generalizable results by using statistical techniques such as panel regression. However, the primary focus of most such studies (largely originating in political science) are political processes which lead to the adoption of renewable energy policies. As a result, these studies tend to neglect other factors (economic, engineering, geographic, technological, social) shaping energy transitions and overlook important distinctions between different technologies or different stages of technology development.[6]

In summary, neither national case studies nor large-N multi-country comparisons have so far provided insights that are empirically grounded, sufficiently multidisciplinary to account for all important factors, and generalizable on the global and long-term scales. My thesis aims to build upon and go beyond the existing scholarship in order to improve the understanding of energy transitions which would be both nationally-differentiated and globally relevant,

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[2] This body of literature is reviewed in sections 2.4 and 2.5 of this thesis.

[3] Furthermore, the identification of causality in individual cases may be difficult due to the problem of overdetermination characteristic to case-based analysis (too many plausible causes for the outcome) (Goertz 2017).

[4] Some studies deal with later adopters such as India or China (Lewis 2007; Gosens and Lu 2013). However, they remain interested in countries developing their own renewable energy equipment manufacturing, approaching them from an innovation perspective, and leave aside the countries simply deploying the equipment produced elsewhere.

[5] This literature is reviewed in section 2.8 of this thesis.

[6] For example, some of them merge hydro power – a traditional energy source that has reached saturation in most industrialized countries – with rapidly growing and developing "new renewable" technologies.

grounded in empirical data, and would integrate conceptual insights from relevant social science disciplines.

In my thesis, I am focusing on a transition to renewable energy in the electricity sector – an ongoing process which has progressed far enough, at least in in certain countries, to offer useful lessons for other countries and sectors – and rely on a combination of case-based and statistical analysis. I am going to achieve the aim of the thesis by meeting four specific objectives:

1. **Develop a conceptual approach to integrating different bodies of knowledge explaining energy transitions.** The two conceptual foundations for this approach are (a) generic national energy transitions mechanisms and (b) three disciplinary perspectives on national energy transitions. I understand transition mechanisms as causal mechanisms (Tilly 2001; Little 2015) which connect explanatory factors with outcomes and are characterized by a high degree of regularity. I aim to explain national energy transitions through identifying regularly recurring mechanisms and their unique combinations which lead to specific outcomes in different contexts.

My approach also assumes that national energy transitions involve relatively autonomous but co-evolving systems which can be categorized into three distinct types: energy flows and markets, energy technologies, and energy policy systems. This systemic diversity gives rise to three disciplinary perspectives on national energy transitions: techno-economic, socio-technical, and political. The concept of interacting mechanisms helps to bring together different disciplinary perspectives, whereas the hierarchical nature of mechanisms and associated variables bridges different levels of empirical analysis.

2. **Identify generic mechanisms of national electricity transitions.** Generic mechanisms and associated variables form essential building blocks of mechanism-based accounts of transitions. I identify an initial repertoire of mechanisms and a scheme of their interaction based on the literature from three different disciplinary fields representing the three perspectives on energy transitions.

3. **Validate and refine the identified mechanisms using national case studies.** I use a detailed comparison of national electricity transitions in two countries – Germany and Japan – to validate the identified mechanisms in case of a long-term transition in major economies involving diverse energy sources and technologies. Subsequently I analyze twelve national case studies focusing on “new renewables” (wind and solar PV power) and on an early period of renewable energy deployment known as the “formative phase”. Through the case studies I both validate the theoretically identified mechanisms and identify new mechanisms, especially with respect to the formative phase of renewable energy deployment.

4. **Explain the timing of deployment of wind and solar power across a global sample of countries in terms of the transition mechanisms.** This analysis is conducted through a set-theoretical exploration and statistical techniques of event history (survival) analysis.

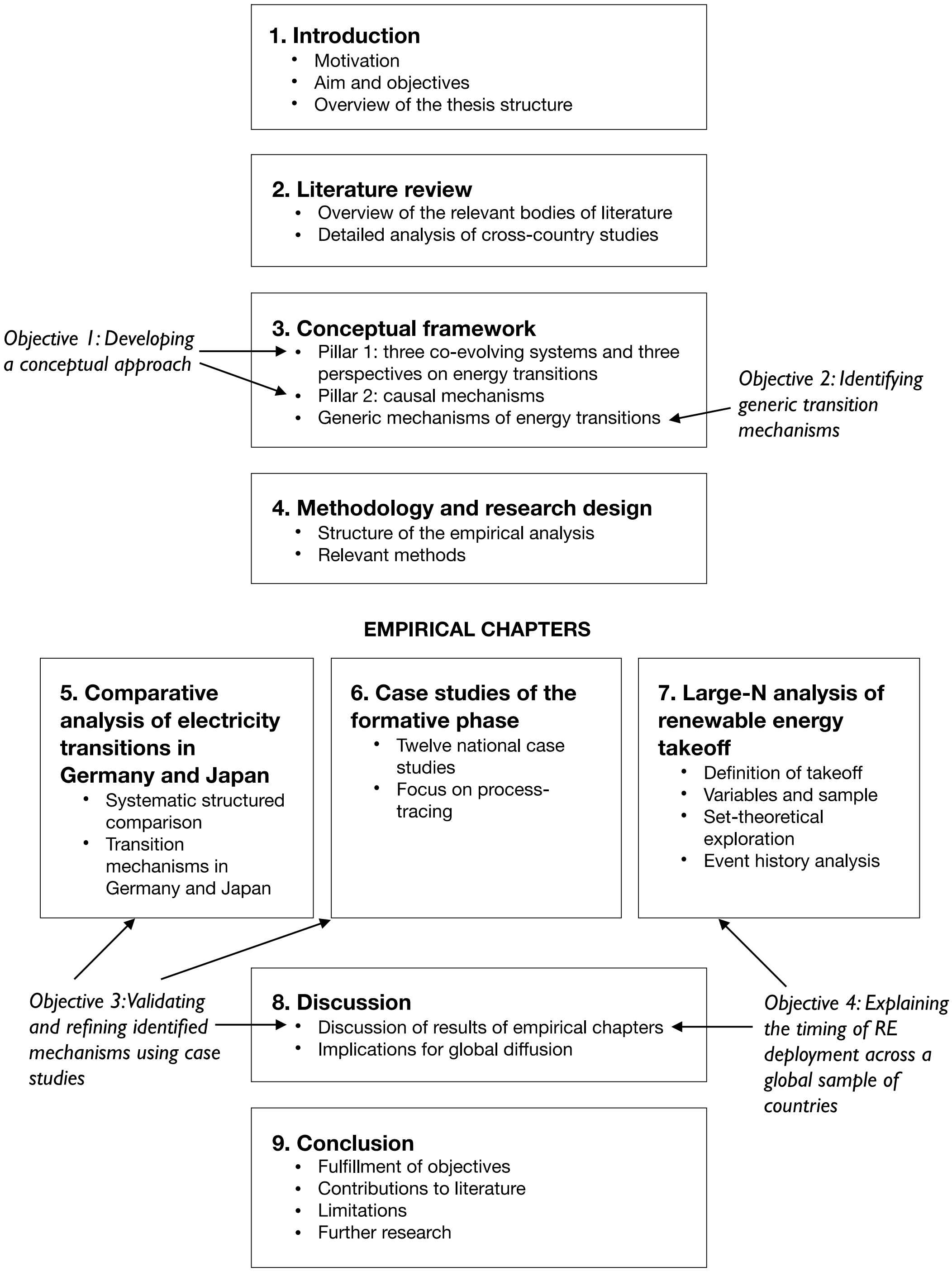
My study aims to lay a foundation for an interdisciplinary mechanism-based understanding of national energy transitions. I demonstrate the ability of this approach to combine disciplinary knowledge, integrate case-based insights with statistically derived regularities, and formulate a framework where further concepts and empirical findings can be integrated without disrupting the foundation of this understanding.

The structure of my thesis is shown on Figure 1.1. This Introduction is followed by the literature review (Chapter 2) covers the main bodies of literature related to energy transitions including energy-economic models; technology diffusion theories; socio-technical theories of innovation systems, regimes, and niches; the spatial and the political perspectives. The chapter concludes with a review of quantitative cross-country studies of renewable energy deployment.

My conceptual framework (Chapter 3) includes two pillars. The first pillar is the idea of three types of co-evolving systems and three disciplinary perspectives on energy transitions. The second pillar is causal mechanisms of national energy transitions which provide a way of integrating heterogeneous knowledge produced within these different disciplinary perspectives. The framework also includes the concepts of capacity, motivation, and interaction of actors which characterize mechanisms of energy transitions. Then it proceeds with presenting the generic energy transitions mechanisms which provide a starting point for the empirical inquiry in the subsequent chapters. I also elaborate the concept of the formative phase found in different strains of literature and propose a conceptual model connecting the transition mechanisms to stages of technology deployment.

Chapter 4 outlines the overall approach to building mechanism-based accounts of energy transitions. Then it describes the key components of my research design: a longitudinal comparative analysis of two countries, twelve national case studies, and a large-N analysis of 60 of countries.

Figure 1.1. Chapters and objectives of this thesis



Note: Numbered boxes represent thesis chapters. Italic text represents objectives; arrows point to chapters or sections where the respective objectives are immediately addressed.

Chapters 5–7 present the results of the empirical analysis. Chapter 5 contains a comparative analysis of two national cases of energy transitions – Germany and Japan. Relying on scholarly sources, national policy documents, and quantitative data, I use the mechanism-based approach to explain the differences in the use of nuclear, wind, and solar power in these countries. In doing so, I also validate the mechanistic framework for analyzing energy transitions as well as the relevance of all three disciplinary perspectives.

Chapters 6 and 7 expand the range of counties while narrowing down the scope of analysis focusing on a single period – the formative phase – and a single type of energy technologies – "new renewables" (wind power and solar PV). Chapter 6 reviews twelve national case studies based on secondary sources. The analysis in the chapter is focused on mechanisms eventually leading to the beginning of sustained growth of renewable energy sources driven by positive feedback loops. Collectively, the case studies support a view of early renewable energy deployment as a gradual expansion of the entire socio-technical system including physical installations, networks, policies, practices, local deployment systems etc. with complex causation among these elements. A special attention is paid to interaction between countries, placing the national histories in the global context.

Chapter 7 contains the main empirical contribution of this thesis. It analyzes renewable energy takeoff – the end of the formative phase opening the way for sustained growth of renewable sources – in a broad sample of 60 countries collectively accounting for some 95% of global electricity supply. The chapter starts with the definition of takeoff based on a simple model of renewable energy uptake and diffusion. The takeoff year (the year when the combined capacity of wind and solar power for the first time reaches 1%) is used as the dependent variable in my analysis, which makes it possible to use statistical techniques of event history analysis later in the chapter. The statistical analysis is preceded by an exploratory set-theoretical examination. Finally, an event history (survival) analysis of renewable energy takeoff is undertaken in order to identify factors that make countries achieve the sustained growth phase sooner or later. The analysis is performed for the entire global sample and, separately, for two major country groups. To cross-validate the results, I am using two methods of survival analysis – Cox regression and logistic regression with time variables – demonstrating that they produce largely similar results.

Chapter 8 contains a discussion bringing together the findings of the empirical analysis, using transition mechanisms as a language to relate these findings to each other. Then the chapter proceeds with a broader discussion of renewable energy deployment processes on the global scale, exploring a question of what places a country into the core or the periphery in the global diffusion process.

Chapter 9 presents the conclusions of the thesis. It starts with summarizing how the four objectives of this thesis have been fulfilled. Then it discusses contributions of the thesis to various bodies of literature and outlines the limitations of my research. Finally, an agenda for future research is discussed.

2 Literature review

2.1 Introduction

This literature review covers several bodies of literature seeking to explain energy transitions from different disciplinary standpoints, particularly those connected to the three perspectives on energy transitions defined in this thesis – techno-economic, socio-technical, and political (Chapter 3). This review pays special attention to both limitations and mutual complementarities of these disciplinary traditions. Section 2.2 reviews approaches based on neoclassical economics, which is at the heart of the techno-economic perspective and a foundation of integrated assessment models generating transitions pathways for mitigating climate change. Section 2.3 deals with theories of technology diffusion that are relevant to my analysis of the worldwide deployment of RE technologies. Sections 2.4 and 2.5 discuss the other socio-technical approaches to technology transitions. Section 2.4 deals with the innovation system approach with a particular focus on technological innovation systems (TIS). Section 2.5 discusses the concepts of socio-technical regime and niche, which form the basis of two additional scholarly traditions: strategic niche management (SNM) and the multi-level perspective (MLP). Section 2.6 deals with the "spatial perspective" which complements socio-technical accounts of transitions by incorporating insights from geography. Section 2.7 reviews literature on the role of policy and politics in energy transitions. Section 2.8 reviews comparative multi-country studies of RE deployment primarily conducted within the tradition of political science. Section 2.9 is a conclusion that summarizes key ideas found in different bodies of literature and bridges this literature review with the rest of the thesis.

2.2 Modelling energy transitions and neoclassical economics

Energy commodities (e.g. firewood, coal, town gas), infrastructure (e.g. mines, steam engines, railroads), and services (e.g. heating, lighting) have been at the heart of industrial revolution and development of modern capitalist societies in the 18th and 19th centuries. It is therefore not surprising that they received keen and extensive attention of economists who sought to understand how capitalist societies function (e.g. Jevons 1866). Therefore the theories concerning energy extraction, transformation and use by societies were first developed within the discipline of classical economics, subsequently branching into more specific fields of energy and natural resource economics.

One of the central ideas within this body of knowledge is that of supply-demand balance as market equilibrium. It is based on the assumption that societies allocate resources to energy commodities and technologies in an "optimal" fashion which is determined on the one hand by the costs of these commodities and technologies and on the other hand by consumers' willingness to pay for various energy services that these resources and technologies provide. This idea implies that the energy mix used by a particular society approximates efficient allocation of resources under given costs and societal preferences or, in other words, is on the "production possibility frontier" (PPF) (Grubb 2014). Neoclassical economics can explain not only stability of energy systems but also some of their changes. For example, resource depletion leads to increasing extraction costs and thus may prompt shifts to other resources, more efficient equipment, or reduced consumption. Population growth leads to increasing demand and thus may trigger additional supply of resources and infrastructure.

This neoclassical economic view is confirmed by extensive historical observation that societies prefer more easily available (i.e. cheaper) energy sources and technologies. For example, economic historians Kander et al. (2014) and Fouquet (2008) convincingly demonstrated that shifts from biomass to fossils first occurred in the regions where wood was scarce and expensive and coal was abundant and cheap (e.g. Great Britain). Allen (2009) showed how relative costs of coal and labor led to England embarking on industrial use of fossil fuel and eventually becoming a pioneer of industrial revolution.

The formal and quantitative nature of the neoclassical view enables its relatively straightforward translation into energy-economy models. Nordhaus (1973) developed one of the first neoclassical models of efficient allocation of energy resources over time. The interests in such models dramatically increased in the 1970s in connection not only with advances in computing but also with the oil crises (see e.g. Winebrake and Sakva 2006; Laitner et al. 2003; Wene 2003; Kavrakoğlu 1987). Trajectories of future energy transitions developed under different assumptions have been called "scenarios" (later – "pathways") and combined forward-looking projections of economic and population growth and resource availability with empirical observations on how energy conversion and use changed historically (e.g. Anderer et al. 1981). In addition to neoclassical economics, these scenarios incorporated engineering and economic theories, such as technological substitution (Fisher and Pry 1971), which Marchetti and Nakicenovic (1979) extended to energy sources (Grübler 2012).

The purpose of these models and scenarios was primarily not to explain the past, but rather to predict future changes in energy systems, for example those that could follow from changing price or availability of oil. In the 1970s and the 1980s, such scenarios addressed widespread concerns about oil scarcity by portraying futures dominated by nuclear power and natural gas (Anderer et al. 1981). More complex models of the 1990s and the 2000s (e.g. Nakićenović, Kram, et al. 2000) came especially handy with the increasing concerns over the risks of climate change and the effort needed to stop it, which required understanding the evolution of energy systems on the global scale over the next century. Energy-economy modelers rose to this challenge by creating Integrated Assessment Models (IAMs), which coupled energy-economy models with climate and other Earth system models (Houghton et al. 1992; Legget et al. 1992; Nakićenović, Alcamo, et al. 2000). Since then, IAMs have become the common language of climate scientists, energy experts and the policy community. It was IAMs[7] that most clearly rang the alarm bell that under reasonable assumptions about the availability of energy resources, economic growth, and historic patterns of renewing energy infrastructure, catastrophic climate change in this century is almost a near certainty, unless decisive policies avert it.

Most long-term scenarios developed within IAMs portray dramatic shifts in energy systems in the future. The four main mechanisms driving these shifts are: (1) population and economic growth; (2) resource depletion; (3) technology development; and (4) government policies. The IAM community uses a range of agreed assumptions about the first two mechanisms, that are exogenous to most IAMs (Riahi et al. 2017; O'Neill et al. 2013).

The third mechanism is based on the idea that the costs of energy technologies change over time, making it possible to produce "more with less" thus expanding the production possibility frontier (Grubb 2014). Starting from the 1920s, economists have documented the evolution of the cost of technologies (Wright 1936) and applied these "experience" or "learning" curves to the costs of renewables (Neij 1997), nuclear (Grübler 2010), and other energy technologies. In most IAMs, technology learning occurs equally fast in different regions and countries, and when low-carbon energy technologies (LCETs) become competitive with existing technologies the neoclassical theories predict almost immediate "flipping" of energy systems to new configurations. Such "flipping" or very rapid transformations resulting from the assumption of perfectly efficient resource allocation[8] do not seem realistic or reflecting historical experience. Furthermore, many IAMs model investment decisions based on full information about future technology costs and other constraints ("perfect foresight"). For this reason, IAMs tend to "over-optimize" the required socio-technical shifts compared to a gradual "wait-and-see" approach usually observed in real-life investors and other social actors. Small changes in parameters of technologies in such models may lead to dramatic changes in modeling results (Wilson et al. 2013).

[7] In the last two decades, IAMs have become increasingly sophisticated and influential, especially in the work of the IPCC, and other bodies which need long-term outlooks of global energy development, for example, the IEA's World Energy Outlooks (OECD 2017), the Global Energy Assessment (GEA 2012) and the UN Secretary General's Sustainable Energy for All (SE4All) initiative (Rogelj et al. 2013).

[8] Optimal resource allocation can be interpreted as resulting from actions of rational agents in a perfect market, or from decisions of a perfectly efficient social planner.

To make the representation of technological change more realistic, most IAMs calibrate the growth rates of technologies against historical experience or even impose external constraints based on historical data (Wilson et al. 2013). For example, Marchetti and Nakicenovic (1979) and Wilson and Grübler (2011) analyzed long-term macro trends in energy supply and rates of growth of energy supply technologies for use in forward-looking models. However, these comparisons and calibrations are typically global and do not take into account regionally unequal adoption of technology. Recognizing this limitation, a recent exploratory model represented more realistic technology diffusion in MESSAGE IAM based on a stylized three-region world (Leibowicz et al. 2016). However, attribution of regions to “core”, “rim” or “periphery” in this model was not based on empirical evidence. To compensate for the deficiencies of the “perfect foresight” assumption, some models use “myopic” behavior of investors as if they were not aware about the future trends and developments and would make investment decisions based only on immediately available information (van Vuuren 2007).

The fourth mechanism of energy transitions modelled in IAMs are public policies restricting or promoting certain energy sources or technologies. Most frequently, IAMs model decarbonization policies that aim to limit GHG emissions from energy transformation and use. Whereas technology learning reduces costs of LCETs, decarbonization policies modelled in IAMs limit the use of fossil fuels (e.g. through emissions constraints or carbon tax) thereby making LCETs more competitive. IAMs have also been used to estimate the intensity and the costs of such climate stabilization policies (Clarke et al. 2014; Tavoni et al. 2014) as well as policies to achieve other energy goals such as universal access to modern energy (Pachauri et al. 2013) or reducing energy imports (Jewell et al. 2016). Though this work gained IAMs a central role in the climate change debate (Clarke et al. 2014; Edenhofer et al. 2014), it leaves open the question of whether some policy choices are more likely than others or indeed can be made at all (Geden 2015). For this reason, IAMs have been criticized for neglecting political and institutional factors (Geels, Berkhout, et al. 2016; Lane and Montgomery 2013). Another related criticism of policy modelling within IAMs is that decarbonization constraints in IAMs are typically determined by global considerations (e.g. carbon budgets) rather than by national priorities (e.g. energy security). This does not reflect the fact that the willingness and abilities of governments to pass and implement effective decarbonization policies varies from one country to another. This variance is another factor behind the regionally uneven uptake of LCETs (Baldwin et al. 2016), which is not adequately reflected in IAMs’ global decarbonization pathways.

Closely related to but distinctly different from neoclassical economic modelling literature is the body of knowledge coming from economic history and environmental economics. Within this tradition, scholars sought to discern empirical macro-patterns of the evolution of energy use by societies. For example, they have shown that wealthier societies use more and "higher quality" energy per capita (Bashmakov 2007; Burke 2010; Burke and Csereklyei 2016; Csereklyei et al. 2016; Kander et al. 2014).

Grubb (2014) and Grubb et al. (2015) highlight two key limitations of the neoclassical view of energy transitions. Both arise from the central assumption that the use of energy resources and technologies is perfectly efficient, i.e. corresponds to the PPF. First, Grubb et al. observe that most energy uses in societies deviate from the optimal equilibrium primarily due to the fact that very few, if any, social actors behave as "homo economicus" (i.e. optimize the outcomes of their decisions in light of nearly perfect information) in most of their decisions. This means that the use of energy resources is almost always "suboptimal", i.e. below the PPF. This is likely to be even more true when we consider not a single energy market but a global set of heterogenous energy systems, each of which may be suboptimal in its own way. The bodies of knowledge dealing with suboptimal ("satisficing") behavior include behavioral economics and theories of organizational decision-making.

Secondly, Grubb et al. (2015) observe that the PPF is not static, but it is constantly expanding because of technological and social innovation. This observation is partially incorporated in neoclassical "endogenous growth models" where technological advance results from dedicated investment, which can be interpreted as R&D expenditures or investment in human capital, or from accumulated experience in capital goods production[9] (Romer 2011). While helping to "endogenize" economic growth in neoclassical representation of the economy, these models say little about actual nature of innovation. Many IAMs also include technological advance as "technology learning", but Grubb et al.'s point is wider. They allude to the whole body of knowledge (evolutionary or institutional economics) that deal with outward expansion of the PPF.

2.3 Technology diffusion

The IAMs described in the previous section rely on technology diffusion studies for realistic technology expansion and learning rates and patterns. The concept of diffusion describes "adoption of a technology over time within a population and geography of potential adopters" (Grübler et al. 2016, p.19), both within a single location (temporal diffusion) and across several locations (spatial diffusion). Having originated in sociology and marketing research, diffusion concepts are now widely used in the analysis technology change.

[9] These two mechanisms are similar to "learning by search" and "learning by doing" described in section 2.3.

2.3.1 Diffusion of individual innovations

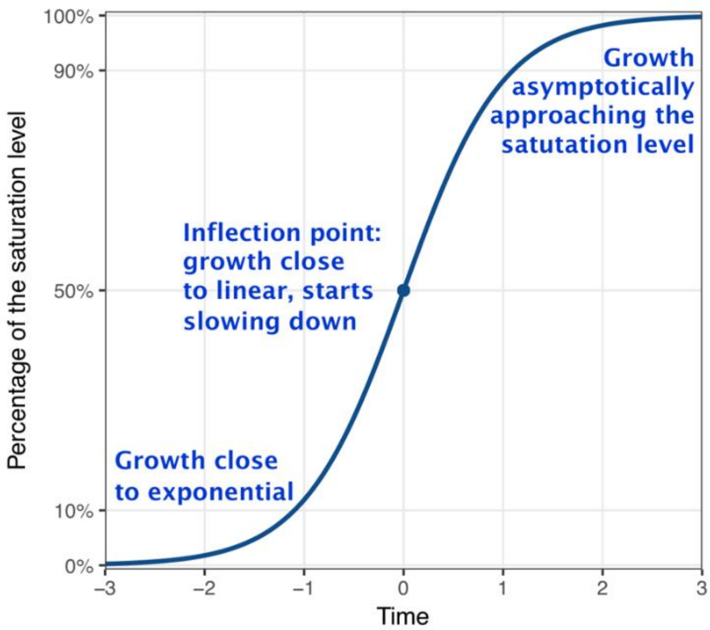
In his seminal book, Rogers (2003) discusses diffusion of innovation from a sociological perspective. He defines innovation as "an idea, practice, or project that is perceived as new by an individual or other unit of adoption" (Rogers 2003, p.12). Rogers describes a typical process of innovation diffusion in a potential market, which includes slow uptake by early adopters, acceleration, subsequent slowdown, and a protracted period of spread among very late adopters. In Rogers' model, innovation adoption is driven by information exchange, and the rates of innovation diffusion are explained by the timing of information exchange processes (which, in turn, depends on the nature of information channels and their network topology) and differential propensity for adoption among actors. The innovation itself does not change in the process. Characteristics of a particular innovation affecting its faster or slower diffusion may include: its relative advantage; compatibility with user needs, experiences, and values; complexity; trialability; and observability (Rogers 2003).

One popular way of representing diffusion of a product, practice, or technology in a stylized way is the 3-parameter logistic growth function (Wilson 2012), which takes the form:

$$y = \frac{K}{(1 + e^{-b(t-t_0)})}$$

where K is saturation level, b – growth rate, and t_0 – the inflection point of maximum growth rate (see Figure 2.1).

Figure 2.1. Logistic curve representing innovation diffusion



The parameters of the function correspond to three mutually independent characteristics of a diffusion process: whether it happens earlier or later, measured by the inflection point t_0 (alternative measures may include the moment where the market share reaches 10% or 90% of the saturation level); how rapid it us, measured by *b* (an alternative measure is the time period over which the market share growth from 10% to 90%, which is inversely related to b as log(81)/*b*); and the saturation level or maximum potential market, measured by *K*. The shape of the function fits the qualitative description provided by Rogers (2003) – a long period of slow growth followed by exponential acceleration, slowdown and saturation. The function is symmetrical, and the market share at the inflection point, where the growth rate peaks and starts slowing down, is exactly 50% of the saturation level. The logistic function is a member of a broader class of "sigmoid" functions that can be used to model diffusion processes[10] (Höök et al. 2011).

While the function itself does not imply any particular underlying mechanism, one possible mechanism is based on so-called "contagion" or "recruitment" model (Schelling 1998): individuals in the population randomly contact each other and, if one individual of the two has already adopted the innovation, the other one adopts it too. In this model, accelerating adoption rate at the beginning is explained by cascading recruitment, and the subsequent slowdown reflects the fact that there are increasingly few potential adopters who have not adopted the innovation yet. The logic remains the same if potential adopters constitute only a part of the entire population – contacts with those who are unlikely to adopt the innovation simply do not count. This mechanism explains the shape of the logistic function, however, this is only one possible underlying model, and the same logistic curve may result from quite different mechanisms (Schelling 1998). For example, the contagion mechanism does not include users' differential propensity for adoption, which is essential to Rogers' (2003) concept of diffusion.

2.3.2 Diffusion of systems and infrastructures. Temporal hierarchy of diffusion processes

While early diffusion studies developed in sociology and marketing research (see e.g. Bass 1969), since the 1970s diffusion approaches have been applied to the dynamics of energy and other infrastructures seen not as individual products or practices, but as "pervasive systems" whose lifetime spans several decades or even centuries (Anderer et al. 1981). These studies were driven by the interest in the "finite world" and necessary transitions dictated by its

[10] One example is Gompertz curve – an asymmetric curve that reaches inflection point at 37% of the saturation level (Höök et al. 2011).

limited resources – a problem emphasized by the Limits to Growth report (Meadows et al. 1972). An important motivation for these studies was to identify transition pathways and rates to be used in models (Grübler et al. 1999), and to check feasibility of model predictions. For example, Wilson et al. (2013) compare historic growth rates of energy technologies to those envisioned by transition scenarios modelled in IAMs. The mechanisms behind the expansion of large energy systems are very different from point-to-point information exchange between individual actors, and what is being expanded is a system comprised of products, devices, processes, practices, associated knowledge and institutions, as opposed to an individual practice or product (Grübler et al. 1999). Furthermore, at the timescales of interest the technology does not remain the same – "coal", "oil", or "railway" technology may undergo significant changes in terms of its technological, social, and economic characteristics (Grübler 1991; Silverberg 1991). Nevertheless it was found that logistic-type functions reasonably well represent the long-term dynamics of energy and other infrastructures and their constituent technologies.[11] Furthermore, they can be used to model the share of a technology in an expanding market and also be applied to a reverse process – the contraction of a technology being substituted by a newer one (Anderer et al. 1981).

There is a hierarchy of diffusion timescales associated with the hierarchy of technology systems (Grübler 1991). On one side of the hierarchy are major technology clusters – groups of compatible technologies using each other's positive externalities and thus supporting each other, providing a barrier against potential competing clusters ("lock-in") (Grübler et al. 1999). Such clusters are also supported by particular organizational and institutional arrangements (Grübler et al. 2016). Particularly pervasive clusters often have infrastructures at their center. On the opposite side of the hierarchy are individual technologies and products relying on existing infrastructures and established practices. While characteristic diffusion time for a single product may be several years or, in some cases, even a few months, diffusion times for infrastructures span several decades (Grübler:1991vp; Grübler et al. 2016). This may reflect not only the complexity of an emerging cluster, but also resistance of the incumbent cluster being substituted. Diffusion rates are generally lower in larger markets (Grübler 1991).

Grübler (1991) illustrates the difference between substitution within an existing system and expansion of the system with the example of draft horses and cars in the US. Cars used the same road infrastructure as horse carriages and provided the same kind of services. The substitution of horses with cars was rather quick, characteristic diffusion time being close to 12 year (comparable with the lifetime of a horse). Having replaced horses within the existing

[11] For example, Wilson (2012) reports that simple logistic function fitted diffusion of selected energy technologies better than other "sigmoid" curves.

market, the car sector continued expanding, but at a much slower rate representing the expansion of the entire market. Interestingly, the expansion rate of the entire non-rail land transport sector was approximately the same whether it was based on horses or cars. Another similar example is the replacement of railroad rolling stock. Grübler's examples of substitution do not involve any resistance from the outgoing technology, so in his model substitution generally happens faster that market expansion "into the void". Overall, Grübler (1998) characterizes system size and the process type – whether it is one of substitution or pure diffusion – as two main macrolevel factors determining diffusion rates.

2.3.3 Phases of diffusion

According to Grübler (1991), in case of energy infrastructures and other pervasive systems a regular S-shaped pattern does not have a single underlying mechanism, but is an aggregate of a variety of adoption processes. Therefore diffusion of such systems is best described as a sequence of stages in a *technology lifecycle*, with each stage driven by a different set of mechanisms (Grübler et al. 1999). The first phase of diffusion is characterized by a slow adoption rate and a high level of uncertainty and volatility; it usually ends with the emergence of a dominant design, a technological style seen as a set of best technological and engineering practices, and a social and institutional framework capable of supporting subsequent diffusion. The second phase is usually characterized by accelerated expansion of the technology, incremental improvements, economies of scale, cost reduction, and expanding demand, sometimes due to the spillover of applications to other sectors. Various benefits give rise to numerous positive feedback loops that drive exponential growth. Over time, the expansion slows down due to the accumulation of adverse social and environmental effects in addition to a limited market size, and eventually the technology reaches saturation (Grübler 1991). This may be followed by the phase of "senescence" or contraction, when the old technology is being substituted by a new one (Grübler et al. 1999). All in all, these stages and underlying mechanisms explain why the diffusion of "pervasive systems" can be described by the same S-curve as adoption of individual technologies.

Wilson (2012; 2013) discusses the role of early stages in the diffusion of various energy technologies focusing on one aspect of technology – unit size (i.e. power of a steam engine or capacity of a wind turbine). He finds a consistent sequence of phases – formative, up-scaling, and growth. During the formative phase, the growth in both unit size and the total size of the industry (as measured e.g. by total capacity of installed or produced units) is slow – this phase generally corresponds to the flat segment of the S-curve prior to market take-off (Grübler et al. 2016). The formative phase involves experimentation with many small-scale units that "contributes to the knowledge, technical skills, and institutional developments which underpin subsequent increases in the unit scale of a technology" (Wilson 2012, p.89). A small unit size is important because it makes experimentation less risky at an early stage characterized by a high level of both technical and commercial uncertainty. Only when fundamental design issues have been resolved, a successful unit up-scaling phase, e.g. marked by a rapid increase in the capacity of a single wind turbine, may follow (Wilson 2013).

The formative stage of a technology typically lasts for several decades and is a necessary precursor for the subsequent up-scaling (Wilson 2012) – attempts to artificially "short-circuit" the formative phase by prematurely promoting or incentivizing large units often lead to failure. In line with Grübler's et al. (1999) earlier findings, shorter formative periods are generally expected for individual technologies substituting existing ones within an established system, whereas clusters of interrelated technologies and technologies that require additional infrastructure or institutions have longer formative phases (Grübler et al. 2016). The up-scaling phase is followed by a growth phase, when the growth in industry size (measured e.g. by total installed capacity) is driven mainly by the growth in the number of installed units, while their size remains constant or grows slowly (Wilson 2012).

2.3.4 Spatial diffusion. Core and periphery

Most studies of diffusion focus on *temporal* aspects of the process, looking at diffusion within a single market or population. Grübler (1991) discusses *spatial* patterns of technology diffusion arising from two main processes described as the hierarchy effect and the neighborhood effect. The *hierarchy effect* implies that technology spreads from the primary center to secondary centers, sometimes quite remote form the original one. For example, railroads, having emerged in England, were then adopted in secondary centers like Belgium or Bohemia, then in tertiary ones like Saint Petersburg in Russia and Naples in Italy etc. The *neighborhood effect* accounts for the gradual spread of the technology from a center to its hinterland. Grübler does not explicitly discuss factors making a location a likely center of spatial diffusion[12] or mechanisms of hierarchical spread of innovation.

Originally, the two effects giving rise to patterns of spatial diffusion were described in a seminal study by Hägerstrand (1967), who developed a formal model producing these effects. In terms of underlying mechanisms Hägerstrand's approach is similar to Rogers' one – unchanging practice travels across a population of individuals differing in terms of their

[12] A quick observation can be made that secondary centers of railroad diffusion are among secondary centers of industrial revolution in Europe. The Russian Empire, where one of the tertiary centers was located, was not a major center of industrialization at the time of the technology adoption. At the same time it was a large and politically influential power capable of accumulating significant resources despite low income per capita.

propensity for innovation adoption. While the diffusion of railroads obviously relied on different mechanisms, it followed remarkably similar general patterns.

Diffusion studies provide comparative analysis of innovation diffusion in “core” markets, where innovation is adopted first, and “periphery” or later-adopting markets.[13] According to Grübler (1991; 1998), diffusion rates in periphery markets are generally higher due to knowledge spillovers from core markets, but saturation levels are lower. Furthermore, as no technology is adopted simultaneously across all possible markets, global (or multi-sector) diffusion takes more time than diffusion in any individual market (Grübler et al. 2016). In his analysis of formative and up-scaling stages, Wilson (2012) observes that formative periods in adopting (“rim” or “periphery”) markets are usually shorter than in initial “core” markets or even can be omitted. However, no comparable decrease in the duration of the unit up-scaling phase in the adopting markets is observed (Wilson 2013). The impossibility for later adopters to completely short-circuit the up-scaling phase reflects the fact that “[l]ocal knowledge and institutions are needed to develop, manufacture (or import), adapt, install, and above all, use a new energy technology effectively” (Wilson 2012, p.92). Overall, diffusion studies presenting their findings in terms of core and periphery do not discuss factors that makes countries or other markets early or late adopters and do not focus on specific forms of interaction between core and periphery markets.

2.3.5 Diffusion and technology learning

As noted above, energy technologies do not remain unchanged in the process of their diffusion that may span decades. One important aspect of this change is cost decline (enhanced performance can also be expressed as a decline in cost per unit of performance). Cost decline over time is an important factor explaining non-instantaneous adoption – increasingly affordable technology becomes competitive across more markets and segments. This is captured by the concept of learning (Wright 1936; Grübler et al. 1999). One type of learning is “learning by doing” – decrease in unit cost as a result of accumulated experience in production[14] (Arrow 1962). Mechanisms of learning by doing may include experience gained by individuals, organizational improvements, or economies of scale (Grübler et al. 1999). Learning by doing is often characterized by learning rates and learning curves relating accumulated “experience” (measured e.g. as cumulative output, investment, or sales) to technology costs. Learning curves are generally described by power function – a doubling of

[13] Wilson (2012) uses the three-part taxonomy of “core”, “rim”, and “periphery” broadly similar to “core”, “semi-periphery”, and “periphery” in Wallerstein (1979).

[14] A related concept of “learning by using” captures decrease in costs of technology use.

experience leads to a certain percentage decrease in technology costs. Typical learning rates in the manufacturing of energy equipment are 10–30%, although they may reach 50% at early stages of technology commercialization (Grübler et al. 1999). Another type of learning is "learning by searching" – decrease in technology costs as a result of deliberate "searching" usually understood as R&D activities (Kouvaritakis et al. 2000). Learning-by-searching rates and curves relate cost decline to cumulative R&D expenditures. Measuring both types of learning rates is important for "endogenizing" technology change in energy–economy models (Grübler et al. 1999). Grübler et al. (1999) combine two types of learning into a single learning curve based on technology investment, which includes the sum of R&D expenditures and product sales as a measure of total experience. Kouvaritakis et al. (2000) suggest a "two-factor learning curve" (2FLC) in which R&D expenditures and experience of "doing" are two independent parameters. Klaassen et al. (2005) estimate parameters of this model for wind technology in several early adopter countries.

2.4 Innovation systems

According to scholarship on technology diffusion reviewed in the previous section, social, organizational, and institutional arrangements are important determinants of both the rate and success of innovation diffusion. However, these studies do not provide a detailed analysis of how these arrangements facilitate or hamper the diffusion. The innovation systems literature discussed in this section focuses on the role of such arrangements, especially at early stages of technology diffusion.

2.4.1 Evolutionary economics

A common predecessor of innovation systems studies (Carlsson and Stankiewicz 1991) and literature on regime–niche dynamics discussed in the next section (Geels 2002) is evolutionary economics. Evolutionary economics focuses on sources of economic growth and, more broadly, qualitative economic change, seeking to overcome limitations of neoclassical supply-demand theories discussed in section 2.2 (Nelson and Winter 1982; Grubb 2014). The field of evolutionary economics was defined by a seminal book by Nelson and Winter (1982) that "treated technical advance as an evolutionary process, in which new technological alternatives compete with each other and with prevailing practice, with *ex post* selection determining the winners and losers, usually with considerable *ex ante* uncertainty regarding which the winner will be" (Nelson 1994, p.50). Thus, technological change involves generation of various technological alternatives, which are then subjected to a process of selection that may be driven by conscious choice, but also by survival and expansion of firms using more effective technologies. Selected technologies are retained and replicated by other firms; they may undergo subsequent "mutations" contributing to the further generation of variety (Nelson 1994; Nelson 2005). The direction of technological advance is strongly affected both by the selection environment and the processes of the generation of alternatives, which are usually far from random. Further exploration of these processes and the selection environment gave rise to several bodies of literature, including those focused on innovation systems and regime–niche dynamics.

Two interrelated contributions of evolutionary economics that are important to my work are the idea of co-evolution of technologies, industrial structure, and broader institutions (Nelson 1994), as well as parallelism between "physical" and "social" technologies (Nelson 2005, Beinhocker 2006). Evolutionary economics sees any technology as one or several "routines" – defined ways of doing things (Nelson and Winter 1982). Whereas routines for producing and using physical artifacts constitute physical technologies, social technologies involve both organizational practices at the company level and routines underpinning broader institutions, including policies and regulatory structures (Nelson 2005). Sometimes physical and social technologies are closely intertwined and require each other for effective functioning, as in the case of mass production combining specific manufacturing techniques with organizational approaches (Nelson 2005). Beinhocker (2006) even suggests that it is "packages" of physical and social technologies and not individual technologies that constitute the minimum unit of variation and selection in evolutionary economics.

2.4.2 Technological systems

Innovation system studies build upon Nelson and Winter's (1982) evolutionary approach, focusing on the "generation of variety" part of the evolutionary process,[15] but posit that generation of innovations is better analyzed at the level of systems rather than individual firms. There are several strands of literature on innovation systems, which all emphasize systemic nature of innovation, linkages among different actors involved, and the role of organizational aspects and the broader institutional framework, but differ in how they define the boundaries and composition of the systems. Historically, the first approach was the National Systems of Innovation dealing with national-level factors and processes (Freeman 1995; Lundvall 1998), followed by Regional Innovation Systems (Cooke et al. 1997) and Sectoral Systems of Innovation (Malerba 2005). In this review, I focus on the Technological Innovation Systems (TIS) framework that deals with innovation systems for a particular technology or a group of related technologies. This framework is particularly relevant to my

[15] The interaction of innovations with a broader selection environment is the theme of regime–niche studies discussed in the next section.

research that deals with the emergence and diffusion of specific renewable energy technologies.

The TIS studies started with a broader concept of technological system (TS) proposed by Carlsson and Stankiewicz (1991; 1995), who emphasized the role of networks and defined a technological system as “network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology” (Carlsson and Stankiewicz 1991, p.111). According to Carlsson and Stankiewicz (1991), it is the middle level of networks as opposed to the micro-level of individual firms or entrepreneurs or the macroeconomic level that is central for understanding the processes of generating innovations and their subsequent diffusion. Flexible interactions within a broader network support search for information and competence building better than hierarchies within isolated companies, especially at early stages of the innovation process when uncertainty is high. Initially, a technological system relies on knowledge and competence networks, which support information flows, facilitate learning, and help to reduce uncertainty. Later, if these networks succeed in accumulating a sufficient “critical mass” of resources, they may be transformed into development blocks – “synergistic clusters of firms and technologies within an industry or a group of industries” (Carlsson and Stankiewicz 1995, p.49) – which support broader diffusion of the technology.

2.4.3 Technological innovation systems and their functions

The scope of the TS as defined by Carlsson and Stankiewicz (1991) includes not only generation and diffusion, but also utilization of technology. Such a system may support both emerging and established technologies and can be seen as comprising both an “innovation part” and a “production part” (Markard and Truffer 2008). A closer focus on the innovation part resulted in the formulation of the TIS framework, which is often used for analyzing innovation in the field of renewable energy and other “clean” technologies (Bergek et al. 2015). The approach has been used for comparing innovation activities across countries and explaining success or failure of RE expansion based on the features of TIS – its functions and associated inducement and blocking mechanisms.

A distinct feature of the TIS framework is the notion of innovation system functions – the key processes that support the “overall function” of the innovation system – “developing, diffusing and utilizing new products (goods and services) and processes“(Bergek et al. 2008, p.408) – and determine its performance. The functional perspective on TIS is complementary to the structural perspective dealing with actors, networks, and institutions. It is intended to support more systematic comparison of different TIS’s, as well as TIS performance evaluation and enhancement (Bergek et al. 2008). There are several variants of TIS function lists (Bergek and Jacobsson 2003; Edquist 2005; Hekkert et al. 2007; Bergek et al. 2008), which differ in details but generally agree on the essence. Bergek et al. (2008) propose the following key functions:

1. Knowledge development and diffusion
2. Influence on the direction of search
3. Entrepreneurial experimentation
4. Market formation
5. Legitimation
6. Resource mobilization
7. Development of positive externalities

The functions are interdependent and may interact with each other – the TIS perspective emphasizes interaction and systemic interdependence between system components and its functions (Bergek et al. 2015). The development of each function is supported by inducement mechanisms and hampered by blocking factors. Having identified underdeveloped functions and relevant blocking factors, an analyst then can define policy issues which need to be addressed in order to weaken these factors and enhance the system's performance.

A limited set of key functions has been introduced as a way of dealing with complexity of innovation systems, and each such function is effectively is an aggregate representation of many underlying processes and factors (Bergek et al. 2015). Due to the heterogeneity of innovation processes and factors, a single function may depend on substantially different mechanisms. For example, legitimation may involve slow processes of social acceptance of innovation best described by sociology, as well as explicitly political coalition building. Resource mobilization may involve rising financial capital, as well as mobilizing human resources with necessary competencies through the development of the education system (Bergek et al. 2008). Because the TIS approach is a framework rather than a theory, various theories from different disciplinary fields can be used for analysis. Presenting their version of the TIS framework, Bergek et al. (2008) note that it includes insights from political science, sociology of technology, and organization theory. In particular, they discuss the relevance of the advocacy coalition framework (Sabatier 1998) from political science for the analysis of technology-specific coalitions and the legitimation function.

The TIS approach is focused on the functional dynamics of innovation systems, which means that the realization of functions and their interaction patterns may change over time. Different phases of technology innovation and diffusion may rely on different key functions or the same functions working in a different way, and therefore may require different criteria for evaluation (Bergek et al. 2008). TIS scholars often distinguish between the formative phase and the growth (market expansion) phase (Bergek and Jacobsson 2003; Jacobsson and Bergek 2004; Bergek et al. 2008). The first phase is focused on the creation of variety and experimentation, but also involves such processes as early market formation, entry of firms and other actors, institutional change (alignment of relevant institutional elements), and formation of technology-specific advocacy coalitions (Jacobsson and Bergek 2004). Eventually, these processes lead to the formation of positive externalities and feedback loops, as well as the strengthening legitimacy of the emerging technology. This may lead to the launch of "cumulative causation"– sustained market expansion driven by "increasing returns" or positive feedback loops[16] between various elements and functions of TIS. The end of the formative period is marked by "a change of gear" – a shift to different underlying mechanisms allowing the system to function in a self-sustaining way (Bergek et al. 2008). A successful formative period is a necessary condition for subsequent market expansion, but not a sufficient one, as demonstrated by the case of the Dutch wind industry in the 1990s (Jacobsson and Bergek 2004) (see section 6.2.5 for detail). Overall, in the TIS perspective the end of the formative period is marked primarily by the emergence of self-reinforcing mechanisms as opposed to more technical indicators (e.g. the emergence of a dominant design) (Bergek and Jacobsson 2003).

The TIS tradition produced a large number of detailed empirical studies. Although a TIS, unlike a national innovation system, is not necessarily limited by national boundaries, most studies within the approach focus on the national scale or provide a comparative analysis of two or several national-level systems (Bergek et al. 2015). Bergek and Jacobsson (2003) used the TIS approach for a comparative analysis of the early development of wind power technology in Germany, the Netherlands, and Sweden, and connected observed problems to specific functions. For example, they attribute slow growth of the Dutch wind industry in the 1990s to failures in two functions – influence on the direction of search (which produced turbine designs incompatible with the growing German market) and market formation (the inability to support sustainable growth of the domestic markets).

The limitations of the TIS framework stem from its focus on innovation and networks contributing to it. Markard and Truffer (2008) note that it would be analytically productive to keep the definition of TIS limited in terms of its scope and lifetime. For example, it would make little sense to include into a TIS actors and coalitions opposing innovation, although they can be considered in the analysis as contributing to blocking factors. Similarly, they

[16] A more detailed discussion of increasing returns and positive feedback is provided in section 2.5.

suggest that a TIS is limited in time and ends at some point in the growth phase, when the "production part" of the technological system becomes more relevant (Markard and Truffer 2008). Relating the TIS framework to the multi-level perspective (see section 2.5.2) they suggest that the TIS exist mainly at the niche level, where it may encompass several related niches and associated institutions (Markard and Truffer 2008). Thus, the approach can be less productive in analyzing dynamics of established technologies or broader transitions. Recent conceptual contributions to the TIS literature (Hekkert and Jacobsson 2015; Bergek et al. 2015) pay more attention to the broader context of TIS and system–context interaction. Bergek et al. (2015) discuss four important types of contextual structures: technological, sectorial, geographical and political.

2.4.4 Innovation systems in latecomer countries and local technology deployment systems

To study technology adoption in "receiving" or "latecomer" countries that introduce technology developed elsewhere, scholars build upon approaches developed for analyzing innovation in leading countries. Viotti (2002) discusses the use of the National Innovation System (NIS) framework (Freeman 1987) for explaining technical change in late industrializing countries.[17] He finds that the applicability of this framework is limited, since it is focused on the processes of innovation in the narrow sense,[18] whereas "[t]he dynamic engine of late industrialization is […] technological learning, rather than innovation" (Viotti 2002, p.658). Learning includes technology absorption and associated incremental innovation. Some learning-by-doing inevitably takes place even if a country simply adopts a technology – Viotti calls this "passive learning". However, a country or firms may practice "active learning" strategies involving deliberate efforts at technology improvement, adaptation, reverse engineering etc. Viotti suggests an umbrella notion of the National System of Technical Change, which covers National Innovation Systems in advanced industrialized counties, as well as National Learning Systems in late industrializing countries. The latter concept as an analytical tool is focused on learning strategies as opposed to initial innovation and commercialization, and pays more attention to indicators of adoption and incremental improvement. National Learning Systems can be active or passive depending on the prevailing strategy of the respective firms (Viotti 2002).

[17] Both his case studies – South Korea and Brazil – are "semi-periphery" countries according to Wallerstein (2004).
[18] Associated e.g. with R&D programmes and initial commercialization.

Two related articles by Gosens and Lu (2013) and Gosens et al. (2015) use the TIS framework to explore transnational linkages of clean technology innovation systems in emerging economies, particularly in China. Most earlier studies based on this framework had been nationally delineated, giving little consideration to cross-national interaction and focusing on countries close to the "global technological forefront". At the same time, the initial challenge faced by latecomer countries is "to catch-up with advanced economies, i.e. to increase domestic innovative capabilities and activity vis-à-vis the global technological forefront" (Gosens and Lu 2013, p.235), and transnational linkages are essential for addressing this challenge. Many of these linkages can be conceptualized as relationships between the global TIS resulting from previous activities of leading countries and the national TIS in the country in question.[19] The relationships between the global and the domestic systems are not necessarily static (Gosens et al. 2015) – the domestic innovation system may evolve from dependency to self-sufficiency to being able to contribute to the global system. Gosens et al. (2015) identify a number of relevant transnational linkages organized into two broad categories – transnational actor-networks and transnational institutions – and follow a scheme of TIS analysis proposed by Hekkert et al. (2007) and Bergek et al. (2008). While Gosens and Lu (2013) retain the original list of TIS system functions, they demonstrate that the same key functions may rely on very different underlying processes compared to leading countries. For example, knowledge diffusion in China's wind turbine sector was underpinned not by disseminating results of domestic R&D activities, but by international technology transfer programmes and later by private licensing deals with foreign manufacturers. The two articles also connect specific forms of transnational linkages to particular TIS functions, seeing these linkages as inducement or blocking factors. For example, global mobility of skilled workforce may facilitate access to foreign experience or be a source of brain drain. Using this approach, Gosens and Lu (2013) formulate several suggestions for the improvement of the innovation system in China's wind turbine industry. They also note the difficulty of determining whether a country has a "truly domestic" innovation system when, for example, many wind turbine components are produced within China but at production facilities owned by major foreign companies.

Bento and Fontes (2015) use the TIS framework to analyze wind technology diffusion in Portugal seen as a receiving country as opposed to Denmark, a core country. They conclude that rapid technology deployment in a follower country depend on the interaction between two groups of factors – transnational linkages (see discussion above) and absorptive capacity

[19] This is in line with a recent suggestion by Bergek et al. (2015) that in some cases the analysis of "nested TIS's" at different geographical scales and of the interplay between global and national-level TIS elements and functions can be productive.

necessary for the effective use of these linkages. Absorptive capacity is the ability to exploit external knowledge (Cohen and Levinthal 1990), which can be improved through organizational and institutional changes. Like Gosens et al. (2015), Bento and Fontes (2015) use the original list of TIS functions, associating transnational linkages and national actions to enhance absorptive capacity with specific functions. Their analysis emphasizes the active role of a receiving country in adopting the technology.

Vidican (2015) applies the TIS framework to the case of solar energy innovation system in Morocco with a particular focus on governance aspects. While the country does not pursue innovation with regard to the core technology – Morocco is not developing or producing solar panels – the framework turns out to be relevant because of the need to build technical, economic, and institutional systems supporting the planned large-scale deployment of the technology.

Strupeit (2017) introduces the notion of technology deployment system that comprises "downstream" or deployment structures and processes, as opposed to the "upstream" – the development and manufacturing of the core hardware, e.g. wind turbines or PV panels. The deployment system includes numerous heterogeneous actors, their networks and deployment knowledge. Analyzing the case of photovoltaic solar energy in several countries, he observes that, despite of the use of the same core technology, deployment business models are rooted in the national or even local context and strongly differ between countries in terms of the types and interactions of actors involved, financing mechanisms, and customer value proposition. In the residential PV sector, there are significant differences between the American third-party ownership model, the Japanese model of cross-selling by prefabricated house producers, and the German "host-owned feed-in" model. Elements of each model fit each other and the broader national context of the respective countries (Strupeit 2017; Strupeit and Palm 2016). Typically, deployment systems use elements of pre-existing national "regimes" unrelated to renewable energy: the PV deployment system in Japan is closely connected to the prefabricated buildings industry, whereas the German one relies on small businesses installing home equipment.

The deployment system is characterized by soft deployment costs which, in addition to the costs of installation and auxiliary equipment, are associated with technical planning, obtaining necessary permits, transaction costs (finding reliable business partners and customer acquisition), financing and support systems. In Germany in 2013, soft deployment costs accounted for 38% of total upfront costs of a residential-scale installation, and this was the lowest percentage in the world (comparable numbers for the US and Japan were 58% and 44% respectively). Even within Europe, soft deployment costs can strongly vary between national markets. Soft deployment cost have their own dynamic – like core equipment costs they reduce over time, but at a slower rate (Strupeit 2017). Within the broader tradition of technological/innovation systems, technology deployment system can be seen as a part of the technological system (TS) as defined by Carlsson and Stankiewicz (1991) – it may include both innovation (at the deployment side, e.g. business process innovation) and technology use, and it is essential for technology utilization.

2.5 Regime–niche dynamics

The analysis of regime and niche dynamics (Rip and Kemp 1998; Geels 2002) starts from the same broad premises that innovation system studies described in the previous section but takes a broader "transition perspective" instead of an "emergent technology perspective" (Markard and Truffer 2008) and combines insights from evolutionary economics with those from sociology of technology (Rip and Kemp 1998). Studies in this tradition usually have explicit normative interest associated with the need for a large-scale transition to more sustainable technologies. The idea of regime–niche dynamics underpins the multi-level perspective (Geels 2002; Geels 2004) on socio-technical transitions. The analysis of regime–niche dynamics emphasizes social embeddedness of technology, assuming that technology is a part of a broader socio-technical landscape and exists as a system comprising hardware (artifacts), software (skills), orgware (organizational practices) and socioware (social contexts of technology) (Rip and Kemp 1998).

2.5.1 Regime and niche

The concept of a technological regime was first introduced by Nelson and Winter (1982) in the context of evolutionary economics to explain the continuity of technological advance. Originally it was applied to the "variety generation" aspect of the evolutionary modes, emphasizing cognitive aspects of innovation – engineers' beliefs regarding problems that need to be addressed and possible solutions to these problems. According to Nelson and Winter (1982), the stability of technological regimes together with the fact that new solutions usually build on existing ones accounts for the cumulative nature of technological advance and the existence of technological "trajectories".[20]

Building on this concept, Rip and Kemp (Rip and Kemp 1998) note that the broad selection environment also plays a significant role in structuring and directing innovation, especially if the focus is on wide adoption of a new technology as opposed to its invention. Therefore they

[20] This idea of regime is close to Dosi's (1982) concept of technological paradigm.

expand the notion of technological regime defining it as “the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures” (Rip and Kemp 1998, p.338). This formulation: (1) defines regime as a set of rules; (2) encompasses the selection environment in addition to “variety generation”; and (3) includes the rules that exist not only as cognitive structures (beliefs), but are also embedded in institutions and infrastructures.

Given the complexity of socially embedded technology and multiple linkages between its different elements, the role of regime is to reduce uncertainty by stabilizing these linkages. Technological regime is seen as an intermediate layer between “specific innovations as these are conceived, developed, and introduced, and overall socio-technical landscapes” (Rip and Kemp 1998, p.338). The rules comprising regime exist at the collective level and cannot be changed by a single actor. The gradual consolidation of innovation into a regime leads to decreasing uncertainty, making it possible for designers, producers, and users to effectively deal with technology, but also to increasing irreversibility. This makes it difficult for new technologies to compete with incumbent ones, even if the former are more desirable (Rip and Kemp 1998). In this perspective, major technological change is seen as a “regime shift” – a transition from one regime to another, or at least a significant change in the regime.

Borrowing a metaphor from evolutionary biology, Rip and Kemp (1998) observe that successful new technologies often emerge in niches – spaces protected from direct competition due to special performance requirements or deliberate policies. The functions of the niche include: (1) demonstrating the viability of a new technology; (2) providing initial resources for its further development; (3) building a constituency behind a new technology; (4) launching interactive learning processes and institutional adaptations necessary for widespread diffusion (Kemp et al. 1998, p. 184). The key processes within an emerging niche are the formation of networks, shared visions, and expectations, as well as a range of articulation processes, focused on technical aspects, policy, market, cultural meanings, etc. and leading to the reduction of uncertainty around the emerging technology. Thus, the role of the niche goes far beyond purely economic or engineering functions – reducing costs or enhancing performance – and effectively implies fostering an embryonic regime for a new technology. A successful transition (regime shift) takes form of niche proliferation and, possibly, substitution of the incumbent regime with a new one.

2.5.2 Multi-level perspective

The multi-level perspective (MLP) proposed by Geels (2002; 2004) takes a more structured view of the interaction between niches and regimes and offers a framework for describing socio-technical transitions in terms of such interaction. It also seeks to overcome the "niche-driven bias" characteristic of early studies in the regime–niche tradition, which tended to view niche-level processes as key drivers of change. Building on the concepts of niche, regime, and landscape, the MLP intends to bring together a micro-view of evolution focused on its mechanisms (variation, selection, and retention) and a macro-view concerned with large-scale shifts and reconfiguration processes. Geels (2004) also introduces the concept of socio-technical system, which serves a broad societal function and encompasses technology production, diffusion, and use.[21] Schot et al. (2016, p.2) define socio-technical system as "a configuration of technologies, services and infrastructures, regulations and actors (for example, producers, suppliers, policy-makers and users) that fulfils a societal function such as energy provision." Socio-technical regime in the MLP is a set of rules that form the "deep structure" or "grammar" of the respective socio-technical system and are carried by social groups. Geels (2004) emphasizes the semi-coherent and heterogeneous nature of the socio-technical regime that comprises elements of other regimes, e.g. technological regime, policy regime, science regime etc., to the extent that they are aligned with each other and support the socio-technical system in question. While regimes are stable rule-sets underpinning stable socio-technical systems, niches are emerging, less stable socio-technical systems. Rules and networks in niches are more fluid, providing space for experimentation and potential radical innovation unconstrained by existing regimes. Landscape, the third key concept in the MLP, is understood as an environment in which regimes and niches are embedded, and a source of exogenous impacts on regimes. Using the framework, Geels and Schot (2007) developed a typology of socio-technical transitions pathways defined by the nature of landscape changes, compatibility of niches with the existing regime, and maturity of niche innovations.

The MLP has been applied both to historical technological transitions (Geels 2002; Geels and Schot 2007) and to ongoing sustainability transitions in various sectors, including electricity (Verbong and Geels 2010; Geels, Kern, et al. 2016), mobility (Nykvist and Whitmarsh 2008), and heating (Geels and Johnson 2018), among others. The framework has typically been used for analysis of individual cases or comparative analysis of a small number of cases, although there are some exceptions – for example, Li and Strachan (2016) report using the MLP as a conceptual foundation for a quantitative model of energy transitions. Recent studies

[21] In this, the socio-technical system is similar to the technological system as defined by Carlsson and Stankiewicz (1991).

emphasize the role of actors in effecting change and mobilize insights from political science for exploring this role (Geels 2014; Osunmuyiwa et al. 2017). The framework does not have a particular focus on spatial diffusion of innovation. Gees and Deuten (2006) propose a model of the aggregation of local niches into a global regime through the phases of "inter-localization" and "trans-localization".

2.5.3 Lock-in, path dependence, and increasing returns

The concepts of increasing returns, positive feedback, path dependence, and lock-in are frequently used to describe the mechanisms of regime stability and niche expansion. The model of increasing returns, which was applied to technology by Arthur (1989; 1994), implies that increased adoption of a technology makes its further adoption more likely or, in other words, that there is positive feedback to adoption. "Cumulative causation" in the TIS described in section 2.4 is also driven by increasing returns. Using this model, Arthur (1989) explains why a suboptimal technology may prevail and persist in the market despite apparent availability of better alternatives – a condition characterized as lock-in (Unruh 2000). Increasing returns can result from different mechanisms, including scale economies, learning economies, adaptive expectations, and network economies also known as network externalities (Arthur 1994; Unruh 2000). The concept of increasing returns has also been applied to institutions in political science (Mahoney 2000). A notion closely related to increasing returns is one of path dependence, which describes a situation whereby once a system has started along a certain path, it becomes increasingly difficult to reverse the course and switch to a different path (Pierson 2004). Increasing returns is a possible mechanism underpinning path dependence.[22] The term "path dependence" is often used to describe system stability and resistance to change, whereas the concept of "path creation" is applied to processes similar to niche formation, e.g. early development of the Danish wind industry (Garud and Karnøe 2001). Strambach (2010) comes up with the concept of "path plasticity", which emphasizes the role of existing institutional arrangements and resources in the emergence of a new path. Recast in terms of regime–niche dynamics, this concept implies that new niches do not emerge "out of nowhere", but rely on elements and resources of existing regimes.

Unruh (2000) in his analysis of carbon lock-in expands the concepts previously applied to specific technological and institutional systems to a society-wide heterogeneous system described as a techno-industrial complex (TIC). This complex is a result of co-evolution of different system driven by technological and institutional increasing returns. In the process

[22] Mahoney (2000) notes that there are other types of path-dependent processes.

of this co-evolution, policies, incentives, and expectations supporting a technological system and essential for its initial deployment later become a factor preventing socially beneficial changes. While such mechanisms as economies of scale and economies of learning may apply to individual technologies or practices, it is network externalities that play the key role in holding together the entire system. Adaptive expectations can be embedded both in formal public institutions and informal social ones. The notion of TIC is broadly similar to the concept of socio-technical system underpinned by the regime.

2.6 Spatial perspective on energy transitions

Several scholarly contributions point to the insufficient attention to spatial aspects of transitions in prevailing socio-technical accounts and suggest incorporating insights from various strands of geography into these studies. In a seminal paper, Bridge et al. (2013) note that transitions studies typically focus on the temporal dimension of transitions, while paying less attention to their spatial aspects. Energy systems are organized in space, and transitions are both influenced by this organization and involve changes in it. In comparative studies, countries or regions are usually treated as “containers” rather than localities with rich context (Coenen et al. 2012). This makes it difficult to distinguish between choices made by actors, on the one hand, and effects or local conditions strongly favoring a certain path, on the other hand.

2.6.1 Institutions and evolution in geography

Coenen et al. (2012) and Hansen and Coenen (2015) propose a spatial perspective on sustainability transitions, relying on insights from economic geography. The relevant branches of this discipline include relational, evolutionary, and institutional geography (Hansen and Coenen 2015). *Relational* approach is based on the premise that space is not an empty container but is construed through social interactions between actors. This perspective is particularly sensitive to networks and flows (e.g. of capital or knowledge) as opposed to discrete entities (Hansen and Coenen 2015). *Evolutionary* economic geography seeks to demonstrate “how geography matters in determining the nature and trajectory of evolution of the economic system” (Boschma and Martin 2010, p.6). Three major frameworks in this field are: generalized Darwinism relying on concepts from modern evolutionary biology, such as population, variation, or selection; complexity theory with a focus on adaptive systems and self-organization; and path dependence theory with a focus on self-reinforcing dynamics and lock-ins (Boschma and Martin 2010). *Institutional* economic geography focuses on the “role of institutional variations as foundations for geographic differences in economic activity and performance” (Hansen and Coenen 2015, p.95). The premise is that a combination of formal and informal institutions in a given location forms an “institutional setting”, which may affect the nature and pace of sustainability transitions in this location. Coenen et al. (2012) describe *territorial institutional embeddedness* as a major dimension of the proposed spatial perspective. There is no clear-cut boundary between evolutionary and institutional approaches, one area of overlap being the evolution of institutions or their co-evolution with other entities.

The proposals stemming from the evolutionary and institutional branches of economic geography are generally similar to the proposals for incorporating institutional theories from political science discussed in the next section. They all focus on interrelated configurations of institutions[23] and factors of their change and stability, although “spatial” proposals emphasize connections of institutional configurations with particular localities. Hansen and Coenen (2015) use a broader notion of “place specificity”, which, in addition to local institutional setting, may include natural resource endowment, local technological and industrial specialization, specifics of local customers and markets etc. Bridge et al. (2013) also discuss “spatial embeddedness” as a source of path dependence, focusing not on institutional arrangements, but on the sunk costs of existing infrastructures and place-based consumption cultures.

2.6.2 Proximity, scales, and uneven development

A theme relevant to spatial diffusion of innovations is different types of proximity and their role in the formation of innovation networks (Hansen and Coenen 2015). Boschma and Frenken (2010) identify five types of proximity: cognitive, organizational, social, institutional, and geographical, and note that higher proximity typically facilitates network formation. Hansen and Coenen (2015) discuss two mechanisms associated with proximity – the *substitution mechanism* whereby other forms of proximity (e.g. cognitive or social) substitute for geographical proximity, and the *overlap mechanism* whereby geographical proximity facilitates other forms of proximity. Thus, geographical proximity (often found in clusters) is particularly important at the early stages of the formation of innovation networks. Lundvall (1988), an innovation systems scholar, similarly observes that network relationships in such systems may work over long distances when the technology is stable and standardized; at an earlier stage, when the technology is in flux and involves a lot of tacit knowledge, short distances are essential. This implies two parallel processes – increasing standardization and

[23] Characteristically, Coenen et al. (2012) use the same example of the varieties of capitalism framework as Lockwood et al. (2017) in their proposal for incorporating historical institutionalism in transition studies.

codification of knowledge, on the one hand, and spread of networks, which become less dependent on spatial proximity for effective functioning, on the other hand.

Another key component of the spatial perspective proposed by Coenen et al. (2012) is the *multi-level, multi-scalar approach* to sustainability transitions. A *multi-scalar perspective* is sensitive to processes unfolding at different spatial scales (local, national, and global) and the interaction between these scales – e.g. dependence of global actors on particular localities or role of specific regions in a country's competitive advantage. It also emphasizes the fact that global processes are always locally enacted – they unfold through the actions of local actors and are affected by local conditions (Coenen et al. 2012). Finally, the multi-scalar approach underscores that, from the standpoint of geography, levels used in the MLP are "metaphors" and do not necessarily directly correspond to geographical scales. Bridge et al. (2013) also discuss the role of scale in energy transitions. In particular, they note the role of assumptions about scale in energy policy – these assumptions determine at what level a certain issue is addressed.

Bridge et al. (2013) discuss relationships between low-carbon transitions and patterns of uneven development. They note that such transitions are not only determined by existing patterns, but can also change them, contributing to the "production of difference" and shifting the distinction between "core" and "periphery" at multiple scales. Thus, transitions create not only economic or political winners and losers, but also geographical ones, which may lead to opposition from vested interests associated with certain localities.

2.7 Policy and politics in energy transitions

The theories of technology transitions discussed in the previous sections demonstrate that a new technology needs to overcome many difficulties before it achieves a stage of launching positive feedback loops driving its increasing adoption, and policies can play an essential role in this process. Both historical accounts (Jacobsson and Lauber 2006; Jacobs 2014) and normative recommendations (Kemp et al. 2001) emphasize the critical role of policies in modern transitions to sustainable energy. At the same time, prevailing socio-technical approaches have been criticized for their failure to fully account for the role of politics (Meadowcroft 2009; Meadowcroft 2011), which plays a critical role in energy transitions by formation of policies that support or hinder transition. In this section I review theories of policy change, innovation, and diffusion relevant to explaining energy transitions.

2.7.1 Theories of policy change[24]

State, state goals, and vested interests

Because most energy policies are adopted and implemented by governments acting on behalf of nation states, the state is the key analytical unit in the study of policies, but its conceptualization is debated (Dunleavy and O'Leary 1987; Hay et al. 2006). Seeking to explain actions of the state, scholars make varying assumptions regarding its autonomy and the way it aggregates preferences of various groups. Hall divides theories of state into two broad groups: state-centric and state-structural (Hall 1993). State-centric approaches assume that states are autonomous actors (Skocpol 1979) pursuing national interests (Krasner 1978) or state imperatives such as internal order, external independence, and economic growth (Dryzek et al. 2003). In the state-centric approach, the goals of energy policies are dictated by national interests: for example, striving towards a secure supply-demand balance (Helm 2001), minimizing energy imports or maximizing exports (Yergin 1991), ensuring reliable access to electricity, securing industrial competitiveness, and increasing employment (Keohane and Victor 2016).

In contrast, state-structural (neo-pluralist) approaches assume that states' policies aggregate and reconcile competing interests of various actors such as voters, political parties, social movements and industrial lobbies. In this strand of research, scholars focus on the "politics of energy policies" (e.g. Jacobsson and Lauber 2006). For example, governments may seek to maximize votes from constituencies with preferences for specific energy options – this is known as "vote-seeking" behavior (Downs 1957).[25] Following this line of argument, political science literature sometimes hypothesizes that left-leaning governments would stimulate the promotion of renewable energy to provide widely distributed social benefits (Aklin and Urpelainen 2013; Dumas et al. 2016). State policies may also be influenced by special or vested interests. Sustainability transition studies often focus on the interests of incumbent sectors as a source of resistance. For example, Geels (2014) argues that incumbent firms can resist transitions by using various forms of power and concludes that "socio-political struggles with fossil fuel companies and other incumbent firms [...] will be crucial in the case of low-carbon transitions" (p.37). However, the configuration of this struggles is often more nuanced

[24] This section is largely based on a section from the following article which I co-authored as a second author: Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research and Social Science*, 37, pp.175–190.

[25] For example, German Chancellor Merkel's decision to impose a moratorium on the operation of nuclear power plants in 2011 has been widely viewed as reflecting her concerns not to lose regional elections in Baden-Württemberg and Rheinland-Pfalz with strong anti-nuclear preferences (Wittneben 2012).

than “sustainable technologies vs. incumbent sectors”. In Germany, the dynamic between two incumbent sectors – nuclear energy and coal – played a role in the expansion of renewable energy (Jacobsson and Lauber 2006; Cherp et al. 2017). Moe (2012) suggests that differing levels of adoption of two renewable electricity technologies – solar and wind – in Japan are explained by different compatibility with incumbent vested interests.

Institutionalist approaches

A key concept in the analysis of policy change and stability is that of institutions, i.e. structures and rules that enable and constrain the state and other actors (Knill and Tosun 2012). In one of the earlier political studies of energy transitions, Ikenberry (1986) provided a comparative analysis of responses of several industrialized countries to the oil shocks of the 1970s. One of his key conclusions is that the main factor explaining cross-national differences in these responses is policy instruments and institutional resources available to the government, which collectively constitute the state’s institutional capacity.

In exploring the role of institutions, scholars follow three distinct streams of neo-institutionalism: rational choice, sociological, and historical (Hall and Taylor 1996). The rational choice tradition views institutions as mechanisms that enable collective action of rational self-interested actors through lowering transaction costs and increasing predictability of other actors’ behavior. Sociological institutionalism takes a more “cultural” perspective on the nature and dynamics of institutions; as such, it belongs to the disciplinary fields of sociology and organizational studies. Andrews-Speed (2016) argues that this type of institutionalism, unlike the other two, has already been incorporated into socio-technical accounts of low-carbon transitions to some extent.

It is historical institutionalism (HI) that is at the center of recent proposals for the incorporation of institutional studies into the analysis of sustainable transitions (Andrews-Speed 2016; Lockwood et al. 2017). Upholding the common view of institutions as norms, rules, and procedures, HI pays particular attention to norms embedded in political organizations and closely associates institutions with these organizations. As such, it is especially useful for “cross-national comparisons of public policy, typically emphasizing the impact of national political institutions” (Hall and Taylor 1996, p.938). Lockwood et al. (2017) identify two themes within this approach that are particularly relevant to studying energy transitions – the way in which institutional arrangements (such as federal vs. centralized structure or proportional vs majoritarian electoral system) affect the outcomes of political struggles, and the explanation of institutional change and stability. The significance of institutional arrangements is illustrated by the argument that countries with proportional representation electoral systems are more likely to adopt environmental measures, because such systems provide more opportunities for small issue-based parties to make it to the parliament and then play a key role in the governing coalition (Lockwood et al. 2017). A case in point is the role of the German Green party in the country's energy policy change in the early 2000s (Jacobsson and Lauber 2006). HI is also sensitive to how institutional arrangements favor some groups and views over other, thus creating or reinforcing power inequalities (Lockwood et al. 2017).

Speaking of institutional change, Thelen (1999) notes a key difference between rational choice institutionalism and HI – the former is concerned with equilibria and "equilibrium order", whereas the latter is interested in concrete historical processes of institutional formation and change. Therefore historical institutionalism deals with the concepts like path dependence, increasing returns, positive and negative feedbacks, as well as unintended consequences (Thelen 1999; Pierson 2004; Lockwood et al. 2017), which were discussed earlier in section 2.5.3.

An example of a theory in the HI tradition is the framework known as varieties of capitalism (Hall and Soskice 2001), dealing with systems of interrelated national institutions and originally focused on industrialized democracies. The framework identifies two ideal types of market economies defined by differing levels of acceptable non-market coordination – liberal market economies (LMEs), e.g. the US and the UK, and coordinated market economies (CMEs), e.g. Germany and Japan. These two types of economies have distinct systems of complementary institutions in a number of areas, including financial markets, industrial relations, inter-company relations, corporate governance, and workforce education and training. The two different systems are conducive to different types of innovation – LMEs tend to give rise to radical innovation, whereas CMEs are better equipped to support incremental innovation (Hall and Soskice 2001). The varieties of capitalism framework has been used for explaining energy transitions. Geels et al. (2016) refer to the difference between Germany's CME and the UK's LME as one of the factor explaining the difference in electricity transition between the two countries. Lockwood et al. (2017) discuss the hypothesis that CMEs tend to produce more sustainable economies, although they conclude that the evidence is mixed. Ćetković and Buzogány (2016) apply the framework to renewable energy policies of EU countries, using an additional category – dependent market economies (DMEs) (Nölke and Vliegenthart 2009) – for Central and Eastern European countries.

Idea-centric approaches

A newer strand of institutionalism – discursive institutionalism (DI) – departs from the criticism of all the three previous strands as too static and constraining, prioritizing structure over agency, and not being able to explain change, typically attributing its source to exogenous factors (Schmidt 2010). To overcome these limitations, DI focuses on ideas and discourse of sentient actors, seeing them as an endogenous source of institutional change.

An example of idea-centirc thinking of policy change is the concept of policy paradigm change proposed by Hall (1993) as a way to reconcile state-centric and state-structural approaches. Hall identifies several levels of policy change, the most profound of them being shift in a policy paradigm – a set of ideas and standards that define not only overarching policy goals, but also the very nature of problems the policy is supposed to address. Whereas lower-level policy changes are often introduced by state bodies acting as autonomous entities, a policy paradigm shift typically results from the failure of the previous paradigm and involves the opening up of the policy process to new ideas and pluralist politics with the participation of various interest groups. Kern et al. (2014) use Hall's theory to explain the change in the UK energy policies in the 2000s when the concept of self-regulated energy markets gave way to more active state intervention. Their account views the paradigm shift as driven by "crises narratives" (Widmaier et al. 2007) and tracks parallel changes in energy policy ideas and institutions. The policy paradigm shift in this theory bears some resemblance to socio-technical transitions discussed in a previous section. The policy paradigm can be seen as a "regime" disrupted by "landscape" events – external shocks and crises.[26] As Hall (1993) notes, even a perceived failure of the incumbent paradigm may not result in its replacement if no substitute ideas have been developed within a certain group – this parallels the idea of maturity of niches necessary for a regime shift (Geels and Schot 2007).

Comprehensive policy change frameworks

Comprehensive policy change frameworks go beyond individual theories in order to provide a detailed and multi-faceted picture of policy change processes. One such framework is the Advocacy Coalition Framework (ACF) (Sabatier and Weible 2007), which "absorbs many of the explanatory variables advanced by other theories" (Nohrstedt 2010, p.310). ACF views policy change as shaped by interactions of competing advocacy coalitions and exogenous shocks that might lead to policy-oriented learning constrained by constitutional rules (Knill and Tosun 2012, p.253). ACF has been used in the TIS tradition, where technology-specific coalitions contribute to the legitimation of new technologies and development of positive externalities (Bergek et al. 2008).

[26] Widmaier et al. (2007) note though that crisis events are never completely exogenous, because their effects depend on the way actors interpret their meaning. This understanding is in line with DI (Schmidt 2010).

2.7.2 Policy diffusion and innovation

Policy diffusion

Berry and Berry (2007) discuss models of policy innovation based on theories of innovative behavior of individuals and organizational innovation. Policy innovation is defined as "a program that is new to the government adopting it" (Berry and Berry 2007, p.232), as opposed to policy invention – "the process through which original policy ideas are conceived" (Berry and Berry 2007, p.232). Effectively, they focus on the adoption of the same policy by different jurisdictions and not on changes the policy may undergo in the process. Berry and Berry (2007) discuss two major groups of models explaining adoption of a given policy by different jurisdictions: diffusion models and internal determinants models.

Diffusion models imply that the adoption of a policy by a jurisdiction is influenced by previous adoptions by other jurisdictions. Diffusion is understood in line with Rogers' (2003, p.5) definition – "the process by which an innovation is communicated through certain channels over time among the members of a social system," the social system in question being national (or US state) governments.[27] Mechanisms of international diffusion identified in the literature include learning, competition, and coercion,[28] often through the imposition of standards by federal or supra-national entities. Tosun and Croissant (2016) shift the focus from mechanisms to actors in international diffusion processes. They propose a conceptual framework based on diffusion routes defined by different types of actors involved and their motivations. The effectiveness of different routes depends on characteristics of political regimes in receiving countries.

The main two diffusion models include the "national interaction model" and the "regional diffusion model". The former is a "contagion" model of point-to-point information exchange producing an S-curve of adoption over time (cf. section 2.3 above). The latter emphasizes the interaction between jurisdictions proximate to each other – sharing a common border or belonging to the same region.[29] There are several other models of diffusion – the leader–laggard model that assumes that certain jurisdictions are adoption pioneers emulated by other governments; the isomorphism model that implies that a jurisdiction is more likely to

[27] There is a distinct tradition of studying policy diffusion among US states, to which Berry and Berry themselves belong. Most of the approaches developed within this tradition can be used for studying policy diffusion among countries.
[28] Gilardi (2014) adds emulation to the list of mechanism. Emulation implies policy adoption driven by shared "norms of appropriateness" as opposed to learning driven by the desire for a certain outcome.
[29] This mechanism can give rise to the "neighborhood" pattern of spatial diffusion described in section 2.3, whereas other mechanisms may lead to the "hierarchical" pattern.

emulate a policy from a similar jurisdiction; and the vertical influence model, in which innovation comes from a higher level of governance (Berry and Berry 2007).

Internal determinants models focus on a jurisdiction's own political, economic, and social characteristics as the key factors of policy adoption. Berry and Berry (2007) discuss two broad groups of such factors – those reflecting the motivation to innovate (for example, poor economic conditions motivate a state to adopt social aid programmes) and those reflecting obstacles to innovation and resources available for overcoming these obstacles (e.g. financial resources of the jurisdiction). These two groups of factors are broadly similar to the concepts of capacity and motivation discussed in Chapter 3.

The existence of two groups of models does not mean that most real-life policy innovation processes can be reduced to either one or the other group of factors – they often interact. Berry and Berry (2007) advocate the incorporation of both external (related to diffusion) and internal explanatory variables in quantitative studies of policy innovation. Gilardi (2014) discusses the choice of a metric of proximity (in his terms, "connectivity") for quantitative analysis of policy diffusion and notes that this choice depends on the assumed mechanisms of diffusion. While geographic proximity[30] is the most straightforward metric, in some cases commuter flows or investment flows can be more relevant.

Diffusion, transfer, and translation

Stone (2012) discusses differences between the concepts of policy diffusion and policy transfer. Studies of policy diffusion originate in the analysis of policy adoption by American states, tend to use quantitative methods, and are focused on patterns and structural factors of policy adoption, while paying limited attention to actual processes behind this adoption, including struggles of political interests. Studies of policy transfer emphasize the role of actors, focus on processes, and tend to rely on qualitative methods. Gilardi (2014) observes that both concepts essentially apply to the same phenomena, but are used in different bodies of literature and rely on different methodologies. Stone (2012) lists several partially overlapping modalities of transfer, including: transfer of policy ideas and goals; transfer of institutions; transfer of specific policies; transfer of broad ideas and ideologies; and transfer of personnel, which can serve as a vehicle for other types of transfer.

Stone (2012) also discusses the concept of policy translation as an important correction to the linear model of policy transfer, in which a policy from one location is adopted in another one without changes. The translation perspective emphasizes contextual embeddedness of

[30] See discussion of different types of proximity in section 2.6.

policies in both the original and the receiving jurisdiction, the complex nature of policy learning, and re-interpretation of meanings associated with policies. Even if a policy is originally adopted without significant changes, it then becomes influenced by local dynamic. Mukhtarov (2014) notes that policy translation may involve destabilization of its meaning, destabilization of geographical scale, and increased contingency.

Formative period, regime, and niche in policy innovation

Jacobs (2014) with his article on the emergence of feed-in tariffs (FITs) for renewable electricity contributes to the debate on what constitutes a policy invention.[31] Jacobs describes invention of FITs not as momentary event but as a process which started with the introduction of the first FIT-like mechanism in the US in 1978 and ended with the adoption of the German Renewable Energy Act in 2000. Although the policy instrument was undergoing some changes during subsequent adoption in other countries, the 2000 act effectively codified major features of FIT as a policy instrument. Jacobs (2014) describes the evolution of three key features of FIT – utilities' obligation to purchase, purchase tariff size, and duration of the payment period – through a process of incremental changes that he characterizes as "evolutionary tinkering" and "experimental learning". For example, the approach to determining tariff size evolved from generator's short-term avoided costs to long-term avoided costs (including cost of capital) to the inclusion of avoided external costs (environmental damage) to a percentage of retail prices and finally to a tariff based on actual generation costs and differentiated by technology. It was technology-specific tariffs that made possible wide adoption of PV solar technology, too expensive to compete on the basis of technology-neutral support schemes at the time. The process of "tinkering" was unfolding in several early adopter countries learning from each other's experience.

In the terminology of technology diffusion literature (e.g. Wilson 2012), the process Jacobs describes resembles not an invention but a formative phase which starts with a first application of an innovation and ends with the emergence of a "dominant design" (codification of a policy suitable for broad use). Furthermore, evolutionary tinkering and experimentation are the functions of niches as described in the regime–niche tradition (Kemp et al. 2001). Using similar language, Jacobs (2014) recommends creating protected spaces and maintaining them for sufficient time for policies to evolve. Although Jacobs discusses the experience of several interacting countries, his focus is not on policy diffusion but on the evolution of a specific policy instrument.

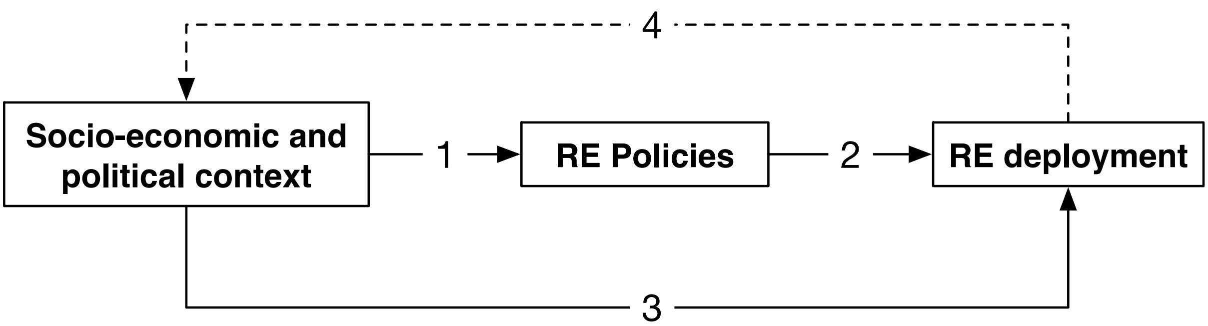
[31] Couture and Gagnon (2010) describe several different designs of feed-in tariff schemes.

Several studies link policy innovation to socio-technical transitions usually understood in terms of regime–niche dynamic. Upham et al. (2014) discuss climate policy innovation using concepts from the MLP. They define three types of policy innovation: original innovation – policy invention on the global scale; diffusion – adoption of an existing policy in a new jurisdiction or a new policy domain; and reframing – adding a new rationale to an existing policy. For example, support for an energy technology initially introduced to enhance security of energy supply can be reframed as a climate policy measure. Upham et al. (2014) conclude that existing regimes constrain policy innovation, favoring policies leading to incremental change and technological substitution within the regime. Policies with a wider systemic focus would likely require support from actors in multiple regimes. Lovell et al. (2009) also note the role of existing regimes in constraining policy change and emphasize the role of niches in fostering policy innovation in addition to other innovation types.

2.8 Large-N studies: multi-country quantitative comparisons of renewable energy deployment

A distinct body of literature emerged in the mid-2000s comparing the deployment of RE across countries. The authors of these studies were primarily political scientists and public policy scholars, with a small fraction representing transition studies and other disciplines. The common analytical framework of these studies included four general causal links involved in energy transitions (Figure 2.2), although not all of these links received equal attention.

Figure 2.2. Analytical framework of multi-country comparative studies



Causal link (1) was the adoption of state policies supporting RE. The main research question here has been "Why do countries adopt renewable energy policies?" (Chandler 2009; Schaffer and Bernauer 2014; Matisoff 2008; Baldwin et al. 2016) with the sub-question "How and why do renewable energy policies differ across countries?" Causal link (2) was the effect of RE policies on RE deployment with the main research question "How does the presence and design of RE policies affect RE deployment?" (e.g. Delmas and Montes-Sancho 2011; Menz and Vachon 2006; Carley 2009; Yin and Powers 2010; Jenner et al. 2013; Zhao et al. 2013; Shrimali and Kniefel 2011). Most studies asking this question recognized that the deployment of RE can be influenced not only by RE policies but by a broader socio-economic and political context (causal link (3) in Figure 2.2). In light of this recognition, some studies sought to carefully separate the influence of RE policies from the influence of other factors (e.g. Delmas and Montes-Sancho 2011; Carley 2009; Jenner et al. 2013; Shrimali and Kniefel 2011) whereas other studies argued that such separation is impossible or unnecessary and therefore thought to answer a different and more general research question: "How does the socio-economic and political context affect the deployment of renewable energy?"

Though in principle this third research question combined causal link (3) with (1) and (2), some studies (e.g. Cheon and Urpelainen 2013; Cadoret and Padovano 2016) argued that this distinction is not important because RE cannot be deployed without strong policy (more exactly, *environmental* policy) support. In other words, these studies considered the deployment of RE as a direct indicator of both presence and effectiveness of RE policies with causal link (3) being insignificant for a comparative analysis.

> *"[W]ithout regulatory policies that increase the profitability of renewable energy vis-á-vis fossil fuels, either by subsidizing renewables or punishing fossil fuels, it is very hard to increase substantially the share of renewables in electricity and other energy production… although we are unable to measure renewable electricity policy directly, there are very good a priori reasons to believe that robust renewable electricity growth cannot be attained without appropriate public policies. For these reasons, we are confident that* ***our dependent variable*** **[growth in RE generation – VV]** ***is an acceptable proxy for public policy****. Indeed, most previous studies of environmental policy using quantitative methods also focus on predicting outcomes instead of actual policies"* (Cheon and Urpelainen 2013, p.879) (emphasis mine – VV).

> *"We select the share of RE in gross final energy consumption as the endogenous variable …. As such, the regressand measures the stringency of the environmental policies of each country"* (Cadoret and Padovano 2016, p.263).

The second argument is particularly surprising because Cadoret and Padovano (2016) measure the deployment of not only new renewables such as solar and wind but also hydroelectricity – a traditional energy technology that can clearly be deployed *without* envronmental policy support. Although widespread, the argument that RE policies drive RE deployment has not always been found true when systematically analyzed (e.g. Delmas and Montes-Sancho 2011; Jenner et al. 2013; Zhao et al. 2013). Nevertheless, it has persisted possibly due to common misconception that the *correlation* between the presence of policies and higher RE deployment actually means a causal link between the two factors.

The final causal link ((4) in Figure 2.2) was only explicitly explored in a small number of studies (e.g. Cheon and Urpelainen 2013; Gosens et al. 2017) that were interested in mechanisms through which RE deployment could potentially influence its socio-economic and political context that would in turn stimulate or hinder further RE deployment. These causal links are akin to feedback loops such as "cumulative causation" discussed in section 2.4.3 of the Literature Review.

2.8.1 Scope, methodological approaches, and dependent variables

The **scope** of this literature has gradually expanded over time starting with only handful of cases (small-N) (Lipp 2007) mostly limited to North-Western Europe and the US states and single-point cross-sectional analyses (Menz and Vachon 2006) to medium- and large-N samples up to almost 150 countries over more than two decades (Baldwin et al. 2016; Zhao et al. 2013; Carley et al. 2017). Still, most detailed and rigorous studies have been limited to OECD or EU countries because of better data availability. While most earlier studies focused only on wind power, the later ones often included all "new renewables" (solar, wind, biomass, geothermal energy) in electricity or the entire contribution of renewable energy to the primary energy supply (Table 2.1).

Table 2.1. Geographic, time and sectoral scope of selected quantitative multi-country comparisons of renewable energy deployment

Study	Geographic scope	Time scope	Sectoral scope
Econometric studies of non-hydro RE in electricity			
Menz and Vachon (2006)	39 US states	2003	Wind power
Carley (2009)	48 US states	1998-2006	Non-hydro RE in electricity
Yin and Powers (2010)	50 US states	1993-2006	Non-hydro RE in electricity
Shrimali and Kniefel (2011)	50 US states	1991-2007	Non-hydro RE in electricity
Delmas and Montes-Sanchos (2011)	48 US states (650 utilities)	1998-2007	Non-hydro RE in electricity
Cheon and Urpelainen (2013)	19 OECD countries	1989-2007	Non-hydro RE in electricity
Jenner et al. (2013)	26 EU countries	1998-2010	Solar PV and onshore wind
Zhao et al. (2013)	122 countries	1980-2010*	Non-hydro RE in electricity
Sequiera and Santos (2018)	100-126 countries	1960-2004*	Solar, wind, geothermal, ocean
Econometric studies of renewables including hydro power			
Marques et al. (2010)	EU + CH, IS, TR	1990-2006	RE incl. hydro in TPES
Marques et al. (2011)	EU + CH, IS, TR	1990-2006	RE incl. hydro in TPES
Aguirre and Ibikunle (2014)	38 OECD + BRICS countries	1990-2010	RE incl. hydro in TPES
Cadoret and Padovano (2016)	26 EU countries	2004-2011	RE incl. hydro in TPES
Baldwin et al. (2016)	149 countries	1990-2010	RE (incl. and excl. hydro) in electricity
Econometric studies of policies			
Matisoff (2008)	US states	1990-2007	RE and energy efficiency
Chandler (2009)	US states	1997-2008	RE and energy efficiency
Schaffer and Bernauer (2014)	26 OECD countries	1990-2010	Non-hydro RE in electricity
Qualitative studies			
Butler and Neuhoff (2008)	DE, UK	1990-2000	Wind power
Lipp (2007)	DK, DE, UK	Ca 2004 and preceding period	Wind power (+ other RE in electricity)
Held et al. (2006}	25 EU countries	1998-2008	Wind power
Haas et al. (2011)	25 EU countries	Ca. 2008 and preceding period	Non-hydro RE in electricity

Note: * Studies with unbalanced samples, i.e. where data for different countries were available for different periods of time.

A common methodological approach of these studies has been distinctly different from both abstract economic modelling (see section 2.2) and from historically focused detailed case analysis which characterized TIS and regime–niche literature (sections 2.4 and 2.5). This literature predominately used quantitative statistical methods commonly found in comparative political analysis to analyze empirical data on renewable energy policies and deployment. In addition, it included a smaller number of multi-country comparisons (usually small-N) that used qualitative approaches based on similar theoretical premises (Table 2.1) to analyze quantitative data.

The most common **dependent variables** in these studies were indicators of renewable energy policies and deployment. However, different studies defined these indicators in different and sometimes incompatible ways. To begin with, different studies measured utilization of different renewable energy technologies depending on their sectoral and technological scope (Table 2.1). Especially sharp divide has been between the studies that included hydro power – one of the major and most mature energy technologies primarily limited by natural factors – and those that focused on "new renewables" – emerging technologies primarily constrained by the speed of innovation and adoption. Including hydropower in statistical analysis generally "overwhelms" the dynamics of "new renewables" and therefore produces very different results. A similar distortion can be observed if geothermal energy is included over longer time periods such as in Sequeira and Santos (2018).[32] Among modern renewables, the studies sometimes included all renewables and sometimes excluded some of them (e.g. Sequeira and Santos (2018) exclude biomass), sometimes focusing only on specific technologies (e.g. solar PV and onshore wind in Jenner et al. (2013)). Furthermore, some studies aggregated the utilization of all studied technologies while some others sought to explain the utilization of particular technologies (e.g. wind power) separately.

The next layer of differences has been *how* the deployment of renewable energy technologies has been measured. Several studies (e.g. Jenner et al. 2013; Shrimali and Kniefel 2011) measured **installed capacity** of renewable electricity. While a good metric of the investments, it is technically difficult to aggregate across technologies (due to different capacity factors), and apply outside the electricity sector. Other measures included **renewable energy supply** either in absolute terms or relative to the total supply of electricity or primary energy (Sequeira and Santos 2018). Some studies used the **growth** in production (Cheon and Urpelainen 2013; Gosens et al. 2017) or capacity (Jenner et al. 2013) as their dependent variable to capture the change over time (Table 2.2). Finally, certain qualitative studies used additional indicators such as the cost of renewable energy installations, investments in RE capacity etc. (Lipp 2007).

[32] Geothermal energy has been used in the USA in the 1970s and the 1980s at scale dominating all non-hydro renewables (IEA 2017d).

Table 2.2. Dependent variables in multi-country comparative studies

Indicator	Installed capacity		Annual production			RE policies presence	Adoption in a given year
Technology	Absolute	Additions	Share	Absolute	Growth		
Wind and solar★ power	Menz and Vachon (2006), Lipp (2007), Butler and Neuhoff (2008)	Jenner et al. (2013) ★			Held et al. (2006}		
Non-hydro RE in electricity	Delmas and Montes-Sanchos (2011), Shrimali and Kniefel (2011)*		Carley (2009), Yin and Powers (2010), Zhao et al. (2013), Sequiera and Santos (2018)	Carley (2009)	Cheon and Urpelainen (2013)		
RE (incl. hydro) in electricity or TPES			Cadoret and Padovano (2016), Marques et al. (2010), Marques et al. (2011), Aguirre and Ibikunle (2014)	Baldwin et al. (2016)			
RE policies						Delmas and Montes-Sanchos (2011), Matisoff (2008), Baldwin et al. (2016)	Chandler (2009), Schaffer and Bernauer (2014)

Note: * Shrimali and Kniefel (2011) used the ratio of nameplate capacity of RES-E to the total generation in the state

A number of studies were specifically interested in the presence and type of renewable energy policies. Such research used different dependent variables such as the presence of renewable energy policies or their introduction in a given year (Schaffer and Bernauer 2014). Some of these studies also differentiated between different types of RE policies such as feed-in-tariffs, subsidies and renewable portfolio standards (Baldwin et al. 2016). Many of the studies that did not use renewable energy policies as *dependent* variables used them instead as *independent* variable to explain the adoption of renewable energy technologies as discussed in the next subsection.

2.8.2 Explanatory theories and independent variables

The majority of the studies that analyzed causal link (1) – on its own or in combination with (2) and (3) relied on theories of policy change and policy diffusion reviewed in section 2.7. It largely depicted RE policies as cases of environmental policies[33] resulting from a combination of internal and external factors[34] (Chandler 2009; Schaffer and Bernauer 2014) with **internal** factors including:

- **state goals** such as reducing energy import dependence and greenhouse gas emissions;
- **special interests**, including those supporting RE, those of competing energy technologies and those of energy-intensive industries;
- **political ideology** of the government or the legislature; since RE policies were viewed as environmental policies the ideological correlates of environmental policies were often used: left-wing vs right-wing orientation, democratic vs. republican orientation (in the US), the presence of green parties, the track-record of environmental voting, and memberships in environmental organizations such as Sierra Club;
- **institutions** such as varieties of capitalism, the level of democracy, federalist structure of the state, and proportional representation;

and **external** factors including:

- policy **diffusion** from neighboring jurisdictions;
- **membership** in international integration organizations such as the **European Union**;
- participation in **international environmental treaties** such as the Kyoto Protocol.

In contrast to well-elaborated theories explaining the **presence** of RE policies, there were no detailed theories explaining their **design**, although the design has been shown to be critically important for their effectiveness (Yin and Powers 2010; Jenner et al. 2013) and shown to vary significantly between countries (Baldwin et al. 2016). Neither did this literature refer to many theories concerning the **effectiveness** of RE policies. It primarily relied on one economic theory, well-articulated by Jenner et al. (2013), namely that such policies should make investments in RE technologies economically attractive. A couple of studies also argued that higher economic or institutional capacity should make implementation of RE policies more effective (Baldwin et al. 2016; Carley 2009). Finally, the theories explaining the impact of non-

[33] For example, one influential study was titled "*How do Competing Interest Groups Influence Environmental Policy? The Case of Renewable Electricity in Industrialized Democracies, 1989-2007*" (Cheon and Urpelainen 2013).
[34] Cf. section 2.7.2.

policy factors on RE deployment (causal link (3) in Figure 2.2) were also rarely spelled out in sufficient detail. Jenner et al. (Jenner et al. 2013) were probably most specific by pointing out the costs of technology and the prices for electricity, which together define the Return On Investment (ROI) in renewables as the most direct factor influencing capacity additions of solar and wind power. Through detailed analysis they were able to separate the component of ROI determined by government policies (FITs) and thus disentangle the effect of policies from the effect of socio-technical and economic factors.

A distinct group of explanatory variables include **renewable energy policies** (which some studies considered as their *dependent* variable) included in some studies specifically to investigate policy effectiveness. Table 2.3 lists independent variables used in these various studies.

Table 2.3 Independent variables in multi-country comparative studies

Groups of variables	Examples/studies
Political variables	
State goals	Import independence of energy – Zhao et al. (2013), Cadoret and Padovano (2016), Sequiera and Santos (2018), Marques et al. (2011eh), Aguirre and Ibikunle (2014); electricity – Jenner et al. (2013) CO_2 or other emissions per capita – Delmas and Montes-Sanchos (2011), Schaffer and Bernauer (2014), Zhao et al. (2013), Cadoret and Padovano (2016), Sequiera and Santos (2018), Marques et al. (2011), Aguirre and Ibikunle (2014)
Political ideologies	LCV house score – Delmas and Montes-Sanchos (2011), Carley (2009), Shrimali and Kniefel (2011) Green party share, left/right divide – Schaffer and Bernauer (2014), Cheon and Urpelainen (2013), Cadoret and Padovano (2016) Democratic governor/representative, membership in Sierra club – Delmas and Montes-Sanchos (2011) Share of environmental taxes in GDP – Cadoret and Padovano (2016)
Political institutions and capacities	Employees in natural resource offices – Carley (2009) Varieties of capitalism, executive constraints – Cheon and Urpelainen (2013) Proportional representation, federalism – Schaffer and Bernauer (2014) Parliamentary vs. presidential governance, diversity of parties in government – Cadoret and Padovano (2016) Freedom house rating – Baldwin et al. (2016) Democracy indicators – Sequeira and Santos (2018)
Special interests	Supportive Share of non-hydro RE in electricity – Delmas and Montes-Sanchos (2011), Cheon and Urpelainen (2013) Renewable associations – Delmas and Montes-Sanchos (2011) Installed capacity of solar and wind – Schaffer and Bernauer (2014) Opposing Share of energy-intensive manufacturing in GDP – Cheon and Urpelainen (2013); share of manufacturing in GDP – Cadoret and Padovano (2016); share of industry in GDP – Sequeira and Santos (2018) Share of fossils and nuclear in electricity – Schaffer and Bernauer (2014), Jenner et al. (2013), Sequiera and Santos (2018), Marques et al. (2010), Marques et al. (2011), Aguirre and Ibikunle (2014) Production of coal per capita – Shrimali and Kniefel (2011) Fossil fuel rents (exports as share of GDP) – Baldwin et al. (2016)

Groups of variables	Examples/studies
Policy diffusion	Participation in Kyoto Protocol – Cheon and Urpelainen (2013), Aguirre and Ibikunle (2014) Participation in CDM – Baldwin et al. (2016) EU membership – Cheon and Urpelainen (2013); SandB (2014) Proximity to states with RE policies – Chandler (2009) Proximity to countries with RE policies – Schaffer and Bernauer (2014)
Effect of RE support policies	Presence of policies: RPS – Carley (2009); RPS vs. FIT – Lipp (2007), Butler and Neuhoff (2008), Haas et al. (2011); 6 types of policies – Zhao et al. (2013); RPS, FIT or subsidies – Baldwin et al. (2016); 11 types of RE policies – Aguirre and Ibikunle (2014) Presence and design of RPS – Yin and Powers (2010); RPS and FIT – Jenner et al. (2013) Enactment of EU Directive 2001/77/EC – Marques et al. (2011)
Techno-economic variables	Wind, solar, biomass potential – Delmas and Montes-Sanchos (2011), Carley (2009), Aguirre:2014dr} Geographic area – Marques et al. (2011) Energy consumption per capita – Marques et al. (2011) GDP (absolute) – Schaffer and Bernauer (2014), Marques et al. (2010), Marques et al. (2011); total electricity generation – Shrimali and Kniefel (2011) GDP per capita – Delmas and Montes-Sanchos (2011), Schaffer and Bernauer (2014), Jenner et al. (2013), Zhao et al. (2013), Shrimali and Kniefel (2011), Cheon and Urpelainen (2013), Cadoret and Padovano (2016), Sequeira:2018hh, Marques et al. (2011), Aguirre:2014dr} GDP growth – Schaffer and Bernauer (2014), Cadoret and Padovano (2016) Oil, energy or electricity price – Delmas and Montes-Sanchos (2011), Shrimali and Kniefel (2011), Cheon and Urpelainen (2013), Cadoret and Padovano (2016), Marques et al. (2011), Aguirre and Ibikunle (2014) Domestic credit to the private sector, FDI (foreign direct investment) – Zhao et al. (2013)
Socio-technical variables	RE patents per capita – Cheon and Urpelainen (2013) Secondary school enrollment, share of females – Zhao et al. (2013) Unemployment, utility ownership – Delmas and Montes-Sanchos (2011)

2.8.3 Method and models

The main method of finding relationships between the dependent variables (the rate of RE utilization or the presence of RE policies) and the independent variables have been linear regression models[35] conducted on panel samples.[36] The ontological premise behind such models is that variations in each explanatory variable produce independent variations in the dependent variable. Such variations can be “isolated” by statistical techniques to “distill” the effect of each explanatory factor all else being equal. For example, such a model can show that *all else being equal* higher representation of green parties in the Parliament or adoption of feed-in-tariffs leads to increasing renewable energy deployment.

[35] Some studies (e.g. Zhao et al. 2013) used more sophisticated techniques to validate and improved robustness of their models.

[36] In a panel (time-series cross-sectional) sample each datapoint represents a particular country in a particular year. Some of earlier studies (e.g. Menz and Vachon 2006) used cross-sectional analysis with a single datapoint for each country.

In principle, regression models can also be used to investigate combined effect of two or more variables through the use of the so-called “interaction terms”. However, only a few studies in this group systematically used this technique. Cheon and Urpelainen (2013) explore the “countervailing lobbying” hypothesis, namely that political resistance to renewable energy depends on two factors: the strength of energy intensive industries and the actual rate of penetration of renewable energy, using the interaction term of these two variables. Cadoret and Padovano (2016) interact the left-wing orientation of the government with the coherence of the government coalition (a diversity index of party representation).

More sophisticated statistical models, e.g. used by Delmas and Montes-Sanchos (2011) sought to disentangle the factors that affect the presence of RE policies (in their case – RPS) and their effects through two-stage regression.

Another notable method used in these studies was “event history analysis” (also called “survival analysis”) designed to investigate the probability that a certain event will occur in certain circumstances (see Chapter 4 for detailed explanation). Chandler (2009) and Schaffer and Bernauer (2014) used this technique to explain the timing of introducing or changing renewable energy policies across the US states and advanced industrialized countries respectively.

2.8.4 Results of large-N studies

Given the large effort, the contribution of this literature to the theories of energy transition has been surprisingly limited. Perhaps the most important observation is that all these studies have not consistently demonstrated significant correlation between the deployment of renewable energy and most of the potentially explanatory variables listed in Table 2.3. In other words, no theory that could convincingly explain national differences in transitions to renewable electricity has been identified.

However, several insights from these studies are relevant to my analysis. First, some studies demonstrated that renewable energy policies are more numerous and more sophisticated in **high-income** countries (Baldwin et al. 2016). High-income countries also deploy more RETs (Baldwin et al. 2016; Jenner et al. 2013; Zhao et al. 2013). Despite the leadership of high-income countries, many studies failed to establish a significant correlation between GDP per capita (expressed as a continuous variable) and the adoption of RE policies (Schaffer and Bernauer 2014) or the adoption of renewables (Baldwin et al. 2016).

Second, the **European Union (EU) membership** has been a significant factor in early adoption of RE policies (Schaffer and Bernauer 2014) and more rapid deployment of renewable electricity (Cheon and Urpelainen 2013).

Third, at least two of the studies have clearly demonstrated that **the rate of growth** of RET deployment correlates with the already **existing scale of their deployment** (in other words the growth of RETs is exponential). Cheon and Urpelainen (2013) explained this phenomenon by potential political lobbying on behalf of special interests promoting renewable energy. As the size of the sector grows, they argued, so does its political power. Stronger RE policies are enacted which in turn stimulate stronger growth, leading to further strengthening of the pro-renewables lobbies and even stronger policies etc. Gosens et al. (2017) document the same phenomenon but see it as a case of a general feature of diffusion of social novelties (S-curve, see section 2.3). Delmas and Montes-Sanchos (2011) found that the presence of RPS in a state is correlated with the share of renewables used for electricity generation in the state (although they do not explicitly discuss the direction of that causality.

Fourth, Schaffer and Bernauer (2014) find significant correlation of early adoption of RE policies with **federal structure** of the countries they study.

Results of large-N studies are summarized in Table 2.4.

Table 2.4. Most common hypotheses and corresponding results of multi-country comparisons of RET deployment

Overarching hypotheses	Independent variables	Empirical validation	Notes
Political			
State goals: Import dependence motivates countries to adopt renewables	Energy import dependence	Unconfirmed	Correlation with RE shares (Zhao et al., 2013) No correlation with RETs growth (Cheon and Urpelainen, 2013) No correlation of electricity imports with RE capacity growth in the EU (Jenner et al. 2013) No correlation in low- and middle-income and negative in high-income countries (Baldwin et al. 2016) No correlation in some models and positive correlation in other models in Sequiera and Santos (2018) but possibly an artefact because absolute trade volumes used for relative dependent variable
State goals: Higher GHG emissions might either stimulate countries to introduce RETs or shape strong resistance to RETs	CO2 emission intensity (energy, GDP, per capita)	Mixed	Positive correlation between CO2 intensity of energy use and adoption of RE policies in some models (Schaffer and Bernauer 2014) Negative correlation with CO2 emissions and the share of RE in TPES in (Zhao et al., 2013) and in (Sequiera and Santos 2018)
Political orientation of cabinet affects the chances of adoption of RE policies. Left-wing governments and higher representation of green parties or environmental inclination of lawmakers would stimulate higher RE deployment/policy adoption	Left- or right-wing orientation of executive or cabinet Green party representation LCV score	Mixed	Correlation with LCV score (Carley 2009) Significant correlation with left orientation of cabinet but no correlation with right- orientation of cabinet (Schaffer and Bernauer 2014) No correlation with right or left orientation of the chief executive (Schaffer and Bernauer 2014, Cheon and Urpelainen, 2013) Negative correlation with political right in low- and high- but not in middle-income countries (Baldwin et al. 2016) No or negative correlation with the representation of green parties (Cheon and Urpelainen, 2013)
Vested interests: RE deployment is slowed down by conventional energy lobbies	Share of nuclear and fossils in electricity Fossil fuel rents	Unconfirmed	Positive correlation between RE policies and the shares of nuclear and fossils in electricity mix in OECD (Schaffer and Bernauer 2014) and with the growth in wind capacity in the EU (Jenner et al. 2013) Negative correlation between nuclear and solar (Jenner et al. 2013) Negative correlation between fossil fuel rents and RE production (absolute) in high-income countries (Baldwin et al. 2016)
Vested interests: RE growth is stimulated by the larger size of RE sector due to either lobbying for stronger RE policies or other factors	The size of RE sector	Confirmed	Positive correlation between RE growth and RE deployment found by Cheon and Urpelainen (2013) in OECD especially in 1996-2007 and by Gosens et al. (2017) worldwide

Overarching hypotheses	Independent variables	Empirical validation	Notes
Constitutional organization of countries and variety of capitalism would affect the adoption and effectiveness of RE policies. In particular, federalism would allow policy learning and experimentation; proportional representation would support "diffuse" interests associated with decentralized energy sources. Inclusive democracy would promote environmental values and policies	Federalism Proportional representation POLITY IV and other democracy indices	Partially confirmed	Correlation between federalism and proportional representation and the timing of FIT and RPS (Schaffer and Bernauer 2014) No correlation with VoC (Cheon and Urpelainen, 2013) Sequiera and Santos (2018) find strong correlation with democracy but do not control for time effects and dataset dominated by US geothermal
Policy diffusion: Countries are likely to adopt RE policies or deploy RETs if their neighbors or trade partners do it	Adoption of RE policies of members, trade partners	Unconfirmed	Weaker evidence of policy diffusion from neighboring states (Chandler 2009) No significant correlation between adoption of RE policies and trade links or other proximity with countries with such policies (Schaffer and Bernauer 2014)
Policy diffusion: Membership in the European Union facilitates adoption of RE policies through policy harmonization and convergence	Membership in the EU	Partially confirmed	Positive and significant correlation between the membership in the EU and the adoption of FIT/RPS in two of three models (Schaffer and Bernauer 2014) Small correlation with RE growth in one model (Cheon and Urpelainen, 2013)
Policy diffusion: International climate cooperation motivates countries to develop RETs	Kyoto protocol ratification	Unconfirmed	No correlation in Kyoto Protocol ratification and RET growth (Cheon and Urpelainen, 2013)
Presence and design of RE policies stimulates the deployment of RETs	Presence and type of RE policies	Mixed	Presence of RE policies correlates with RE deployment, but more so in 1980-1995 than in 1995-2010 (Zhao et al., 2013) FITs work better than RPS in Europe – Lipp (2007), Butler and Neuhoff (2008), Held et al. (2006), Haas et al. (2011). FITs affect deployment of solar PV, but not wind (Jenner et al. 2013) RPS are effective in the US when accounted for their features (Menz and Vachon 2006, Yin and Powers 2010) RPS have no significant or even negative effects in the US (Delmas and Montes-Sanchos 2011, Carley 2009, Shrimali and Kniefel 2011) Subsidies correlate with deployment in low-income countries (Baldwin et al. 2016)
Economic factors			
Higher income per capita and larger size of the economy support faster deployment of RETs	Income per capita Size of the economy	Partially confirmed	**GDP/ca**: Small marginally significant correlation with RE policies in some models (Schaffer and Bernauer 2014), no correlation in OECD (Cheon and Urpelainen, 2013) and in high-income (Baldwin et al. 2016) Correlation with RE deployment in OLS, but not in PPML models (Zhao et al., 2013) Correlation in low- and middle-income countries and in the US states may be an artefact of DV definition (as absolute value) (Baldwin et al. 2016, Carley 2009) **GDP:** No correlation of policies in OECD (Schaffer and Bernauer 2014).

2.9 Summary

This chapter presents a review of diverse bodies of literature dealing with energy transitions. Such a broad scope is necessary because, as will be demonstrated later, individual bodies of literature cannot provide a comprehensive account of energy transitions. However, taken together they support constructing an analytical framework based not only on specific ideas in each field, but also on their parallels and complementarities.

The key ideas in the reviewed literature are listed in Table 2.5. Parallels and complementarities between different bodies of literature are presented in Table 2.6.

Table 2.5. Key ideas from the reviewed literature used in the thesis

Literature	Key ideas used in the dissertation
Neoclassical economics, energy-economy models and IAMs	The scale and speed of transformation necessary for decarbonization Critical role of supply-demand balance Mechanisms driving the shifts in energy composition: costs of resources and technologies and demand for energy services
Diffusion studies	Patterns of diffusion of both individual technologies and pervasive systems (S-curve) Different stages of diffusion involving distinctly different mechanisms Complexity of diffusion mechanisms of “pervasive systems” Diffusion from core to periphery Cost decline due to learning Formative stage marked by the emergence of a dominant design Different underlying mechanisms giving rise to similar patterns
TIS	Various mechanisms are involved in functioning of TIS: economic, sociological, political Formative stage ends with self-reinforcing mechanisms, cumulative causation National learning systems functioning similar to TIS in late-comer countries The importance of local deployment systems
Regime–niche studies	Stability of regime; lock-in and path dependence Fluidity of niches, learning and experimentation in niches Regime-niche interaction and consolidation of niches into regimes
Spatial perspective	Place specificity and spatial embeddedness as necessary components of technology diffusion
Policy change	State imperatives may shape transition policies Institutional design may influence policy change and innovation

Policy diffusion	Diffusion as an important factor in policy change Difference between policy diffusion and translation (adaptation of policies to local conditions)
Multi-country comparative studies	Lack of robust and consistent conclusions on significance of a large number of proposed explanatory variables High-income status, EU membership and federalism correlate with earlier adoption and sophistication of RE policies. High-income status and EU membership correlate with shares of renewables. The existing shares of renewables correlate with the rates of their growth

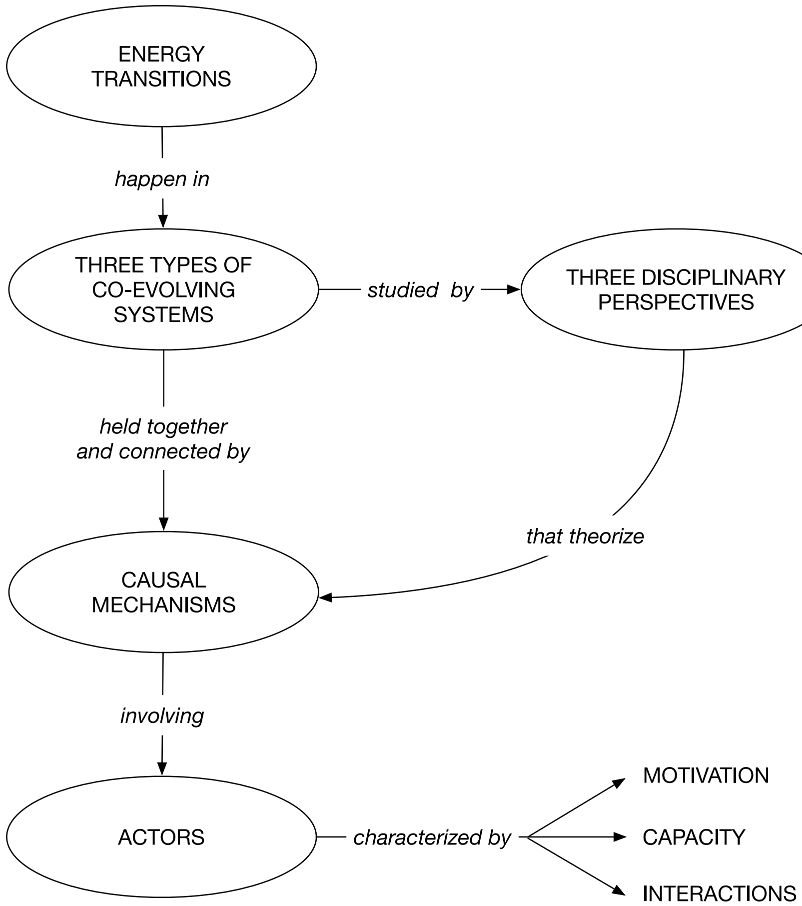
Table 2.6. Parallels and complementarities in the literature on energy transitions

Bodies of literature	Parallels	Complementarities
Energy-economy models and IAMs and Technology diffusion		Technology diffusion literature provides historic diffusion and learning rates which are used in energy-economy models
Technology diffusion, TIS and regime-niche literature	Distinction between "formative" (niche evolution) and "growth" (regime consolidation) phases of technology adoption	TIS literature explains the mechanisms of early uptake of technologies; regime-niche explains the pathways from innovative niches to dominant regimes and why they may fail
Technology diffusion, TIS, spatial perspective	Local deployment systems/national learning systems/local embeddedness in the periphery	Spatial literature describes mechanisms underlying distinction between core and periphery of technology deployment
Technology diffusion, policy innovation, TIS	Learning and experimentation at the formative phase precede the emergence of dominant design	Policy innovation can support TIS and thus speed up technology diffusion
Technology diffusion, policy diffusion, spatial perspective	Importance of local learning, policy translation and local deployment systems	

3 Conceptual framework

In this chapter, I develop a conceptual framework for the analysis of energy transitions based on two key pillars (Figure 3.1). The first pillar is three different disciplinary perspectives on national energy transitions which align with the three main types of systems co-evolving in the process of transition. The second pillar is the idea of causal mechanisms as a distinct mode of explanation in social sciences. Mechanism-based accounts seek to represent larger-scale social processes through a combination of interacting causal mechanisms. They can explain path-dependency and contingency in such phenomena, while not rejecting significant regularity at the level of individual mechanisms. I argue that mechanism-based accounts are an appropriate mode of explaining energy transitions, given their complex and heterogeneous nature that requires insights from different disciplinary fields. Theories developed within three disciplinary perspectives provide a repertoire of possible transition mechanisms. In section 3.3 I outline hypothetical generic mechanisms of energy transitions and present a conceptual model linking these mechanisms to stages of the innovation deployment and diffusion process.

Figure 3.1. Conceptual framework



3.1 Co-evolving systems and three perspectives on national energy transitions[37]

3.1.1 Co-evolving systems in transition studies

The first component of my conceptual framework is a concept of co-evolving systems involved in such transitions and disciplinary perspectives focusing on each type of systems. Several studies conceptualize different types of transitions – low-carbon transitions, technological revolutions, or broader socio-economic development – as co-evolution of natural, technological and social systems.[38] Different scholars delineated these co-evolving systems differently, frequently mentioning Technology, Economy, and Institutions or Politics (Table 3.1). Despite different delineation of systems, these works subscribe to a similar concept of co-evolution, stressing that co-evolving systems are semi-autonomous (i.e. they have their own elements, boundaries and dynamics) but interacting. No single system is assigned universal causal primacy, even if change leading to a particular transition may originate in one type of system, or one system may "lead the way" of change at a particular moment.

Table 3.1. Co-evolving systems identified in seminal studies of socio-economic or technological change

Publication	**Scope**	**Co-evolving systems**
Norgaard (1994)	Socio-economic development	Technologies, Knowledge, Organization, Values, Environment
Freeman and Louçã (2001)	Technological revolutions	Technology, Science, Politics, Culture, Economy
Perez (2002)	Technological revolutions	Economic, Technological and Institutional [spheres]
Foxon (2011)	Sustainable low-carbon transitions	Technologies, Institutions, Business Strategies, User Practices, Ecosystems

[37] This section is largely based on a section from the following article which I co-authored as a second author: Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research and Social Science*, 37, pp.175–190.

[38] Though Safarzyńska et al. (2012) recommend reserving the term co-evolution strictly for systems with a Darwinian mechanism of variation, selection, and differential reproduction, in this thesis I follow the tradition of using this term in a broader sense, to denote interaction between semi-autonomous systems regardless of specific mechanisms of system dynamics.

In this type of studies, it is the relative autonomy of interacting systems that accounts for the uneven pace of transition processes. According to both Perez (2002) and Freeman and Louçã (2001), distinct phases of a transition process (in their case – technological revolutions) are characterized by a different level of alignment between co-evolving systems – loss of integration and subsequent reintegration. According to Perez (2002), most transition processes occur through the combination of the forces of conservation (inertia) and the forces of transformation, which at any given moment can be associated with different systems.[39] The process of change usually starts in one system and eventually either overcomes the inertia in other systems, or runs into a barrier associated with this inertia. In case of a successful transition, it is restored alignment and harmony between systems that underpins rapid growth at a later stage.

Conceptualized as a co-evolutionary process, a transition involves two types of processes: (1) those occurring within each of the systems and (2) those connecting these systems. Therefore, neither atomized studies of strictly additive systems, nor subsuming all systems into one is a productive approach to studying transitions. "It is ... essential to study both the relatively independent development of each stream of history and their interdependencies, their loss of integration, and their reintegration" (Freeman and Louçã 2001, p.127).

3.1.2 Three types of systems in national energy transitions

In my approach to national energy transitions, I am building on the concept of semi-autonomous co-evolving systems. Grübler et al. (2016) define an energy transition "as a change in the state of an energy system as opposed to a change in individual energy technology or fuel source". They contrast complex and pervasive systemic transitions with more trivial and shallower shifts in individual energy technologies in particular markets. These authors' view reflects the wider scientific consensus that mitigating the risks of the climate change and addressing other sustainability challenges would require pervasive "grand" transitions encompassing national and global scales (see also GEA (2012) and Smith et al. (2010)). This type of transition has historically involved several distinct kinds of systemic changes.

The first has been change in the magnitude and type of energy flows and the nature of physical and chemical processes involved in energy "production" and "consumption" coordinated through energy markets.[40] The second has been change in technologies used for

[39] In a mechanism-based account (see section 3.2 below), the forces of inertia and transformation can be interpreted as mechanisms of stability and change.

[40] Although physically energy cannot be "produced" or "consumed" since it is always preserved, these terms have a clear economic sense. By using energy services, economic actors "consume" energy depending on its

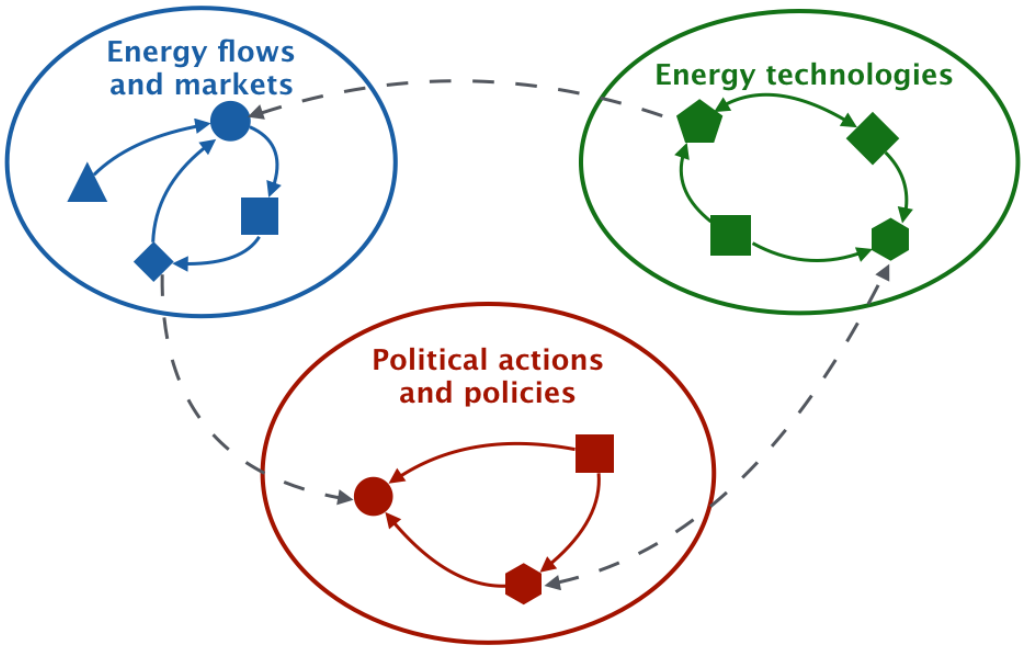
extracting, transforming and utilizing energy. Modern energy transitions may also involve the third kind of change: in policies regulating the socio-political role of energy systems, for example to prevent dangerous climate change, reduce poverty or empower certain countries or social groups. These three types of changes involved in national energy transitions occur in three distinct types of systems (Figure 3.2):

(1) **techno-economic systems** delineated by energy flows, extraction, conversion and use processes involved in energy production and consumption as coordinated by energy markets;

(2) **socio-technical systems** delineated by knowledge, practices and networks associated with energy technologies; and

(3) **systems of political actions[41] and institutions** influencing energy-related policies.

Figure 3.2. Co-evolving systems in national energy transitions



This definition of the three systems involved in energy transition partially overlaps with the approaches discussed above but exactly coincides with neither of them. This difference stems mainly from the focus on different type of change (e.g. "sustainable low-carbon transitions"

costs and their means and preferences and they can also "produce" energy by extracting or capturing it from nature and transforming it to useful forms.

[41] Easton (1957) called such systems of political actions "political systems". I avoid using this term as it is often understood in a narrower sense as a country's constitutional and government order.

in Foxon (2011) and "technological revolutions" in Freeman and Louçã (2001), as opposed to national energy transitions in my case).

The systems involved in national energy transitions co-evolve, which means that they are (1) **distinct** systems, (2) largely **autonomous** from each other, but at the same time (3) **interacting** with each other. First, each of the three systems has **distinct boundaries, elements, and relationships between these elements**. Techno-economic systems include energy resources and flows found in the natural environment, transportation of fossil fuels from production sites to power plants, conversion of primary energy into electricity and transmission of electricity through grids, final energy "consumption", as well as markets coordinating the flow of energy carriers and services. Socio-technical systems include networks of developers, manufacturers and installers of energy equipment, R&D institutions, knowledge, as well as various user practices. Political action systems include what Easton (1957, pp. 384-385) terms "inputs" such as demands and support for certain policies from voters, parties, lobbies and bureaucracies and "outputs" such as energy-related laws, regulations, and international agreements as well as feedbacks between the two. They also include political institutions that play a key role in transforming "inputs" into "outputs".

One and the same real-world object may be viewed as an element of two or more systems. For example, a gas-fired power plant can be seen as an energy transformation node in a system of energy flows and markets, an economic actor purchasing gas and selling electricity, and an element of a socio-technical system using certain technologies for electricity generation linked to networks of equipment designers and manufacturers and organizational practices of utilities and grid operators. Finally, a gas power plant is also an element of a system of political actions where it is both an object of regulation and an asset of certain political actors (utilities, municipalities, states, investment banks etc.).

Second, each of the three systems can **evolve autonomously,** independently from the other two. For example, energy flows may change because of the depletion of fossil fuel deposits, decommissioning of old power plants, or people buying larger houses that require more heating. None of these changes require political or technological shifts. Socio-technical systems may change because of the invention or diffusion of new technologies, independent of the changes in energy flows or policies. Finally, policies may change because of changed perceptions of energy security or other political shifts, not necessarily in sync with energy flows or technology change. In terms of causal mechanisms, this means that each system is underpinned by a plethora of interacting mechanisms.

Third, the co-evolving systems **affect each other** as shown with dashed lines in Figure 3.2. Politically motivated taxes and subsidies may influence the use of existing and diffusion of new technologies. Increasing energy imports may trigger political action to promote the development of domestic resources. Technological innovation may stimulate new energy uses and therefore increase energy demand. This means that there are causal mechanisms that cross boundaries of individual systems, thus supporting their interactions.

Additionally, the concept of co-evolving systems underscores macro-level patterns described above – dis-integration and subsequent re-integration of systems, or one system being a source of change and overcoming inertia of other systems. Some examples of co-evolution – parallel development of technological solutions, actor networks, and policy support mechanisms – in the field of renewable energy are demonstrated by national case studies in Chapter 6.

Thus, national energy transitions involve co-evolution of techno-economic, socio-technical, and political action systems. These three types of systems are in the focus of three distinct scholarly fields, which I call the *perspectives on national energy transitions*, each with its specific disciplinary roots, concepts, variables, and theories explaining change and continuity in the relevant system, as well as causal mechanisms.

3.1.3 Three perspectives on national energy transitions

The concept of three types of co-evolving systems is an ontological one – it posits that the distinct system types with their interactions are actually "out there", which has implications for transition processes. At the same time, the concept has an epistemological aspect, explaining the existence of three different disciplinary perspectives. The following three disciplinary perspectives correspond to the three types of co-evolving systems:

Techno-economic perspective. The techno-economic perspective focuses on energy systems defined by energy flows, conversion processes and uses coordinated through energy markets. On the one hand, these are connected to elements of natural systems such as oil or uranium deposits and the flows of water, wind and sunlight. On the other hand, energy delivers services valued by people. These services (such as lighting and mobility) are produced and distributed similarly to other economic goods, for example bought and sold in markets. Therefore, physical energy flows and conversion processes can be matched with energy "production", "consumption" and trade in societies, which makes it possible to represent these flows and processes in techno-economic terms and models.

Explaining stability and change of techno-economic systems involves theories from Earth sciences (e.g. geology, hydrology, climatology), engineering, and economics. Neoclassical economics with associated concept of supply-demand balance as a result of market equilibrium play a central role in Integrated Assessment Models (IAMs) commonly used for analyzing climate change and developing transition scenarios (see section 2.2). More nuanced understanding of long-term changes in energy systems requires systematic historical observations and insights from evolutionary and ecological economics that go beyond neoclassical theories. The literature representing the techno-economic perspective on energy transitions is reviewed above in section 2.2 and, partially, 2.3.

Socio-technical perspective. The socio-technical perspective focuses on technological change, especially on the emergence and diffusion of new technologies, building on evolutionary economics, sociology of technology, and science and technology studies (STS). In contrast to the techno-economic perspective, where technology is simply a method of extracting, converting, or using energy by means of particular equipment, the socio-technical perspective has a more complex and nuanced view of technology as a social phenomenon, i.e. knowledge and practices embedded in technical artifacts, shared by human actors, and circulating in social networks, which is captured by such concepts as *technological system* (Carlsson and Stankiewicz 1991) or a broader *socio-technical system* (Schot et al. 2016).

The socio-technical perspective includes several major strands of research relevant to energy transitions. One strand, focusing on innovation systems that support the generation and spread of novelties and particularly on technological innovation systems (TIS) (Bergek et al. 2008), is reviewed in section 2.4. Another strand, which takes a broader view of socio-technical transitions and relies on the central concepts of the socio-technical regime and niche, is reviewed in section 2.5. The two main bodies of literature within the latter strand deal with strategic niche management (SNM) (Kemp et al. 2001) and the multi-level perspective on technology transitions (Geels 2002). The third strand include a socio-technical component in technology diffusion studies reviewed in section 2.3. Finally, socio-technical components are prominently featuring in literature on spatial aspects of transition reviewed in section 2.6.

Political perspective. The central focus of the political perspective on energy transitions is on change in policies which affect energy systems. Policy change is studied within several domains of political science with different ontological assumptions and epistemological practices (Capano 2009). Studies within this perspective also look into political institutions, which are closely related to policies. The respective literature is reviewed in section 2.7.

Table 3.2 summarizes the three perspectives on national energy transitions. An explanation of such transitions should include theories and variables from all three perspectives as well as account for their interactions.

Table 3.2. Three perspectives on national energy transitions

Perspective	Disciplinary roots	Systemic focus	Examples of concepts and variables	Examples of causal mechanisms*	Examples of applications	Limitations
Techno-economic	Economic history, neoclassical, evolutionary, ecological economics; energy systems analysis	Energy flows, conversion processes, and markets	Energy resources, energy infrastructure, energy demand	Supply-demand balance, market equilibrium, energy ladder, resource depletion	Long-term climate-energy scenarios in IAMs	Poor representation of technology inertia and innovation as well as policy change
Socio-technical	Sociology and history of technology, STS, evolutionary economics	Energy technologies embedded in socio-technical systems	Socio-technical regimes, niches, innovation systems, innovation diffusion	Technological lock-in, learning, diffusion of technology, network formation	Transition management, innovation policies	Excessive focus on novelty, poor representation of politics
Political	Political science, political economy, policy studies, international relations	Political actions and institutions influencing formulation and implementation of energy-related policies	National interests, special interests, institutional capacities	Institutional lock-in, coalition formation, aggregation of interests by institutions, policy learning and diffusion	Design of policies and international regimes	Poor representation of material factors

Note: * Causal mechanisms are discussed below in section 3.2

3.2 Causal mechanisms as a mode of explanation

3.2.1 Causal mechanisms

The second pillar of my conceptual framework are causal mechanisms, which are at the center of a distinct mode of scientific explanation, particularly in social sciences (Little 1991; Tilly 2001; Hedström and Ylikoski 2010). This mode is often contrasted with Hempel's (1965) "covering law" type of explanations, where researchers seek to produce high-level generalizations about processes or events and then explain individual phenomena as instances of this general law (Little 2015). Because completely deterministic laws are unlikely in social sciences and history, the proper mode of explanation for these fields, according to Hempel, is "probabilistic-statistical", which implies that the presence of certain conditions leads to an increased probability of a given event. These approaches associated with the positivist philosophy of science are based on observed regularities, deterministic or probabilistic, but neither of them implies that these regularities necessarily reflect cause-and-effect relationships that really exist.

The causal mechanisms approach takes a different stance: it makes an ontological assumption about the existence of mechanisms that have real causal powers and connect effects to causes (Little 2011). As such, this approach is positioned within scientific realist, critical realist (Hedström and Ylikoski 2010), or, more broadly, post-positivist traditions (Geels, Berkhout, et al. 2016). Causal mechanisms can be identified and demonstrated, and phenomena can be explained by referring to mechanisms bringing about these phenomena. A mechanism-based explanation "should detail the cogs and wheels of the causal process through which the outcome to be explained was brought about" (Hedström and Ylikoski 2010, p.50). There are several formal definitions of causal mechanisms differing in details but consistent with this general view. In one of the earlier writings on the subject, Little (1991) defines causal mechanism as "a series of events governed by law-like regularities that lead from the *explanans* [explanatory factors] to the *explanandum* [event or phenomenon to be explained]" (p. 15). According to Hedström (2005, p.11), a mechanism is "a constellation of entities and activities that are linked to one another in such a way that they regularly bring about a particular type of outcome". All definitions agree that individual mechanisms function in a law-like or at least a regular manner, and should lead to a certain outcome, which can be explained through these mechanisms – "[a] mechanism is always a mechanism for something" (Hedström and Ylikoski 2010, p.50), be it social revolution or energy transition. Examples of causal mechanisms in social sciences include rational choice, increasing returns, adaptive expectations etc. (Falleti and Lynch 2009). As seen from Chapter 2, possible mechanisms related to energy transition include, among others: state responding to energy security challenges by developing domestic energy sources; vested interests affecting policy-making; policy diffusion; technology and policy learning.

Similar mechanisms can occur in different settings (something Little (2015) calls "recurring mechanisms"). For example, as demonstrated in Chapter 2, such mechanisms as increasing returns (and associated positive feedback loops) are found in infrastructural investments, technology learning, and policy change. Mechanisms may operate at different levels and involve different types of actors from individuals to large social systems. For the purpose of explanation, mechanisms can be invoked at different levels of abstraction – more general or more specific (Falleti and Lynch 2009). For example, "learning" is a general type of a mechanism, but its more specific subtypes include social learning, policy learning, technological learning, as well as "learning by search" and "learning by doing" discussed in section 2.3 above. Furthermore, mechanisms are "nested" in the sense that a mechanism often can be broken down into several more detailed underlying mechanisms. For example, the mechanism of increasing returns is an aggregated result of several underlying mechanisms – economies of scale, learning economies, adaptive expectations, and network economies – as discussed in section 2.5.

3.2.2 Nature of social reality and mechanism-based explanations in social sciences

Causal mechanisms as a mode of explanation are particularly relevant to social science,[42] given the nature of the social world, which “demonstrates a substantial degree of contingency, heterogeneity, and path-dependence” (Little 2015, p.470). Thus, while large-scale social events like revolutions (or energy transitions) often display a significant degree of regularity, this regularity does not take the form of a “general law of revolutions” relating explanatory variables to the outcome, and a particular revolution cannot be explained as an instance of this general law. Tilly (1995, p.1601) argues that "regularities in political life are very broad <…> but do not operate in the form of recurrent structure and processes at a large scale. They consist of recurrent causes which in different circumstances and sequences compound into highly variable but nonetheless explicable effects”. These large-scale events are driven by a set of interconnected mechanisms, each of which, acting in isolation, would generally work in a regular, predictable, or even “law-like” way. However, individual mechanisms are rarely found in isolation. In a real social setting, “their aggregate, cumulative, and longer-term effects vary considerably depending on initial conditions and on combinations with other mechanisms” (Tilly 2001, p.25). The outcomes of mechanisms also substantially depend on contextual factors (Falleti and Lynch 2009). For example, the mechanism of vested interests influencing policy-making, which was discussed in section 2.7, taken in isolation and with regard to a particular interest group, would lead to the adoption of policies increasingly favoring this group. But in combination with similar mechanisms involving other interest groups, other mechanisms, and contextual factors (e.g. material limitations) this outcome cannot be taken for granted.

According to Tilly, frequently occurring combinations or sequences of mechanisms form larger social processes, which usually have some degree of regularity, but are less regular than individual mechanisms. “Interactions among mechanisms, processes, and initial conditions” constitute mechanism-based explanations (Tilly and Tarrow 2015, p.242) of more general social phenomena. For example, Tilly and Tarrow (2015) posit a limited range of social mechanisms behind political contention and show how the diversity of contentious episodes

[42] In the context of social science, the term “social mechanisms” is also used (see e.g. Hedström and Ylikoski 2010).

– from peaceful protests to violent revolutions – is produced by different combinations of these mechanisms and different contextual conditions.

Theories identifying and describing individual mechanisms are "theories of the middle range" in Merton's (1968) sense – they explain a limited class of phenomena but do not seek to explain all social phenomena (Hedström and Ylikoski 2010). Large-scale social processes are typically heterogeneous in nature and involve several mechanisms defined by different theories. This justifies eclectic use of social theories and mobilizing insights from different disciplinary fields for dealing with such processes (Little 2018). "[B]ecause causal mechanisms can be investigated through largely independent bodies of theory and research, the causal mechanisms approach permits for a degree of cumulativeness in social science knowledge that is more difficult to achieve when guided by other ontological assumptions" (Little 2015 p.463).

Because configurations of relevant mechanisms and contextual conditions may change over time, it often makes sense to divide a longer process into **episodes** characterized by distinct configurations of mechanisms (Tilly and Tarrow 2015, p.39). The episodes can be used for robust comparison, including across different countries; for this purpose, a researcher may identify causally similar and dissimilar episodes (Tilly 2001).

Thus, a mechanism-based strategy of explaining a large-scale social phenomenon involves identifying interdependent causal mechanisms at play in the particular situation and demonstrating how these mechanisms and the actions of the actors involved produce the outcome to be explained (Little 2018). The analysis may also include dividing longer processes into shorter episodes with different combinations of mechanisms at play. This produces an "analytical narrative" different from a simple narrative account in that it relies on well-defined and theorized mechanisms, but also different from a "covering law" explanation that would simply relate input variables to a certain outcome.

Two pillars of my conceptual framework complement each other. There is a close connection between mechanisms and societal systems, which are held together and linked to each other by mechanisms. In his works on mechanism-based explanations in social sciences, Bunge (1997; 2004) emphasizes this connection, as well as the role of mechanisms in the system's change or stability. To him, a mechanism is "a process in a concrete system, such that it is capable of bringing about or preventing some change in the system as a whole or in some of its subsystems" (Bunge 1997, p.414). He discusses three societal systems – the economy, the policy, and the culture – each of which held together by the respective type of mechanisms. There is also coupling between mechanisms of different type, which accounts for the interaction between different systems.

Different types of mechanisms are studied by different disciplinary perspectives. Specific lower-level mechanisms are usually theorized within a particular perspective. Even if the explanatory factors and outcomes they connect belong to different systems, the mechanism itself is usually explained within one of the perspectives. For example, socio-technical theories may use explanatory factors related to energy resources and markets – e.g. resource depletion of price shocks – but these factors are seen as inputs to a socio-technical mechanism (e.g. regime disruption as a result of landscape shocks) rather than analytical foci of these theories. However, the analysis of more complex and general mechanisms may require contributions from several perspectives. For example, feedback loops underlying the high-level mechanism of "increasing returns" may include causal links within the purview of the techno-economic (e.g. expansion of the market share), socio-technical (e.g. strengthening of the respective socio-technical regime), and political (e.g. increasing ability to lobby for favorable policies) perspectives.

3.2.3 Mechanisms in energy transitions

Existing studies of energy or sustainability transitions often invoke the notion of mechanisms. For example, Bergek et al. (2008) discuss inducement and blocking mechanisms in their analysis of technological innovation systems. Turnheim and Geels (2013) mention "lock-in mechanisms" as a source of regime stability. However, these studies neither formally define mechanisms nor seek to provide systematic mechanism-based explanations. One of the rare references to the causal mechanism tradition is found in an article by Geels (2010) on social science ontologies and their potential use for studying socio-technical transitions. The article proposes causal agents and causal mechanisms for each of the discussed ontologies, building on a paper by Mahoney (2004), a proponent of the mechanistic approach. Lockwood (2015) provides a scheme of political and economic relationships among actors and outcomes in the energy system. Some of these relationships are similar to transition mechanisms discussed later in this chapter (e.g. vested interests). Lockwood identifies positive and negative feedback loops formed by these relationships and uses them to explain cross-national differences in energy transitions.

I consider the mechanism-based approach to be highly relevant to the study of energy transitions. As I demonstrated in the literature review, energy transitions involve heterogeneous processes, which can be interpreted as causal mechanisms or combinations of such mechanisms. The mechanisms involved in a particular transitions process may be studied by different disciplines, which is in line with potentially eclectic nature of the mechanism-based approach (Little 2018). At the same time, similar types of mechanisms (e.g.

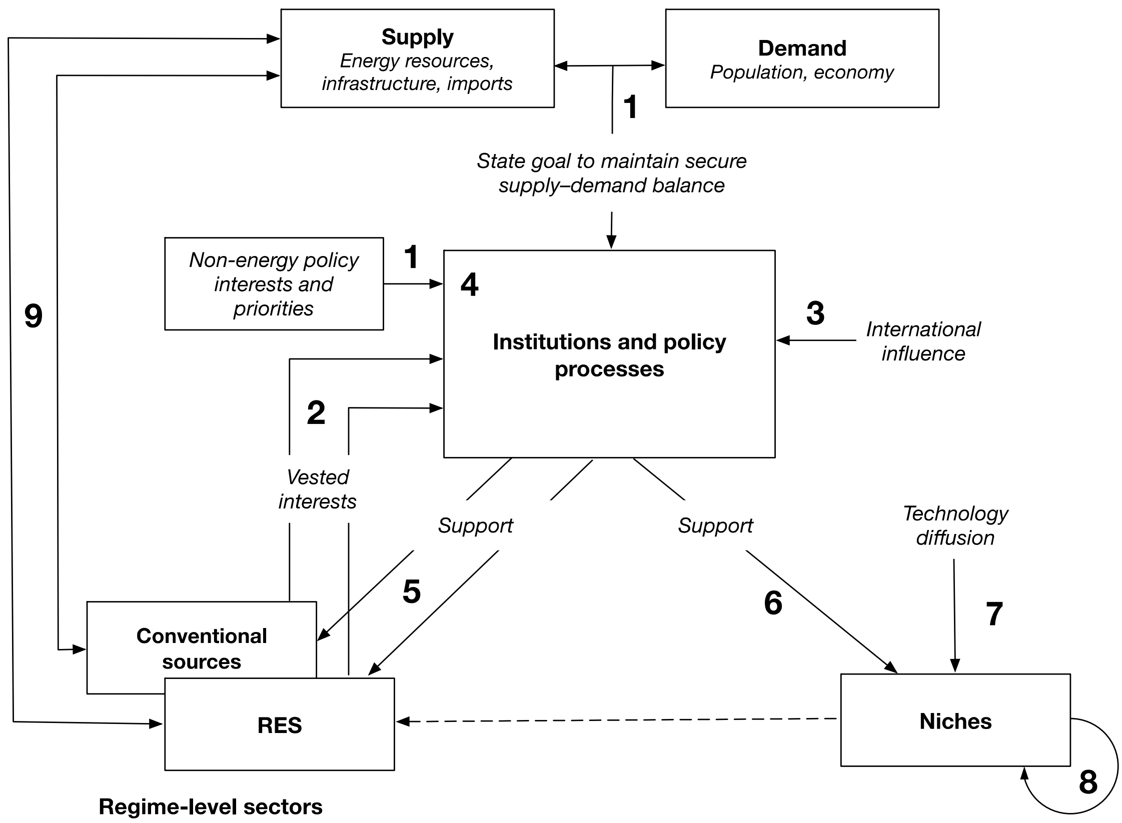
increasing returns) are found in theories relevant to energy transitions with different disciplinary roots.

3.3 Generic transition mechanisms and stages of the diffusion process

3.3.1 Generic transition mechanisms

Figure 3.3 schematically shows the conceptual foundation of my analysis – a repertoire of generic energy transition mechanisms identified on the basis of insights from the literature reviewed in Chapter 2.

Figure 3.3. Generic mechanisms of energy transitions



Note: Explanation of numbers is in the main text.

Figure 3.3 shows several interacting mechanisms of energy transitions. Boxes represent major descriptive concepts associated with the three perspectives on energy transitions, whereas solid lines represent causal mechanisms. Some links may represent more than one causal mechanism, and not all mechanisms are "unpacked" in this scheme – as explained below, some of them remain "folded" within boxes. The scheme takes into account the critical role of policies in contemporary energy transitions, particularly involving renewable energy

(Fouquet and Pearson 2012); therefore mechanisms involving the state and policies are "unpacked" to a greater extent than purely socio-technical or techno-economic mechanisms.

Mechanism 1 involves formation of state energy goals in response to vulnerabilities of supply–demand balance and other priorities. These goals influence state policies and measures (section 2.7.1). A major state goal is balancing energy demand with secure supply. Energy security is defined as "low vulnerability of vital energy systems" (Cherp and Jewell 2014), and I assume that a modern state sees its electricity supply system as vital. I pay particular attention to import dependence of electricity supply, although there are other aspects of energy security (e.g. diversity of supply) (Cherp and Jewell 2011). This is in line with Helm's (2001) observation that "governments have always intervened for security-of-supply reasons, although their enthusiasm depends on the supply-demand balance" (p. 174). In addition, state goals may be affected by various non-energy concerns – e.g. climate change mitigation, anti-nuclear sentiments etc. Another input to the policy process comes from the mechanism of vested interests (2) associated with incumbent energy supply and demand sectors with their socio-technical systems. These are "regime-level" socio-technical systems, relatively stable and powerful enough to sustain themselves. Vested interests may be associated not only with electricity generation sectors, but also with closely related industries – e.g. domestic coal mining sector in case of coal-based generation, or nuclear fuel and equipment manufacturing sector in case of nuclear energy as well as with energy-intensive industries. Some of these interests may promote and some – impede introduction of renewables. Yet another input into policy-making is international influence (3), which includes a variety of mechanisms discussed in section 2.7.2 – policy diffusion, policy translation, several mechanisms of policy convergence etc. All these inputs to the policy process are transformed into outputs through a variety of mechanisms (4) discussed in section 2.7.1, including coalition formation, aggregation of interests by institutions, policy paradigm change etc.

I focus on two key types of the state's policy response: aimed at incumbent sectors (5) and nurturing protected niches (6). These links may represent financial support (e.g. R&D spending in case of new technologies) or other support policies (e.g. simplified permitting procedures for new wind turbines). With respect to incumbent sectors, two further processes are essential: seeking self-reproduction through vested political interests (2), and the two-way interaction with material elements of the energy system – energy resources, infrastructure, and energy supply – as well as energy markets (9). On the one hand, the strengths of incumbent sectors are affected by the type of energy resources (domestic vs. imported) as well as by construction, operation, and aging of related technical infrastructure. On the other hand, their contribution to energy supply makes them valuable in light of state imperatives, which creates a sustaining feedback loop (9-1-5). Another possible feedback loop involves the sector becoming weaker or stronger as a result of better or worse market performance, regardless of supporting policies (9-9). Vested interests able to secure supporting policies that lead to a more powerful sector and more powerful vested interests is another feedback loop sustaining an incumbent sector or driving it growth (2-5).

The dynamics of protected niches is affected by both state policies (6) and international technology diffusion (7) as well as general market factors. In addition to these external influences, there is internal socio-technical dynamics within the niche, which involves innovation and learning processes (8). In my analysis, I am particularly interested in the process of "takeoff" by which a niche becomes a fledging regime-level sector capable of self-reproduction (both through political influence and noticeable contribution to energy supply) and competition with other regimes. This process is represented by a dashed line.

3.3.2 Capacity, motivation, and interactions of actors as characteristics of transition mechanisms

Most transition mechanisms involve certain social actors and can therefore be characterized by motivations, capacities, and interactions of such actors. One of the most important actors in energy transitions are states and therefore state motivation and capacity are particularly important for defining the strength of different transition mechanisms and thus the outcomes of transition processes. For example, Jewell (2011) systematically uses the motivation–capacity framework to analyze historical conditions for countries to build a nuclear power plant (NPP) and then apply these criteria to potential newcomer countries. She identifies three aspects of national motivation (energy demand, energy security, and military security) and three aspects of capacity (technical, financial, and institutional). Thus, the concept of state motivation implies that one source of differences between countries is different challenges that they face, for example, with regard to energy supply (see e.g. Jewell 2011; Cheon and Urpelainen 2012). The concept of state capacity was originally developed in political science, where it was associated with state "strength" or the ability to achieve its goals, but then has made its way to the analysis of energy transitions (Ikenberry 1986). Ikenberry (1986, p.106) provides a general definition of state capacity – "the differential ability of states to assert control over political outcomes" – emphasizing the usefulness of the concept for cross-country comparison ("the differential ability"). Analyzing policy responses of several industrialized countries to the oil crises of the 1970s, he demonstrated how these responses were shaped by institutional capacity of these countries. The concepts of state motivation and capacity are also used in policy diffusion and innovation studies (see section 2.7.2 above). The internal factors determining the probability of policy adoption can be divided into two groups – those reflecting "the motivation to innovate" by adopting a given policy and those reflecting "obstacles to innovation and the resources available to overcome them" (Berry and Berry 2007, p.236). The latter group of factors echoes the idea of capacity, although in addition to resources it also includes potential obstacles.

More specifically, with respect to generic transition mechanisms shown in Figure 3.3, the motivation of the state to support emerging niches and incumbent regimes (mechanisms 2 and 6) depend on the strength of three policy inputs: the imperative to balance energy demand with secure supply and other goals (mechanism 1), the strength of vested interests (mechanism 5) and international influence (mechanism 3). The international influence is by definition an interaction of actors from two or more nations and thus depends not only on characteristics of these actors but also on the type of their interaction (e.g. free trade, geographic and cultural proximity, membership in the same international bodies etc.) The ability of the state to execute mechanisms 2 and 6) depends on its capacity. This capacity can be economic (reflecting the ability of the state to mobilize necessary resources) or institutional (the ability to develop and implement support programmes).

Departing from the traditional approach in which motivation and capacity are seen as attributes of the state, in my analysis I also use these concepts to characterize mechanisms not necessary dominated by state actors. For example, in the "vested interests" mechanism, the motivation of an incumbent sector to support or resist a particular policy depends on how much this policy benefits or harms that sector. In the same mechanism, the capacity to affect a policy depends upon the strength of the regime (as measured for example by the number of stakeholders it benefits through employment etc.). The niche innovation and learning (mechanism 8 in Figure 3.3) involves actions of diverse state and non-state actors comprising the "national innovation system" and can be characterized in terms of individual or systemic capacities of these actors and the system as a whole.

In methodological terms, capacity, motivation, and interaction of actors can be used to compare mechanisms across countries, which I undertake at the last stage of my empirical research, the large-N study (Chapter 7). In some cases, capacities of actors involved in different transition mechanisms are closely related and can be estimated through common indicators. For example, the level of economic development would indicate both the state capacity to support emerging niches (mechanism 6) and the capacity of niche actors to learn (mechanism 8).

3.3.3 Mechanisms and stages of technology deployment and diffusion

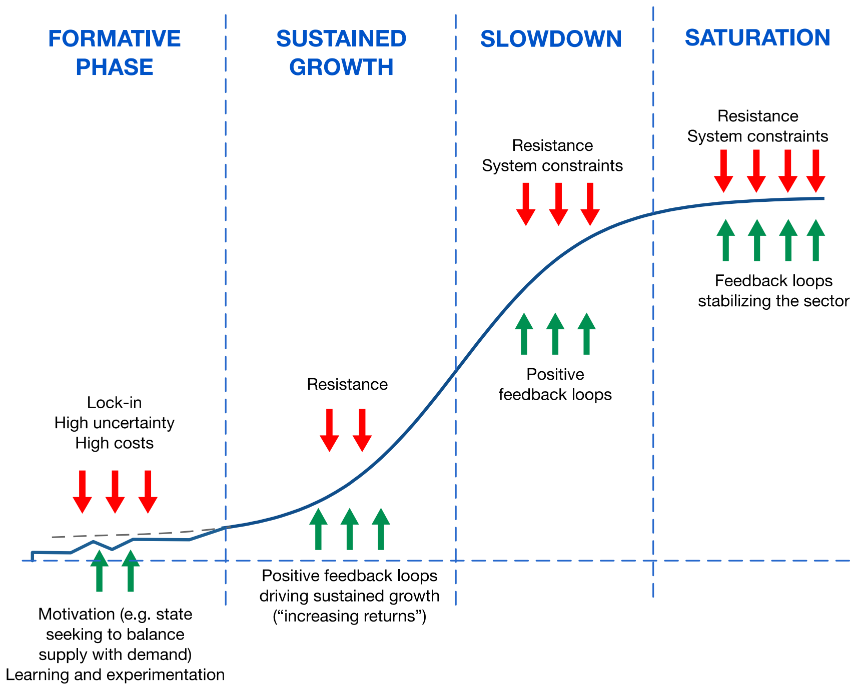
Different mechanisms shown in Figure 3.3 can be relevant at different stages of energy transitions. The idealized technology deployment model discussed in Chapter 2, the logistic curve, has a single underlying mechanism, be it contagion (Schelling 1998) or adoption by user groups with differing propensity to adopt (Rogers 2003). This mechanism is active at all stages of the process described by the curve, and there is no natural point separating the early "shallow" section of the curve, its steeper part and its "saturation plateau". At the same time, studies from different disciplinary fields summarized in Chapter 2 point to the qualitative difference between processes at different phases of technology deployment. Often they focus on the difference between the early phase(s) of technology deployment and the subsequent phase of sustained growth.

For example, technology diffusion studies (e.g. Grübler 1991) identify the initial phase of technology diffusion characterized by a slow adoption rate and a high level of uncertainty and volatility. This phase ends with the emergence of a dominant design and a distinct technology style or trajectory, setting the stage for sustained diffusion driven by self-reinforcing loops of declining costs and expanding demand. Wilson (2012; 2013) identifies two stages preceding the "growth" phase: first, the "formative" phase, when experimentation takes place, and second, the "unit up-scaling" phase. In later-adopting national markets the formative phase can be shortened or skipped (Grübler et al. 2016), but no significant decrease in the duration of the unit up-scaling phase has been observed (Wilson 2013). Gosens et al. (2017) distinguish between the initial "demonstration" and the subsequent "deployment" phases, arguing that the two phases have different "mechanics" driving the growth; at the demonstration phase, both market forces and institutional pressures or support mechanisms are underdeveloped. Even if a country does not develop domestic technology manufacturing, it has to build a technology deployment system that brings together the hardware, owners, installers, investors, and policy support systems in a way specific to the country (Strupeit and Palm 2016).

TIS scholars also recognize the existence of a distinct formative phase (Bergek and Jacobsson 2003; Jacobsson and Bergek 2004). They argue that the formative phase is characterized by uncertainties concerning the technology itself, its application, markets, prices, performance, and relevant actors. Consequently, the formative stage processes involve resolving these uncertainties through experimentation, creation of early markets or niches, and establishment of relationships between key actors. At some moment, the level of certainty and network connections become sufficient for positive feedback loops to kick in, and a "change of gear" happens – the system switches to a growth mode driven by "cumulative causation" – self-reinforcing dynamics of these feedback loops (Jacobsson and Bergek 2004). In terms of niche–regime studies (e.g. Geels and Schot 2007), the formative period can be related to the existence of a socio-technical system at the niche level with fluid and unstable rules. The beginning of the sustained growth period can be associated with the emergence of a fledging regime – a more stable set of rules underpinning the growing system and helping to reduce uncertainty.

In quantitative terms, a signature of positive feedback loops or self-reinforcing processes is exponential growth, where the growth in certain quantity (e.g. market share) is proportional to that quantity. Empirical studies of RE growth find significant linear dependence between RE share in the electricity system and annual growth of this share, thus demonstrating the exponential nature of the growth (which may be accelerated of slowed down due to additional factors) (Cheon and Urpelainen 2013; Gosens et al. 2017). However, Gosens et al. (2017) exclude from their analysis the periods when installed capacity is below a certain threshold, arguing that at that stage the growth is too volatile and irregular.

Figure 3.4. Stages and mechanisms of the technology deployment process



A stylized representation of different stages of the technology deployment process and underlying mechanisms is shown in Figure 3.4.[43] At the formative phase, when the growth is

[43] In reality, the boundaries between these stages are fuzzy and not as clear-cut as shown in the figure.

uneven and unstable, the deviation from the theoretical S-curve can be particularly significant. At this stage, the new technology evolves in the niche, facing high costs and incumbent systems in the condition of lock-in and. The niche technology is promoted by some actors who have both motivation (e.g. perceived societal need) and necessary capacity. One example is the state supporting an emerging niche in order to balance energy demand with secure supply (this corresponds to the combination of mechanisms 1 and 6 in Figure 3.3). This period involves significant niche-level learning and experimentation (mechanism 8). Learning is not limited to the formative phase – as demonstrated by the concept of "learning by doing", it inevitably results from the use of the technology and comprises one of the mechanisms underlying "increasing returns" at the subsequent diffusion stages. However, the role of learning mechanisms is particularly important at the formative phase, which is characterized by a very high level of uncertainty regarding all components of the emerging socio-technical system, including the technology itself, supporting policies, and deployment models. At this stage, learning often leads to radical innovation, whereas at the subsequent stages it is more incremental.

Different scholarly fields agree that the key result of the formative phase is the launching of "cumulative causation" – positive feedback loops driving sustained growth, which can be characterized by the broad mechanism of "increasing returns". As discussed in section 2.5.3 of Literature Review, some more specific mechanisms underpinning increasing returns include economies of scale, learning economies, and network effects. Another positive feedback loop is associated with the growth of vested interests linked to the new technology, that are increasingly capable to lobby for the further support of the growing sector (this corresponds to mechanisms 5 and 2 in Figure 3.3). As technological, business, financial and regulatory practices standardize and stabilize, increasing certainty provides for a more stable system of rules comprising the foundation of a fledgling socio-technical regime. I call the transition from the formative phase to the sustained growth period "takeoff".

Unchecked positive feedback loops would lead to infinite exponential expansion of the growth, but its eventual slowdown is inevitable as a result of increasing resistance and/or system constraints limiting the expansion. The latter may include the finite demand, limited resources, or other factors. For example, in Norway's electricity system, where more than 95% of electricity is already produced from renewables (hydro), the space for wind energy is limited. Finally, the sector reaches the state of saturation, in which factors supporting its expansion are balanced by resistance or system constraints.

Figure 3.5. National technology deployment and global diffusion

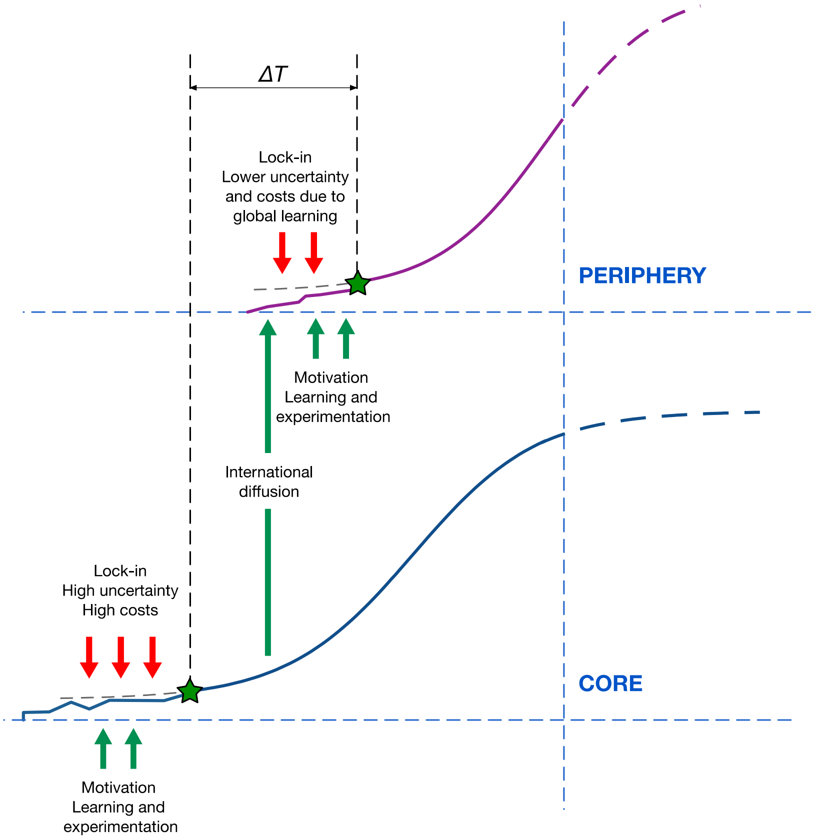


Figure 3.5 depicts national processes of technology uptake in the global context, thus illustrating spatio-technical diffusion processes which involve both expansion within each individual market and the spatial diffusion from the core to the periphery. The technology first “takes off” in the counties with the strongest motivations and capacities, which form the core of the global diffusion. Countries at the periphery start deploying the technology later, but they benefit from the diffusion of artifacts, knowledge, practices (e.g. deployment models), and policy ideas (e.g. feed-in tariffs or policy goals). This adds another important mechanism that corresponds to mechanisms 3 and 7 in Figure 3.3. Furthermore, due to global learning (which also result from national learning processes but may not necessarily be traced to links between individual countries) they face lower levels of technology costs and uncertainty. This tends to make the formative period in the periphery countries shorter, and the growth rates higher, although the saturation levels for countries in the periphery tend to be lower (Grübler 1991). The difference between takeoff dates of different countries is what I study using event history analysis in Chapter 7. Overall, in line with the logic of the mechanism-based approach, stages of the technology deployment process can be seen as

different episodes characterized by different combinations of mechanisms. In Chapters 6 and 7 I focus of the formative phase of renewable energy deployment.

3.4 Summary

In this chapter I have presented a conceptual framework which I use to study energy transitions. In line with the causal mechanism framework I propose to analyze energy transitions as driven by a combination of causal mechanisms, which can interact and recombine to produce different outcomes. Ontologically, I view energy transitions as unfolding in three types of co-evolving systems: energy flows and markets, energy technologies, and policy action systems. I argue that each of the systems is best analyzed within the corresponding perspective: techno-economic, socio-technical, and political. Each such perspective corresponds to a major field in social science with their theories explaining major mechanisms of energy transitions. In addition, there are mechanisms which link the three co-evolving systems together. The mechanism-based approach allows synthetizing heterogenous insights from the three perspectives into a coherent picture of energy transition ensuring cumulation of knowledge when new insights are added. In Figure 3.3, I identify eight generic mechanisms, which, as I hypothesize, explain the major elements of transitions to renewable electricity. I also propose a conceptual model linking mechanisms to stages of the diffusion and deployment of a new technology. I identify capacity and motivation as generic characteristics of social actors within the mechanisms and thus mechanisms themselves.

4 Methodology and research design

4.1 Introduction

The choice of methodology for my research is determined by the assumed ontology of energy transitions, which is based on causal mechanisms. Hall (2003) emphasizes the importance of alignment between ontology and methodology in social science. Ontology is defined as "the fundamental assumptions scholars make about the nature of the social and political world and especially about the nature of causal relationships within that world" (p.374). According to Little (2015), a methodology is a set of recommendations about how to proceed in gathering and validating knowledge about a subject matter encompassing “assumptions and heuristics at a range of levels (ontology, epistemology, scope, hypothesis formation, data collection, data analysis, empirical validation)” (p.465) and involving “a mix of substantive assumptions about how the world works, logical assumptions about good explanations, and concrete prescriptions about data collection and analysis” (p.467).

In this thesis, I use a methodology appropriate for my ontological assumptions based on the causal mechanism approach. According to Little (2015), the central ontological assumption of this approach is one of scientific realism, which postulates that there are real underlying causes, structures, processes and entities that give rise to the observations we make of the world, and these underlying causes can be studied empirically to arrive at explanations of what we observe. As discussed in the previous chapter, a more specific aspect of the mechanism-based ontology is that large social outcomes are produced by combinations of multiple mechanisms, which gives rise to the contingency and heterogeneity of social phenomena. Little (2015) argues that the ontology of causal mechanisms approach has methodological implications and highlights several research methods that are especially well aligned with the approach because they help researchers to identify causal mechanisms. In line with his remark, I investigate energy transitions using several methods, which include:

- A comparative longitudinal case study.
- Individual national case studies.
- Large-N analysis incorporating both set-theoretical and statistical methods.

These three methods also define my research design and correspond to three empirical chapters in this thesis (Chapters 6 to 8). Both comparative and individual case studies include elements of process-tracing. The large-N analysis (and to a smaller degree the individual case studies) also involve empirical validation of the conceptual model of new technology adoption and diffusion presented in the previous chapter. This is a mixed-method study design, combining both qualitative and quantitative methods. A mixed-method approach involving statistical analysis and case studies was used e.g. by Tosun (2013) in her study of environmental policy change in emerging market democracies.

The rest of this section provides more details on each of the methods.

4.2 Comparative longitudinal case study

Comparative case study research derives causality from concurrent observation of phenomena and circumstances that cause them across cases. In order to do that it has to satisfy three general criteria:

- Selection of cases so that they agree and/or differ on observed outcomes and causal factors in accordance with Mill's methods (method of agreement, method of disagreement etc.) (Levy 2008).
- Structured approach to cases (asking the same questions based on the research objective and theoretical focus of all cases under study).
- Focus on the relevant aspects of cases.

The latter two points describe the two main characteristics of the method of structured, focused comparison (George and Bennett 2005).

4.2.1 Case selection

My cases for a longitudinal comparison were selected because of their difference on an overall generalized transition outcome (commonly expressed as "Energy transition has happened/is happening in Germany but not in Japan") noted in diverse scholarly and policy literature but poorly explained by the "covering law" explanations (many of them based on a single factor like "democracy", "values" etc.). A detailed overview of such explanations is provided in section 5.2 of this thesis. Another attractive feature was that Germany and Japan had a comparable size, level of economic development, as well as a stable and democratic political system. Therefore one could expect that many relevant mechanisms would be similar. Moreover, a preliminary analysis confirmed that the resemblance between the two countries ran even deeper: until the 1980s their energy policies and energy systems were very similar (Ikenberry 1986). This allowed to focus the analysis on the more recent divergence of energy paths (i.e. precisely on the differences in *transitions* rather than *starting points*). Thus, the case of Germany and Japan presented a proper research puzzle and could be justified as the "most similar systems" design (Przeworski and Teune 1970) similar to Mill's method of disagreement. The aim of the analysis was to identify causal mechanisms that led to differences in the period between 1990 and 2010.

Another consideration in my case selection was a relatively large range of hypothesized mechanisms. Therefore it made sense to select cases of large countries with diverse energy sectors, which was an additional reason for selecting Germany and Japan and for investigating more than one technology (nuclear, solar, and wind power).

4.2.2 Focus of the analysis

The relevant aspects of cases for my analysis were determined by my conceptual framework based on causal mechanism and three perspectives on energy transitions. Having hypothesized certain mechanisms associated with or incorporating economic, socio-technical, and political phenomena, I included analysis of these phenomena in the case studies. For example, I considered the presence of domestic energy resources, aging of infrastructure, and energy demand growth (economic factors); technology innovation and learning, employment in different energy sectors, geographic conditions (socio-technical factors); energy security concerns, political parties and coalition building (political factors). Furthermore, since some of the mechanisms work on longer time scales, the analysis spanned at least 3 decades (extending in some aspects up to 4-5 decades).

4.2.3 Structure of the analysis

In line with the principles of mechanism-based explanations, the larger outcome of energy transitions in the two countries was dissected into a number of smaller outcomes defined in terms of specific energy sources and periods. Some of these outcomes (e.g. the growth of nuclear power in the 1980s and of solar power in the 1990s) were similar and some (e.g. the growth of nuclear power in Japan vs. its stagnation in Germany and the growth of wind power in Germany vs. its absence in Japan in the 1990s) – different between the countries. Likewise, the existing "covering law" explanations (e.g. "energy insecurity of Japan" or "environmental values in Germany") were broken down into specific potential mechanisms (e.g. growth of electricity demand leading to government action or political power of pro-renewable coalitions influencing policy-making). As a result, the inquiry into a single macro-case of two large and complex economies undergoing changes over several decades was split into more structured inquiries dealing with specific sectors and periods of time. These micro-cases were compared using Mill's logic in order to identify causal explanations.

For example, rapid increase of electricity demand in both countries was accompanied by massive construction of nuclear power plants in the 1970s and the 1980s. In the 1990s, electricity demand continued to grow rapidly in Japan which was constructing additional nuclear power plants, but it stagnated in Germany which did not construct any NPPs during this period. This, alongside with other considerations explained in Chapter 5, allowed to conclude that electricity demand growth is a causal factor explaining construction of new nuclear power plants in the 1990s.

This example demonstrates that, while the primary research focus was on comparing countries, the analysis also included comparisons of different periods. Effectively, my analysis was a combination of cross-section and longitudinal design, which could provide “additional inferential leverage” (Levy 2008, p.10).

Hypothesized mechanisms also helped to structure my analysis. Little (2015) remarks that research guided by the causal mechanism approach in most cases identifies the role of the already known mechanisms in explaining novel outcomes but can also identify new mechanisms. In this way, the mechanisms identified in Chapter 3 and explanatory factors associated with them structured the analysis. In addition, I identify additional mechanisms, one of them explaining the electricity demand growth in Japan (energy convergence) and another – connecting the strength of a regime to the life-stage of the relevant industrial sector (growth, stagnation, decline).[44] With respect to the latter, I explain the relative weakness of German nuclear sector by the lack of construction and manufacturing orders (which was in turn explained by the stagnation of electricity demand) and the strength of the Japanese nuclear by the rapid expansion of the industry in the 1990s (caused by the rapidly growing electricity demand). A similar explanation contrasted the relative strength of wind power industry in Germany and Japan.

In conducting the Germany-Japan comparison I faced the task of comparing similar causal mechanisms in two different countries. To accomplish this task, I have applied a systematic method of such comparison, which I subsequently used in the large-N study. This method identifies actors involved in each mechanism and compares their motivations, capacities and interaction. For example, I show that the motivation of Japan’s state for developing nuclear energy in the 1990s was stronger than that of Germany. In another example, I demonstrate how the capacity of Germany’s coal sector to influence national policies was much larger than that of Japan’s coal sector.

Finally, while being conducted along the lines of structured, focused comparison (George and Bennett 2005), my analysis of Germany and Japan also included substantial elements of process-tracing within each case. Levy (2008) notes that Mill’s methods, when applied to complex causation with interacting factors, may lead to spurious results and therefore

[44] This one of the more specific mechanisms underpinning mechanism 9 in Figure 3.2.

recommends complementing them with within-case process-tracing. In the case of Germany and Japan I traced how outcomes of some transition episodes and mechanisms were inputs of other mechanisms dominating subsequent episodes. Individual case studies in the next stage of my research featured more process tracing as explained below.

My data sources for the comparative analysis included energy statistics from the IEA, IRENA and the IAEA, scholarly literature, as well as national governmental, corporate and media documents.

4.3 National case studies

4.3.1 Focus of the analysis

The Germany–Japan comparison conducted as the first stage of my research already confirmed the explanatory power of the proposed conceptual framework. In particular, it resulted in the validation of several hypothesized mechanisms and identification of some additional ones. However, the conclusion of this case also presented a research dilemma. On the one hand, it was not clear whether the identified mechanisms would retain their explanatory power beyond Germany and Japan, two large industrialized democracies significantly relying on imported energy. Figuring this out would demand extending research to a wider circle of countries. On the other hand, the case study demonstrated how complex and time-consuming such a research is. It would not be possible to extend this research to any meaningful number of additional countries, especially since the analysis beyond Germany and Japan might need to incorporate additional mechanisms (e.g. international influence, industrialization) and thus be even more complex.

Therefore I decided to analyze a broader range of countries, while at the same time narrowing the scope of my research in two important aspects – technologies and causal mechanisms. In terms of technologies, I focused on “new renewables” in electricity, specifically on wind and solar (PV) power. This reflects several choices related to the aim and framework of my research. First, the focus on renewables reflects my interest in exploring low-carbon technologies potentially contributing to climate change mitigation. Solar and wind power are particularly interesting in this regard because they were commercialized in the 1980s-2000s and thus were growing from either zero or a very low base in all countries precisely at the period of increasing political awareness of the climate change and other energy challenges. This makes them particularly suitable for investigating the relationship between political and socio-technical aspects of energy transitions. This also sets solar and wind power aside from more mature renewable energy technologies such as geothermal and hydro-power as well as the use of biomass for electricity production. In addition, solar and wind resources are more evenly distributed across the world than for example tidal or geothermal resources, and thus are less affected by geographic conditions which makes cross-national comparison of social, economic and political factors easier.

In terms of causal mechanisms, in my case studies I decided to focus on those that play role in the formative phase (see section 3.3.3). This ruled out some of the mechanisms that operated in more mature regimes in Germany and Japan (e.g. infrastructure aging, strong vested interests etc.). Therefore my primary focus in these case studies was on such mechanisms as niche innovation and learning, various forms of international interactions including technology and policy diffusion, as well as formation of state energy goals and provision of state support to emerging technologies. In terms of time, each case study covers the period approximately to the moment when the share of wind or solar energy in the total electricity supply of the respective country reached 1% (see section 7.2 for a detailed discussion of this boundary as an indicator of the end of the formative phase).

In all the case study countries either wind or solar energy was clearly dominating in the year when its share reached 1%. In 10 out of 12 cases wind power was dominating, including by the factor of 45 or more in 9 cases. In 2 cases (Switzerland and Thailand), solar power was dominating by the factor of 7-8 (Table 4.1). This means that 10 cases were essentially the cases of the formative phase of wind power and 2 – of predominantly solar power. Nevertheless, the mechanisms of the formative phase observed in all case-studies were similar for these two technologies. This was one of the factors shaping my decision to investigate the combined share of wind and solar power as the dependent variable in the third step of my research, a large-N study (see below).

Table 4.1. Share of wind and solar power in 37 countries in the year when their combined share first exceeded 1%

Country	Year	Wind + Solar	Wind	Solar
Denmark	1989	1.32 %	1.32 %	0.00 %
Germany	1999	1.00 %	1.00 %	0.01 %
Spain	1999	1.31 %	1.30 %	0.01 %
Greece	2001	1.36 %	1.36 %	0.00 %
Netherlands	2003	1.18 %	1.16 %	0.02 %
Portugal	2003	1.01 %	1.01 %	0.01 %
Austria	2004	1.46 %	1.44 %	0.03 %
New Zealand	2005	1.43 %	1.43 %	0.00 %
UK	2006	1.06 %	1.05 %	0.00 %
India	2006	1.26 %	1.26 %	0.00 %
Australia	2007	1.12 %	1.07 %	0.04 %
Italy	2007	1.15 %	1.14 %	0.01 %
France	2008	1.10 %	1.09 %	0.01 %
Sweden	2008	1.35 %	1.35 %	0.00 %
US	2008	1.32 %	1.27 %	0.05 %
Belgium	2009	1.32 %	1.13 %	0.19 %
Canada	2009	1.17 %	1.15 %	0.02 %
Bulgaria	2010	1.85 %	1.81 %	0.04 %
China	2010	1.08 %	1.07 %	0.02 %

Country	Year	Wind + Solar	Wind	Solar
Czech Rep.	2010	1.35 %	0.48 %	0.88 %
Egypt	2010	1.17 %	1.03 %	0.14 %
Hungary	2010	1.26 %	1.25 %	0.00 %
Poland	2010	1.07 %	1.07 %	0.00 %
Turkey	2010	1.39 %	1.39 %	0.00 %
Norway	2011	1.04 %	1.04 %	0.00 %
Romania	2011	2.31 %	2.31 %	0.00 %
Japan	2012	1.11 %	0.45 %	0.66 %
Mexico	2012	1.22 %	1.20 %	0.02 %
Brazil	2013	1.08 %	1.08 %	0.00 %
Switzerland	2014	1.46 %	0.16 %	1.30 %
Chile	2014	2.70 %	2.02 %	0.67 %
Finland	2014	1.30 %	1.29 %	0.01 %
Israel	2014	1.51 %	0.01 %	1.50 %
Peru	2015	1.71 %	1.23 %	0.48 %
Philippines	2015	1.08 %	0.91 %	0.17 %
Thailand	2015	1.43 %	0.17 %	1.25 %
South Africa	2015	1.82 %	0.93 %	0.89 %

Note: The twelve case study countries are highlighted with blue.

4.3.2 Case selection

This focus also influenced the selection of cases. The first consideration was to have a globally representative sample demonstrating a broad inventory of mechanisms and transitions paths. For that purpose I first identified a "long list" of countries – 60 largest electricity producers collectively accounting for almost 95% of global electricity production (more detail on this sample is provided in section 7.4). This sample represents "almost the entire" global electricity system and includes countries with very different economic, social, and political status, as well as very different levels of renewable energy deployment – ranging from the global leaders to countries that have not yet deployed any noticeable amounts of renewables. The same sample of sixty countries is also used at the last, quantitative stage of my analysis (Chapter 7). Within that sample, I was interested in countries that had already completed the formative period, i.e. reached a combined share of wind and solar energy in total electricity production of 1% by 2015. There are 37 such countries. For my case studies I selected 12 countries – approximately one-third of that number.

First and foremost, my approach to selecting countries for this "short list" was driven by my aim to investigate cases representing as diverse mechanisms and country types as possible (assuming that different types of countries feature different combinations of mechanisms). Therefore my case studies include at least one country from each of the groups[45] which I more formally identify in Chapter 7 based on their characteristics relevant to the key mechanisms (see Figure 7.9 and Figure 7.10). Thus, my sample for case studies includes both early and later adopters also differing in terms of the level of economic development.

The sample is dominated by "early starters", all of them being "old" EU members (EU-15 countries) – 7 out of 12 countries. In part, this is due to the fact that they were more systematically researched in scholarly literature. But the main reason was my expectation that these countries would have more complex mechanisms at the formative stage, because they had to deal with a high level of uncertainty, higher costs and other barriers. These mechanisms could include more pronounced learning and innovation with regard to technology and policy, and perhaps political struggles over stronger support policies necessary at the early stages of technology deployment. Later adopters would face lower barriers due to the availability of more mature and commercially suitable technologies and processes of international diffusion, so their mechanisms would likely be simpler (as was eventually confirmed by case studies). However, my sample still includes later starters from different country groups. Some countries were selected due to their seemingly "anomalous" takeoff timing – Egypt starting very early compared to its group and Switzerland starting late. The exploration of causes of these anomalies provided additional insights into the mechanisms underpinning the formative stage.

Availability of data was another consideration in selecting those countries. My main sources of information were secondary scholarly literature in English, reports of international and national renewable energy associations, as well as national energy statistics and governmental reports in English. While these sources were not available for all countries in equal measure, I was able to obtain sufficient information not only for well-documented core countries but for such less-researched countries as Egypt or Thailand.

[45] Except for the group that did not have a single member completing its formative period by 2015.

4.3.3 Process-tracing in case studies

The twelve individual case studies presented in Chapter 6 do not include as strong comparative element as the analysis of Germany and Japan. Instead, causality in these studies is derived from "within-case" process-tracing – investigating causal sequence of events leading to each other and then to a particular outcome (George and Bennett 2005). This can be contrasted to "covering law" explanations that focus only on initial conditions (e.g. Chernobyl nuclear accident seen as an "input") and outcomes (e.g. phase-out of nuclear power seen as an "output"), while setting aside intervening processes. Thus, process-tracing as a method has an affinity with the idea of causal mechanisms. Summarizing George and Bennet's (2005) argument, Little (2015) notes that "the method of process-tracing has substantial power in social research, permitting the researcher to move from the details of a particular historical case to more general hypotheses about causal mechanisms and processes in other contexts as well" (p. 471).

Process-tracing focuses not only on individual mechanisms, but also on how different mechanisms were connected in time so that outcomes of one mechanism would trigger another mechanism, and so on until the final outcome could be explained.

For example, the Germany–Japan comparison in Chapter 5 (which already includes substantial elements of process-tracing) demonstrates how diffusion of wind from Denmark to Germany in the early 1990s had led to a rapid increase of pro-wind political actors by the end of the 1990s who supported a powerful Renewable Energy Act of 2001, that in turn led to expansion of solar power. The case study of Greece discussed in section 6.2.4 demonstrates how early EU-financed renewable energy programmes, while producing limited outcome in terms of installed capacity, had helped to shape domestic actors that later formed a backbone of the national wind energy sector driving its expansion.

4.4 Large-N study

Although the national case studies helped to articulate the mechanisms of the formative stage, they lacked a quantitative and an explicitly comparative element. They could answer the question what mechanisms led to the completion of the formative stage in a given country, but could not explain, for example, why some countries completed the formative stage earlier than the other. In the absence of such explanations, my study would be of limited use for understanding the timing and pattern of the global deployment and diffusion of renewables. Therefore, my ambition at the last stage of the empirical research was to use the conceptual framework based on causal mechanisms and three perspectives combined with the insights of the previous two empirical stages to comparatively analyze the formative stage in the world's sixty largest electricity producers including those that have not yet introduced wind and solar to any significant degree.

The challenge was to design a large-N methodology aligned with my conceptual framework. This methodology is based on the model of new technology deployment and diffusion which depicts the interplay of distinct transition mechanisms (Figure 3.4 and Figure 3.5). Constructing models, i.e. symbolic representations of real-life phenomena, with their subsequent empirical validation, can be used to study causal mechanisms because such mechanisms can be represented in a model (Little 2015).

Developing this methodology included three steps: defining the outcome (dependent) variable, defining explanatory (independent) variables characterizing relevant causal mechanisms, and identifying a method for testing the relations between these variables.

4.4.1 Variables

I use a combined market share of wind and solar (PV) power in defining a dependent variable for my large-N analysis (see section 7.2 for details). The dependent variable is the year in which the combined share of these two sources in a given country reaches 1% for the first time ("takeoff year"). This variable corresponds to the "change of gear" (Bergek et al. 2008) at the end of the formative phase, which marks the beginning of sustained growth driven by positive feedback loops. The basic assumption behind this type of dependent variable is that the association of the presence of certain mechanisms or their relative "strength"[46] with faster "takeoff" signals relevance of this mechanisms to the formative phase. Conceptually, reaching the end of the formative period should reflect the mechanisms active at that period (and not later mechanisms), thus allowing me to concentrate on a narrower range of mechanisms and limit potentially significant variables in the large-N study.

Obviously, this decision departs from a focus on a single technology. Solar PV and wind technologies are based on different physical principles; solar power reached maturity later than wind technologies but faces lower barriers associated with unit size and costs. However, although my choice is sub-optimal from the socio-technical perspective, it is justified in terms my integrated conceptual framework which also includes techno-economic and political aspects. Within this integrated framework, many mechanisms determining the uptake of solar and wind technology are similar. These include state goal formation (energy security, climate change mitigation, etc.), state responses to support emerging technologies through

[46] E.g. we can expect that the mechanism of state goal formation in response to energy security challenges is present in all or most import-dependent countries, but is generally "stronger" in countries with a higher level of import dependence.

such policy measures as feed-in-tariffs, subsidies and renewable portfolio standards as well as political increasing returns triggering sustained growth. Where these mechanisms are somewhat different between solar and wind power (e.g. learning involved in local deployment systems) they often reflect the same capacities and motivations of similar actors.

While focusing on one technology would take some differences in technological parameters (unit sizes, parameters of learning curves etc.) out of the equation, it would introduce other analytical problems. The first of such problems reflects the differences in national geography that affect both solar and wind power. If my analysis only considered wind power it would produce somewhat similar results, with only 7 countries out of 37 not achieving the 1% threshold by 2015. However, these 7 countries include Japan, Israel and Switzerland, technologically advanced wealthy democratic countries lacking domestic fossil resources that would logically be expected to be among the pioneers of renewable energy deployment.[47] These countries lagging behind Peru, Philippines, and South Africa among others would be hard to explain without reference to geographic factors limiting their use of wind power (see Chapter 5 for Japan and Chapter 6 for Switzerland).[48]. A similar problem would arise if I only analyzed solar power: in this case the Netherlands, Sweden, Canada, and Finland would lag behind Romania, Bulgaria, Chile and Thailand among others, once again something that most likely is linked to geography. I have not been able to identify a rigorous way in which these geographic differences, especially related to wind power, could be systematically taken into account.[49]

The second difficulty is that the deployment of solar and wind power clearly affected each other through political rather than technological mechanisms. For example, in Germany the advocacy coalition primarily based on wind power interests lobbied for support for solar power (see Chapter 5). In contrast, Moe (2012) argues that of the strong political focus on solar power in Japan slowed down policies supporting wind power. Irrespective of the specific arguments, these links would need to be taken into account.

Using the combined share of wind and solar power as an input to my dependent variable reduced these difficulties. The differences in geography are smoothened out because some countries with limited wind potential have sufficient solar resources and vice versa. And the political mechanisms involving both technologies could be investigated through the same

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[47] Though Israel discovered large offshore natural gas resources, until recently its electricity generation was primarily based on imported coal.

[48] A similar situation is observed in South Korea where solar power (0.88%) exceed wind power (0.29%) by the factor of 3 in 2016.

[49] In particular, I found at the exploratory stage of my research that country-level estimates of total wind and solar energy potential were not able to adequately capture these limitations.

variables. To illustrate this point with a concrete example, Japan which has sufficient capacity and motivation to deploy renewable energy but with geography (earthquakes, tsunamis, mountain terrain) limiting wind power, is logically among the global leaders in solar energy, so that its combined share of wind and solar power compares meaningfully to other countries.

Using the combined share of wind and solar power introduces a methodological limitation because globally solar power matures one or two decades later than wind. This means that all other things being equal, countries where the dominant source of new renewables is solar power would take off later than countries where the dominant source of new renewables is wind. However, since the timing of global maturity of these two technologies is still relatively close and overlapping, my results by and large remain meaningful, which would not be the case if the timing of global maturity would differ by a much longer time period.

Since directly observing mechanisms leading to the outcome is impossible for a large number of countries, I define a set of independent variables that characterize the presence and strengths of the identified formative phase mechanisms. A significant number of these variables builds on the idea explained in section 3.3.2 that a causal mechanism can be characterized by motivations and capacities of social actors involved in this mechanism. Therefore variables indicating the presence of certain mechanisms are by and large indicators of motivation and capacity.

The third step after defining the outcome (dependent) variable and explanatory (independent) variables was to identify a method to explore the relationships between these variables. In my large-N analysis I use two methods. At the first, exploratory stage of large-N analysis I use a set-theoretical approach; then I use a statistical method – event history (survival) analysis.

4.4.2 Exploratory analysis: set-theoretical approach

The first, exploratory stage of the analysis of takeoff in sixty countries uses a set-theoretical approach. Set-theoretical methods involve constructing Boolean logic expressions of explanatory variables being a necessary and/or a sufficient condition for a given outcome[50] (Goertz and Starr 2002; Ragin 2008). One variant of set-theoretical analysis is qualitative comparative analysis (QCA), which identifies sufficient conditions for the outcome in question (Schneider and Wagemann 2012). Set-theoretical approaches are based on the concept of configurational causality. Blatter and Haverland (Blatter and Haverland 2012, p.80) formulate

[50] Boolean logic operators, as well as necessary and sufficient conditions have natural interpretations in terms of set theory; hence the name of the approach.

the key assumptions of **configurational thinking** (i.e. configurational models of causality) in the following way:

- almost all social outcomes are the results of a combination of causal factors;
- there are divergent pathways to similar social outcomes (equifinality); and
- the effects of the same causal factor can be different in different contexts and combinations (causal heterogeneity).

The first point implies that a social outcome is a result of causal pathway including several factors. For example, the decisions to phase out nuclear energy and support the development of renewable energy sources made in Germany in the early 2000s and eventually leading to the substitution of nuclear energy with RES in electricity generation were driven by a number of factors: weakness of the country's nuclear industry, presence of a fledging renewable energy sector and a traditionally influential coal sector, and a political alliance between interests related to coal and renewable energy (see Chapter 5 for more detail). Equifinality means that the same observed outcome can be a result of different combination of factors (causal pathways). For example, a phase-out of oil-fired electricity generation in a country may result from declining domestic resources combined with the development of nuclear energy, or increased international oil prices combined with the tapping of domestics coal deposits. Causal heterogeneity means that outcomes of such combinations are not additive in the sense that they are determined by a sum of effects of independent factors (the model of causality characterized as "net effects thinking" by (Ragin 2008)). Instead, in such combinations or configurations the effect of one factor or variable depends on other factors or variables, which can enable or disable specific causal pathways. In a mechanism-based approach, it is causal mechanisms that combine and interact to produce an outcome.

My initial aspiration was to identify combinations of conditions that would perfectly or almost perfectly separate country groups defined by different conditions in terms of their takeoff time, which would effectively mean applying QCA (Schneider and Wagemann 2012). However, in all my attempts there was significant overlap between country groups. Therefore, I ended up using a weaker version of the set-theoretical approach relying on graphical presentation of the data.

First, I divided my sample into groups (sets) defined by combinations of independent variables (either binary or binarized), which signal the presence and strength of certain mechanisms. Then I constructed a chart showing the presence and absence of the outcome in these groups. This allowed me to make important observations, e.g. the absence of takeoff in major energy exporters outside the OECD or the fact that the old EU members takeoff earlier than other countries. Subsequently I developed a method to present dynamic data ("the takeoff chart", Figure 7.10) which graphically depicted the sequence of takeoff in different country groups and could be used to both validate the mechanisms and compare their strengths across countries. The takeoff chart demonstrated significant differences in takeoff times of different groups. Furthermore, it can be interpreted as a depiction of the global mechanism of technology diffusion thus directly contributing to the ultimate aim of my thesis to understand global patterns and futures.

4.4.3 Event history analysis

Finally, I used statistical analysis to test the connection between the outcome and the explanatory variables. Little (2015) notes that searching for statistical regularities is usually associated with the "covering law" approach and therefore has limited use in a mechanism-based inquiry. However, my approach to statistical analysis is consistent with a mechanism-based view of causality for several reasons:

- I narrow the range of mechanisms being investigated by restricting the scope of my analysis in three ways:
  - I focus on similar renewable energy technologies whose deployment is likely to involve similar mechanisms and I exclude other renewables (e.g. hydro, biomass) whose deployment may involve very different mechanisms;
  - I focus on a particular period (formative phase), characterized by a distinct and narrower combination of mechanisms.
  - I conduct my statistical analysis separately for two different country groups (see section 7.4) which, as I hypothesize, may differ in terms of formative phase mechanisms thus further narrowing the range of mechanisms under analysis.
- I use a model of technology deployment based on causal mechanisms (see section 3.3.3) in defining my dependent variable, an outcome of a specific interaction of causal mechanisms.
- I choose independent variables on the basis of mechanisms hypothesized in Chapter 3 and empirically explored in Chapters 5 and 6. Many of these variables reflect capacities and motivations of actors involved in specific mechanisms. This allows me to compare the strengths of the same mechanisms across countries.

- I use statistical analysis in combination with case-based analysis in Chapter 6. In particular, I use the results of case studies in the interpretation of results of my statistical analysis in Chapter 8.

These elements of my research design depart from “covering law” approaches characteristic of most statistical studies.

With the outcome variable defined as an event happening at a particular moment in time, event history analysis (also known in survival analysis) is the natural choice of a statistical method to study it.

Statistical methods

Event history analysis (also known as survival analysis) is a method for researching events that happen at specific moments in time; times of events constitute the dependent variable. That is why they are suitable for studying policy adoptions including policy diffusion processes, which can be represented as discrete events (Berry and Berry 1990). Two such studies dealing with renewable energy policies (Chandler 2009; Schaffer and Bernauer 2014) were discussed in the literature review (section 2.8). For the same reason, event history analysis has not been used to study renewable energy deployment, a continuous process and not an event. My innovation is to introduce the concept of takeoff as a discrete event that allows applying event history analysis to the deployment of renewable energy.

For event history analysis I use Cox regression as the main method and logistic regression with time variables as a secondary method to validate results of Cox regression. Both methods assume that takeoff is a probabilistic event, whose probability in a given year is determined by independent variables. While renewable energy takeoff is certainly not a random process (as demonstrated by numerous case studies in this thesis), this type of statistical models can provide useful generalized insights into the role of different factors (and mechanisms associated in this factor).

The essential concept in event history analysis is hazard rate – the probability of event per unit of time, provided that the event did not happened (i.e. the subject “survived”) to that time (Box-Steffensmeier and Jones 2004). Effectively, this is a conditional probability density or intensity. Statistical methods used for event history analysis attempt to fit a function defining hazard rate so that it is consistent with the observed timing of events.

Cox regression analysis is based on the so-called Cox proportional hazard model (Box-Steffensmeier and Jones 2004). This model assumes that the hazard function determining hazard rate for subject *i* is:

$$h_i(t) = h_0(t)\exp(\beta'\mathbf{x}_i) \ .$$

where $h_0(t)$ is a baseline hazard function, which is the same for all subjects, β' is the vector of regression coefficients, and $\mathbf{x}_i$ is the vector of covariates (independent variables) for the subject *i*. Thus, the relative hazard or the ratio of hazard rates for two subjects can be written as:

$$\frac{h_i(t)}{h_j(t)} = \exp(\beta'(\mathbf{x_i} - \mathbf{x_j}))\ .$$

This equation does not include baseline hazard function, so Cox model assumes that relative hazards do not depend on that function. The estimation of regression coefficients uses only information on relative hazards, and does not make any assumptions about the baseline hazard function.[51] This is one of the advantages of Cox regression, because a wrong assumption about baseline hazard may lead to wrong results. Furthermore, this makes the method compatible with any pattern of time-dependence that affects all subjects (e.g. growing hazard rate or probability of the event, which is characteristic of my situation where the availability of the technology is growing with time due to global learning).

Another advantage of Cox regression is straightforward interpretation of regression coefficients. The previous equation can be re-written in the following form:

$$\frac{h_i(t)}{h_j(t)} = \exp(\beta_1(x_{1i} - x_{1j}))\exp(\beta_2(x_{2i} - x_{2j}))\ \dots\ .$$

where x_{1i} is the first covariate for subject *i* and so on. If all covariates but the first are equal for the two subjects, and the difference between the first covariates is unity, the hazard ratio for the two subjects is simply $\exp(\beta_1)$. This also demonstrates why the Cox model is called "proportional hazard model". It assumes that a given change in a covariate always leads to the same change in hazard rates, regardless of the absolute values of hazard rates. For example, a high share of nuclear power in the generation mix (defined as a binary variable) reduces the hazard rate by the same factor in any year (irrespective of the global maturity of renewable energy technologies). Model specification should be compatible with the proportional hazard assumption, and there are several tests for that (I describe and use them in section 7.6 and Annex B). In my analysis, I had to reject certain variables because the models including them did not meet some of these criteria.

Cox regression also has some disadvantages and limitations. First, because Cox regression does not make any assumptions about the form of the baseline hazard function, the implied function can be very noisy and rugged. This can lead to overfitted estimates, which are

[51] This effectively means that the estimation uses only information about the sequence of events, and not time intervals between them (Box-Steffensmeier and Jones 2004).

adapted to the observed data as closely as possible at the expense of general patterns that can be found in the data (Box-Steffensmeier and Jones 2004). Second, while the method is perfectly compatible with baseline hazard rates changing with time, it does not allow to measure or characterize this change (Cleves et al. 2010).

Therefore I use a secondary method to validate the results of Cox regression and demonstrate the role of time. One possible alternative is "parametric" models, where a particular form of the baseline hazard function is assumed (e.g. Weibull regression) (Cleves et al. 2010). I use a different approach – logistic regression with time variables – which has been used in studies of policy adoption. Shaffer and Bernauer (2014) used it to study factors leading to the adoption of RE support policies.

Logistic regression ("logit") is commonly used for binary outcomes (Kleinbaum and Klein 2010). The function being fitted in logit is:

$$P = \frac{1}{1 + \exp(-(\alpha + \beta'\mathbf{x}))} \ .$$

where P in probability, α is a constant "intercept term", β' is a vector of regression coefficients, and $\mathbf{x}$ is a vector of covariates. For event history analysis, time-series cross-sectional data (country-year data points in my case) are pooled (grouped); outcome is coded as a binary variable (positive, if the event in question occurs in a given year); data points for a subject after event (in my case, a country after takeoff) are removed. This produces binary time-series-cross-sectional data (BTSCS) (Beck et al. 1998). Although technically this dependent variable is different from duration time used in traditional survival analysis, it contains the same information as duration data (Box-Steffensmeier and Jones 2004). Because the probability of an outcome may depend on time (which is certainly the case with technology deployment), the regression model should incorporate time. Beck et al. (1998) suggest using cubic splines of time, which are flexible enough to accommodate for a broad range of possible patterns of time dependence. Carter and Signorino (2010) suggest using a cubic polynomial of time (i.e. including time, time-squared, and time-cubed as independent variables in the regression model) and demonstrate the applicability of this approach. This method was used by Shaffer and Bernauer (2014), and I also use this approach in Chapter 7.

Statistical tests and criteria

In the process of statistical analysis, I use several criteria to assess model quality or compare different models.

1. **Assessing model quality.** To evaluate model quality, I use the Akaike information criterion (AIC) – an estimator of goodness of fit, which also rewards model parsimony by penalizing

additional independent variables (covariates) (Cleves et al. 2010). The AIC is a measure of relative model quality, which can be used for comparing models with differing specifications, provided they are applied to the same dataset. A smaller AIC value means better model quality. AIC cannot be used to compare models with different number of observations.

2. **Comparing nested models.** Two statistical models are nested if covariates used in one of them comprise a subset of covariates used in another one. These two models are called a "reduced" and a "full" model respectively, and it is said that the former is "contained" within the latter (Cleves et al. 2010). To test the quality of the reduced model compared to the full one, I use the Wald test (Kleinbaum and Klein 2012). In this case, the Wald test estimates whether the difference between a full and a reduced model is significant.[52] In a sense, it measures collective statistical significance of several variables and produces a p-value. A high p-value means that the difference between the two models is not significant, and substituting the full model with the reduced one is justified.

3. **Testing the proportional hazard assumption.** The applicability of Cox regression depends on the validity of the proportional hazard (PH) assumption (Cleves et al. 2010). This assumption means that a given change in a covariate always changes hazard rate by the same multiplier at any moment in time. There are several tests for this assumption. The main technique I use for this purpose is a test based in Shoenfeld residuals (Cleves et al. 2010). This test produces p-values for individual variables and the entire model. Low p-values mean that the PH assumption is not valid. For selected models, I also use graphical tests of hazard proportionality (Cleves et al. 2010) that are presented in Annex B.

Dataset

For my analysis I use a dataset that includes both a range of countries (sixty countries described in section 4.4) and a range of years (1989–2015). This is a time-series cross-sectional dataset, in which each datapoint is defined by a country-year pair. The dependent variable is a binary one that takes a positive value if takeoff happens for a given country in a given year. The independent variables and data sources used for them are described in section 7.3. My dataset is unbalanced (does not have data for all subjects for the same period of time), because for certain countries data are not available for early years. Furthermore, in the analysis of the OECDHI/EU sub-sample (see section 7.4) countries are included only from the moment they meet the criteria defining this subset (and they are excluded from the

[52] Technically, the Wald test tests the hypothesis that all coefficients for the variables found only in the full model are not equal zero at the same time.

dataset for non-OECDHI/EU countries). Both Cox regression and logistic regression are compatible with unbalanced datasets.

Due to the nature of survival analysis, it assumes that the hazard rate depends only on the value of variables at the current moment and changes immediately when these values change (Cleves et al. 2010). This is different from the logic of renewable energy takeoff demonstrated by e.g. the case studies in Chapter 6, that show that takeoff may be influenced by developments taking place in the formative phase, years or decades prior its occurrence. However, most variables used in my analysis rarely experience major changes within a short period of time. Changes of constitutional arrangements are rare, and economic and energy system indicators tend to shift relatively slowly. So generally I assume that the value of a variable at the moment of takeoff is a reasonable proxy for its value in the period leading to takeoff. One exception is the ideological orientation of the cabinet, which may change quickly as a result of a single election. For this variable, I am using the average (mean) value of the indicator over the five years preceding the given year. While there may be significant year-on-year fluctuations of electricity demand growth, my indicator of demand growth also covers five years leading to the given year, helping to smooth out these fluctuations. For import dependence of electricity supply I carried out a sensitivity analysis using a five-year average, which did not produce different results (not reported in this thesis).

4.5 Summary

The methods used my study and research design are summarized in Table 4.2.

Table 4.2. Research design and methods

Chapter	Chapter 5. Comparative analysis of electricity transitions in Germany and Japan	Chapter 6. Case studies of the formative phase	Chapter 7. Large-N analysis of renewable energy takeoff
Countries	2 (Germany, Japan)	12	60
Technologies	Nuclear, wind, solar	New renewables (wind and solar PV)	New renewables (wind and solar PV)
Periods	40 years, 3 periods	Formative phase	Formative phase and its outcome as "takeoff"
Methods	Qualitative (comparative longitudinal case study and process-tracing)	Qualitative (individual case studies with elements of process tracing)	Quantitative (survival analysis) Set-theoretical exploratory analysis
Case selection	"Most similar cases", well-documented history of transitions, large and diverse energy systems	Early starters (demonstrating more complex mechanisms at a low level of "global availability") + representative cases for different country groups	All countries with large enough electricity system (~95% of global electricity generation)
Objective	Demonstrate the applicability of the mechanism-based framework to a broad range of transition episodes. Confirm relevance of the proposed generic mechanisms and identify additional ones.	Identify mechanisms and mechanism combinations relevant to the formative stage of RE deployment in different countries. Demonstrate the applicability of the mechanism-based framework to the formative stage of RE deployment.	Explain the timing of "RE takeoff" and identify factors determining the sequence of RE takeoff across countries. Identify transition mechanisms at the formative stage relevant to different country groups.

5 Comparative analysis of electricity transitions in Germany and Japan

5.1 Introduction

This chapter contains a comparative analysis of electricity transitions in Germany and Japan from the 1970s to the 2010s. It explains the differences between two countries in terms of mechanisms of energy transitions hypothesized in the conceptual framework (Figure 3.3). It also aims to compare the explanatory power of the mechanism-based approach to the explanations of the same differences in the existing literature in the “covering law” style. The chapter also clarifies the nature of each relevant mechanism as well as its key characteristics, which is used for analysis in the subsequent chapters.

The choice of Germany and Japan as the comparative cases has been briefly explained in Chapter 4. One reason for this choice is that the two countries have some of the most diverse energy systems which have been undergoing significant transformations and thus are likely to feature diverse energy transition mechanisms. The second reason is the unique combination of differences and similarities between the characteristics of the two countries and the outcomes of energy transition which presents several opportunities to infer about causal mechanisms leading to different outcomes.

At the macro level, both countries have advanced market economies, depend on oil and natural gas imports, and share a similar history of post-war reconstruction. Writing in the middle of 1980s, Ikenberry (1986) pointed out that in the 1960s-1980s Germany and Japan had pursued a similar energy policy of “competitive accelerated adjustment” integrated with industrial policy and relying on formal and informal mechanisms of coordination between government and industry, which later were described as a distinct feature of “coordinated market economies” within the varieties of capitalism framework (2001). Until the late 1980s, both countries responded to the insecurities of oil supply by expanding nuclear power, restructuring industries, and promoting energy efficiency. This resulted in very similar configurations of their energy systems in 1990 with about 30% of electricity provided by nuclear, supplemented by a small share of hydro power and a much larger share of fossil fuels (Figure 5.1).

However, in the 1990s their energy paths diverged. While Germany expanded wind and solar and is phasing out nuclear power, Japan deployed much smaller amounts of renewables but became a world leader in the nuclear sector.

The many commonalities between the two countries make them compatible with the "comparable case – most similar system" study design (Przeworski and Teune 1970) where the cases are different on a dependent variable and similar on as many explanatory variables as possible. These overarching similarities make it easier to pinpoint differences that could explain variations in energy transitions. Further in line with this design, I compare the use of specific low-carbon technologies – nuclear, wind, and solar (PV) power[53] – between the two countries and the use of the same technology between different periods. This effectively increases the number of "cases" I am dealing with which I investigate using the same comparative logic.

In the next section, I review several explanations for energy transitions in the two countries either specifically proposed in or plausibly inferred from the relevant literature on energy transitions. I show that each of these explanations involves one (rarely two) of the causal mechanisms of energy transitions presented in my conceptual framework (Figure 3.3). I demonstrate that none of these explanations/mechanisms can on its own explain the key observed differences between Germany and Japan although some of them are useful in explaining certain episodes or aspects of transition in one or both countries. In the third section of this chapter I present a history of energy transitions in Germany and Japan primarily focusing on the 1980s, 1990s and 2000s but extending to the 1970s, the 2010s and further into the future. My presentation is a comparative process-tracing of economic, socio-technical and political developments in the nuclear, wind and solar power sectors with particular attention to the causal mechanisms of energy transitions identified in Chapter 3 and section 5.2. The sources of information for this analysis are scholarly literature, government documents, and official energy statistics of the two countries. In section 5.4 I demonstrate how these mechanisms can explain the observed differences in the three focus sectors over the period of analysis. Section 5.5 concludes the chapter.

5.2 Existing explanations of differences[54]

The existing literature, as well as my conceptual framework stress the central role of the state in energy transitions with most causal mechanisms involving state action. The differences in energy transitions in Germany and Japan are also often explained by the differences in their

[53] I exclude other low-carbon electricity sources because these either did not change much (hydro power), followed comparable trajectories in both countries (waste and biomass), or have not been significant (geothermal power).

[54] This section is largely based on a section from the following article which I co-authored as a second author: Cherp, A., Vinichenko, V., Jewell, J., Suzuki, M. and Antal, M., 2017. Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan. *Energy Policy*, 101, pp.612–628.

state policies. For example, Lovins (2014) argues that Japan does not expand renewable electricity fast enough because “its leaders [...] worship old policies that retard wide use of [renewable] energy sources” (see Huenteler et al. (2012) for a similar view). Though policy differences indeed explain some (but, as I will show, not all) divergences in energy transitions, such policy differences themselves reflect more fundamental factors, e.g. the differences in the problems the states seek to solve or in the available means to solve these problems. As Ikenberry (1986) notes, explanations of national energy policies should take into account “the way in which […] problems were defined and … [which] policy responses [were] perceived as possible” (p. 105). The literature review in Chapter 2 identifies several mechanisms contributing to the formation of state goals.

Historically, the mechanism of **pursuing energy security** was clearly relevant to Germany and Japan. Ikenberry (1986) described how both Germany and Japan pursued energy security by seeking to reduce their dependence on oil imports. More recently, governments of both countries used targets of energy self-sufficiency in formulating their energy strategies: Germany's 2010 Energiekonzept (Knaut et al. 2016) and Japan's 2010 Basic Energy Plan (BEP) (Duffield and Woodall 2011). Germany with its large coal reserves has been less concerned about importing fuels for electricity generation. In contrast, Japan always connected energy self-sufficiency with national security (Atsumi 2007). Suzuki (2014) and Price (1990) linked these energy security concerns to the fast development of nuclear power in Japan, and Feldhoff (2014) further explained this development by the isolation of Japan's electric grid (in contrast to Germany which can trade electricity with its neighbors). The mechanism of states pursuing energy independence can explain faster expansion of nuclear power in Japan after 1990, but not why nuclear power was growing similarly fast in both countries in the 1970s–1980s or why Germany initiated a nuclear phase-out in the early 2000s. More importantly, this mechanism fails to explain why it was the more energy secure Germany and not the less energy secure Japan that more actively developed domestic renewables, particularly wind power.

Another state goal potentially driving energy transitions is climate change mitigation (Duffield and Woodall 2011; Jacobsson and Lauber 2006; Lauber and Mez 2004). However, this mechanism cannot explain the difference between Germany and Japan. Although climate-related arguments have been used in both countries to support nuclear power, renewables or both, there is no evidence that commitment to climate mitigation has been higher in either country[55] and, more importantly, climate concerns cannot explain the policy focus on either nuclear or renewables as both are low-carbon options.

State policies can be driven not only by “state imperatives” such as energy security or climate change mitigation, but also by diverse social interests. For example, some scholars argue that **anti-nuclear sentiments** were the main driver of Germany's *Energiewende* (Hake et al. 2015; Mez and Piening 2002; Schreurs 2012). Such ideas clearly played a role in Germany, but cannot convincingly explain its difference with Japan where anti- nuclear sentiments have also been strong both pre- and post-Fukushima[56] (Valentine 2010; Aldrich 2012; Feldhoff 2014). Other public attitudes used to explain energy transitions, such as the “environmentalist tradition” in Germany (Geels, Kern, et al. 2016) and “national prestige” in Japan (Valentine and Sovacool 2009) also lack explanatory power for the same reason of the lack of evidence that they were stronger in one country than in the other. More importantly, comparing the effects of public sentiments on energy transitions is methodologically difficult because the **causality** between public opinion, state-backed ideologies, and energy system change is difficult to establish (Laird and Stefes 2009), as is the effectiveness of any public opposition in altering government or investment decisions.[57]

Another type of social interests often invoked in explaining state energy policies are so-called **vested or special interests** associated with specific economic sectors. Pro-nuclear vested interests may have promoted nuclear power and suppressed renewables in Japan (Huenteler et al. 2012; Kingston 2014; Valentine and Sovacool 2009). In contrast, a pro-renewables coalition supported wind and solar while pushing for the nuclear phase-out in Germany (Jacobsson and Lauber 2006; Lauber and Jacobsson 2016; Mez and Piening 2002). In Germany, the nuclear power regime exerted significant political influence in the 1970s-1980s (Mez and Piening 2002) and the coal regime – in the 1950s–2000s (Frondel et al. 2007; Pahle 2010; Storchmann 2005). Several scholars, e.g. Kingston (2014) and DeWit and Kaneko (2011), have

[55] According to Pew Research Center (2015; 2009), in 2009 65% of the Japanese considered global warming as a very serious problem and 64% were prepared to protect the environment even if it slows growth and costs jobs, whereas in Germany the relevant numbers were 60% and 77% respectively. In 2015, 42% of the Japanese and 34% of Germans considered global climate change as a very serious threat.

[56] Joas et al. (2016) point out that the last systematic study of energy-related values in Germany (Keeney et al. 1987) is 30 years old. The only *comparative* (and very general) study of public narratives by Hermwille (2016) relates to the post-Fukushima period when anti-nuclear sentiments were similarly strong in both countries and resulted in even more drastic adjustment of nuclear plans in Japan (see section 5.3.2).

[57] In Germany, the peak of anti-nuclear protests was in the 1970s, when they stopped construction of an NPP in 1974 and fuel cycle facilities in the 1980s (Mez and Piening 2002). But it was before the bulk of the NPPs was constructed. The extension of the lifetime of NPPs in 2010 triggered national demonstrations, but the opposition was “not overwhelming” (Schreurs 2012, p.35). In Japan, anti-nuclear protests prevented siting over one-half of its planned nuclear reactors (Aldrich, 2012). In a related observation, Pahle (2010) writes that “public protest proved little effective to hamper new coal plants [in Germany], which otherwise had broad political support” (p.3441)

described the so-called "nuclear village" in Japan, which includes businesses, government, and political institutions.

However, there are several limitations to these explanations. When energy transition is framed as a struggle between a monolithic "conventional fossils–nuclear lobby" (Strunz 2014) vs. all types of renewable energy, it cannot explain more complex dynamics between incumbents and newcomers found both in Germany and Japan. In Japan the pro-nuclear interests suppressed wind but not solar (Japan has been and remains a world leader in solar power deployment). Moe (2010) suggests that there is a solar (but not wind) lobby in Japan. But if solar and wind had separate interests in Japan, what made them cooperate in Germany? There are similar puzzles related to conventional energy sectors, for example it seems that coal and nuclear sector in Germany co-existed until the late 1990s when pro-coal interests started to actively support nuclear phase-out. What was behind this dynamics? Furthermore, if nuclear sectors in Germany and Japan were equally strong in the in the 1980s, why did the nuclear regime collapsed in Germany during the 2000s, whereas the nuclear regime in Japan remained strong? And why did coal regimes in both countries not collapse?

Innovation and technology diffusion is another mechanism which was documented as playing a significant role in energy transitions in Germany and Japan. Both countries had some of the world's highest public energy RD&D spending and pioneering research and demonstration schemes. Both countries were early adopters of nuclear power from the US (Poneman 1982) and Germany adopted wind power from Denmark in the 1990s (Heymann 1998; Klaassen et al. 2005). Mizuno (2014) explains socio-technical obstacles facing wind power and Kurokawa and Ikki (2001) describe much more successful development of solar in Japan, the global frontrunner in solar power in the 1980s–2000s. Yet, it is less well-studied how and why these niche developments affected large-scale differences in the use of nuclear, wind and solar power. For example, why did wind power not take off in Japan and why did solar power develop faster in Germany in the 2000s when Japan was the world's technology leader?

Thus, each of the existing explanations of energy transitions in Germany and Japan refer to one of the general energy transitions mechanisms that I identify in Chapter 3. In this sense they confirm the importance of such mechanisms for explaining energy transitions. However, on their own, none of these theories can explain the overall divergence of energy paths in Germany and Japan. In the next section I systematically trace the history of the electricity sector in the two countries to show how an ensemble of several causal mechanisms explain the differences between transition outcomes.

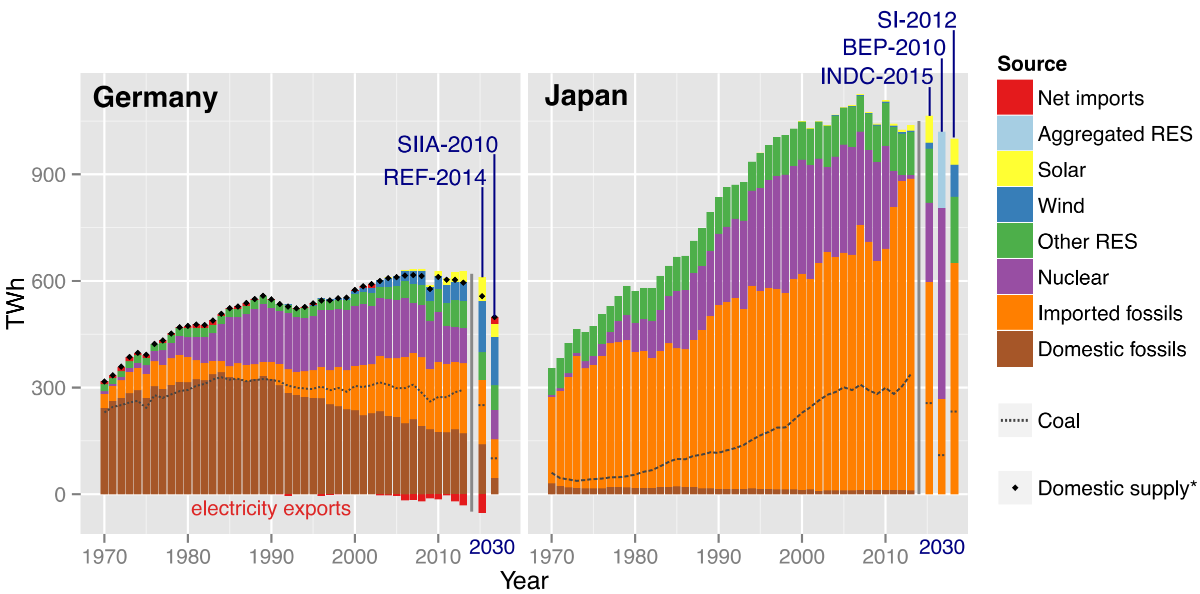
5.3 History of electricity transitions in Germany and Japan

This section[58] provides an explanation of electricity transitions in Germany Japan between the 1970s and the 2010s. It starts with an overview of the electricity sector and then considers nuclear, wind and solar power in more detail.

5.3.1 Electricity supply, demand, and overarching state strategies

Figure 5.1 shows the evolution of electricity generation in Germany and Japan between 1970 and 2013, as well as plans and scenarios for 2030 (see also Table 5.1). One obvious difference is the faster growth of **electricity demand** in Japan. In 1970, the two countries had similar electricity consumption (though per capita it was much lower in Japan), but by 2010, Japan used almost 80% more electricity than Germany. In the 1970s and the 1980s, electricity demand grew in both countries, but in the 1990s it stagnated in Germany while continuing to grow in Japan. What was the reason for faster consumption growth in Japan: difference in industrial structure, life styles, energy efficiency, or other factors?

Figure 5.1. Electricity mix in Germany and Japan, 1970-2013 and projections for 2030



* Domestic supply = domestic production + net imports for Germany; in Japan it equals domestic production.

Sources and notes: The bars to the right of the vertical lines depict plans and scenarios for 2030. 1970-2013 data: IEA (2017d). For Germany, **Ref-2014** is the reference scenario from Schlesinger et al. (2014) based on the current policies and **SIIA-2010** is the SIIA scenario from Schlesinger et al. (2010) which formed the basis for the Energy Concept 2010 (Bundesregierung 2010). For Japan, **S1-2012** is the post-Fukushima scenario from Japan's Ministry of the Environment (2012) and EXResearch Institute et al. (2011); **BEP-2010** is based

[58] This section is largely based on a section from the following article which I co-authored as a second author: Cherp, A., Vinichenko, V., Jewell, J., Suzuki, M. and Antal, M., 2017. Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan. *Energy Policy*, 101, pp.612–628.

on the Basic Energy Plan (BEP) of 2010 (Duffield and Woodall 2011); **INDC-2015** is derived from INDC of Japan (Government of Japan 2015) based on METI (2015). Aggregation into categories by the author.

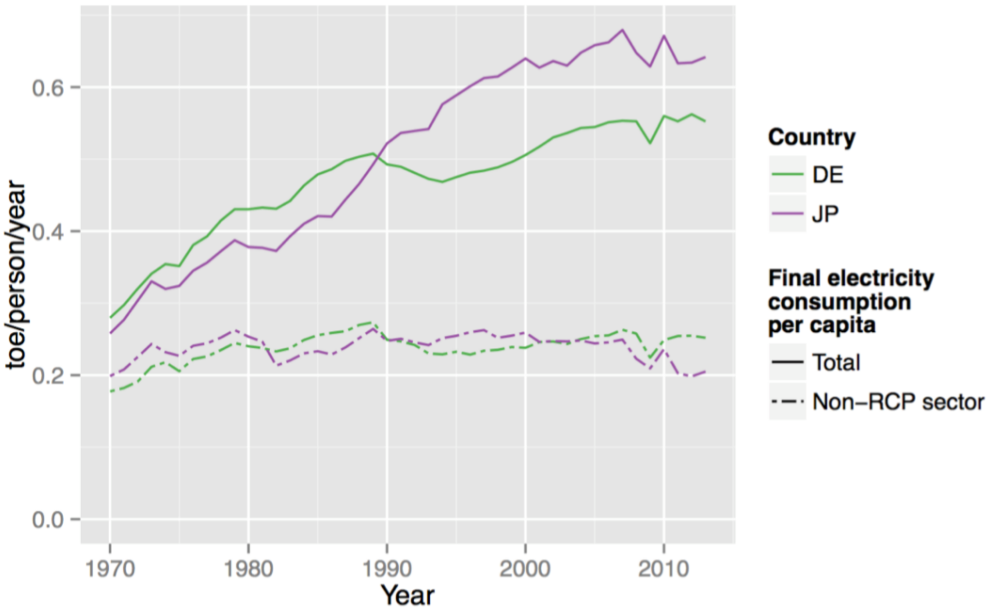
Table 5.1. Electricity production and trade in Germany and Japan in 2010 and 2030 (plans and projections), TWh

	Germany			Japan				
	2010*	2030		2010*	2030			
Source		Reference**	SIIA 2010***		INDC*	BEP 2010**	2012-S1 ***	2012-S2 ***
Nuclear	141 (23%)	0	84 (17%)	288 (26%)	213-234 (20-22%)	537 (53%)	0	150 (15%)
Coal	274 (44%)	249 (41%)	102 (21%)	299 (27%)	277 (26%)	113 (11%)	232 (23%)	220 (22%)
Wind	38 (6%)	143 (23%)	137 (28%)	4 (0.4%)	18 (2%)		90 (9%)	66 (7%)
Solar	12 (2%)	67 (11%)	36 (7%)	4 (0.4%)	75 (7%)	124 (12%)	72 (7%)	67 (7%)
Other RE	41 (7%)	59 (10%)	49 (10%)	39 (4%)	55 (5%)		68 (7%)	57 (6%)
Hydro	20 (3%)	19 (3%)	19 (4%)	82 (7%)	96 (9%)	90 (9%)	120 (12%)	110 (11%)
Other fossils	99 (16%)	73 (12%)	52 (11%)	392 (35%)	320 (30%)	156 (15%)	418 (42%)	330 (33%)
Total production	**626**	**611**	**485**	**1109**	**1065**	**1020**	**1000**	**1000**
Net imports	-15	-53	19	-	-	-	-	-
Total domestic supply	**611**	**558**	**504**	**1109**	**1065**	**1020**	**1000**	**1000**

Sources and notes: * IEA (2017d); ** Schlesinger et al. (2014); *** Schlesinger et al. (Schlesinger et al. 2010); * METI (2015); **METI (2010b); *** Japan's Ministry of Environment (2012), EX Research Institute et al. (2011); and Tsukamoto (Tsukamoto 2012); percentages indicate share in the domestic electricity production; negative values for net imports are exports of electricity.

To begin with, the growth of electricity consumption per capita was almost entirely limited to the residential, commercial, and public services (RCP) sector; whereas non-RCP (transport, industry and agriculture) consumption has remained stable and similar between the two countries (IEA 2017d) (Figure 5.2).

Figure 5.2. Electricity use per capita by sector in Germany and Japan in 1970-2013

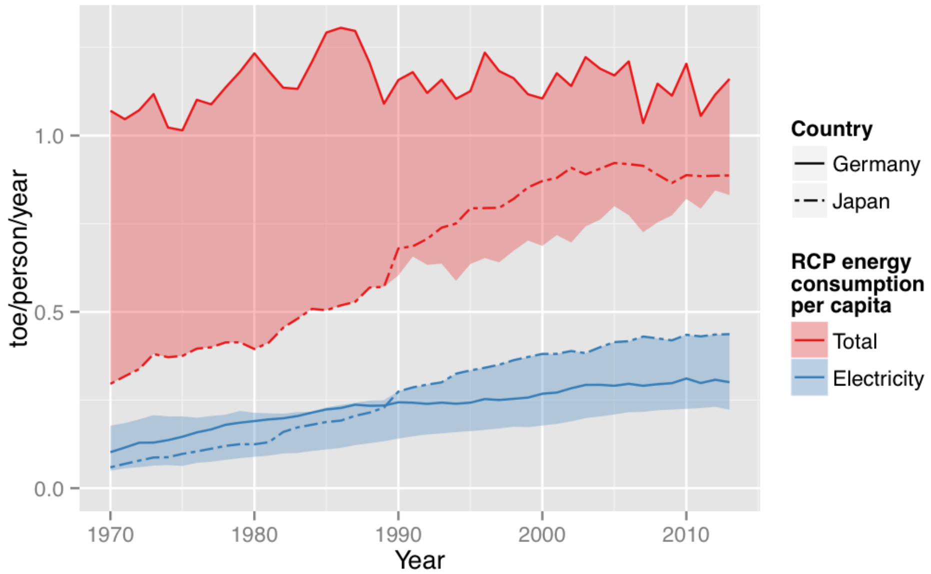


Source: IEA (2017d), aggregation by the author.

Note: The increase in the electricity demand is primarily driven by the increase in residential, commercial and public (RCP) electricity consumption, whereas non-RCP electricity consumption remains stable and similar in Germany and Japan.

The *total energy* consumption in the RCP sector per capita in Germany has been the highest among European G7 countries and relatively stable. In contrast, RCP energy consumption in Japan increased from the lowest among G7 countries in the 1970s to the levels of Italy, France and the UK in 2013, with electricity responsible for most of this growth (IEA 2017d) (Figure 5.3). Thus, the higher electricity consumption in Japan was a consequence of (1) convergence of per capita total energy use (Csereklyei et al. 2016) and (2) preference to electricity in Japan and to other forms of energy (e.g. natural gas) in Germany (Figure 5.4).

Figure 5.3. Energy and electricity consumption per capita in the RCP sector in Germany, Japan and European G7 countries, 1970-2012

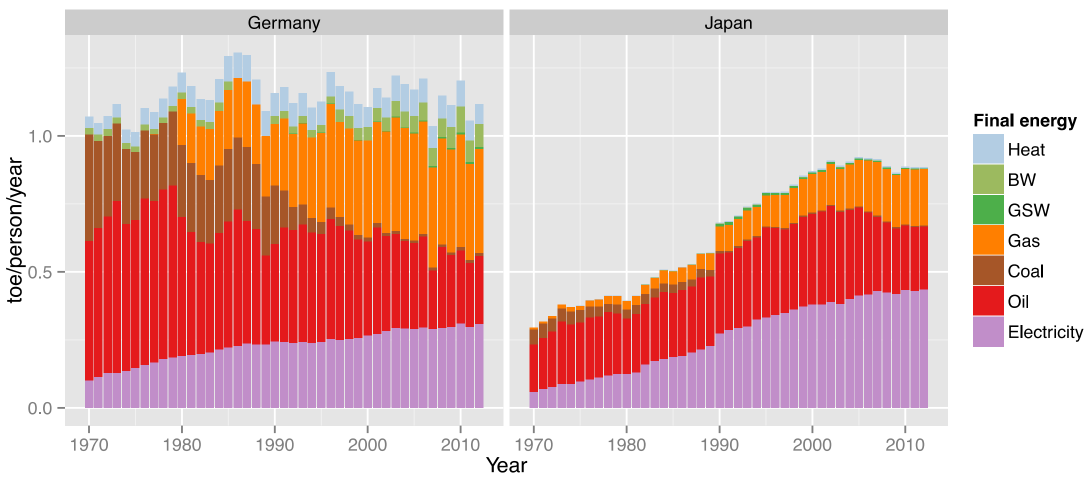


Source: IEA (2017d)

Notes: The shaded areas show the ranges of electricity (blue) and total energy (red) use in the RCP countries for European G7 countries (Germany, UK, France and Italy) and Japan.

The overall energy and electricity consumption in Japan starts with the lowest level among all G7 countries and eventually achieves a level comparable to the UK, France and Italy but lower than Germany. Comparatively larger share of this consumption in Japan is in form of electricity.

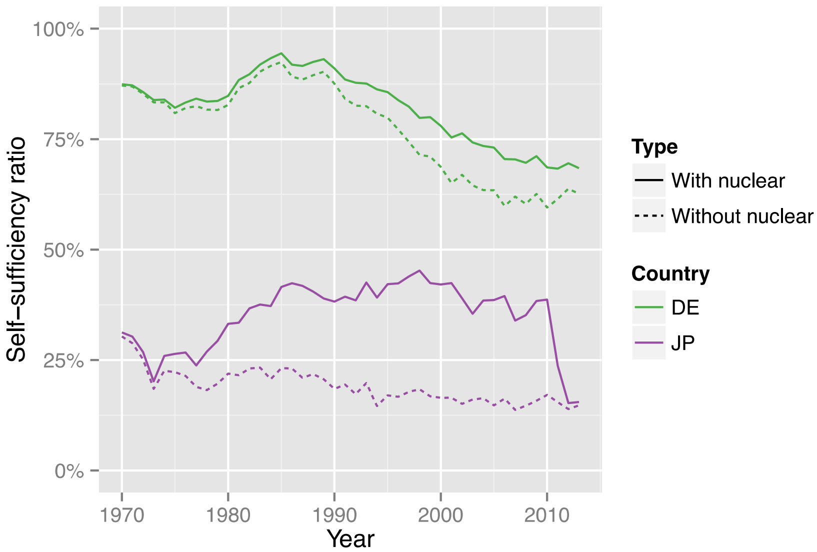
Figure 5.4 Energy consumption per capita by final form of energy in the RCP sector in Germany and Japan, 1970-2013



Source and notes: IEA (2017d); calculations by the author. Germany has been using more residential energy per capita than Japan, but a higher proportion of this energy was in form of coal and subsequently natural gas as well as heat and biomass.

Electricity supply in both countries has been dominated by fossil fuels, but with an important difference: these were primarily domestic in Germany and almost entirely imported in Japan (Figure 5.1). Therefore electricity self-sufficiency of the two countries has been dramatically different. In Germany, 75-90% of electricity was generated using domestic sources,[59] compared to 20-45% in Japan (IEA 2017d) (Figure 5.5).

Figure 5.5. Electricity self-sufficiency with and without nuclear power in Germany and Japan, 1970-2013



Source and notes: Author's own calculations based on IEA (2017d). Electricity self-sufficiency is calculated as a ratio of electricity produced from domestic sources to the overall domestic electricity supply. Self-sufficiency without nuclear excludes nuclear energy from both domestic sources and domestic supply.

In Japan, nuclear power significantly improves its otherwise very low self-sufficiency. In Germany, nuclear power has a smaller impact on its otherwise high self-sufficiency.

The main reason for Germany's high self-sufficiency has been the abundance of domestic coal. Germany has world's 7th largest coal reserves (US EIA 2011), was the third largest coal producer until 1989 (IEA 2017d), and remains by far the largest producer of lignite (WCA 2014). Coal was crucial for Germany's post-war restoration and the welfare of several regions (Jungjohann and Morris 2014). In the 1960s, the coal industry employed up to 600,000 people; in the early 2000s – close to 70,000 (Frondel et al. 2007; Storchmann 2005). Since the late 1940s, the German government justified its support to domestic coal extraction and use by economic and energy security arguments (Frondel et al. 2007; Lubell 1961). The main

[59] In my analysis, I assign nuclear to domestic sources. More accurately, it is "quasi-domestic" because not all elements of the fuel cycle (e.g. uranium mining and fuel reprocessing) are located within the country.

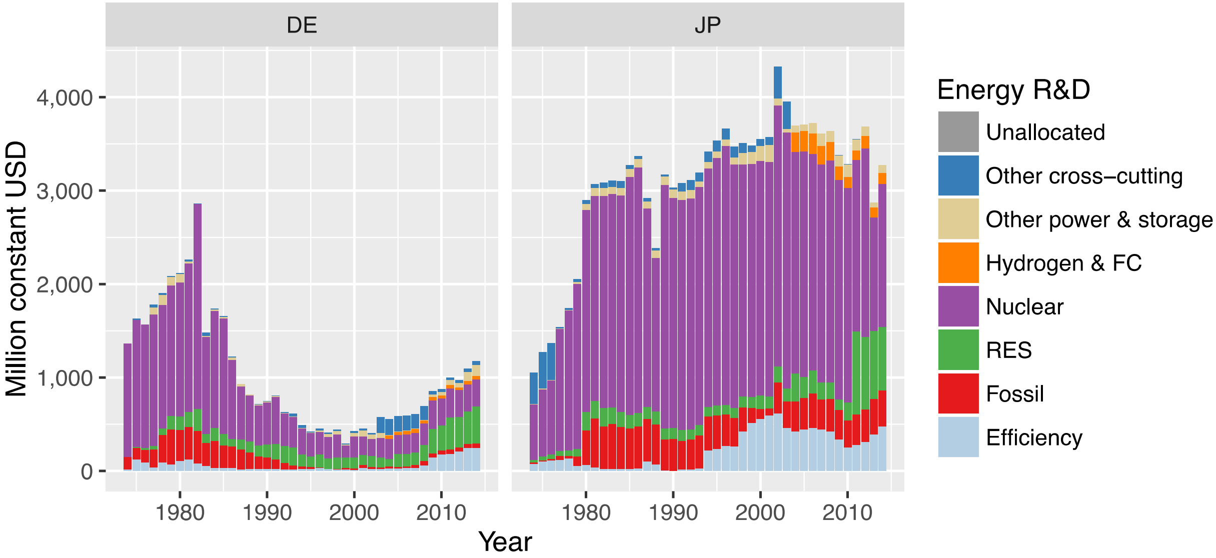
political voice for coal interests has been the Social Democratic Party (SPD), a major political party (Lauber and Jacobsson 2016). Since 1980, coal has received over €150 bln in subsidies (Frondel et al. 2007), reaching over €7 bln/year in the mid-1990s (Ecofys 2014; Küchler and Wronski 2015; Storchmann 2005).[60] In contrast, in Japan domestic coal was hardly used for electricity generation after 1970 and coal extraction had become negligible by 2000. Coal mining jobs declined from 122,820 in 1963 to 4,651 in 1990, 1,336 in 2000, and 600 in 2007 (Kunitomo 2009). By the 2000s, there were no mining unions or coal-dependent regions that would seek political support.

Other than the difference related to coal, energy policies of both countries were by and large similar in the 1970s and the 1980s and included industrial restructuring to reduce energy intensity (Ikenberry 1986) as well as extensive RD&D spending on nuclear, fossil and "alternative" energy as well as energy efficiency. The successful introduction of nuclear power was more important for Japan, where it significantly improved its otherwise low self-sufficiency ratio, than for Germany, where it had a small effect on its already relatively high self-sufficiency (Figure 5.5).

In the 1970s, West Germany started "pipes for gas" deals with the USSR and in the 1980s natural gas deliveries increased substantially (Stern 2005) as the oil prices went down. At that time, Germany's energy RD&D spending started to decline, a trend that continued until the early 2000s (IEA 2017c) (Figure 5.6). In the 1990s, with continuously low prices and improved access to Eurasian hydrocarbons resulting from the end of the Cold War, energy security concerns decreased further and there was less justification for the hard coal subsidies though they will not be fully removed until 2018.

[60] The coal subsidies were regulated by the so called *Jahrhundertvertrag* which assured that until 1995 a specified quantity of domestic hard coal was purchased at a price equal to the domestic extraction cost to be used in electricity generation (Welsch 1998, p.204). Since the mid-1990s this subsidy was reduced, and the share of cheaper imported hard coal has been increasing. Hard coal mining is projected to end in 2018, but the use of both hard coal and lignite in electricity generation will likely continue almost undiminished until 2030 (Table 5.1, Figure 5.1). The most recent attempt at curbing coal use through introducing a levy on the most polluting lignite power plants was aborted after backlash from the coal industry and unions (Vasagar 2015).

Figure 5.6. Public Research, Development and Demonstration (RD&D) spending on energy in Germany and Japan, 1970-2013



Source: IEA (2017c)

Japan's energy security concerns have been graver than Germany's not only because of the scarcity of domestic coal. Japan has an isolated and fragmented electricity grid[61] whereas Germany has a single grid well-connected to the European electricity market[62] and in addition can rely on its neighbors countries for emergency gas supplies (European Commission 2014a). Secondly, starting from the 1990s Japan grew concerned with global and Asian energy markets, in part due to China's switch from being an oil exporter to the world's largest oil importer, along with its growing appetite for coal and natural gas imports.[63] Third, Japan's tragic experience of the Second World War associated with energy supply issues made a strong imprint on national energy policy priorities (Sagan 1988; Suzuki 2014). Nuclear power offered an alternative and allowed Japan to diversify away from these persistent energy security concerns.

Echoing these concerns, Japan's energy-related RD&D spending consistently increased from the 1970s until the 2000s (Bointner 2014) (Figure 5.6). In 1980, Japan passed the pioneering *Alternative Energy Act* which supported solar and other "alternative" energy through financial, technical, and regulatory measures. Prior to the adoption of the Act, Hamakawa

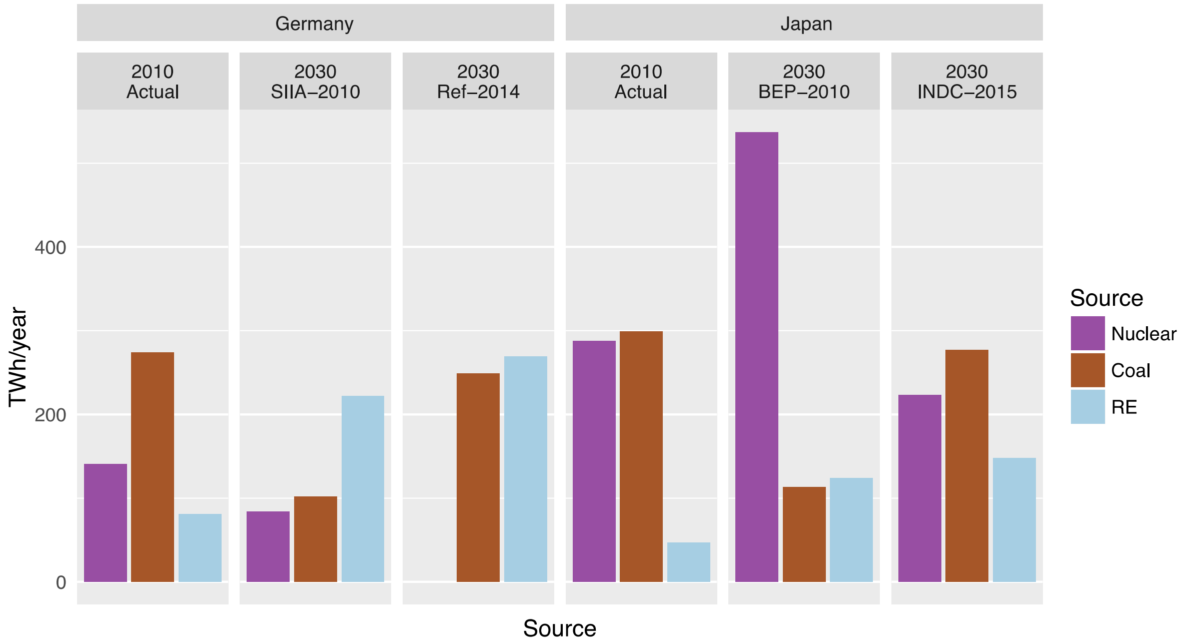
[61] Japan's national grid consists of 10 largely isolated grids, which operate on different frequencies in the East and the West (FEPC 2013).
[62] This also allows Germany to balance intermittent electricity from wind and solar by exporting or importing electricity, the possibility that does not exist in Japan (see Figure 5.1).
[63] China also mimicked Japan's strategy of acquiring overseas fossil fuel assets (Leung et al. 2014) which sometimes put the two countries in direct competition with each other (Atsumi 2007).

(1979) argued that solar energy is needed to face the "prospective future energy crisis" to which Japan is especially vulnerable due to its extremely high rate of demand growth (p.444). Japan's other energy security policies included diversification of supply away from Middle Eastern oil (including to Australian coal and gas), acquisition of overseas energy assets, and "energy diplomacy" in Asia (Atsumi 2007; Toichi 2003).

In 2010, both countries adopted comprehensive and somewhat similar energy plans for the next two decades. In Germany, the *Energiekonzept* aimed to reduce the use of coal 2.7 times and boost non-hydro renewables 2.4 times. In Japan, the 3rd Basic Energy Plan (BEP) proposed to reduce the use of fossils 2.5 times and almost triple non-hydro renewables. Both plans also envisioned a larger role for nuclear power: in Germany, the *Energiekonzept* proposed extension of the lifetime of NPPs and in Japan the BEP proposed to double nuclear power output (Duffield and Woodall 2011; Bundesregierung 2010). The rationales for these plans cited both climate and energy security considerations. The Fukushima nuclear accident in 2011 changed both plans in a similar way: the targets for renewables were practically unchanged while nuclear plans were significantly downscaled: Germany essentially reversed to its nuclear phase-out schedule established in 2002[64] and Japan more or less cancelled its plans for new nuclear power plants construction (see section 5.3.2 for detail). Naturally, this meant that the share of fossil fuels in the electricity mixed projected for 2030 had dramatically increased – see scenarios in Table 5.1 and Figure 5.1, and also Figure 5.7 (Knaut et al. 2016; Government of Japan 2015; METI, Ministry of Economy, Trade and Industry of Japan 2014).

[64] However, as a whole the 2010 *Energiekonzept* was not updated and thus the 2010 GHG reduction target for 2030 is likely to be missed unless new policy measures are adopted. In the reference scenario where nuclear power is phased out by 2022, the output of solar and wind will be some 18% higher than in the 2010 Energy Concept, the output of natural gas some 50% higher, and the output of coal-fired power plants some 140% higher (Schlesinger et al. 2010; Schlesinger et al. 2014) (Figure 5.1, Table 5.1).

Figure 5.7. Nuclear, coal and renewables (excluding hydro) in electricity production in Germany and Japan in 2010 and in plans for 2030



Sources and notes: IEA (2017d) for 2010; For Japan, **BEP-2010** is based on Duffield (2011) and METI (2010b); **INDC-2015** is based on METI (2015). For Germany, **Ref-2014** is the reference scenario from Schlesinger et al. (2014) based on the current policies and **SIIA-2010** is the SIIA scenario from Schlesinger et al. (2010) which formed the basis for the Energy Concept 2010 (Bundesregierung 2010).

5.3.2 Nuclear power

The history of nuclear power in both Germany and Japan dates back to the 1960s when both states worked with the US (and in the case of Japan – UK) manufacturers and local industries and utilities to build their first commercial reactors (Poneman 1982; Smith and Rose 1987). Deployment of nuclear power required public RD&D spending, financial, and political support, which was hastened by the 1970s oil crises (Mez and Piening 2002; Suzuki 2014). This support was not without political opposition, especially after Chernobyl accident in 1986 (Jacobsson and Lauber 2006; Schreurs 2012; Aldrich 2012; Feldhoff 2014). This, however, did not have practical consequences for new reactor connections[65] whose output peaked in Germany in the 1990s contributing 29% of electricity supply and reaching 27% in Japan (Figure 5.1, Figure 5.8).

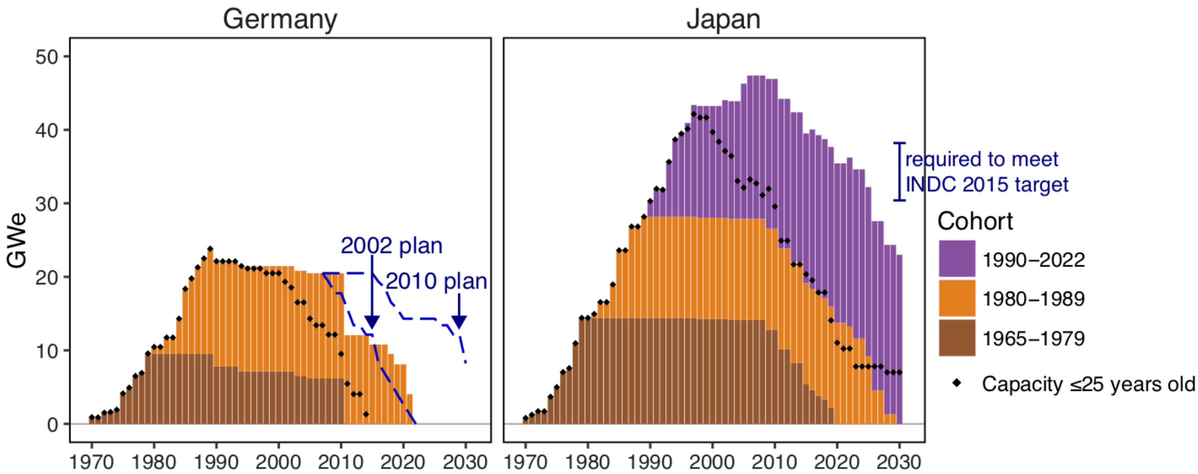
[65] The German government successfully argued that the Chernobyl accident resulted from unsafe Soviet reactor design, which prompted the shut-down of five East German reactors of the same design during the unification, but did not affect the "safe" West German plants (Schreurs 2012). In Japan, the safety concerns following Chernobyl were counteracted by a similar narrative (Nakano 2011).

In the 1990s, Germany did not formally change its nuclear power policy, but did not connect any new NPPs to the grid[66] and continued reducing its public RD&D energy spending, a large part of which was for nuclear energy (IEA 2017c) (Figure 5.6). Without new reactor builds, domestic nuclear equipment manufacturers sought contracts abroad and non-nuclear opportunities including in the nascent wind turbine industry. Siemens, which was involved in the construction of all German nuclear reactors, sold its reactor business to French Framatome in 2001[67] and in 2011 announced the end of its nuclear activities (BBC 2011). In contrast, Japan built 15 new reactors and increased state support for nuclear power. In addition to large and stable RD&D funding, the Japanese government overpowered local resistance to nuclear power (Feldhoff 2014) through increasing monetary support to siting NPPs from about ¥10 bln/year in the mid-1970s to ¥120-180 bln/year in the 1990s-2000s, with the majority of the funds being allocated to host communities (Suzuki 2014).

[66] In 1989-1990 in the process of German reunification, five smaller nuclear reactors of Soviet RBMK design in Eastern Germany were disconnected. One of them operated only for three weeks in 1989 (IAEA 2017; WNA 2015b).

[67] Subsequently it established a joint venture between its "conventional island" business (i.e. hi-tech components of NPPs which are not part of the "nuclear island" – fuel rods and reactors – and thus include pressurized vessels, turbines, safety systems etc.) and Framatome's successor AREVA to participate in a problematic construction of a reactor in Finland, then dissolved this partnership to consider a deal with Russian Rosatom which was eventually cancelled as well.

Figure 5.8. Nuclear power capacity in Germany and Japan by cohort of nuclear power reactors and the capacity of reactors 25 years old and younger, 1970-2030



Source and notes: Reactors are assigned to a cohort depending on the year they enter commercial operation. Capacity for a given year accounts for all reactors in operation on the last day of the year including all reactors in temporary shutdowns, but not permanently retired reactors. The age of a reactor in a given year is calculated based on the year of connection to the grid and rounded up to the nearest year. IAEA (2017) is used for 1970-2015 data in both countries. **For Germany**: projections (bars) are based on WNA (2015b) referring to Atomgesetz (2011); **2002 plan** shows own calculations based on 32 years of service according to Atomgesetz (2002); **2010 plan** shows retirement according to Atomgesetz (2010). **For Japan**: projections for decommissioning are based according to Takahashi (2015) and own calculations based on projected 40 years of service including finishing the construction of the reactors at Shimane-3 (1325 MWe, originally planned commissioning in 2016) and Ohma (1325 MWe, originally planned commissioning 2022) (scenario 2012-S2 in Table 5.1); the vertical line shows the capacity bracket required to meet the INDC's (Government of Japan 2015) target for 2030: the lower end corresponds to 20% share of nuclear power with the capacity factor of 80%; the upper boundary corresponds to 22% share of nuclear power with the capacity factor of 70%.

In the 2000s, nuclear power policies of the two countries further diverged as a result of decisions by the German "red-green" coalition government of the SPD and the Green Party (1998-2002). Though the Greens had been in the Parliament since 1983, it was only during this period that they could achieve their ultimate political goal: the end to nuclear power (Jacobsson and Lauber 2006; Schreurs 2012). Why did the other coalition partner, the SPD, agree to support this goal? SPD had been traditionally linked to pro-coal interests and was represented by several pro-coal politicians in the red-green government (Lauber and Jacobsson 2016; Lauber and Mez 2004). The tension between the coal and nuclear agendas, competing for base-load power, started already in the 1970s,[68] but it clearly intensified in the 1990s when SPD started supporting a nuclear phase-out (Lauber and Jacobsson 2016). During that time stagnating demand and falling electricity prices did not allow for simultaneous

[68] According to Mez and Piening (2002) the nuclear sector in the 1960s insisted on subsidies similar to coal, and electric utilities resisted surcharges on using domestic coal (Jacobsson and Lauber, 2006 p.265).

expansion of coal and nuclear, especially if wind and solar were to grow as well. Moreover, nuclear power was cast as “climate-friendly” (in comparison to coal), the *Jahrhundertvertrag*[69] expired in 1995 and cheap coal imports combined with international energy markets liberalization threatened the main trump cards of the domestic coal: energy security and jobs (Welsch 1998). By 2002, the Greens and the SPD negotiated a law (Atomgesetz 2002) prohibiting construction of new NPPs and limiting the lifetime of existing reactors to 32 years on average.

This decision was a clear loss for electric utilities which owned NPPs (Mez and Piening 2002), but barely damaged nuclear manufacturers who by that time had largely left the sector. And it was a huge win for coal. Not only did the output of coal-based electricity remain stable, but coal power industry also received the biggest investment since post-war (Lauber and Jacobsson 2016, p.159), amounting to almost 15% of the standing capacity and triggered by both projected capacity deficit due to the nuclear phase-out and to strong political support (Pahle 2010). Between 1997 and 2003, coal subsidies, totaling around €35 bln, only decreased slightly (Storchmann 2005, p.1419). In 2003, a decision to continue support for mining until 2012 was made (Bosman 2012, p.8), and coal was exempted from the “eco-tax” which was imposed on other fossil fuels (Lauber and Mez 2004, p.608). Furthermore, in negotiating SPD’s support for renewables, the Greens agreed to higher taxes on natural gas which kept coal competitive (Bechberger 2015, p.33).

Tensions between coal and nuclear power in Germany continued through the late 2000s when a broad political coalition negotiated the *Energiekonzept* adopted in 2010 (Bundesregierung 2010). It envisioned slashing the use of coal in electricity and extending the lifetime of seven NPPs by 8 years and of the remaining ten by 14 years (Table 5.1, Figure 5.4.) (Atomgesetz 2010). A year later, following the Fukushima accident in 2011, the government returned to the previously agreed phase-out timeline (Atomgesetz 2011). Since 2003, Germany has stopped eleven reactors with plans to decommission the remaining seven by 2022.[70]

The developments were different in Japan. Its nuclear sector did not face political competition from strong coal or renewables interests; its powerful supporters included not only electric utilities but also equipment manufacturers; it commanded many more jobs than in Germany (Mitsui Knowledge Industry 2013) and it had the energy self-sufficiency argument firmly on

[69] See footnote 60.
[70] All decommissioned reactors were or will be between 31-36 years old at the moment of their retirement. The Krümmel reactor built in 1983 was stopped first in 2007 and then in 2009 for safety reasons (IAEA 2017). Despite the drama of closing seven reactors in 2011 immediately following Fukushima, they all fit this age pattern and the shut-down schedule agreed in 2002 (Figure 5.4).

its side. In the 2000s, Japan constructed five more reactors, though the share of nuclear power in its electricity declined to 26%[71] by 2010. It expanded its nuclear R&D spending to twice the size of all other OECD countries combined[72] and achieved the largest knowledge stock in nuclear power, at least 15 times larger than Germany's (Bointner 2014). Toshiba, Mitsubishi Heavy Industries, and Hitachi have all acquired nuclear manufacturing capacities overseas.[73] Besides these industrial giants, Japan's $15 bln nuclear market involved about 10,000 companies, including more than 400 with dedicated nuclear technologies, and provided jobs to 80,000 people in 2010 (Mitsui Knowledge Industry 2013). Japan's nuclear business has also been active globally: Japan helped build reactors in South Korea and has recently signed cooperation agreements with Turkey, U.A.E., Jordan, and Vietnam, among others (AIF 2014; Jewell and Ates 2015).[74]

Japan's New National Energy Strategy (METI 2006a) and the 2010 BEP (METI 2010a) aimed to increase the role of nuclear power. The 2010 BEP cited climate concerns and energy security as the rationale that "the government itself will continue taking the lead in the further development of nuclear energy". It aimed to increase the share of nuclear power to 53% of total electricity production in 2030 by constructing 14 additional reactors (Duffield and Woodall 2011). After the Fukushima nuclear accident, this plan was cancelled and several other scenarios for the future of nuclear power were proposed. The 2014 Strategic Energy Plan (METI 2014) also communicated in Japan's INDC (Government of Japan 2015) is for nuclear power to contribute 20-22% of electricity in 2030. This goal would require that either new reactors are constructed and/or some of the existing get their licenses extended beyond the statutory 40 years (Figure 5.8), although no official policy in this respect is known.

5.3.3 Wind power

Similar to nuclear, wind power technology matured outside of both Germany and Japan. It was commercialized during the 1980s in Denmark (Quitzow et al. 2016), which remains a global leader in the technology (Bointner 2014). Germany supported research into wind

[71] This was due to the overall growth in electricity production and to the temporary shut-downs responding to accidents and safety concerns e.g. following the scandal at the Tokyo Electric Power Company (TEPCO) in 2002-2003 and suspension of several NPPs in 2007 after the Chuetsu Offshore Earthquake (Suzuki 2014).

[72] This R&D is spearheaded by the Japan Atomic Energy Agency with its 4400 employees at ten facilities and an annual budget of $US 1.7 bln (WNA, World Nuclear Association 2015a).

[73] In 2006, Toshiba acquired Westinghouse, the world largest nuclear reactor manufacturer, which ironically built the first nuclear power plants in both Germany and Japan in the 1970s. In 2007, Hitachi formed a joint venture with General Electric, another world leader in reactor manufacturing (METI, Ministry of Economy, Trade and Industry of Japan 2006b). Mitsubishi Heavy Industries has closely cooperated with AREVA, a global leader in nuclear industry.

[74] Japan also viewed nuclear energy cooperation as a way to reduce energy-related tensions in Asia (Toichi 2003).

power in the 1970s and 80s, but it failed to produce a commercially viable design and abandoned the project (Heymann 1998; Klaassen et al. 2005; Lauber and Mez 2004). In 1990, Germany passed a Feed-in-law (StrEG) (Stromeinspeisungsgesetz 1990) backed by the "unlikely coalition" (Laird and Stefes 2009) of the Greens, liberal-conservatives and the SPD. The StrEG was primarily intended to benefit small hydro-power plant owners by requiring utilities to buy electricity at 90% of retail prices, but unexpectedly led to an "unimaginable" 100-fold increase in wind power in the 1990s (reaching about 1% of the total electricity generation by 1999) (Lauber and Jacobsson 2016; Jacobsson and Lauber 2006). This explosive growth of wind power in Germany in the 1990s was initially based on Danish technology and manufacturing (Heymann 1998; Klaassen et al. 2005) (see more detail in section 6.2.2).[75]

Following this expansion, many German manufacturers, including Siemens, entered the market and by the early 2000s the German wind turbine industry had become the second largest in the world (Jacobsson and Lauber 2006, p.267; Siemens 2015); the number jobs in the wind industry was comparable to, if not larger than, in the stagnating nuclear power industry without any new manufacturing. Germany established the world's second largest knowledge stock on wind energy after the U.S. (Bointner 2014). Additionally, individual citizens and cooperatives invested extensively in wind energy installations.[76]

Thus, over the 1990s, wind power in Germany evolved from a protected niche to a fledging regime which started to compete with existing regimes and gained political influence. Political battles over the StrEG began in the second half of the 1990s, when the law was challenged in courts by electric utilities (Jacobsson and Lauber 2006). These battles intensified as low electricity prices around 2000 made the position of all electricity actors, including the nascent wind manufacturing industry, more precarious (Lauber and Jacobsson 2016, p.150). The pro-wind coalition allied with the "red-green" government not only managed to defend support for wind, but also succeeded in replacing the StrEG with a much stronger law on renewable energy, EEG (2000). The EEG established a guaranteed (for 20 years) feed-in-tariffs (FIT) for wind and solar PV (Jacobsson and Lauber 2006). As a result, Germany installed 3.5 times more wind in the 2000s than in the 1990s (Figure 5.11). The 2010 *Energiekonzept* envisioned that onshore and offshore wind output would increase 3.5 times and supply over 28% of electricity

[75] Since the early 1990s, Vestas installed over 7000 turbines with a total capacity over 10 GW in Germany, its second largest market after the US (Vestas Wind Systems AS 2014).
[76] According to Morris (2015) about 46% of solar and wind installations in 2012 were owned by some 1,4 million citizens and their cooperatives (including through indirect investment). Borchert (2015) estimates the number of direct and indirect owners at between 1 and 2 million in 2010.

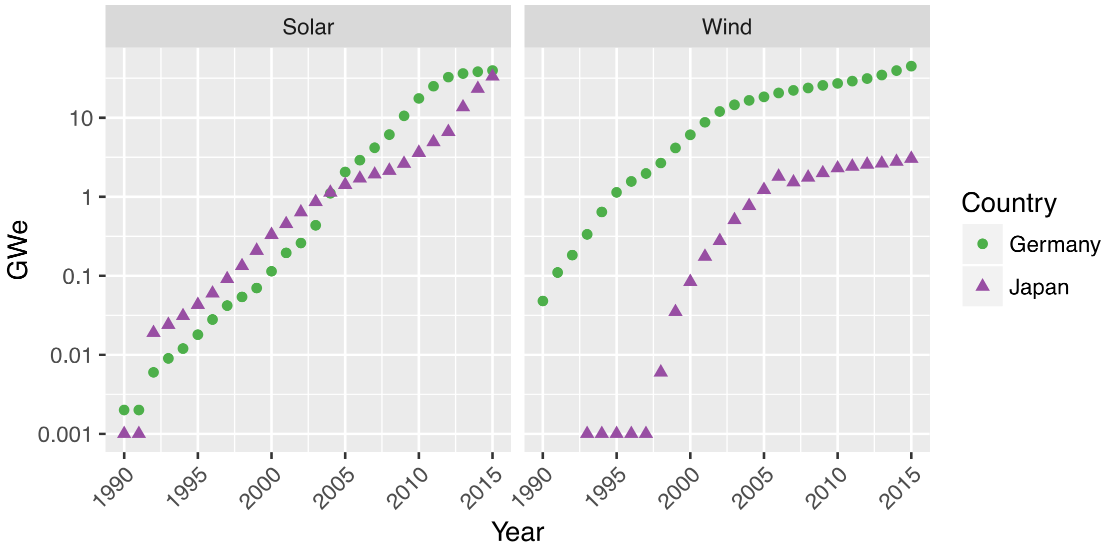
by 2030 (Table 5.1, Figure 5.3). The 2014 EEG re-affirmed this commitment but set a ceiling on the maximum capacity of renewables (Lauber and Jacobsson 2016).

In contrast to Germany, Japan did not support research in wind energy in the 1970s or 1980s (Mizuno 2014; Moe 2010). Technical conditions for wind in Japan are more challenging than in Germany or Denmark, where wind power first took off. Mizuno (2014) and Ushiyama (1999) document a lack of viable turbine designs suitable for Japan's strong turbulent winds, lighting strikes, and high seismicity. Lu et al. (2009) estimates the technical potential of onshore wind in Japan as about 6 times smaller than in Germany and IRENA (2012) and IEA (2015) assess the cost of a wind farm in Japan as significantly larger than in other countries (see also Mizuno 2014, p.1011). The areas with the largest onshore wind potential are far from Japan's electricity consumption centers and transmission and balancing is complicated due to the national grid fragmentation and island topography. Finally, it has been difficult to site wind turbines due to siting and construction rules made more stringent after a series of accidents (Mizuno 2014).

Nevertheless in the 1990s, Japan introduced technical and fiscal measures, regulations and voluntary commitments[77] supporting wind power (Mizuno 2014), which were similar to Germany's but did not result in similar developments. Danish Vestas installed its first commercial wind turbines in Japan in the mid-1990s but the market did not grow as it did in Germany, the US, and elsewhere.[78] By 2001, foreign firms (German Siemens and Enercon, Dutch Lagerwey and Danish Vestas) had provided some 95% of wind turbines in Japan (Mizuno 2014).[79] Without becoming a mature regime, the wind power sector did not have political influence to trigger a policy similar to Germany's EEG and it was not clear whether such a policy would give similar results in Japan. The gap in wind deployment between Japan and Germany has continued to grow (Figure 5.9). Japan's planned wind power deployment for 2030 is 4.5 times larger than in 2010, but still less than half of Germany's capacity today (Table 5.1). [80]

[77] Interestingly, the rates established by these commitments at some ¥11.2/11 US cents per kWh were similar to the FIT rates used in Germany in the same period of ca DM 0.17/9.5 US cents per kWh (Table 1 in Lauber and Mez (2004) and Mizuno (2014, p.1002))
[78] The latest Vestas installation in Japan was in 2008 (Vestas Wind Systems AS 2015).
[79] Japanese companies, Mitsubishi, Hitachi, and Japan Steel Works (JSW) started to play a role by 2010 and 2011 (Mizuno 2014).
[80] Proponents of wind power have made more proposals for wind expansion which are more ambitious and more similar to German plans (JWPA 2015; Ministry of the Environment of the Government of Japan 2012; Mitsui Research Institute 2015).

Figure 5.9. Installed capacity of solar PV and wind power in Germany and Japan, 1990-2015



Source: IRENA (2018) for 2014 and 2015 data; IEA (2017b) for all other data.

5.3.4 Solar power

Solar PV power technology was promoted in both countries since the 1970s through public RD&D funding (IEA 2017c), and pilot programmes such as Germany's "Solar Roofs" (Jacobsson and Lauber 2006) and Japan's "Sunshine" started in 1974 and expanded in 1980 with the *Alternative Energy Act* (Kimura and T. Suzuki 2006; Kurokawa and Ikki 2001). It was Japan rather than Germany that first became a global leader in solar PV technology. In the 1990s, the Japanese electronics industry – in particular Sharp, Sanyo and Kyocera (Moe 2010) – had the world's largest share of PV panels manufacturing and installations. During the 1990s, the use of solar PV was still at a low level, but increased in both countries with Japan installing 6-7 times larger capacity than Germany (Figure 5.9). In a report prepared for the US Government by Lawrence Berkeley National Laboratory in the early 2000s Japan was named as the world leader in solar power policies, from which the US had much to learn (Wiser et al. 2002).

However, the 2000 EEG changed the situation by providing technology-specific FITs for solar power in Germany, which made it possible for owners to recover the cost of the equipment. This decision followed years of experimentation with technology cost-based tariffs at the local level (Jacobsson and Lauber 2006). The rate of solar installations in Germany increased while in Japan it remained the same and in the mid-2000s Germany overtook Japan in both installations and manufacturing of solar PV panels (IEA 2014). After 2012, R&D for renewables in Japan increased (Bointner 2014) and the renewable support policies were strengthened.

Subsequently the rate of solar PV installations increased in Japan and slowed in Germany so that the gap between the two countries has reduced and will most likely close in the near future[81] (Figure 5.9). According to the current plans (as of 2015), the output of solar power will be similar in both countries by 2030 (Table 5.1). Japan remains the global knowledge leader in this technology, followed by Germany and the US (Bointner 2014, p.739).

5.3.5 Summary

The evolution of nuclear, wind and solar power in Germany and Japan is summarized in Table 5.2.

Table 5.2. Differences in the evolution of nuclear, wind and solar power in Germany and Japan in 1970s-2000s and its context

		Period			
		1970s	**1980s**	**1990s**	**2000s**
Context					
Germany		Large domestic coal reserves			
			Wind takes off in Denmark	Optimistic energy security outlook	
				Demand stagnation	Red-green coalition in power
Japan		Demand growth and oil crises		Demand growth	
				Worsening energy security outlook	
Changes in use of nuclear, wind and solar power					
Nuclear power	Germany	Expansion		Stagnation	Phase-out
	Japan			Expansion	
Wind power	Germany	RD&D (abandoned at the end of 1980s)		Rapid uptake	Expansion
	Japan	-		Slow uptake	
Solar PV	Germany	RD&D		Uptake	Rapid expansion
	Japan				Expansion

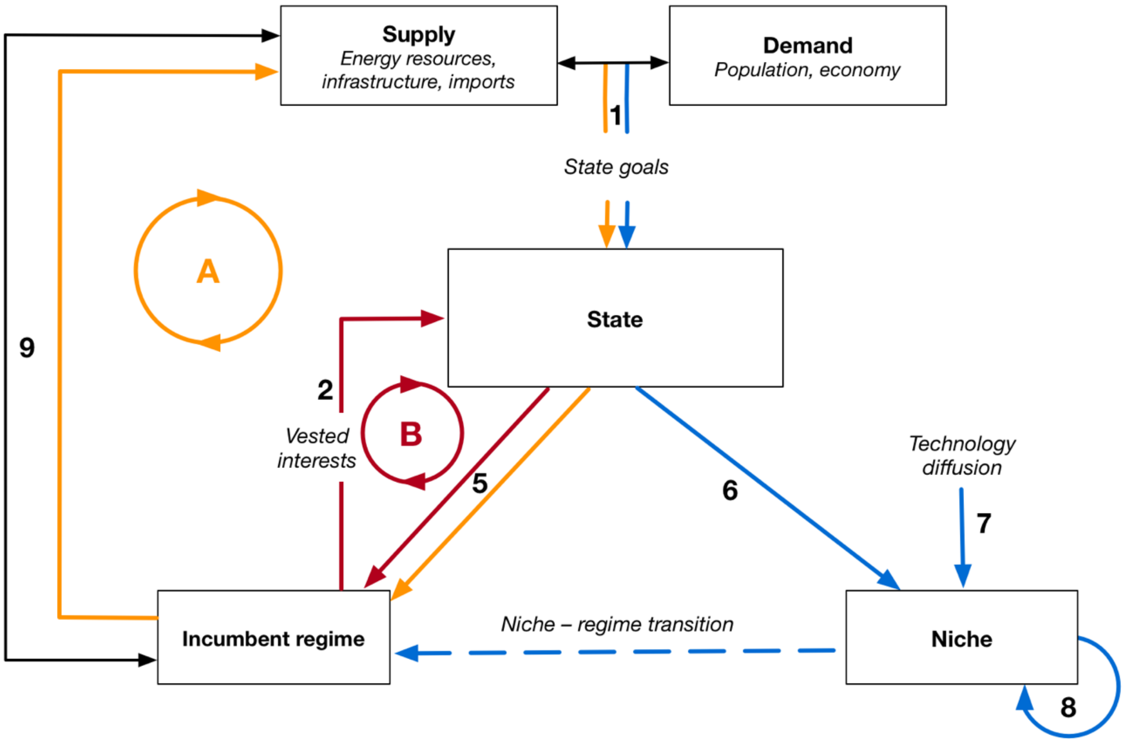
Note: Shaded cells highlight differences between the countries.

[81] In 2015, Japan added 9-10 GW and reached 33.3 GW of solar PV capacity and Germany added 1-2 GW and reached 39.6 GW. By 2020 Germany is projected to have 50.5 GW and Japan 59.3 GW (IEA 2015, p.46 and 59).

5.4 Transition mechanisms in Germany and Japan

The analysis of energy transitions in Germany and Japan validates the presence and demonstrates the explanatory power of most energy transition mechanisms identified in Chapter 3. Figure 5.10 shows these mechanisms using the same numbers as in Figure 3.3, highlighting with different colors and Latin letters mechanisms and their combinations especially significant in the Germany-Japan case.

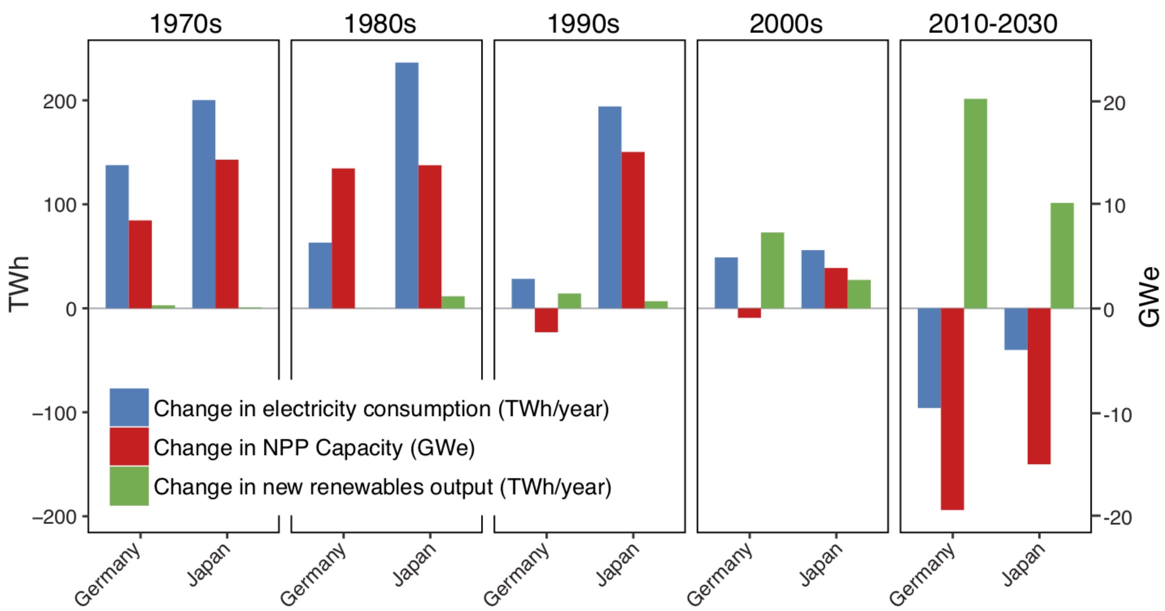
Figure 5.10. Explanatory mechanisms for electricity transitions in Germany and Japan



Note: Each mechanism is designated by a number corresponding to the generic transition mechanisms identified in Chapter 3. Red and orange colors designate feedback loops A and B stabilizing incumbent regimes. Blue color designates mechanisms and processes related to the formative stage and niche-regime transition.

Mechanism 1 (formation of state energy goals, particularly in response to threats to secure supply-demand balance) has been observed in combination with mechanisms 5 (state support to incumbent energy regimes) and mechanism 6 (state support to emerging niches). The **combination of mechanisms 1 and 5** explains Germany's continuous support for domestic coal and both countries' support for nuclear energy in the 1980s. It also explains why in the 1990s Japan, which faced rapidly rising demand and a worsening energy security outlook, continued to support nuclear energy much more intensely than Germany, which had stagnating demand and optimistic energy security outlook. The last observation is especially important for demonstrating an explanatory power of causal mechanisms for national differences in energy transitions. To illustrate on this point further, it is possible to show that electricity demand growth and deployment of nuclear power correlated in the 1970s–2000s in both countries (Figure 5.11). In particular, in the 1990s, Japan experienced a similar growth in electricity demand and connected the same number of new nuclear units to the grid as in the 1980s. At the same time, Germany with its more optimistic energy security outlook and stagnating demand did not construct any new nuclear power plants.

Figure 5.11. Changes in annual electricity consumption, nuclear power capacity and non-hydro renewables output by decade in Germany and Japan, 1970–2010



Sources and notes: For 1970–2030, the bars show the change in final electricity consumption and non-hydro renewables (IEA 2017d) as well as the net change in the installed nuclear capacity (IAEA 2017) in a given decade. For 2030, the bars show the same values calculated by the authors based on Schlesinger et al. (2014). Reference scenario for Germany and INDC for Japan (Government of Japan 2015). The chart illustrates the correlation between the growth in electricity construction and construction of new NPPs in 1970s-1990s and in the 2000s in Japan. The decline in nuclear capacity in Germany since the 2000s and in Japan after 2011 is partially compensated by an increase in non-hydro renewables.

Mechanisms 1, 5 and 9 form **feedback loop A** (already mentioned in Chapter 3) which stabilizes incumbent regimes by locking in state support. Within this feedback loop states support key energy sectors to ensure secure supply-demand balance. One part of **mechanism 9** is the action of a supported regime to expand its resources and infrastructure making these more significant for the national energy system. As a result, the sectors grow even more indispensable for national energy security, which in turn prompts states to provide more support thus closing the feedback loop.

Two more supplementary mechanisms (not shown in Figure 5.10 or Figure 3.3) can be noted with regard to secure supply-demand balance. One is energy demand convergence (Csereklyei et al., 2016) which determines the convergence of energy use per capita in the RCP sector across countries with similar levels of GDP. Energy demand is only marginally malleable to policy intervention and therefore is in most cases a cause, not an effect of state goals. Another is the depletion of energy resources, particularly coal in Japan, which has been at heart of the dire energy security situation of that country.

If mechanism 1 described the formation of “autonomous” state goals, **mechanism 2** describes the effect of vested interests on energy policies. It effects can be most clearly demonstrated by the developments in Germany in the 2000s when the demand growth was sluggish, the energy security outlook positive, and electricity prices low. The energy politics under the “red-green” government of that period was, however, far from tranquil because of the battle between several vested interests. The boost to renewables (the 2000 Renewable Energy Act) was strongly advocated by manufacturers and owners of renewable energy (at that time primarily wind) installations (Jacobsson and Lauber 2006; Lauber and Mez 2004) (Section 5.3.3), whose ranks swelled during the 1990s. This mechanism was very weak in Japan, because it did not have significant renewables industry in the early 2000s.

The German nuclear phase-out occurred because the weakened and fragmented nuclear interests were defeated by competitors including a strong newcomer (wind) and a politically powerful incumbent (coal). These anti-nuclear interests acted through a political coalition of the pro-renewables Greens and pro-coal SPD in the red-green government. This could not have happened in Japan where a larger and more cohesive nuclear regime did not have economically and politically strong competitors. Moreover, the nuclear regime's political influence could also be an explanation (additional to security of supply considerations) for increasingly ambitious plans for its expansion made in the 2000s (Kingston 2014). The idea of monolithic “renewables regimes” deserves an equally careful analysis. Solar and wind technologies have little in common in so far as the underlying research, technological development and manufacturing is concerned. This is why they did not support each other at the niche level (Moe 2010). However, when deployed on a large scale they may benefit the same actors: property owners, cooperatives, municipalities, construction companies. This is probably why pro-wind interests and pro-solar interests were united in advocating for higher FITs in Germany.

Mechanisms 2 and 5 form another **feedback loop B** (Figure 5.10) which is one of the "increasing returns" mechanisms (see section 2.5.3) critically important for understanding energy transitions. For the existing regimes (e.g. coal in Germany or nuclear power in Japan) it ensures receiving state support not directly linked to how effectively they fulfill the relevant social function. It can also work for new technologies such as renewable energy where initial policy support created beneficiaries subsequently lobbying for policy strengthening and continuation.

Mechanism 9 is important to understanding the strength of individual sectors, including their lobbying capacity. The strengths of socio-technical regimes depended on energy resources and infrastructure which they exploit, construct, and operate. Electricity regimes in Germany and Japan were stronger when they were (a) based on domestic rather than imported sources or (b) involved new construction rather than merely operation of existing infrastructure. The latter factor is particularly important to the nuclear sector with a higher share of capital expenditures vs. operating costs. Regimes based on domestic fuels more easily mobilize the "energy security" argument to their advantage but also involve more actors and interests connected to fuel extraction. This explains why the coal regime has been stronger and more influential in Germany than in Japan.

Expanding sectors, where many new facilities are installed, involve not only operators and owners but also equipment manufacturers, installers, and the construction sector. When no new infrastructure is constructed, manufacturers may distance themselves from owners and operators. In the early 2000s, the nuclear regime in Japan was a large and growing industry with extensive supply chains and global leadership, promising employment and exports in addition to energy self-sufficiency. In Germany, the manufacturers were looking for opportunities elsewhere and it was primarily the utilities which fought to profit from already existing plants.[82] Naturally, it was easier to legislate nuclear phase-out in the latter case of a weak and fragmented regime.

In the same time period, the situation was the reverse for renewables. The wind regime in Germany was much stronger because it involved owners, manufacturers and installers of wind turbines. Subsequently, the solar regime gained strength with the increased rate of manufacturing and installation and it recently weakened when manufacturing moved from Germany to Asia (Lauber and Jacobsson 2016). The strength of a regime affects its ability to shape state policies in its own favor as described in the next sub-section.

[82] The split between the interests of utilities and manufacturers was not unique to Germany. Nakata (2002) noted that electric power utilities are "conservative about future investments in nuclear power stations in Japan" (p. 364).

Mechanism 6 describes how, in pursuing their goals, both states nurtured protected niches including nuclear power in the 1950s–1960s and renewables from the 1970s. As measured by state R&D expenses, these efforts were proportional to the perceived threats to energy security (e.g. Germany reducing such expenditures in the 1980s, Figure 5.6). But there were naturally other measures such as FITs and other regulations and direct support to wind power installations especially in Germany. Some of them served goals other than energy security (perhaps most prominently – developing domestic industries in Germany). Although this mechanism was observed in both countries and describe the widespread opinion of its critical importance (see the beginning of this Chapter), it does not actually explain much of the difference between the two countries both of which provided comparable support to emerging technologies, especially at the earlier stages.[83]

Mechanism 7 (technology diffusion) was observed in both countries at different periods and in relation to different technologies. One example is the rapid expansion of nuclear power in both countries from a niche in the 1960s to a full-fledged regime in the 1970s resulting in part from technology diffusion from the US and the UK. An expansion of wind power occurred in Germany in the 1990s with technology diffusing from Denmark, an event which I analyze in more detail in Chapter 6. This diffusion was much more likely in Germany that shared a common border, similar geographic and social conditions (especially in its Northern regions) with Denmark as well as uninhibited movement of equipment, capital and people facilitated by the EU. The difference between Germany and Japan with respect to wind power introduction reflects a wider global pattern investigated in Chapter 7: earlier adoption of wind power in the European Union member states facilitated by technology and policy diffusion.

The main indications of the presence of **mechanism 8** (niche learning) are the sequences of successes and failures in the development of niche technologies. There are plenty of examples in Germany and Japan. For example, Japan's four-decade long pursuit of solar power through massive RD&D resulted in its technological leadership but only marginal installations until very recently. Other niche technologies included in the *Sunshine* program – hydrogen, coal-to-liquid, and geothermal (Kurokawa and Ikki 2001) – yielded even less results. Germany eventually abandoned its attempts to commercialize its own wind power technologies in the 1970s-1980s and Japan failed in a similar effort in the 1990s-2000s. Taken

[83] Jacobsson and Lauber called the wind power expansion in Germany an “unimaginable” (2006, p.264) consequence of a “lukewarm” (Lauber and Mez 2004, p.599) policy backed by an “unlikely” (Lauber and Mez, 2006) broad coalition not specifically aimed at wind support. Lauber and Mez (2004), Jacobsson and Lauber (2006) and Laird and Stefes (2009) suggest that the German reunification distracted the electric utilities from lobbying against StrEG. This may partially explain the difference with Japan in the early 1990s, but not in a longer-term and not in a wider geographic context.

together, mechanisms 1, 6, 7 and 8 describe the development of emergent niches during their "formative stage". The result of their joint action may be transition from a niche to a regime as shown by the dashed blue line in Figure 5.10. These mechanisms leading to this process are the focus of my research in Chapters 6 and 7.

Table 5.3 explains transition outcomes for different energy sources, countries, and periods in terms of the generic transition mechanisms. Shaded cells represent mechanisms explaining differences between the two countries.

Table 5.3. Explanatory mechanisms for transition processes in Germany and Japan

Country and period	Transition processes	Mechanisms*
		Nuclear power
Germany and Japan, the 1970s	Fast uptake, emergence of nuclear power regime	1-6: State support to niche nuclear technology in response to oil crises and demand growth 7: International technology diffusion primarily from the US 8: Niche learning and creation of domestic nuclear industries
Germany and Japan, the 1980s	Expansion	1-5-9: State working with nuclear power incumbents in response to oil crises and demand growth. Regimes expanding the infrastructure
Japan 1990s-2000s	Expansion	1-5-9: State working with incumbent to ensure secure supply-demand balance in response to demand growth and worsening energy security outlook 9: Nuclear regime strengthened based on vigorous growth 2: Emergence of the nuclear lobby/"nuclear village" promoting pro-nuclear policies
Germany 1990s	Stagnation	1-5: Declining interest in energy security due to low prices and optimistic outlook. Cessation of active state support to nuclear construction 9: Lack of new orders results in manufacturers' searching for opportunities elsewhere; nuclear regime weakened and fragmented
Germany 2000s	Nuclear phase-out	2: A coalition of pro-renewables and pro-coal interests defeats weakened and fragmented nuclear regime
		Wind power
Germany 1970s-1980s Japan 1990s-2000s	Niche developments, negligible uptake	1-6: State supports niche technology in response to energy security concerns 8: (mostly failed) niche learning
Germany 1990s	Rapid uptake wind power becoming a fledging regime	7: Wind power diffuses from Denmark. 8: Rapid niche learning
Germany 2000s	Expansion	2-5: Pro-wind interests advocate for strongly supportive FITs (EEG 2000)
		Solar power
Germany and Japan 1970s-1990s, Japan 2000s	Niche developments slow uptake	1-6: State supports niche technology in response to energy security concerns 8: Slow niche learning in Japan in 1980s-1990s
Germany 2000s	Rapid uptake. Solar power forms a fledging regime	2: Pro-renewables/wind interests advocate for strongly supportive FIT (EEG 2000) 8: Rapid niche learning

Note: For numbers designating different mechanisms see Figure 5.9.

5.5 Summary

In this section I presented a comparative case study of national electricity transitions in Germany and Japan based on the causal mechanism approach and insights from the three perspectives on national energy transitions

Through tracing historical processes and comparing phenomena in two countries, this analysis validated 7 out of the 9 generic transition mechanisms proposed in Chapter 3. Furthermore, it identified additional or more nuanced mechanisms underpinning generic mechanisms identified in Chapter 3. These are electricity demand convergence (contributing to mechanism 1) and dependence of the regime strength on the infrastructure life-cycle (an aspect of mechanism 9). By comparing mechanism-based explanations to more general "covering law" or "single-factor" explanations, I demonstrate superior explanatory power of the mechanism-based approaches.

My analysis involves developing integrated explanations of the observed phenomena involving combinations of generic transition mechanisms. Within such explanations, I identify two feedback loops consisting of two or more mechanisms and explaining the lock-in or regime stabilization (Figure 5.10, feedback loops A and B). Such feedback loops can themselves be viewed as aggregated mechanisms, illustrating the idea of nested mechanisms. Furthermore, I show that different mechanisms may be dominant at different time periods. The outcomes of mechanisms in one period form inputs to mechanisms in another period forming causal sequences of events consisting of linked mechanisms.

For example, to explain the presence of nuclear phase-out in Germany but not in Japan in the 2000s I invoke two sequences of events involving at least 5 different mechanisms. In Germany, demand stagnation in the 1990s led to the cessation of new nuclear power plant construction, which weakened the nuclear power sector (mechanism 9). In parallel, wind power diffused from Denmark (mechanism 7) triggering technology learning (mechanism 8) and leading to the emergence of a relatively powerful pro-renewables regime, which together with influential pro-coal interests lobbied for the nuclear phase-out (mechanism 2). In Japan, demand convergence resulted in rapidly increasing demand in the 1990s which caused the state to support massive nuclear expansion (mechanisms 1 and 5) which in turn strengthened the nuclear lobby (mechanism 9) and triggered lobbying for continuation of nuclear support (mechanism 2) in absence of considerable coal and wind interests.

As evident from the above example, I have also been systematically comparing both **motivations** and **capacities** of the actors involved in the explanatory mechanisms. For example, my analysis depends on judging the capacity of the Germany's coal sector as much higher than Japan's based on the size of resources, infrastructure and employment that it commands. Finally, to formulate and validate hypotheses related to causal mechanisms I systematically used variables and insights from the three perspectives on energy transition ranging from coal reserves, energy trade balances and age of infrastructure (the techno-economic perspective), to geographic and cultural proximity to technological core (the socio-technical perspective), to concerns over geopolitical security and party politics (the political perspective).

Although the case study of Germany and Japan validates and refines my approach, its findings cannot be extended to a significant number of other countries as both Germany and Japan are in many aspects unique (they are both very large, technologically advanced, wealthy and politically stable democracies). However, applying the same approach beyond Germany and Japan would require time and efforts beyond my command because of the enormous complexity of transition processes amply demonstrated by this case study. I therefore narrow my scope to only two technologies (wind and solar PV) and to only one phase in their deployment (formative), thus engaging with a smaller number of causal mechanisms (those highlighted in blue in Figure 5.10). The detailed method and the results of this analysis are presented in the next two chapters.

6 Case studies of the formative phase

6.1 Introduction and method

This chapter contains case studies of early phases of introduction of wind and/or solar (PV) power in 12 countries based on national documents, statistics, and secondary sources. The rationale for conducting these case studies and their role in the overall research design are outlined in section 4.3.1. It justifies the scope of the case study analysis limited to two renewable electricity technologies and to the early stage of the introduction to limit the range of potential mechanisms and at the same time broadening the range of countries to include different socio-economic and political settings.

The 12 cases for my analysis have been selected as explained in section 4.3.2 and summarized in Table 6.1. All cases were drawn from the list of 60 largest electricity producers where about 95% of world's electricity is generated. Within that sample, I am interested in countries that have already completed the formative period, i.e. reached a combined share of wind and solar energy in total electricity production of 1% by the end of 2015. There are 37 such countries. For my case studies I selected 12 countries – approximately one third.

These 12 cases represent 5 of the 6 groups identified in the exploratory large-N analysis (Figure 7.9 and Figure 7.10).[84] This research design represents an interaction between case studies and large-N analysis, wherein the cases help to formulate hypotheses for the large-N study and the large-N study allows to identify the "most diverse" cases covering the widest range of variables. Group 1 countries (earlier adopters) are the most represented in this chapter. This reflects the assumption that due to global technological immaturity these countries had to overcome larger barriers in introducing new renewables and thus featured more complex and diverse mechanisms than later adopters. Some other countries were represented as "anomalous" cases (e.g. Egypt starting much earlier than other countries in Group 5; Switzerland as an extremely "late" starter within Group 2). Three case studies are supplemented by a brief discussion of similar countries: Egypt – by North African countries, Bulgaria – by new EU member states, and Thailand – by Southeast Asian countries. The case study of Switzerland is complemented by a note on similar countries with large shares of nuclear energy: Finland, Japan and Korea. Although case studies in this chapter do not have a strong comparative focus, the summary Table 6.6 in section 6.3 lists and compares key

[84] No cases from Group 6 consisting of major energy exporters which are not OECD members (Russian, UAE, Kuwait, and Saudi Arabia) were included because I judged, from the international statistics (IEA 2017d), that none of these countries introduced wind or solar power to any significant degree and therefore would not allow to study formative phase mechanisms.

characteristics for all case study countries and for China, a country playing an especially important role in the global energy transition.

My primary focus in these case studies is on such mechanisms as niche innovation and learning, various forms if international interactions including technology and policy diffusion, as well as formation of state energy goals. To analyze factors shaping these goals, for each country I provide an analysis of its energy supply status and, where relevant, demand growth trends. In terms of time, each case study covers the period approximately to the moment when the combined share of wind and solar energy in total electricity production in the respective country reached 1% (I explain the significance of this threshold in section 4.4).

The source of all unreferenced quantitative information in this chapter is World Energy Balances by IEA (2017d). The case studies often refer to import dependence of electricity supply. The exact way this indicator is calculated is described in section 7.3.4.

Table 6.1. National cases of early stages of wind and solar power deployment analyzed in Chapter 6

Country	**Year when the combined share of wind and solar power reached 1%**	**Justification of selection**
Denmark	1989	First starter globally (Group 1)
Germany	1999	Early starter, globally significant player (Group 1)
Spain	1999	Early starter (Group 1); first starter without physical border with Denmark
Greece	2001	Early starter (Group 1); smaller economy
Netherlands	2003	Early starter (Group 1); failed attempt to become develop viable RE equipment manufacturing
Portugal	2003	Early starter (Group 1); smaller economy
Austria	2004	Early starter (Group 1); first starter in Central Europe
India	2006	First starter outside OECD (Group 4)
Egypt	2010	First starter in Group 5. Very early start among similar countries
Bulgaria	2010	One of the first starters in Group 3.
Switzerland	2014	Late starter in Group 2; country “starting” with solar energy
Thailand	2015	Representing Group 5

Note: “Starter” refers to takeoff time

6.2 Case studies

6.2.1 Denmark

Denmark pioneered the development of renewable electricity by reaching 1% of wind power share in its electricity generation in 1989 – ten years earlier than the second country (Germany). While Denmark's early start results from a combination of unique factors, it can be related to energy transition mechanisms described in Chapters 3.

Denmark has had a long history of experimentation with wind-produced electricity going back to the last decade of the 19th century, which helped to build a substantial *socio-technical capacity* in this area by the 1970s (Gipe 1995). The geographical conditions of a low-lying country with a long coastline provided for a high wind energy potential, and the Danes had been "culturally predisposed toward the wind" (Gipe 1995, p.51) in the form of windmills long before the age of electricity. However, their capacity in the field of wind electricity resulted, to a significant extent, from historical energy import dependence. Over the entire 20th century, Denmark relied on imported energy resources for power generation. In this regard, it was different from all other Northern or Northwestern European countries with a broadly comparable population and/or area, whose electricity generation at some moment relied predominantly on either domestically produced coal (the Netherlands, Belgium) or hydropower (Sweden, Norway).[85] Wind installations, primitive by today's standards, were used to produce electricity during supply disruptions at the time of the First and, to a larger extent, the Second World War (Gipe 1995). By the time of the 1973 oil crisis, the country's electricity supply was relying mainly on imported oil (around 90% of domestic electricity supply in 1972), which made it particularly sensitive to the effects of the crisis. Due to the history of energy dependence among other factors, Denmark already had some technology legacy in the wind electricity sector to build upon. Import dependence provided strong motivation for that – between 1973 and 1989, its takeoff year, Denmark remained uniquely import-dependent among the entire sample. For example, in 1982 its import dependence of electricity supply measured at 98.5%, the value highest among the OECD members, and second only to Israel with its 99%[86] globally. Although Denmark started exploiting its recently discovered oil fields in the late 1970s and gas deposits in the next decade (Campbell 2013), by the end of the 1980s domestic fossil fuels had not made it into the electricity generation sector yet. Denmark's electricity demand in the years leading to its takeoff was growing fast (26% between 1982 and 1989) but, unlike import dependence, it was not unique among

[85] This reflects the situation of the four listed countries around the year 1960.

[86] The third and the fourth countries were Korea and Italy 83% and 67% respectively.

comparable countries. Denmark had been exploring nuclear energy as a supply option from the 1950s. In 1976, shortly after the oil crisis, the government proposed an energy programme that envisioned the construction of five reactors. However, there plans have never materialized, and in 1985 the parliament adopted a ban on nuclear construction in Denmark (Thurner et al. 2017).

Although Denmark's immediate response to the oil crisis was the transition from oil to imported coal in the electricity sector, the government also took steps to promote renewable energy deployment soon after 1973. In 1978, a test station for wind systems was established, which, in addition to developing technical standards, served as an important hub for networking activities in the sector (Gipe 1995; Garud and Karnøe 2003). The same year saw the establishment of two essential non-governmental networks – Danish associations of wind turbine manufacturers and owners respectively. In 1979, first investment subsidies for wind turbines were introduced (Garud and Karnøe 2003). In the same year the first power purchase agreements between utilities and the association of turbine owners were negotiated under the government's supervision. This was in line with the traditional practice of voluntary agreements characteristic of Denmark. These agreements introduced for the first time a mechanism similar to feed-in tariffs – utilities' obligation to purchase wind electricity at a pre-determined price (85% of retail tariffs in the respective area) (de Lovinfosse 2008). Further policies were adopted over the next decade. In 1985, the same year when nuclear power was rejected by the parliament, the government signed an agreement with utilities to install 100 MW of wind turbines by 1990 (de Lovinfosse 2008). The target was revised upwards several times in the subsequent years.

Wind energy diffusion within Denmark relied on its agricultural economy "ecosystem", which comprised several components fitting each other – agricultural production by individual farmers and cooperatives, manufacturing industry serving these customers, and banks (often also cooperative) providing capital for farmers to buy the machinery (Gipe 1995). From the beginning of the 1980s, the same farmers and cooperatives used loan finance from their usual banks to install first wind turbines produced by agricultural machinery manufacturers who were seeking to diversify their products in the face of a crisis of supply (e.g. Vestas, later the world's leading manufacturer of wind turbines). In their "technology style" (Heymann 1998) early Danish turbines were similar to farm machinery,[87] often being less efficient and more material-intensive, but also more robust than their German or American counterparts usually based on the expertise of the aerospace industry (Gipe 1995). Turbine designs relied on

[87] The equipment embodied "[d]esign heuristics based on experience with agricultural equipment: reliability of key concern" (Garud and Karnøe 2003, p.284).

prototypes available in the local engineering industry – for example, producers of turbine blades built on the experience of plough (and also maritime propeller) manufacturing near Aarhus and Aalborg (Cooke and de Laurentis 2010). The process of incremental innovation, building on existing prototypes and relying on learning-by-doing as opposed to radical breakthrough solutions,[88] was consistent with the Danish "variety of capitalism" – coordinated market economy (CME), which, according to Hall and Soskice (2001), was well-suited for incremental innovation. In particular, tight networking and active information exchange among various actors, a characteristic feature of CMEs (Hall and Soskice 2001), was clearly present in Denmark's fledging wind industry (Garud and Karnøe 2003).

The small size of the country played a positive role at early stages of the industry development – all installations were relatively easily accessible to and serviceable by manufacturers (Gipe 1995). This not only improved customer experience, but enabled a fast learning loop involving design, manufacturing, and production use, demonstrating the role of spatial proximity at early phases of innovation (see section 2.6). But it was also typical of Danish manufacturers confronting limited domestic market to look for export opportunities (cf. the episode of looking for export markets for a milk cooler from Vestas' early history (Vestas Wind Systems AS 2017)). Having matured in a small domestic market, Danish manufacturers entered much larger markets of the European Economic Community (later the European Union) and the US. In 1992, Danish turbines accounted for 41% of installed wind capacity in California (Gipe 1995, p.36). Danida, Denmark's international development agency, was supporting wind energy projects using Danish turbines in developing countries, such as India or Egypt (IRENA-GWEC 2013). This access to larger markets helped the industry to weather the inevitable downturns in domestic demand. In a sense, Denmark was a "niche" for early development of wind energy technology in Europe and globally, combining strong motivation with favorable socio-technical conditions and political economy.

Overall, although the integration of wind energy into the electricity system certainly required some changes, in terms of regime – niche dynamics the early process of wind energy diffusion in Denmark looked more like a "repurposing" of an existing socio-technical system related to agriculture than a disruption of the energy regime. This process is captured by the concept of socio-technical "path plasticity" (Strambach 2010).

[88] Garud and Karnøe (2003) characterize this model as "bricolage". Hendry and Harborne (2011) qualify the story of incremental, practice-based learning noting a significant role of formal, science-based R&D at subsequent stages of the industry development.

6.2.2 Germany

Germany has significant reserves of coal, but only limited oil and gas reserves well past peak production levels (Campbell 2013). The country's electricity sector was not hit particularly hard by the 1973 crisis, since the share of oil in electricity supply was relatively small (12%). Import dependence of electricity supply was 18.6%, whereas import dependence of TPES was much higher – around 50% – due to extensive use of imported oil in transportation and heating.

In the late 20th century, Germany did not have a single national utility, but a patchwork of utility companies operating at different levels. The national electricity supply was dominated by a small number of major utility companies relying on coal and nuclear energy, whereas a large number of regional and local companies were involved in electricity distribution (Jacobsson and Lauber 2006). Coal mining was seen as an important source of jobs and a politically important industry connected to the Social Democratic Party (SPD) through labor unions (see Chapter 5). Since 1975, the government had subsidized the use of more expensive domestic coal by allowing utilities to include a special levy (so-called "coal penny") in household's electricity bills – a practice ruled unconstitutional by the Constitutional Court in 1994 (Kommers 1997, p.246). Remarkably, the amount of coal-generated electricity remained broadly the same from the late 1970s to the 2010s, although some domestic coal has been gradually substituted with imported one since the early 1990s.

At the end of the 1950s, the country embarked on a policy of active nuclear power expansion, which resulted in a large number of reactors coming online in the 1970s and 1980s (Thurner 2017). Expanding nuclear sector helped to meet growing electricity demand, while reducing import dependence of electricity supply. In 2002, the decision of accelerated nuclear phaseout was made by the then ruling coalition of the SPD and the Greens (see section 5.3.2), but the policy of nuclear expansion effectively stopped in the 1980s – no construction of a new reactor started after 1982, and several significant projects were halted (Thurner 2017). Furthermore, stagnating electricity demand in the 1990s did not provide sufficient motivation for further expansion (see section 5.3.1). As a result of nuclear expansion, import dependence of ES reached its minimum – around 7% – at the end of the 1980s and then started to grow again. So, unlike other early starter countries, Germany's import dependence of supply was not particularly high in the years leading to its takeoff, but it was growing rapidly – from some 11% in 1991 to 20% in 1999 (the year of takeoff) and 25% in 2001.

Germany started considering RES-based generation as a response to energy crisis as early as in 1974. Approximately for 15 years – a period described as "a formative phase of wind and solar power" (Jacobsson and Lauber 2006, p.261) – support was provided mainly in the form of R&D programmes managed by the Ministry for Research and Technology (BMFT) (Jacobsson and Lauber 2006). The mainstream direction of innovation, in contrast to the one pursued in Denmark, prioritized design elegance, high performance, and material efficiency based on a scientific approach to design. It also built on Germany's experiments with wind electricity going back to the years before and during World War II (Heymann 1998). Among other designs, this approach gave rise to Growian, a 3 MW turbine unprecedentedly large by the standards of the day, developed and built by MAN, an established mechanical engineering company, in collaboration with leading utilities. The turbine launched in 1983 turned out a failure due to time and cost overruns and extreme failure proneness (Heymann 1998). MBB, an aircraft manufacturer, was also experimenting with large turbines without much success in the end (Heymann 1998). However, the R&D programme was flexible enough to accommodate a variety of developers and designs, and a number of smaller turbines have evolved by the end of the 1980s, some of them close to Danish ones (Bergek and Jacobsson 2003). In addition to state support, firms were attracted to the new industry by the experience of the growing Danish turbine industry, Californian wind boom, and also "niche demand" from some utilities and environmentally concerned farmers, especially after the Chernobyl accident (Bergek et al. 2008). In 1987, Westküste, one of Germany's first wind farms was opened by several local utilities as a site to test and compare turbines from different producers (Windenergiepark Westküste 2017). Overall, 14 companies were selling wind turbines in Germany in the 1980s, and 11 of them survived till the end of the decade; a total of 225 turbines were installed in Germany by the end of 1989 (Bergek et al. 2008). In this regard, Germany was a decade behind Denmark, which had 225 turbines installed by the end of 1980 (Heymann 1998), but it was prepared for further expansion of the sector.

In 1988, the government launched the first market creation programme for wind electricity – the installation of 100 MW of wind turbines, which was later upscaled to 250 MW (Lauber and Mez 2004). Programme participants received guaranteed long-term tariffs; private operators, e.g. farmers, could also obtain an investment subsidy (Jacobsson and Lauber 2006). This amounted to a huge expansion of the domestic turbine market – as of the end of 1988, the total installed wind capacity in Germany was about 8 MW (Bergek and Jacobsson 2003). In 1990, Germany adopted its first feed-in tariff law, which introduced non-technology specific tariffs defined as a proportion of electricity retail prices. According to Brand-Schock (2010), proponents of the law were citing a similar practice in Denmark, although at that time it was based bot on legislation but on agreements between utilities and producers. The law was expected to result mainly in a moderate increase in small hydro capacity, but led to an "unimaginable" market expansion for wind electricity (Jacobsson and Lauber 2006). The rapid growth that followed led to the formation of learning networks and the emergence of new interest groups gaining political strengths, launching positive feedback loops (Bergek and Jacobsson 2003). Individual farmers and cooperatives accounted for a significant proportion of wind installations at this stage (Toke et al. 2008).

To Germany with its longstanding traditions of industrial exports, developing domestic turbine manufacturing was a major motivation behind its renewable energy effort.[89] Using "non-market" coordination approaches (Hall and Soskice 2001), Germany was able to establish a temporary "quasi-protected" market for its fledging turbine industry facing Danish competitors by tweaking selection criteria and support categories for both the federal 100/250 MW programme and regional investment subsidies (Bergek and Jacobsson 2003). Importantly, the EU trade regulations would not allow to lock the Danish turbines out of there market completely, so the barrier created by policies turned out "semi-permeable" – while the German industry received 57% of the projects, 35% of the market was taken by Danish manufacturers, and 7% – by the Dutch (Bergek and Jacobsson 2003). Thus, the Danish turbine industry still benefitted from access to the German market, whereas German designs had to deal with international competition. The "quasi-protectionist" regime also provided an incentive for Danish companies to establish subsidiaries in Germany. One example is the company Nordex, which was created in 1985 as a Danish company, established production operations in Germany in 1992, and eventually changed its "citizenship" being acquired by German capital a few years later (Nordex 2017).

In the second half of the 1990s, the feed-in tariff regime faced strong resistance from utility companies (Jacobsson and Lauber 2006), partially due to the spatially uneven pattern of renewable energy growth (see below), which resulted in a disproportionally high financial burden on some companies in the absence of an adequate redistribution mechanisms (Windpower Monthly 1996). The utilities challenged the regime politically and in the courts, within Germany and at the EU level. These attempts were narrowly defeated in parliament, not least due to the participation of manufacturing workers and mechanical engineering companies in the pro-wind coalition (Jacobsson and Lauber 2006), which led to the adoption of a law establishing technology-specific feed-in tariffs in 2000.

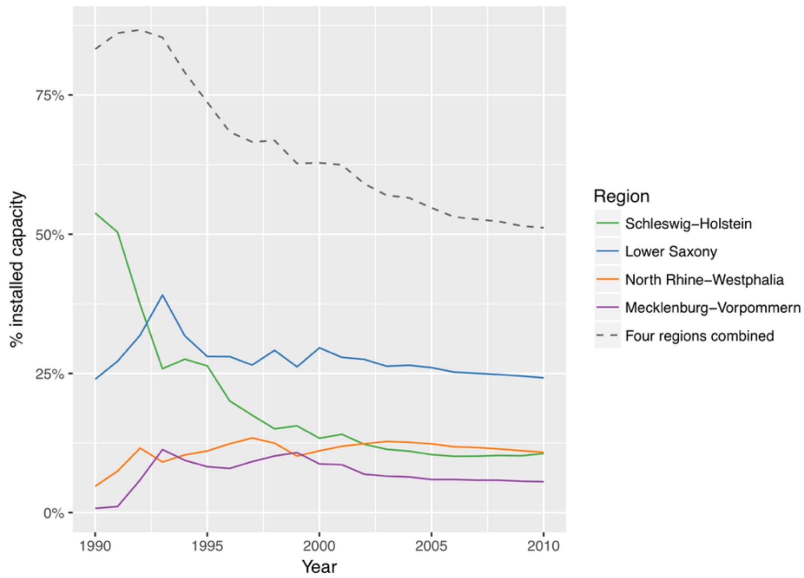
Early wind energy deployment was highly uneven across German regions. Figure 6.1 shows the percentage of Germany's total installed wind capacity[90] in four leading regions –

[89] One priority of early R&D programmes was the development of off-grid solutions to be exported to developing countries (Jacobsson and Lauber 2006).

[90] To estimate the regional distribution of early wind installations, I use Energymap, a project by the German Society for Solar Energy to create a database of all renewable electricity installations in Germany based on data from four major transmission operators (EnergyMap.info 2016). While the database is obviously incomplete, especially for early period of RE deployment, I assume that it representative enough to estimate regional

Schleswig-Holstein, Lower Saxony, North Rhine–Westphalia, Mecklenburg–Vorpommern, and the four regions combined.[91]

Figure 6.1. Shares of four German regions in cumulative national installed wind capacity



Source: Author's own calculations based on EnergyMap.info (2016).

It was two northern coastal states with high wind potential – Schleswig-Holstein and Lower Saxony – that were early leaders in the field. Both of these regions host nuclear reactors and does not have significant coal resources (Thurner 2017). Schleswig-Holstein has been a major net electricity exporter – in 1995 it exported almost half of the electricity produced within the region. The role of this region is particularly remarkable, because being a very small region by German standards (approximately 3% of the country's population and GDP (Federal Statistics Office 2018)) it accounted for more than half of all installed capacity in 1990-1991 and kept on par with a much larger Lower Saxony until 1995. Schleswig-Holstein immediately borders Denmark, so spatial proximity played a role in early wind energy diffusion. Brand-Schock (2010) notes both penetration of Danish turbines, small and cheap by German standards, and direct access to the experience of Danish farmers benefitting from renewable electricity production as factors behind early adoption of wind energy in these two states. The latter were also home to the country's first wind energy associations, which later merged to form

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proportions of installed capacity. Cumulative installed capacity of wind energy in Germany calculated for 1994 and 1995 using Energymap data corresponds to approximately 60–65% of values reported by Eurostat – a coverage high enough for my purposes.

[91] These four regions were leading in terms of installed wind capacity approximately until 2000, when Brandenburg joined the group to assume the second rank eventually.

the German Wind Energy Society. The two leading regions were later joined by Mecklenburg−Vorpommern, another coastal region, and North Rhine−Westphalia, the country's largest region[92] and its biggest "coal stronghold". Interestingly, the shares of regions stabilize soon after 1999 – Germany's takeoff year.

The difference between regions was likely a result of differences in their natural conditions, but also in their policies. Germany being a federal state, regional governments played a significant role in early diffusion of wind energy. Some of them – particularly Schleswig-Holstein and Lower Saxony – offered their own support programmes in addition to federal ones (Grotz 2005), creating particularly favorable "pockets" in the national incentive landscape. They also pursued their own industrial policies, contributing to the creation of the "quasi-protectionist" regime described above (Bergek and Jacobsson 2003).

6.2.3 Spain

The history of wind energy development in Spain started in the early 1980s. The country was vulnerable to the oil crisis of 1973, when its import dependence of electricity supply was around 37%, mainly due to imported oil. The largest domestic source of electricity was hydropower, complemented with a relatively small amount of domestically produced coal. Until the early 1980s, the main policy option for meeting growing electricity demand was a massive nuclear power plant construction programme that the government had been pursuing since the late 1960s (De la Torre 2017). However, in 1984 the newly elected Socialist government reversed that policy by imposing a nuclear moratorium, citing insufficient demand growth and accumulating financial burden associated with the programme[93] as a rationale. While several reactors close to completion were connected to the grid in the subsequent years, the construction of five more units was stopped,[94] and no new nuclear reactor was commissioned in the country after 1988 (De la Torre 2017). With the option of further nuclear expansion foreclosed, the immediate response to the dual challenge of dependence on expensive imported oil and growing demand was the expansion of domestic coal production. However, it peaked in the end of the 1990s and even at its peak was unable to completely substitute imported fossils. Between 1985 and 2000, import dependence of electricity supply increased from 20% to 43%.

[92] Therefore its installed capacity normalized per capita or unit of GDP would not look particularly impressive, unlike that of Schleswig-Holstein.

[93] De la Torre (2017) characterizes the moratorium that involved compensations for private utility companies as a bailout of the utilities, which were heading for a financial disaster.

[94] This decision was considered "temporary" for a decade and was finally confirmed by the government in 1994 (WNA 2017).

As a longer-term solution, approximately at the time of the moratorium the government started actively promoting diversification of energy sources and, specifically, renewable energy development. Several policy documents, building on the framework Energy Conservation Law (1980), introduced the country's first system of incentives for RE development, targeting primarily R&D and demonstration activities (Dinica 2003). In 1984, Spain's renewable energy agency – the Institute for Energy Diversification and Saving (known as IDAE) – was created. After a period of development and demonstration, in 1991 the country's wind sector entered "the market introduction stage" (Dinica 2003, p.247). In 1994, the regime of renewable energy was somewhat strengthened (Dinica 2008); this coincided with the confirmation of the nuclear moratorium. Finally, a new support mechanism relying on cost-based technology-specific feed-in-tariffs was introduced in 1997–1998 (Dinica 2008); this was done at a moment marked by a pronounced acceleration of electricity demand growth.

From the early stages, both central and regional governments pursued industrial policy in the wind energy sector. Investment subsidies sought to encourage domestic manufacturing, but also covered foreign technologies as long as they "allowed national technological participation" (Dinica 2003, p.216). As a result, a number of Spanish manufacturers emerged in the late 1980s and 1990s. By the end of the 1990s Gamesa Eolica, a Spanish company that started manufacturing Vestas-designed turbines under a technology transfer agreement and then developed their own turbines building on that design, came to dominate the domestic market and became an important global player (Lewis 2007).

The ownership and financing model of Spanish wind energy industry was very different from the one in Denmark. According to Dinica (2008), the design of early RE supporting schemes in Spain was characterized by a high level of investment risks (due to the lack of long-term price and contract guarantees), and risk-averse Spanish banks were reluctant to finance projects in an emerging sector. Therefore many early projects were implemented by public-private partnerships with IDAE participating as an equity investor; at a later stages of the sector development its participation signaled project reliability to potential lenders. Effectively, IDAE was a hybrid entity functioning both as a government agency and a business actor. Overall, until the end of the 1990s most wind energy projects in Spain were implemented by partnerships of several entities based on the principle of resource complementarity. Typical participants of such partnerships, in addition to IDAE, included local or regional authorities (providing necessary permits), technology manufacturers, energy companies (guaranteed connection and energy purchase), and sometimes land owners. Dinica (2008) notes that this kind of sector organization, which cannot be captured by quantitative parameters of support schemes, was essential for the early development of the sector. Later, as the investor confidence in the wind sector was built, the industry gradually shifted to loan financing and projects implemented by individual companies, including companies specializing in renewable energy investment (Dinica 2008; Dinica 2003). A parallel process was the change in the prevailing interpretation of economic support originally seen as "subsidies" (which could be easily withdrawn or revised e.g. on the ground of competition rules). By the second half of the 1990s this support came to be seen as a reflection of environmental and energy system benefits not valued by the market, which helped to build legitimacy for long-term fixed feed-in tariffs, providing more investor certainty (Dinica 2008).

Spain is a "quasi-federal" state (Villarroya 2012), where autonomous communities (regions) enjoy significant political autonomy, and the distribution of powers between central and regional authorities is defined by the constitution (Colino 2008). Therefore regional governments played a significant role in the development of renewable energy in the country, using their fiscal powers to introduce additional incentives, and also using their constitutional prerogatives in the field of industrial policy and spatial planning. In particular, regional governments were instrumental in Gamesa's success both indirectly (by introducing project approval criteria favoring domestic producers) and directly (by including the company's manufacturing operations in regional industrial development programmes intended to support regional economies and employment) (Dinica 2003). Lewis (2007) notes "a particularly aggressive" use of local content requirements in Spain at both central and regional levels, which very likely contributed to the success of local manufacturers.

6.2.4 Greece

At the moment of the 1973 oil crisis, power generation in Greece relied predominantly on imported oil (some 50% of the total electricity supply), the other sources being domestic coal (lignite) and hydro energy. Lignite is the only kind of fossil fuel available in the country (Euracoal 2017). Greece's electricity system consists of the mainland interconnected system and over 30 isolated systems of individual Aegean islands powered mainly by diesel systems (Kabouris and Hatziargyriou 2006). In the last decades of the 20th century the country had to deal with the challenge of rapidly growing electricity demand – it grew 2.3 times over the 1970s and approximately 1.5 times both in the 1980s and the 1990s. In terms of demand growth, Greece ranked fourth among 20 OECDHI/EU[95] countries in the 1980s and second in the 1990s.[96] Between 1973 and the end of the 1990s, virtually all this growing demand was

[95] A sub-sample of the sample of sixty countries, comprised of high-income OECD members and EU member countries.
[96] The country was neither an EC member, nor a high-income OECD member in the 1970s; in that period, it ranked second among the entire sample.

met by expanding production and use of domestic lignite. While Greece was unable to completely substitute imported oil due to the structure of its energy system – its absolute use remained approximately at the same level from 1973 to 2008 – the proportion of oil in electricity supply decreased, and so did import dependence of supply.[97] Like most Western European countries, Greece was exploring the nuclear energy option at some moment. Plans for nuclear construction were considered for a few years after the oil crisis, but were effectively shelved after major earthquakes in 1981 which aggravated public concerns (Thurner et al. 2017). Thurner et al. (2017) also note the possible role of the national electricity monopolist owning major lignite deposits – the same factor that presumably contributed to a slow growth of renewable energy in the 1990s (see below).

Table 6.2. Timeline of early history of wind energy in Greece

1975	PPC's Alternative Energy Division starts exploring wind energy potential (Fragoulis 1994)
1982	First experimental wind installation (Kaldellis and Kodossakis 1999)
1985	First renewable energy law (1559/85) (Fragoulis 1994)
1987	Center for Renewable Energy Sources created (Fragoulis 1994)
1991–1993	Several wind farms installed on Aegean islands (Kaldellis and Kodossakis 1999)
1994	Guaranteed tariff and connection for independent producers (Law 2244/94) (Kaldellis and Kodossakis 1999)
1998	First independent wind farms start coming online (Kaldellis and Kodossakis 1999)
1999	Beginning of the electricity sector liberalization (Law 2773/1999) (Manolopoulos et al. 2016)

The key actor in the early history of RE deployment in Greece was the Public Power Corporation (PPC) – a state utility company that, prior to the sector liberalization which started in 1999, controlled the entire sector as a vertically integrated monopoly (Danias et al. 2013), also being the main lignite producer in the country (Euracoal 2017).

PPC viewed Aegean islands with their electricity supply dependent on oil as a natural niche for wind projects. In 1991–1993, the company installed several wind farms there (Kaldellis and Kodossakis 1999). These projects partially financed by the EC increased the total installed capacity of wind turbines in Greece from 4 MW in 1991 to 26 MW in 1993 (HWEA 2017). Most of these projects used Dutch turbines from Windmaster and Danish ones from Vestas. The

[97] It decreased from 57% in 1973 to 28–33% in the years leading to Greece's takeoff in 2000.

Hellenic Aerospace Industry (HAI) made an attempt to set up local turbine manufacturing in cooperation with the Danish company Windmatic, but this project turned out to be short-lived and did not have lasting effect on the development of wind power in Greece (Kaldellis and Kodossakis 1999). In 1992, the minister of energy announced plans to have 400 MW of wind capacity installed by 2000, including 150 MW by PPC (Fragoulis 1994).

However, after the series of island projects the activity in the wind sector all but stopped – almost no new capacity was added in 1994–1997 (HWEA 2017). PPC seemingly was not interested in active development of the sector – it was meeting growing demand on the mainland by expanding its own lignite production, and "cheap oil" of the 1990s created less financial pressure than in the early 1980s. The 1985 renewable energy law was not friendly to independent energy producers – only companies producing renewable power for their own consumption were able to sell surplus electricity, and the conditions were to be defined by the PPC, so only a handful of turbines were installed by non-PPC entities under this regime. The legal framework changed substantially in 1994, when the first system of feed-in tariffs for independent producers was introduced. In combination with already existing investment subsidies, this immediately made the sector profitable for private investors, and applications for over 500 MW were soon filed (Kaldellis and Kodossakis 1999). But it took several years for companies to negotiate power purchase agreements with PPC and get past bureaucratic obstacles, so first wind farms approved under the new regime started coming online only in 1998, and the process accelerated in 1999–2000. Guarantees for RES-based producers were strengthened by the law on the power sector liberalization adopted in 1999, which granted them priority access to the grid (Manolopoulos et al. 2016). As a result of these measures, by the end of 2001 installed capacity in the wind sector reached 270 MW (IRENA 2018), and wind-based generation exceeded 1% of the total electricity supply. This happened at the moment when expanding lignite production was not able to keep up with the rapidly growing demand anymore – from the late 1990s the country's electricity sector had to rely increasingly on imported gas and, later, imported electricity, whereas lignite production almost plateaued and then peaked a few years later.[98]

Among early private actors in the Greek wind sector were Terna Energy, an RE subsidiary of the construction group Terna (Terna Energy 2017), and the engineering company Rokas (Rokas 2017), which gained its first experience in the wind sector being contracted by PPC for its projects in the early 1990s. Both companies have come to play a prominent role in the subsequent development of the sector (HWEA 2017).

[98] As a result, import dependence of electricity supply increased from 29% in 1997 to 45% in 2008.

6.2.5 Netherlands

Historically, the Netherlands relied on fossil fuels for electricity generation. The country had some coal deposits, which were the main energy sources for generation at the early stage of the country's electrification. Until the middle of the 20th century, the country could rely on oil imported from the Dutch East Indies (modern-day Indonesia), the key part of its colonial empire (Vickers 2013). In the end of the 1950s, a giant Groningen gas field was discovered in the Netherlands, and since then "natural gas has been at the centre of the Dutch economy, energy supply and power generation for about half a century" (Oxford Institute for Energy Studies 2017, p.6). Gas production, export and use were rapidly growing, and in 1973 domestic gas accounted for approximately 80% of electricity generation (import dependence of electricity supply being some 13%). However, after the oil crisis the government decided to limit the extraction in order to preserve domestic resources, and gas production peaked in 1976 as a result of a political decision rather than resource depletion (Oxford Institute for Energy Studies 2017). Consequently, gas in electricity generation was partially substituted by imported coal. Between the early 1980s and the late 2000s, the import dependence of electricity supply remained roughly at the level of 40% with some fluctuations. The first (and the only) nuclear power plant in the Netherlands was connected to the grid in 1973, but its contribution to domestic electricity supply was relatively small even at that time (some 6% in 1974). In the wake of the oil crisis, the government considered construction of several more nuclear units, but these plans were eventually cancelled after the Chernobyl incident (Aarts and Arentsen 2017).

Like Denmark, the Netherlands has had a historical tradition of using wind energy,[99] so wind-based generation was among the first proposed responses to the oil crisis. Shortly after the crisis, the Ministry of Economic Affairs was considering RES, including wind energy, as an option for diversification of energy supply (Breukers and Wolsink 2007). Experimentation with wind turbine designs began in the end of the 1970s; the installation of commercial turbines started in the beginning of the 1980s, and by the middle of the decade there were 15–20 companies developing or producing turbines (Bergek and Jacobsson 2003). Similarly to Denmark, many manufacturers were driven to the sector by a declining demand in their original markets. In 1985, an official target of having 1000 MW of installed wind capacity by 2000 was set (Bergek and Jacobsson 2003). The Dutch R&D programme was relatively successful (Gipe 1995), and by the end of the 1980 the industry converged on a dominant

[99] The country even has an official National Windmill Day (Gipe 1995).

design and moved past the experimentation phase, entering the period of market growth ahead of Germany (Bergek and Jacobsson 2003).

The main driving force behind early wind energy efforts was a coalition of the Ministry of Economic Affairs and utility companies (first electricity producers and later distributors), with the involvement of some research institutions. The government considered renewable energy in the context of large-scale centralized energy supply, which determined the direction of R&D activities and the nature of the expected demand (Breukers and Wolsink 2007). Together with the system of incentives, these factors pushed manufacturers to developing larger turbines compared to typical Danish or German designs of the time[100] (Gipe 1995; Breukers and Wolsink 2007).

From the mid-1980, the government was offering investment subsidies for wind turbines, in addition to financing R&D programmes. From 1991, wind projects were subsidized as an environmental policy measure under national Environmental Action Plans (MAPs) (Reiche 2005; Breukers and Wolsink 2007). Funds collected through a special environmental levy and additional subsidies were allocated under voluntary government-business agreements (covenants), an approach typical to the Netherlands. Unlike electricity distributors[101] being a party to the agreements, smaller independent producers were not entitled to this kind of support; furthermore, tariffs for independent producers were also controlled by distribution companies (Breukers and Wolsink 2007). Thus, it was the electricity distributors that played the key role in the wind energy development over the next several years. Early in the 1990s, they came up with a major initiative named Windplan, which would result in a major demand for domestic turbines, but the initiative was abandoned in 1993. This was a serious blow to the manufacturers that had already made efforts to adapt their products to the expected demand (Gipe 1995; Bergek and Jacobsson 2003). At the same time, the products of the Dutch turbine industry, having evolved within the national innovation system, turned out to be incompatible with the large German market, which was rapidly growing "next door" in the 1990s. Partially this was a result of the unusual two-blade design, but the main reason was that Dutch turbines developed with utility customers in mind were too large for individual farmers and cooperatives which were driving the demand in Germany at the time (Bergek and Jacobsson 2003). Attempts to enter other foreign markets – e.g. in the US (Gipe 1995) and Greece (Kaldellis and Kodossakis 1999) – were successful to a very limited extent. As a result, the industry found itself locked into the domestic market with its limited demand, and

[100] Based on data on wind installations in California at the end of 1992 cited by Gipe (1995, p.36), the average capacity of a Dutch turbine installed in California was 3 times higher than that of a German one.
[101] After the unbundling of electricity distribution from production, RES-based generation was one of the few production options legally available to distributors (Breukers and Wolsink 2007).

most manufacturers went out of business by the end of the decade.[102] The subsequent growth in Dutch wind installations in 1998–2002 relied mainly on Danish and German turbines (The Wind Power 2018). Wilson (2012) attributes the Netherlands' failure to build a sustainable wind turbine industry to an attempt to "short-circuit" the necessary formative phase by initiating premature unit up-scaling.

Thus, despite the progress made in the 1980s, the virtuous cycle of "market growth, increased industry resources and growing political strength" (Bergek and Jacobsson 2003, p.215) failed to materialize in the 1990s. Neither manufacturers nor independent electricity producers had become powerful enough as interest groups to secure strong and consistent support policies, whereas for utility companies RE-based generation remained at the periphery of their business. As a result, the growth of wind energy turned out to be much slower than expected – by the end of 2000, installed capacity was some 440 MW instead of the 1000 MW target (IRENA 2018). As a result, the country surpassed the 1% threshold only in 2003, four years later than Germany.

These failures pose a puzzle to explanations that presume environmental concerns to be the main driver of renewable energy. The Netherlands with its national environmental action plans was one of the global leaders in the field of environmental policy and a paradigmatic example of "ecological modernization" (Hajer 1995). The inconsistency of government support policies is often cited as a reason for slow wind energy growth in the Netherlands before 2000 (Reiche 2005). Although the government had been generally supportive of renewable energy deployment since the 1970s and considered it a matter of environmental policy since the end of the 1980s, it "never showed a strong political commitment to wind energy development, regardless of (changes in) the political composition of the government" (Breukers and Wolsink 2007, p.104). Frequent change in support policies resulted in uncertainty among investors (Reiche 2005). Presumably, the government did not have a motivation strong enough. The status of the country's security of supply can be one reason for the insufficient motivation. Despite significant import dependence of both TPES and electricity supply, the country was a fossil fuel exporter and had a significant "safety cushion" in the form of gas deposits. So in the short term import dependence was more of a choice than a necessity.

Another frequently cited reason for the slow growth in the wind sector (including the failure of the Windplan initiative) is the difficulty of obtaining siting permits at the municipal level (Bergek and Jacobsson 2003; Breukers and Wolsink 2007). However, such pioneering

[102] The only significant survivor was Lagerwey, which went bankrupt in 2003, falling victim to another turn in government support policies (Lagerwey 2017).

countries as Denmark and Germany also encountered resistance to wind projects at the municipal level, and both of them took steps to overcome this resistance (Toke et al. 2008). While the Netherlands had the legislation that would allow the central government to impose siting decisions on municipal authorities, the government chose not to use it.

The situation started to change in 1996–1998, when a number of fiscal incentives and other measures made the support system more inclusive, opening it up for smaller independent producers; finally, a technology-specific feed-in tariff scheme was introduced in 2003 (Reiche 2005; Breukers and Wolsink 2007), when the share of wind in the total electricity supply reached 1%.

6.2.6 Portugal

At the time of the oil crises of the 1970s, Portugal generated electricity mainly from hydro (74% in 1973), the second largest source being imported oil (19%); domestic coal reserves were limited and close to depletion. While the share of oil at that moment was not particularly high, it was continuously increasing in line with rapidly growing domestic demand,[103] and this trend continued for several years after the crisis. At the same time the government started exploring ways to address the challenge of import dependence by developing domestic energy sources and enhancing energy efficiency to limit the demand growth, although it also had to resort to importing other fossil fuels (coal and later gas). The next few decades were marked by active efforts to formulate a comprehensive and detailed national energy policy.

Nuclear power had been considered a feasible option since the 1960s. Two National Energy Plans released in 1982 and 1984 respectively (though never formally approved) included plans for the construction of nuclear power plants, which were finally abandoned after the Chernobyl disaster in 1986 (Santos Pereira et al. 2017). Among renewable energy sources, the policies of early 1980s prioritized hydro energy – a traditional source of electricity to Portugal – and biomass (Netto 2013). Unlike most Western European countries at the time, the country still had significant untapped hydropower potential and was able to add over 700 MW capacity in the large hydro sector in the 1980s and over 800 MW in the 1990s, both by building new dams and adding generators to the existing ones (Platts 2017). Despite major developments in the domestic hydropower sector, it was not able to keep up with the growing demand, and import dependence of electricity supply reached 60–80%[104] in the 1990s compared to 22% in 1973.

[103] Both in the 1980s and 1990s, Portugal had the highest demand growth rate among OECDHI/EU countries; in the 1970s it ranked third across the entire sample.
[104] The large spread of the indicator value reflects year-on-year fluctuations in hydropower output.

Research and experimentation activities in Portugal's wind energy sector started shortly after the country joined the European Economic Community in 1986. This provided access both to European research networks and to EEC development funds. The Institute for Industrial Engineering and Technology started exploring wind energy potential in 1990 (IRENA-GWEC 2013). Bento and Fontes (2015) note the role of international, particularly European collaboration of researches in the mapping and modeling of wind resources. Several wind energy companies, including a renewable energy subsidiary of the national utility EDP, were created. In the early 1990s, a number of experimental wind farms were installed, most of them on the island of Madeira,[105] using Danish Nordtank turbines (Rodriguez 2007). The first investment subsidies for energy production from local sources (including renewables) were introduced in the late 1980s and financed by the EEC programme VALOREN (Portugal joined the EEC in 1986). Later investment subsidies for renewable projects (also financed by EEC funds) were introduced by the Energy Programme in 1994 (Netto 2013). The Energy Strategy for 1995–2015 for the first time incorporated environmental priorities alongside energy security and diversification of supply; the need for financial support of RE projects and development of domestic manufacturing capacity was declared (Netto 2013). The first law guaranteeing grid access and feed-in tariffs for independent energy producers was adopted in 1988 (Netto 2013); according to Jacobs (Jacobs 2012), this was the first feed-in tariff law in Europe. The law was seen as a necessary condition for receiving funds under VALOREN – an EEC programme to support the development of local energy sources. It specifically addressed CHP and small hydropower (IRENA-GWEC 2013), whereas deployment of wind (or solar) energy was not a policy priority at that time. In 1995 the incentives were expanded to include wind power and other RES and somewhat strengthened (IRENA-GWEC 2013). These tariffs were updated again in 1999. Netto (2013) links the introduction of these tariffs to the signing of the Kyoto Protocol by Portugal in 1998. The new tariff scheme was generous enough – Peña et al. (2017) contend that it was overcompensating the costs of energy producers.

In any way, the 1995–1998 support schemes in combination with the availability of increasingly powerful and affordable Danish and German turbines ushered in a period of sustained growth in the country's wind sector. In 1996 the first significant wind farm (10 MW) using Vestas turbines was commissioned; according to Bento and Fontes (2015), this event marked the beginning of the "implementation stage" in the Portuguese wind sector. It was followed a number of farms commissioned in 1998–2001, using mainly German (Enercon) and Danish turbines. Significant players in the Portuguese wind projects included, among others, the RE subsidiary of the utility company EDP, and a Portuguese company Iberwind created in

[105] This is similar to the early Greek experience, when wind farms were installed on Aegean islands.

1998 specifically to operate in the wind market. Another important actor was the Spanish company Acciona Energy, bringing to Portugal the experience from a larger and more mature Spanish wind energy market (The Wind Power 2018). By the end of 2003, installed capacity in the wind sector reached 268 MW (IRENA 2018), and the share of wind in the total electricity supply exceeded 1%.

6.2.7 Austria

As of 1973, Austria was meeting some 60% of its domestic electricity demand with hydropower and the rest with fossil fuels, both imported and domestic. At that time, the country's import dependence fluctuated in the range 8–20% (due to a high variability of hydropower output). The country has been a minor natural gas producer since 1950s, but did not have much opportunity to expand the production (Campbell 2013). Between 1973 and the beginning of the 2000s, Austria was substituting expensive oil in its generation mix and meeting growing demand by expanding the use of hydropower[106] and also imported coal and gas. Furthermore, around the year 2000 the country turned from a net electricity exporter into an importer. As a result, its import dependence of electricity supply increased to 26-39% by the early 2000s.[107] Austria had been considering nuclear generation since the 1960s, and its post-crisis energy plans involved the construction of three to four reactors to cover 20–33% of domestic energy supply. However, in 1978, when the country's first nuclear reactor was completed, a ban on the use of nuclear energy was supported by a thin margin at a national referendum (Müller 2017). The ban, first introduced as an episode of party politics, eventually has made it into Austria's constitutional law, thus becoming a permanent state doctrine (Müller 2017, p.98).

Austria is a federal state comprising nine provinces, which have significant prerogatives in the implementation of federal legislation, including that on energy (Lauber 2002). Like Germany, the country did not have a single national utility company, but a patchwork of regional and municipal companies, some of them well-connected and able to lobby for policies at the regional level (Lauber 2005). However, it was the supra-regional company Verbund that owned most power plants and operated interregional transmission networks. Given almost complete import dependence of heat supply, by the middle of the 1990s the country had been known mainly for two significant and somewhat unusual renewable energy initiatives in the heating sector – biomass-based district heating (Geels and Johnson 2018) and thermal

[106] At the time of the oil crisis, Austria with its rugged landscape still had some untapped hydropower potential. By 2000, it was able to increase its hydropower output approximately twofold compared to 1973.
[107] Import dependence of TPES has been substantially higher – above 60 or even 70%.

solar panels (Dell et al. 1996). The history of renewable electricity support in Austria starts in the early 1990s, when several MPs tried to introduce a feed-in law modelled after the 1990 German law (see Chapter 5) and failed. However, the parliament called on the minister of economic affairs to introduce preferential tariffs for renewable electricity traded across provincial borders (which was within the prerogatives of the federal government); the ministry and many regional utilities introduced such tariffs on a temporary basis, which resulted in a large variety of tariffs applicable to different types producers using different energy sources in different provinces (Lauber 2005).

The first activities in Austria's wind electricity sector also started in the early 1990s. For example, the company WEB GmbH was established in 1994 and installed one of the first find turbines in Austria (a 225 kW Vestas generator) using financing from 96 citizens[108] (WEB Windenergie 2017). On the manufacturing side, Gerald Hehenberger was experimenting with wind turbine designs from the 1980s. In 1992, in collaboration with ABB, he produced turbines for the first commercial wind farm in Israel, and later established Windtec, an Austrian turbine manufacturing company. However, the scale of his activities was not enough to create an economically and politically influential turbine industry or make a significant contribution to the wind energy takeoff in Austria, which used mainly German and Danish turbines (The Wind Power 2018). A 1996 review article does not mention any significant developments in the renewable electricity sector, and notes limited wind energy potential (Dell et al. 1996).

In 1998, a new electricity law implementing the EU's 1996 directive on electricity market liberalization introduced feed-in tariffs for renewable electricity across the country, but determining the actual size of the tariffs was left to regional governments as an "implementation matter" (Lauber 2005). According to Lauber (2002, p.30), this resulted in "a crazy quilt of nine different *Länder* laws accompanied by nine different decrees, leading to about 100 different tariffs for only a tiny portion of total electricity production". In particular, the ratio of lowest to highest wind electricity tariffs available across different provinces was approximately 1:5 (OECD 2001). Conservative politicians were more interested in supporting biomass-based generation[109] (Lauber 2005), and the highest tariff for biomass electricity available across provinces was almost 1.5 times higher that the highest tariff for wind-based generation.

[108] The company is active to this day, developing and operating wind projects in the Central Europe.
[109] Presumably, because the country already had a "biomass regime" associated with the existing biomass heating sector.

Finally, the Eco-Electricity Act adopted in 2002 completely transferred the matter of tariff-setting to the federal level.[110] Uniform tariffs established by a federal decree in accordance with the law were generous enough to start a wind energy boom (Lauber 2005, p.63). Over 2003, the installed capacity almost tripled to 322 MW, and by the end of 2004 it reached 581 MW (IRENA 2018). This was enough for wind electricity to exceed 1% of the total power supply. However, the new law defined a short time window for eligible wind projects – they had to be licensed by the end of 2004 and completed by mid-2006 – which was not extended (Hein 2013). This effectively created a politically induced boom-and-bust dynamic in the wind sector, a rapid growth in 2003–2006 followed by an almost complete stagnation until 2011 (IRENA 2018).

In 2003, 84% of Austria's total wind generation was concentrated in two eastern provinces – Lower Austria and Burgenland (52% and 32% respectively) (Austria Statistik 2018). Remarkably, Burgenland is Austria's smallest province by population and one of the smallest by area. In Lower Austria wind projects were implemented by a variety of companies (including WEB mentioned above), whereas in Burgenland the key player was the regional utility, BEWAG (later Energie Burgenland), which did not have its own generating facilities before having engaged with wind energy (Hein 2013).

6.2.8 India

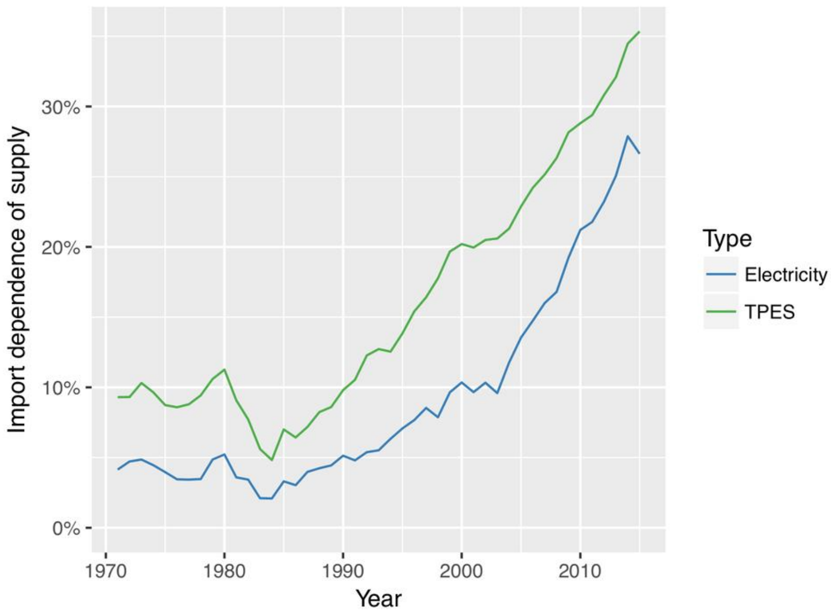
India was the first country outside the OECD where the combined share of wind and solar power in total electricity supply reached 1% (in 2006). The country faced energy challenges very different from those of "early starters" among high-income OECD economies. Instead of reducing import dependence and substituting some energy sources with more acceptable ones, the country still had to meet basic energy needs of a significant proportion of its population and to fuel the growth of its economy from a low starting level. Even around 1990, only 45% of Indian population had access to electricity, compared e.g. to 89% in China (World Bank 2017d). Electricity consumption per capita was 0.27 MWh/person compared to 0.51 MWh/person in China and 2.5–3 MWh/person in such Southern European countries as Portugal or Greece (IEA 2017a; World Bank 2017d).

India has limited oil and gas reserves, and has been net oil and gas importer due to insufficient domestic production of these resources. Despite substantial coal reserves and production, it has also been expanding coal imports. India has a civilian nuclear programme, building nuclear power plants since the late 1960s. In 1990, the country produced 65% of its electricity

[110] The regime was approved by the parliamentary consensus, except for the Greens, who believed that the support system was too modest.

from coal and 24% from hydro, with single-percent fractions of oil, natural gas and nuclear energy. In the subsequent years, the amount of electricity generated from gas and nuclear (and later new renewables) was increasing, but the rapidly growing demand was met mainly by expanding use of coal, so by 2015 the share of coal in electricity generation reached 75%. Overall, the country had relatively low import dependence of TPES and electricity supply until 1990 (within the ranges 5–10% and 2.5–5% respectively), but then both dependence indicators started growing rapidly as domestic fossil fuel production was unable to keep up with the growing demand (see Figure 6.2).

Figure 6.2. Import dependence of TPES and electricity supply in India, 1971–2015



Source: Author's own calculations based on IEA (2017d).

India has been known for providing massive budgetary subsidies both at the federal and the regional levels (Srivastava et al. 2003). An Indian think tank estimated the total amount of direct and indirect subsidies provided at all levels at the end of the 1990s at 85% of the total budget receipts or 13.5% of the country's GDP. Of this amount, approximately one third was provided by the central government and two thirds – by states. Energy subsidies accounted for 9.7% of the total amount of subsidies[111] (Srivastava et al. 2003). Thus, despite relatively low economic capacity expressed as income per capita, India was able to channel large resources to support priorities of the government policy, including those in the energy sphere.

[111] This should be seen as a lower estimate, because it is unclear whether e.g. massive measures to subsidize power for irrigation in agriculture (Monari 2002) are included in this category or recorded as agricultural subsidies.

The first institutional steps in the field of renewable electricity were made in 1980, when the Commission for Additional Sources of Energy (CASE) was created under the Department of Science and Technology (IRENA-GWEC 2013). This was followed in 1982 by the establishment of the Department of Non-Conventional Energy Sources (DNES) under the Ministry of Energy (IRENA-GWEC 2013). The new department initiated the assessment of the country's wind resources and several early demonstration projects. The first 40 kW wind turbine imported from the Netherlands was installed in 1985. Later DNES supported several demonstration projects totaling 550 kW (IRENA-GWEC 2013). Danida, the Danish international development agency, supported the installation of first large grid-connected wind farms in India – a total of 20 MW in the states of Gujarat and Tamil Nadu (IRENA-GWEC 2013). In 1987, the Indian Renewable Energy Development Agency (IREDA) was created in order to provide public support for renewable energy and energy efficiency projects, mainly in the form of soft loans (IRENA-GWEC 2013).

The growth of wind-based generation in India accelerated with the economic reform of the early 1990s aimed at the liberalization of the economy (IRENA-GWEC 2013). In 1992, the DNES was reorganized into a separate Ministry of Non-Conventional Energy Sources (MNES). A number of fiscal incentives for private companies were introduced and complemented by support programmes at the level of states, which led to India's first wind energy "boom" in 1992–1996 (Jagadeesh 2000; Mizuno 2005). At least until 2005, almost all wind turbines in India were installed by industrial companies for their own use, the main motivation factors being tax management combined with energy production for the companies' own consumption[112] (Jagadeesh 2000; Mizuno 2005). Remarkably, while early support programmes included some feed-in tariffs, they were "totally irrelevant" (Mizuno 2005, p.10), because they were lower than electricity tariffs for industrial customers. Growing demand for wind turbines combined with the economic liberalization led to numerous partnerships between established international manufacturers and Indian companies in the form of either joint ventures or licensing agreements. Mizuno (2005) lists over 20 such partnerships, mainly with Danish and German manufacturers, but also with American, Japanese, and Spanish companies. Although most of these partnerships did not survived the wind energy slump of the late 1990s, survivors included such important wind industry players as Suzlon and NEPC (Mizuno 2005).

By early 1996, total installed capacity in India's wind energy sector reached 730 MW, mainly in the states of Tamil Nadu and Gujarat (Jagadeesh 2000). However, the reduction of incentives led to a significant slowdown in the second half of the decade. The growth resumed

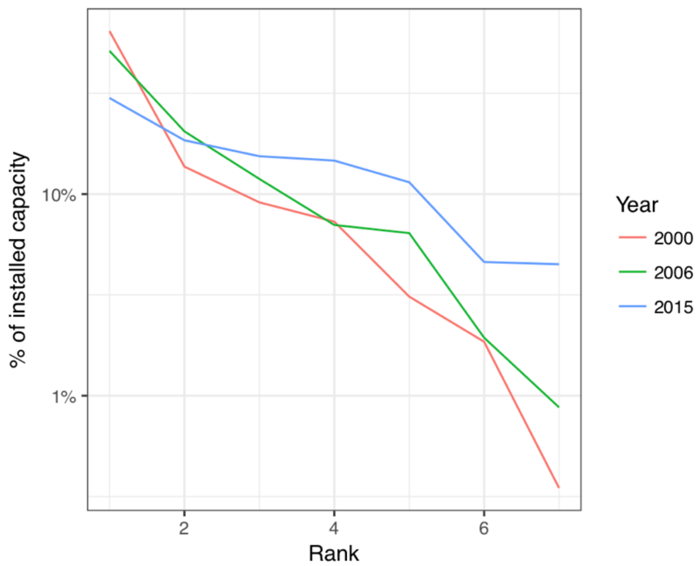
[112] 78% of these companies were energy-intensive manufacturing firms (Mizuno 2005).

only around 2000, eventually putting India's wind sector on a sustained growth trajectory (IRENA-GWEC 2013; Mizuno 2005).

Overall, the early growth of wind energy in India was driven by favorable combinations of federal and state-level incentives as well as peculiarities of state economies, and therefore was highly uneven across states. The first boom (1992–1996) was limited mainly to Gujarat and Tamil Nadu; Maharashtra experienced the period of growth in 1998–2002, when markets in other states were still stagnating, and from the financial year 2002–2003 Tamil Nadu, Karnataka, and Rajasthan became the main growth centers (Mizuno 2005). Jagadeesh (2000) notes that in the state of Tamil Nadu early wind energy boom was driven by profitable cement and textile companies seeking to use tax incentives provided by the state. The second boom in Tamil Nadu was initially kicked off by a single support programme for the state's textile sector, which supported technology upgrade in the sector, including the construction of industries' own generation facilities (IRENA-GWEC 2013).

The uneven distribution of installed wind capacity among states at the early stages of RE deployment is demonstrated by Figure 6.3. The graph shows that the distribution was highly uneven in 2000 (as demonstrated by a steeper line), somewhat less uneven in 2006 (the takeoff year), and much more even in 2015, after a decade of sustained growth. Similarly to the experience of Germany discussed in section 6.3, this demonstrates that certain states play a particularly significant role at the early stage of RE adoption.

Figure 6.3. Share of installed wind capacity in Indian states as a function of their rank in terms of installed capacity



Source: Author's own calculations based on Jagadeesh (2000), MNRE (2007), MNRE (2016).

Note: The x-axis is the rank of a state by installed wind capacity; the y-axis is the share of national installed capacity in the respective state (log scale). A steeper line means a more uneven distribution.

Table 6.3. Installed wind capacity in India as of March 2004, state GDP in FY 2003–2004, and GDP rank of states

State	Installed capacity, MW	State GDP, bln INR	GDP rank
Tamil Nadu	990.3	1754	5
Maharashtra	401.2	3406	1
Gujarat	173.1	1681	6
Karnataka	124.3	1310	7
Andhra Pradesh	92.6	1900	3
Rajasthan	60.7	1116	8
Madhya Pradesh	22.6	1028	9

Sources: Ministry of Power of India (2004), Planning Commission of India (Plannning Commission 2014)

Table 6.3 provides additional illustration of uneven distribution of wind capacity among states. It shows installed capacity approximately two years before the takeoff (March 2004), state GDP in the respective financial year and rank of states in terms of GDP (among 28 Indian states at the time). Only states that had more than 5 MW of installed capacity are included. It also shows that, while there was no straightforward correlation between installed capacity and the size of state economy, only Indian states with high GDP were able to have any non-trivial wind capacity installed. To an extent, this may reflect the fact that states with large economy sizes are likely to have large areas with a variety of natural conditions and therefore more likely to have favorable locations for wind power. However, this may also reflect the logic of takeoff among non-OECDHI/EU countries, which I discuss in Chapter 8 – the economy size is crucial for takeoff, because it means that a country can accumulate and channel significant funds in support of its policy priorities even if the income level per capita is relatively low.

6.2.9 Egypt and the North African countries

Egypt is an anomaly among the countries outside OECD and EU in my sample of sixty countries (see section 7.4). Being the second/third country in this group to take off in 2010, it does not fit the criterion defining all other early starters in this group – a large economy size measured by GDP. Its takeoff resulted from a number of projects financed mainly by grants or low-interest loans from international development agencies of industrialized countries, particularly those having wind turbine manufacturing industries. Four major wind farm projects with the total installed capacity of 140 MW that went online between 2001 and 2004 (Georgy and Soliman 2007) brought the share of wind electricity to 0.5% of the country's electricity supply. These projects were largely financed by development institutions of Denmark and Germany (Danish International Development Agency known as Danida and KfW Development Bank respectively). All projects used equipment from the respective country's manufacturers (Nordex or Vestas), which was financed by a combination of grants and cheap and long-term export financing (Meier et al. 2015). For example, equipment for Zafarana I project (33 MW) was financed by a grant from Danida; equipment for Zafarana II project was financed by a grant (30%) and a 40-year low-interest loan from Germany's KfW (Georgy and Soliman 2007). Egypt followed this model of the RE sector development throughout the rest of the 2000s, with the donor countries being joined by Spain financing equipment from Gamesa, its domestic turbine manufacturer, and Japan, which financed a wind farm project under CDM, a Kyoto financing mechanism (Georgy and Soliman 2007). Thus, early renewable energy deployment in Egypt was largely supported by external economic capacity, mostly of equipment-exporting countries.

However, Egypt's own capacity, mainly institutional and socio-technical, was also essential. The National Renewable Energy Agency (NREA) was established as early as in 1986, signaling the prioritization of renewable energy by the country (Georgy and Soliman 2007). Egypt had been exploring wind energy potential and implementing small-scale demonstration projects since the late 1980s in cooperation with USAID, Danida, and UNIDO, thus gaining experience with the technology and grid integration of wind electricity. In the 1990s, a Wind Technology Center was established in Hurghada in cooperation with Denmark's Risø National Laboratories and with financing from Danida (Georgy and Soliman 2007). A decade-long wind mapping project done in collaboration with the Risø National Laboratories resulted in the publication of a Wind Atlas for the Gulf of Suez in 2003 (Osman 2013). In the end of the 1980s and the beginning of the 1990s, the country was also making some efforts on the localization of wind technology (Osman 2013), although they played little role in later major projects that used equipment produced in donor countries. In any way, even if Egypt's takeoff largely relied on external economic capacity, it still required a long formative period.

NREA designated a single site with a high wind energy potential at Zafarana for major wind energy projects, providing it with grid connection. Almost all projects leading to Egypt's takeoff were implemented at that site, where total installed capacity reached 545 MW by the early 2010s (the country later replicated this approach by designating another multi-project site at El Zait Gulf, another location with a high wind energy potential) (Meier et al. 2015).

A combination of factors determined Egypt's strong motivation for developing domestic non-fossil energy resources. In the late 20th and early 21st century the country experienced rapid population growth and even faster growth of electricity consumption against the backdrop of declining energy exporter status (see Table 6.4). At the same time, oil production in Egypt peaked in 1996 – one of the earliest dates among Arab oil-exporting countries – having effectively plateaued even earlier, in the late 1980s (Campbell 2013). This was compensated by growing gas production, but it was unable to keep up with increasing domestic energy demand, leaving a continuously shrinking amount available for export.[113] If in 1990 Egypt's energy exports amounted to 70% of its TPES, by 2005 this share decreased to 27%, and after 2013 the country turned into a net energy importer.[114] All these trends were likely predictable already in the late 1980s – early 1990s, so Egyptian policy-makers had reasons to take actions.

Table 6.4. Population, total domestic electricity supply, and energy exporter status in Egypt

	1990	**2005**	**2015**
Population, million	57.4	76.8	93.8
Electricity supply, TWh	42.2	107.9	180.9
Net energy exports to TPES	0.70	0.27	-0.13

Sources: Energy indicators – IEA (2017a), population – World Bank (2017d).

Their actions resulted in a highly centralized approach relying mainly on large publicly-owned projects, unusual to most African countries[115] (Mukasa et al. 2013). Overall, the rhythm of wind energy development determined by availability of international donor financing led to a significantly lower and uneven RE growth rate compared to countries relying on domestic economic capacities. Table 7.2 in Chapter 7 demonstrates that it took Egypt 6 years to get from 0.5% to 1% of domestic electricity supply, whereas for most countries this takes one to three years.

North African countries. Two countries not included in my main sample – Morocco (in the top seventy countries in terms of electricity production) and Tunisia (in the top eighty) – share important elements of their renewable energy history with Egypt. Collectively, they comprise a "hotspot" of wind energy deployment in Africa – as of the end of 2011, they accounted for some 96% of the total installed wind capacity on the continent (Mukasa et al. 2013). So, while I do not include Morocco and Tunisia in my large-N analysis, it is still instructive to consider them alongside Egypt as members of a distinct group.

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113 According to Campbell (2013), projected peak gas production date for Egypt is 2017.
114 Which also made it to explore another non-fossil energy option – nuclear energy – leading to a recent deal with Russia (Wardany et al. 2017).
115 Later a similar approach was used by Tunisia, although on a much smaller scale (Mukasa et al. 2013).

Based on my takeoff criterion (1% of the total electricity supply) Morocco would be the first non-OECDHI/EU country to take off in 2001, being the fourth or fifth country to take off globally. However, this is exactly the kind of case I want to filter out by excluding smaller countries from my sample. Morocco's takeoff was a result of the construction of a single major wind farm (50 MW) by a French consortium under a build-own-operate (BOO) concession in a country where only small-scale demonstration installations had existed (Mukasa et al. 2013). No significant activities took place in the country's wind sector for the next few years, and the second major wind farm was launched only in 2007, this time financed by the German bank KfW and owned by the national utility company (Benhamou 2013). Thus, Morocco's "takeoff" was associated with a singular event and did not lead to sustained growth of RE-based generation in the country; it was also inconsistent with the 100 MW threshold used by Gosens et al. (2017). In Tunisia, the first significant wind project was launched early in the 2000s, like in Egypt or Morocco, using a combination of development finance from Spain and commercial loans from Spanish companies (Mukasa et al. 2013). Tunisia crossed the 1% threshold in 2012.

Both Morocco and Tunisia are net energy importers, unlike their North African neighbors – Algeria and Libya (Egypt was still a net energy exporter at the moment of its takeoff, but well on its way to becoming a net importer), so import dependence and growing demand were important motivation factors for them. All three countries have been included in the European Neighborhood Policy since its inception in 2003 and have association agreements with the EU (Whitman and Wolff 2010). They also have a history of being a part of the common Mediterranean economic space which has existed since the Ancient period (Braudel 1995). In the late 19th and/or the first half the 20th century they all were under some form of European colonial control, thus also maintaining close economic ties with European countries (Rogan 2017). Characteristically, while the first major wind farm in Morocco used Danish turbines, it was a French consortium that built and operated it.[116]

Thus, all these countries have historically been a "close periphery" of Europe. All significant wind projects in these countries, at least at the early stages, used some form of European capital provided either in form of development finance, low-interest loans, or direct investments. Major wind projects in Morocco are seen as part of the Sahara Wind Project implemented with a view of exporting surplus energy to Europe (Benhamou 2013), although so far Morocco has been importing energy from Europe.[117] Thus, Northern African countries

[116] Most of modern-day Morocco was under the French protectorate in the first half of the 20th century.
[117] The initiative DESERTEC is another example of the same thinking (Desertec Foundation 2009).

not being major energy exporters constitute a country group representing a distinct pathway toward renewable energy takeoff.

6.2.10 Bulgaria and the new EU member states

Bulgaria is an example of a European post-socialist country, which underwent a transition to market economy and joined the EU in the 2000s. The country has reserves of coal (mainly lignite), but not oil or natural gas. In 1971, the country produced 80% of its electricity from coal, both domestic and imported, whereas imported oil and hydro accounted for 10%. The 1970s and 1980s saw rapidly growing electricity demand, and the country was able to meet it without increasing import dependence of power supply by developing nuclear energy. Like most countries of the former Eastern bloc, Bulgaria acquired Soviet-built nuclear reactors, the first connected to the grid in 1974, and the last one in 1993 (IAEA 2017). Similarly to many economies in transitions, in the 1990s Bulgaria went through a decline in energy (including electricity) consumption due to the retirement of energy-intensive industries inherited from the centrally planned economy, and domestic electricity demand was stagnating in the 2000s. As a result of increased nuclear generation and demand decline, import dependence of electricity supply decreased from 40–50% in the 1970s to around 10% in the 2000. Since the end of the 1990s, the country has been a net electricity exporter, and expanding electricity exports has been a priority of national energy policy (Government of Bulgaria 2011). Energy policies of the 2000s prioritized security of supply and electricity exports to neighboring countries (World Bank 2009; Government of Bulgaria 2011). At the beginning of the 2000s, the two main sources of electricity generation in Bulgaria were coal and nuclear. The Maritsa Iztok Complex – three coal-fired power plants associated with a single lignite mine – accounted for some two thirds of the country's coal capacity (Platts 2017). In the nuclear sector, four older reactor units were shut down in the course of EU accession negotiations, but two newer and larger ones remain in operation (WNA 2018). In the 2000s and 2010s, the country considered various options of building additional nuclear reactors, but neither of them has materialized (WNA 2018).

Bulgaria has coastal areas with high wind energy potential (Duprey 2014), but no significant developments in the wind sector took place before the early 2000s. Wind energy projects implemented before the country's accession to the EU and the introduction of FIT relied on Kyoto Protocol financing mechanisms, particularly Joint Implementation. One example is the Kaliakra wind project initiated in 2004 by Mitsubishi and the Bulgarian engineering company INOS. The 35 MW wind farm used turbines produced by Mitsubishi.

Both early and subsequent RE projects in Bulgaria also enjoyed favorable effects of policies aimed at attracting foreign direct investment. Being one of the poorest EU candidates and then member states in terms of income per capita, Bulgaria sought to attract foreign capital in order to accelerate its economic growth. To that end, in 1997 the country adopted the Investment Promotion Act, which provided for simplified administrative procedures and financial support for technical infrastructure associated with approved projects. By the moment of EU accession, foreign capital was already present in the traditional generation sector, and all power distribution networks were controlled by three foreign companies (Economist 2013).

The rapid growth of wind and solar generation in Bulgaria was associated with its EU accession. Formal accession negotiations started in 2000 (Nikolova 2006) and covered energy policy, including harmonization with the Renewable Electricity Directive (2001/77/EC), among other topics. In 2005, seeking to align its policies with EU legislation, Bulgaria adopted the National Long-Term Programme to Promote the Use of RES (2005-2015) (Duprey 2014). The document's goals included reducing import dependence of energy supply and strengthening the country's role as a major regional electricity supplier (World Bank 2009). In 2007, the year of its EU accession, Bulgaria also adopted the Alternative Energy Sources Act, which introduced technology-specific feed-in tariffs (Duprey 2014). These two developments immediately led to the "gold rush" in the wind energy sector. Investors in major wind projects included German, Italian, Austrian, Spanish, American and Japanese companies.

Sometimes the same companies and financial institutions were simultaneously implementing fossil fuel and renewable energy projects. For example AES, an American energy company, constructed both a new 600 MW lignite-fired power plant (completed in 2011) and, through its joint venture with a German company, one of the largest wind farms in Bulgaria – Saint Nikola (156 MW, 32 Vestas turbines, completed in 2009) (AES Bulgaria 2018). The projects cost EUR 1.3 billion (the biggest foreign direct investment in Bulgaria) and EUR 270 million respectively, and the EBRD played a major role in the lender consortia for both projects. Overall, more than EUR 4 billion was invested in renewable energy projects in Bulgaria from 2009 to 2012 (Martino 2015). The country did not have wind turbine industry of its own, and wind projects relied on turbines from Danish, German, Spanish, and other foreign manufacturers. One project financed by a Swiss investor used Indian Suzlon turbines.[118]

Duprey (2014) characterizes the situation at the moment of Bulgaria's accession as a "flood of European legislation" into a country with limited administrative capacities for its implementation, which resulted in conflicts between different policy priorities. He explores one such conflict using the case of Coastal Dobrudzha – a region with high wind energy

[118] https://www.evwind.es/2010/12/01/new-wind-farm-goes-into-operations-in-bulgaria/8642 (accessed September 25, 2017).

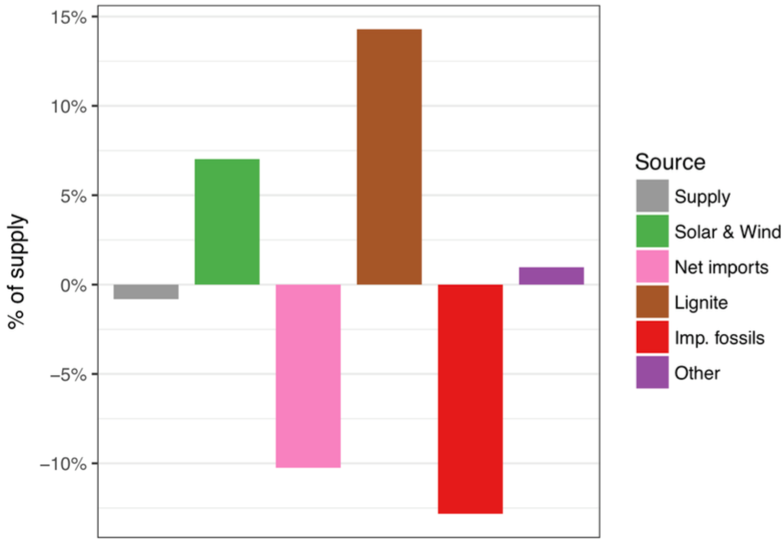
potential but also important in terms of bird conservation. Duprey demonstrates how the priorities of the national authorities – energy security and strive for foreign investments – prevailed over environmental conservation concerns. Regional and municipal authorities were also interested in major renewable energy projects within their areas, seeing them as drivers of local economic development, sources of jobs and tax revenue.

In 2009, a new European Renewable Energy Directive (2009/28/EC) was adopted, which included 2020 renewable energy targets for all Member States, including Bulgaria. In electricity sector, the target was 16% of renewable energy in gross electricity consumption (Duprey 2014). In 2011, the country adopted the National Renewable Energy Action Plan and the Energy Strategy till 2020 (Government of Bulgaria 2011). The key priorities of the strategy included: energy security; development of RES; energy efficiency; creation of a competitive energy market; and protection of customers' interest. Like the previous policies, the strategy envisioned the growth of electricity exports.

Between 2007 and 2012, installed wind capacity in Bulgaria grew from 30 MW to 677 MW (IRENA 2018). In 2010, wind generation reached 1% of domestic electricity supply. Solar generation was insignificant at that time but just two years after, in 2012, it also surpassed the 1% threshold. A new sector was created from scratch in just a few years, and the country was able to meet its renewable energy target for 2020 as early as in 2012 (Martino 2015).

However, the Bulgarian renewable energy boom proved to be short-lived. With state-controlled consumer energy prices, generous feed-in tariffs were one of the factors leading to the growing debt of distribution companies and the national utility company NEK (Linden et al. 2014). An attempt to increase customer tariffs resulted in mass protests that toppled the government in February 2013 (Economist 2013). In 2012–2013, the government stopped approving new RE projects, citing the achievement of the 2020 goal as a justification, and in 2013 it attempted to introduce a 20% tax on revenues from wind and solar projects. This amounted to a retroactive reduction of feed-in tariffs, although the decision was deemed unconstitutional later (Martino 2015). Thus, the dynamic of early renewable energy development in Bulgaria has clear signs of a boom-and-bust cycle, with the boom phase driven by strive for investments and the bust resulting from social constraints – political sensitivity of energy prices in relatively low-income post-socialist economies (Economist 2013).

Figure 6.4. Changes in Bulgaria's electricity generation mix between 2006/07 and 2014/15



Source: Author's own calculations based on IEA (2017d).

Note: Changes are expressed as percentages of total domestic supply in 2006/07. Positive values represent increase in an energy source, negative values – decrease (decrease in net imports represents increase in net electricity exports).

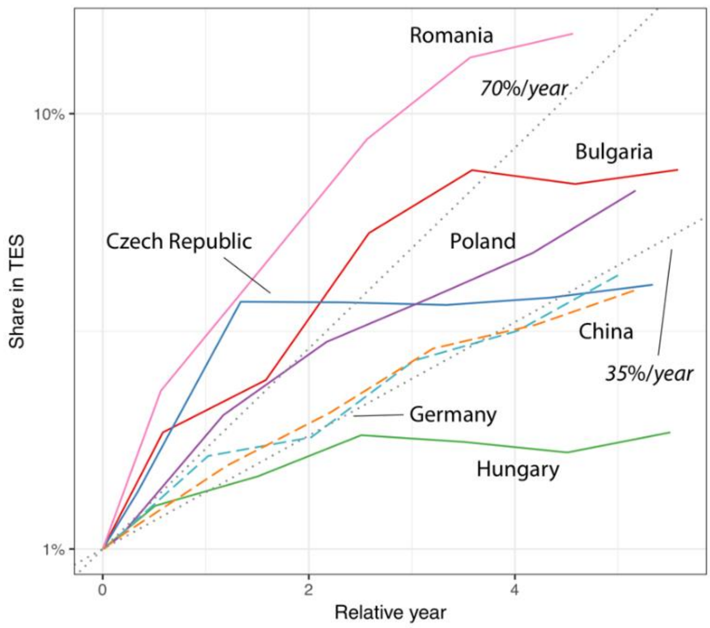
Figure 6.4 summarizes changes in Bulgaria's generation mix between before and after renewable electricity boom (averages for two consecutive years are used to smooth out year-on-year fluctuations). Total electricity supply (grey) changed little. The increase in solar and wind generation (green) is comparable, if somewhat lower, to the increase in electricity exports (pink). The biggest change in the structure of electricity supply was the substitution of imported fossils (red) with domestic lignite (brown), although the total fossil-based generation did not change much. The contribution of other energy sources – hydro, nuclear, and biomass – also remained stable (purple). This shows that renewable energy deployment in Bulgaria has not resulted in a significant decarbonization of its electricity sector.[119] At the same time, the overall picture is consistent with the declared priorities of Bulgaria's energy policy – increasing self-sufficiency of energy supply and expanding energy exports.

New EU members. Figure 6.5 shows the growth of renewable electricity generation (wind and solar combined) in five new EU member states in my sample with two large countries – Germany and China – added for comparison (dashed lines). As seen in the chart, Bulgaria and the Czech Republic both demonstrate "boom-and-bust" cycle with rapid growth followed by stagnation. In Hungary, stagnation follows a period of modest growth. With generation data

[119] Although it is possible that exported electricity substitutes fossil-based generation in other economies, contributing to their decarbonization.

available up to the year 2015, the stagnation phase for Romania is not seen in the picture. However, the data on installed capacity (IRENA 2018) demonstrate that the growth of installed wind and solar capacity in the country stopped after 2014. An industry newsletter (Scott Moskowitz 2014) describes dynamics very similar to the case of Bulgaria – generous subsidies leading to a rapid growth, increasing spending, and the subsequent scaling-down of subsidies. Poland with the relatively stable growth is the only exception to this pattern. Thus, a boom-and-bust cycle is characteristic of most new EU members in my sample. On the contrary, both Germany and China demonstrate much more stable growth close to 35% per year in the first years after crossing the 1% threshold.

Figure 6.5. Growth of renewable electricity (wind + solar, % of total electricity supply) in new EU members, Germany, and China



Source: Author's own calculations based on IEA (2017d).

Note: "Year 0" is the year in which RE generation for the given country first reaches 1% – e.g. 1999 for Germany but 2010 for Bulgaria. The y-axis is in log scale, so exponential growth at a constant annual rate would be represented by a straight line.

6.2.11 Switzerland and the "nuclear expansion countries"

Switzerland is one of the richest OECD members in terms of income per capita.[120] The country with its small land area does not have any fossil fuel resources, relying on oil and gas imports. However, its electricity system has been largely self-sufficient. Until the late 1960s

[120] In 2010, it had the third highest level of income per capita among OECD members after Luxembourg and Norway (World Bank 2017d).

Switzerland with its mountainous terrain had almost exclusively relied on hydropower as a source of electricity, and had been able to export some power. In the second half of the 1960, the country started increasingly using oil for power generation, but this trend soon reversed with the oil crisis of the 1970 (IEA 2017d). Switzerland's first three nuclear reactors went online in 1969–1972, which helped to substitute oil in the generation mix and meet growing demand while maintaining the electricity exporter status in the subsequent years. Two more reactors were connected to the grid in 1979 and 1984, after which the country has been producing approximately 60% of its electricity from hydro and 35% from nuclear energy, with some year-on-year fluctuations (Osorio 2017). However, despite its stable net electricity exports, the country has depended on imports of cheap nuclear electricity from France, particularly during the winter due to the instability of its hydropower production. The looming expiration of supply contracts with French suppliers by 2040 poses a long-term security-of-supply concern (Osorio 2017).

Swiss nuclear policy went through several major reversals. It began as early as in 1946, when the federal parliament adopted the first act on the promotion of nuclear energy (Kriesi 2017). Resistance to nuclear power was growing from the beginning of the 1970s, culminating in major protests in 1975. These protests effectively stopped further expansion of the nuclear sector,[121] but did not stop two reactors already under construction. In 1990, a popular referendum approved a ten-year moratorium on new nuclear construction (Kriesi 2017). After its expiration, the policy-makers and utilities started seeing nuclear expansion as a viable option again; several acts regulating the nuclear sector were adopted. In 2008, utilities applied for permits for the construction on three new reactors. The authorization progress has made significant progress by the moment of the Fukushima nuclear incident in 2011, after which the licensing procedures were promptly stopped (Kriesi 2017). The government came up with the plans for eventual nuclear phase-out, which were incorporated into a proposal for the Energy Strategy 2050. The proposal was finally codified in legislation in 2016 and approved by a popular referendum in 2016 (SFOE 2018). While some earlier proposals included specific dates for the nuclear phase-out, the final version allows continued operation of NPPs as long as their safety is guaranteed.

In the 1990s, Switzerland was on the global forefront of solar energy deployment. In 1995, it had the world's second largest share of solar energy in electricity supply.[122] The country also played a role in renewable policy innovation. While scholars often note the role of municipal

[121] Kriesi (2017) notes that utilities, facing resistance and increasing costs, started seeing imports of cheap electricity from France as a viable and less troublesome option to meet a potential growth in demand.
[122] The world's largest country, both in absolute and relative terms, was the US, where significant solar capacity had been installed during the Californian renewable energy boom of the 1980s, but was stagnating in the 1990s.

and regional initiatives in the early deployment of solar energy in Germany (see e.g. Jacobsson and Lauber 2006), the first such scheme was adopted in 1991 in the Swiss town of Burgdorf (Green 2000). Effectively it introduced cost-based feed-in tariffs for solar energy. In 1996, Zurich introduced another innovative scheme – a "solar stock exchange" for trading solar electricity (Haas et al. 2011). However, since the middle of the 1990s the country had been gradually falling behind global pioneers. The government was implementing programmes to support solar power (mainly rooftop installations), but they were limited in scope and sometimes failed to achieve their target (Haas et al. 2011). This half-hearted support fueled continued growth of the Swiss solar sector, but at a relatively slow rate. In terms of the share of solar energy in power generation, the country was surpassed by Japan in the late 1990s and by Germany in the early 2000s. Wind turbines had not gained traction in Switzerland due to the limited area of suitable land and social acceptance problems.

The situation changed in 2008, when in the wake of the energy policy reform initiated in 2007 feed-in tariffs for renewable energy were first introduced at the federal level (Gipe 2008). The regulation established a maximum share of the renewable energy fund for each energy source and, based on this data, it did not prioritize solar energy (Weibel 2011). The cap for solar energy was established at the level of 5% of the renewable energy support fund, compared to 30% for wind energy or biomass. However, the small but well-established solar niche responded to the tariffs most vigorously. Between 2008 and 2015, solar electricity production increased ten times reaching 1119 GWh, whereas both biomass and wind were growing much slower in relative and absolute terms. In 2017, the country had some 1900 MW of installed solar PV capacity, but only 75 MW of wind capacity (IRENA 2018). Limited support funds led to long waiting times, and in 2011 the quota for solar energy was increased to 10% of the fund. Most installations were building-attached or building-integrated systems, and the share of standalone installations was negligible (Husser 2015). As a result of the rapid growth, in 2014 the share of solar energy in the country's electricity supply reached 1%. Recent changes to the energy legislation attempt to control this growth by introducing a more market-oriented support method based on direct marketing (SFOE 2018). At the same time, the government made another attempt to promote the growth of wind energy, which better complements the seasonal profile of hydropower. Wind energy was declared a matter of national interest, which relaxed spatial restrictions on the siting of turbines (Stalder 2017).

"Nuclear expansion countries". Switzerland is one of the late starter countries among high-income OECD members. There are five longtime members of this group[123] in which "renewable energy takeoff", when the share of wind and solar energy in electricity supply

[123] Two other later starters – Israel and Chile – joined the group only in 2010 or later.

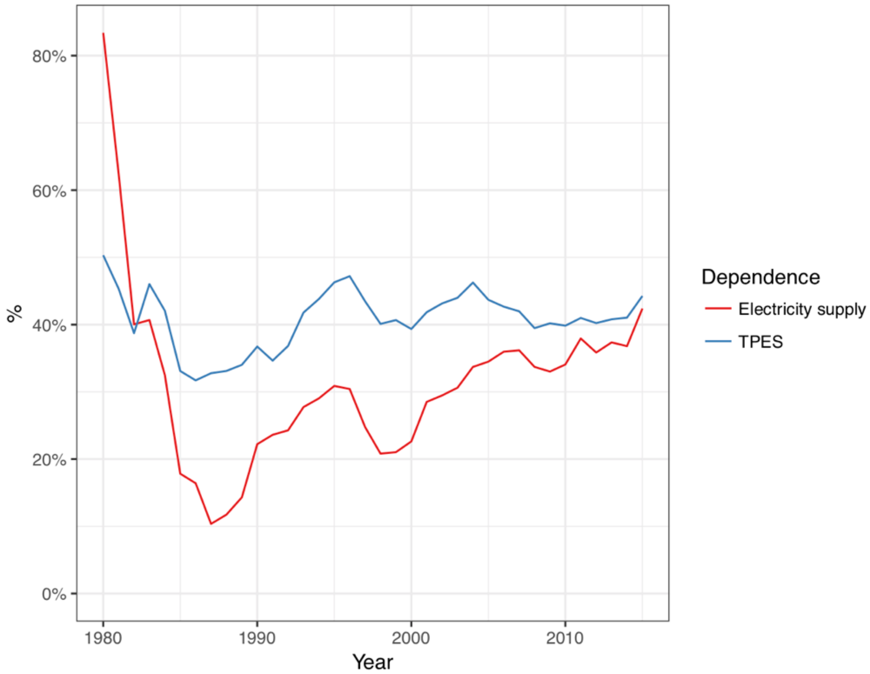
reached 1%, happened after 2009. One of them, Norway, already had a 95%-renewable electricity system (based on hydropower), so the space for wind energy in the system was limited. All of the other four countries – Japan, Korea, Finland, and Switzerland – considered nuclear expansion as an option of meeting energy demand in the 2000s. The first three were building new reactors, and in Switzerland nuclear projects were going through a permitting process. One can hypothesize that this reduced their motivation for supporting renewable energy niches.[124]

6.2.12 Thailand and Southeast Asian countries

The development of Thailand's energy system in the last four decades has been a race between rapidly growing demand and expanding use of domestic energy sources. Electricity demand was driven by fast economic growth – over the three decades to 2015, the GDP per capita annual growth rate was on average 4.2%, whereas the growth of electricity demand was around 7.2% (see Table 6.5). These rates are comparable to those of other broadly similar Southeast Asian countries – Malaysia and Indonesia – but, unlike these nations, Thailand has never been a net energy exporter. Between 1980 and 2015, import dependence of total energy supply varied between 30% and 50%. The country has reserves of all fossil fuels – oil, natural gas, and coal. However, domestic oil production has been covering only a fraction of demand. Gas production was more substantial and rapidly growing, but still unable to keep up with the increasing demand, and from 2000 the country increasingly resorted to gas imports. A 2013 publication (Campbell 2013) predicted both oil and gas production peak for Thailand within the next few years. From the early 1990s, it also imported coal to complement domestic production.

[124] A competing explanation or a part of explanation, at least for Japan and Switzerland, is that they had limited opportunities for developing wind energy, and their late start is a result of later maturity of solar power technology. Yet another explanation is that their nuclear sector lobbied against introduction of renewables.

Figure 6.6. Import dependence of energy supply (TPES and electricity) in Thailand



Source: Author's own calculations based on IEA (2017d).

In 1980, Thailand produced over 80% of its electricity from imported oil, but by 1987 it dramatically reduced import dependence of electricity supply to 10% by expanding the use of domestic gas and coal (see Figure 6.6). Then import dependence started growing again due to increased reliance on imported fossil fuels and later electricity, reaching 36% by 2006 and 40% by 2015. In 2015, gas accounted for 67% of Thailand's electricity supply, coal – for 18%, and electricity imports – for 6%. The remaining 9% were produced from hydro and other renewables.

A recent Thailand Power Development Plan 2015–2036 (Thailand Ministry of Energy 2015) defines three key priorities of the country's policy in the electricity sector: (1) energy security, including diversification of energy sources; (2) economy – producing electricity in a cost-efficient way; and (3) environment – reducing carbon intensity of power generation.

Thailand started experimenting with wind-based generation in 1983 by installing small-scale turbines on islands, but these early experiments did not play a significant role in later developments in the RE sector. The development of renewable-based generation in Thailand was closely connected to the general process of the opening up of the country's power sector to independent producers. Around 1990, the whole electricity sector was controlled by EGAT, a state monopolist (Greacen 2007). By 2013, the utility owned the national grid and around a half of the installed capacity, whereas the other half was owned by different categories of independent producers (Tongsopit and Greacen 2013). The first programme aimed at independent producers was modeled after the American PURPA Act, making it possible for independent producers to sell electricity to the grid at the utility's avoided costs. The programme was intended to support CHP and renewable-based generation, but due to the insufficient level of tariffs it was mainly fossil-based generators (and a limited number of biomass-based producers) that benefitted from it (Greacen 2007). In 2002, the government introduced a new programme specifically targeting small-scale renewable-based generation and based on the principle of net metering. In case of net surplus, distribution companies were required to purchase electricity at a percentage of retail price (usually 80%) (Greacen 2007). Again, this programme with tariffs undifferentiated by technology resulted mainly in the growth of biomass-based generation, although a number of small-scale solar projects were also approved. Overall, biomass was the fastest-growing renewable electricity source in Thailand in the 2000s, given the country's major agricultural sector with a lot of residuals. Most biomass-based generators were agricultural and food processing businesses using a major proportion of produced energy for their own consumption.

Finally, at the end of 2006 the government introduced the mechanism of technology-specific "feed-in premium" on electricity purchase price[125] (Greacen 2007). Thus, the logic of the development of RE support in Thailand was broadly similar to the global logic of FIT innovation described by Jacobs (2014) – from tariffs based on generator's avoided costs to a proportion of retail tariffs to technology-specific feed-in tariffs. The policy was a part of the government's broader effort to strengthen security of energy supply, partially in response to the oil price surge. In 2008, Thailand adopted the National Energy Policy which sought to reduce energy imports, develop domestic energy sources, and increase energy efficiency. A related document was the Renewable Energy Development Plan 2008–2022, which set targets for various RE sources, including in electricity generation (IRENA and Thailand Ministry of Energy 2017). The 2006 scheme had unintended consequences, attracting enormous number of solar project applications against the backdrop of declining cost of PV modules. By the end of 2008, applications for solar projects totaling over 2000 MW were filed, whereas the 2022 target for solar capacity was only 500 MW. Reportedly, many applications were filed by companies that did not have their own capabilities for implementing the projects and intended to re-sell their power purchase agreements (Tongsopit and Greacen 2013). Seeking to contain the unexpected solar boom, the government gradually tightened the requirements and in 2010 effectively stopped granting approvals for new solar projects. However, the projects already in the pipeline were sufficient for the solar sector to maintain rapid growth. In 2013, feed-in

[125] The tariffs was also differentiated by installed capacity and regions.

premiums were replaced with feed-in tariffs. Between 2010 and 2015, installed solar capacity in Thailand increased from 49 to 1420 MW, and the original 2022 target was surpassed in 2013 (IRENA 2018). In 2015, solar and wind generation for the first time surpassed 1% of domestic electricity supply, mainly due to solar – wind provided around one sixth of the solar-based generation.[126] This growth relied on imported equipment. In 2015, an updated renewable energy plan for 2015–2036 with revised targets was adopted (IRENA and Thailand Ministry of Energy 2017).

Southeast Asian countries. Table 6.5 shows some energy supply and economic indicators for Thailand and several other Southeast Asian countries. The table includes members of ASEAN – a regional economic and political association (ASEAN 2018) – except for Singapore and Brunei, two small and very rich countries, and Laos, for which IEA data are not available.

Table 6.5. Energy supply and economic indicators for selected Southeast Asian countries

Country	Electricity supply in 2015, TWh	Average annual supply growth rate, 1985–2015, %	Electricity supply per capita in 2015, MWh/person	GDP per capita in 2006, USD	Average annual GDP per capita growth rate, 1985–2015, %	Import dependence of electricity supply, 2015, %	Import dependence of TPES, 2015, %*	% of solar and wind in electricity supply, 2015	% of other non-hydro renewables in electricity supply, 2015
Malaysia	150.1	8	4.89	9644	3.6	38	-13	0.2	0.5
Thailand	189.9	7.2	2.77	5815	4.2	42	44	1.4	4.1
Indonesia	234.0	9.8	0.91	3336	3.4	4	-89	0	4.8
Philippines	82.4	4.4	0.81	2878	2.2	37	49	1.1	13.8
Vietnam	154.9	12.1	1.69	2107	4.9	4	6	0.1	0
Myanmar	16.0	7	0.3	1195	5.9	0	-35	0	0
Cambodia	5.9	18.5**	0.38	1163	5.5***	66	38	0.1	0.6

Sources: GDP and GDP per capita – World Bank data (World Bank 2017d), other indicators – IEA (2017d).

Notes: * Negative import dependence of TPES means that the country is a net energy exporter. E.g. –50% means that the country exports the amount of energy equivalent to one half of its TPES.

** 1995–2015

*** 1993–2015

[126] In the same year, biomass accounted for some 5% of electricity supply.

As seen from the table, the only two countries in the group that surpassed the 1% threshold in terms of solar and wind generation are Thailand and Philippines – countries with significant import dependence of total energy supply (TPES). Even high shares of other non-hydro renewables (biomass or geothermal) did not prevent these countries from developing wind or solar energy. Cambodia – the only other country with high import dependence of TPES – presumably had too low income level to finance RE support programmes. No net energy exporters reached the 1% level by 2015, including the countries closest to Thailand in terms of income levels – Malaysia and Indonesia.

6.3 Summary

The case studies have demonstrated a variety of specific mechanisms and processes underpinning such high-level generic mechanisms as "technology diffusion" or "niche learning". As expected, early starters featured much more complex mechanisms of the formative phase. Table 6.6 summarizes results of the case studies, identifying several variables which I have found potentially relevant to renewable energy deployment. In order to put the case countries in context, the table lists all other countries in the worldwide sample. Although no case study has been produced for China, the table includes information for this country based on several sources (Lewis 2007; Walz and Delgado 2012; Gosens and Lu 2013; Gosens et al. 2015) due to its importance for the global history of RE deployment.

The table includes two quantitative indicators of energy supply – import dependence of electricity supply in the year of takeoff and electricity demand growth over the five years to the takeoff date (measured as a percentage of the demand in the base year). For each of these indicators, there are three columns – its value, rank of the country within the entire sample of 60 countries[127] in the year of takeoff, and rank of the country within its subgroup (OECDHI/EU or non-OECDHI/EU). The use of ranks is supposed to show whether a particular value is relatively high or low among the respective group of countries. Countries within the first half of the respective group in terms of an indicator value are shown in **bold**; countries within the first quartile of the group are additionally marked with a star symbol (★). For example, in the year when Denmark reached 1% of deployment of renewables, it had the second highest demand growth rate in the world (rank 2 out of 54) and the highest demand growth rate in the OECDHI/EU group (out of 20).

The column "Role in FIT evolution" is based on Jacobs (2012; 2014) and marks countries that made significant contribution to the development of feed-in tariffs as a policy instrument.

[127] There are fewer countries prior to 1990, because former Soviet and Yugoslav republics are not included.

While a more detailed discussion will be provided in Chapter 8, several observations can be made based on the table and additional information provided in the case studies.

1. The first seven countries to take off were **EU members**. The first non-EU country to take off was New Zealand (2005).

2. In addition to EU membership, most of the seven "early starter countries" have other common characteristics. All of them, except Germany, went through a "nuclear reversal" either by considering nuclear power development at some moment but giving up later or by substantially scaling down their original nuclear programmes (like Spain and the Netherlands). Furthermore, the same six countries out of seven had a relatively high level of import dependence of electricity supply – being in the first half of the OECDHI/EU group and often in the first quartile of the global sample with import dependence levels 35% or above. Both these parameters point to the significance of security of energy supply as a motivation factor in all early starters except for Germany.

3. RE equipment manufacturing played a significant role in early RE deployment. Four early starters out of seven made major efforts to establish domestic manufacturing (the Netherlands did not succeed in the end). These countries then contributed to the global diffusion of RE technologies not only by exporting equipment but also by financing international aid programmes that involved the use of this equipment. Two out of three first starters in the non-OECD/EU group – India and China – also developed viable RE equipment industries (the third country, Egypt, heavily relied on external resources).

4. Spain, Greece, and Portugal comprise a distinct group among the early starters. They all joined the EU in the 1980s and were less developed economically than other EU members at the time. Being "new EU members" in the end of the 1980s and the 1990s, they were beneficiaries of EU programmes intended to support regional and local economic development". Some of these programmes, like VALOREN, sought to develop "endogenous energy sources", including renewable ones. Another common feature of these countries in the years leading to their takeoff is high demand growth rates – 25–30% over five years – more characteristic of developing countries at the time. It is likely that a combination of strong motivation associated with growing demand, growing electricity markets providing space for newcomers, and diffusion processes facilitated by the EU allowed these countries to become leaders in RE deployment despite relatively low economic capacity measured by income per capita.

5. Policy instruments of RE support co-evolved with physical RE technologies. It was the early starters that made key contributions to the evolution of feed-in tariffs as a policy instrument.

6. Early starters in the non-OECDHI/EU group did not necessarily have high import dependence of electricity supply, but they had relatively high demand growth rates – in the first half for this country group and sometimes up to 68% over five years (China). It is likely that demand growth was one of the key drivers of RE deployment in these countries, making them pursue all available options to expand electricity supply, combining RE deployment with the expansion of other energy sources, including fossil fuels and nuclear power.

Table 6.6. Summary of case studies

Country	TO year	OECDHU/ EU	EU	Domestic RE manufacturing	Intl. support	Nuclear reversal	Import dependence of el. supply			Demand growth rank			Federal state	Role in FIT evolution
							Value	Rank (all)	Rank (group)	Value	Rank (all)	Rank (group)		
Denmark	1989	+	+	+		+	93%	**2/54★**	**1/20★**	18%	40/54	13/20		+
Germany	1999	+	+	+			20%	**20/60**	11/20	5%	49/60	18/20	+	+
Spain	1999	+	+	+	EU	+	43%	**12/60★**	**6/20**	30%	**21/60**	**2/20★**	+	+
Greece	2001	+	+		EU	+	36%	**16/60**	**10/21**	27%	**23/60**	**4/21★**		
Netherlands	2003	+	+	+/-		+	43%	**13/60★**	**9/21**	11%	36/60	**9/21**		
Portugal	2003	+	+		EU	+	63%	**5/60★**	**3/21★**	26%	**21/60**	**3/21★**		+
Austria	2004	+	+			+	35%	**17/20**	**12/24**	12%	36/60	**9/24**	+	
New Zealand	2005	+												
India	2006			+	Manufacturer countries		14%	**23/60**	**9/36**	32%	**15/60★**	**15/36**	+	
UK	2006	+	+											
Australia, Italy	2007	+	+/-											
France, Sweden, US	2008	+	+/-											
Belgium, Canada	2009	+	+/-											
China	2010			+	Manufacturer countries		4%	40/60	20/33	68%	**4/60★**	**4/33★**		
Bulgaria	2010	+	+				0%	54/60	25/27	3%	46/60	14/27		
Egypt	2010				Manufacturer countries		0%	55/60	30/33	35%	**12/60★**	**12/33**		
Czech Republic, Hungary, Poland, Turkey	2010	+/-	+/-											
Norway, Romania	2011	+	+/-											
Japan, Mexico	2012	+/-												
Brazil	2013													
Switzerland	2014	+				+	–8%	55/60	23/28	0%	47/60	16/28	+	
Chile, Finland, Israel	2014	+/-	+/-											
Thailand	2015						42%	**11/60★**	**3/32★**	15%	**24/60**	23/32		
Peru, Philippines, South Africa	2015													

Note: E.g. 5/60 – the fifth country in terms of the given indicator in the sample of sixty. **Bold** – countries within the first half of the group; ★ – countries within the first quartile of the group. Countries not included in the case studies are shaded.

7 Large-N analysis of renewable energy takeoff

7.1 Introduction

This chapter presents the final empirical component of my study – a large-N analysis of renewable energy takeoff. In section 7.2 I define and justify my dependent variable. In section 7.3 I describe independent variables used in my analysis and their relations to energy transition mechanisms. In section 7.4 I discuss the sample I use for the large-N analysis, including its two sub-samples. Section 7.5 presents an exploratory set-theoretical analysis of RE takeoff. In section 7.6 I present statistical analysis of takeoff using techniques of event history analysis. The chapter concludes with a comparison of variables used in the exploratory analysis with variables found significant in event history analysis (section 7.7).

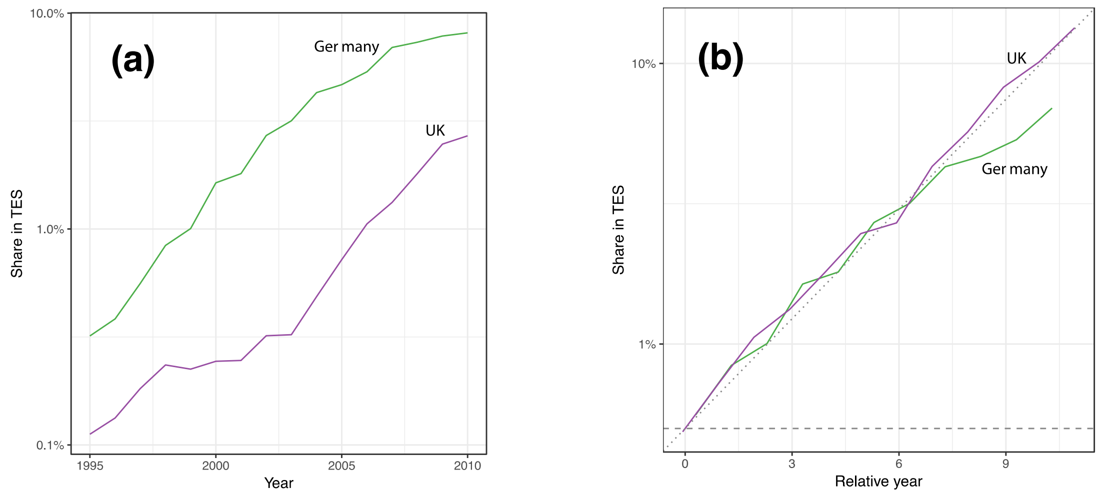
7.2 Dependent variable

As discussed in Chapter 4, the dependent variable for the large-N analysis is the "takeoff year" – *the year in which the combined share of wind and solar energy in total domestic electricity supply first exceeds 1%*. In this section, I first provide some empirical evidence illustrating the analytical relevance of the notion of takeoff. Then I discuss and justify various aspects of this definition.

7.2.1 Renewable energy growth: empirical observations

The pertinence of the concept of takeoff to the analysis of renewable deployment can be demonstrated by the following empirical example. Figure 7.1(a) shows the difference in the deployment of combined wind and solar power between 1995 and 2003 in two major European countries – Germany and the UK. The Y-axis is in the log scale, so exponential growth would be represented by a straight line with a slope corresponding to the growth rate. The UK was lagging behind Germany throughout the entire period 1995–2010. Another observation is that the growth in the UK between 1998 and 2003 (when the RE percentage was around 0.3%) was slow and unstable.

Figure 7.1. Renewable energy (wind and solar combined) growth in Germany and the UK



Source: Author's own calculations based on IEA (2017d).
Notes: (a) absolute dates; (b) shifted dates (the countries reach the 0.5% level at the same moment). Y-axis is in log-scale.

Figure 7.1(b) shows the same data but with the curves shifted in time[128] and data points below 0.5% removed. The figure illustrates that the growth in two countries was close to exponential for several years after crossing the 0.5% threshold (until Germany starts slowing down compared to the UK), and their growth rates were very similar, close to 35% per year (dotted line in the figure).

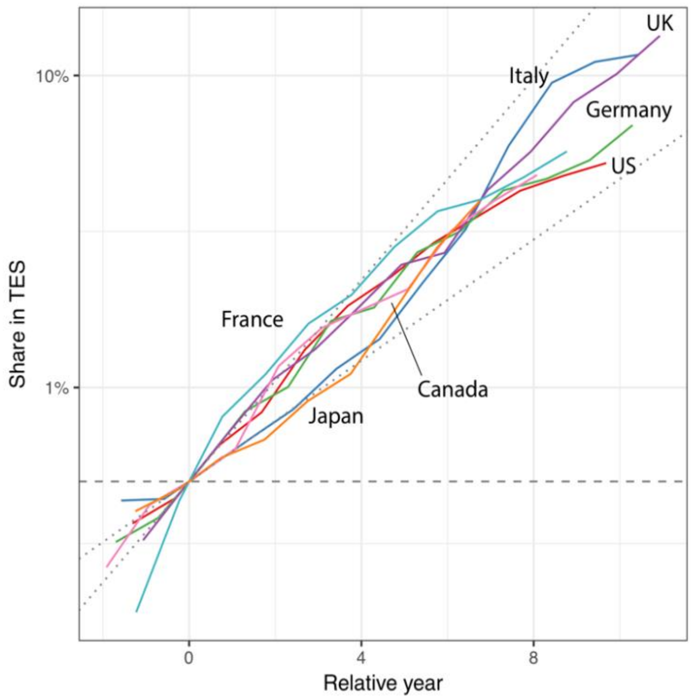
Figure 7.1 is an empirical illustration of the conceptual model of renewable energy diffusion illustrated in Figure 3.3 and 3.4 in Chapter 3, namely the presence of exponential growth after the takeoff phase. In this particular case, since the growth rate of renewables in the two countries is very similar, the difference between the UK and Germany boils down to the difference in the timing of RE takeoff.[129] Thus, the question "Why does Germany deploy more renewables than the UK?" may be substituted by the question "Why does sustained growth of renewables in Germany start earlier than in the UK?".

Figure 7.2 provides a broader illustration of the formative phase and early stages of sustained growth. It shows a graph similar to one on Figure 7.1(b) for G7 countries. The lines for individual countries have been time-shifted so that each country achieves 0.5% of RE in the year 0. The growth pattern is not as regular as for Germany and the UK, and there is a

[128] The curve for the UK has been shifted 7.4 years backward. The "Year 0" in the chart approximately corresponds to 1997 for Germany and 2004 for the UK.
[129] The later slowdown of the growth in Germany requires an additional explanation.

difference in growth rates among countries that requires explanation. However, sustained growth is observed for all countries, and the annual growth rate over several years is within the range of 25-45% (shown by dotted lines).

Figure 7.2. Renewable energy (wind and solar) growth in G7 countries, shifted dates

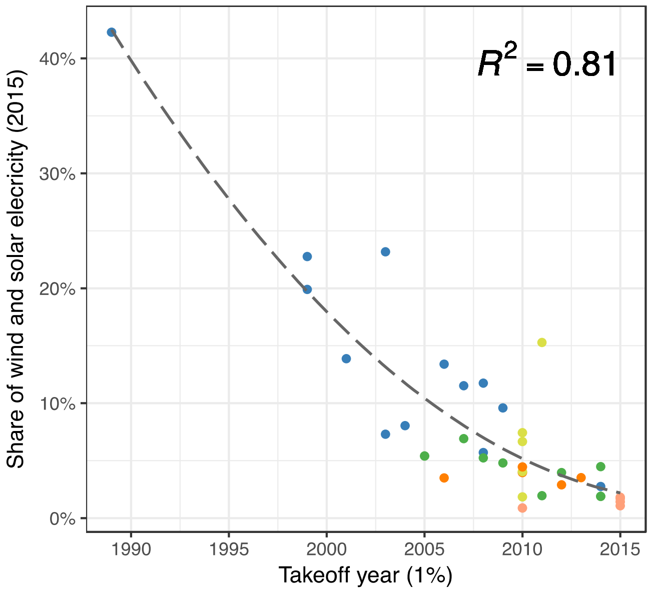


Source: Author's own calculations based on IEA (2017d).

Figure 7.2 illustrates a broader point that the study of takeoff can be analytically separated from the study of subsequent growth. The former answers the question **"How early does renewable energy growth start?"** and the latter – **"How fast does renewable energy grow after this start?"**. My study is primarily concerned with the first question, complementing other studies (e.g. Gosens et al. 2017) which are focused on the second one.

I argue that the "start" of growth occurs at the end of the formative period, when "cumulative causation" results in exponential expansion, as explained in detail in section 3.3.3. The timing of this event, which I associate with the "takeoff year", has profound significance for the deployment of renewables as illustrated in Figure 7.3. It shows the relationship between the year when the combined share of wind and solar power reaches 1% (I explain why this threshold is a reasonable proxy for takeoff in section 7.2.2 below) and the share of wind and solar power in 2015 for the countries used in my large-N study (see section 7.4). The dashed line shows a quadratic regression trend of the share on the takeoff year. R^2 of this regression is 0.81 which means that 81% of variance in the share of wind and solar energy is explained by the year when this share first exceeds 1%. It is remarkable that numerous studies analyzing cross-country differences in the deployment of renewable energy (see section 2.8) have not noted this relationship.

Figure 7.3. Takeoff year and share of renewable energy (wind and solar) in 2015



Note: All countries from the sample taking off by 2015 are shown. Colors represent different country groups (see Figure 7.10).

7.2.2 Definition of takeoff

According to my definition, *a country "takes off" for wind and solar power in the year when the combined share of these sources in the total domestic electricity supply reaches 1% for the first time*. That year is called the "takeoff year" for the given country. This definition involves four methodological choices. The reasons for focusing on the combined share of wind and solar power are explained in section 4.4.1. The other choices include using electricity generation as opposed to capacity, using a relative as opposed to an absolute measure of generation, and the particular quantitative threshold of 1%.

First, I define takeoff in terms of electricity generation, not the installed capacity. The primary reason is that I am following the tradition of technology diffusion studies interested in market shares of a particular product of technology. In my research I am dealing with the electricity market, where it is generated electricity and not the installed capacity which is traded. Furthermore, systematic worldwide data on installed capacity are more difficult to locate and even more difficult to compare due to different load factors (that vary across both countries and technologies).[130]

Second, the takeoff threshold is defined in relative and not absolute terms, i.e. in terms of the market *share* of a given energy source and not in terms of the GWh actually generated.[131] Again, this choice reflects my focus on the systemic aspects of RE deployment and the ability of the sector to sustain itself, particularly through feedback loops associated with policies and politics. Reaching a certain absolute threshold (e.g. 100 GWh of annual generation or 100 MW of installed capacity) can be important in terms of resolving technical and economic uncertainties regardless of whether it takes place in a smaller or a larger country. But it is the relative size of the fledging RE sector on the national scale that determines the ability of associated interests to ensure policy support necessary for sustained growth. For example in 1990, after the California wind boom (Gipe 1995), the US was by far the biggest wind electricity market in the world, producing some 3 TWh per year. But on the national scale this corresponded to approximately 0.1% of the total domestic electricity supply, which was not enough to secure continued support for the sector – after federal and state-level subsidies expired at the end of the 1980s, wind electricity output in the US stalled for a decade. In the same year, Denmark produced only 0.6 TWh of wind electricity, but this amounted to some 2% of domestic electricity supply, marking the beginning of a long period of sustained growth. This example demonstrates that the proportion of renewable energy may be more important for securing long-term support than the absolute output, at least at early deployment stages.

One effect of using relative values is the shifting of takeoff in larger countries later in time, because they need to develop a much larger sector in absolute terms in order to reach the same market share. However, as I show later in this chapter, the resulting picture is far from a trivial pattern of smaller countries starting first and larger countries starting later. While the first country to take off, Denmark, is indeed one of the smallest countries in the sample, the second one, Germany, was the world's third largest economy at the time. The takeoff sequence in non-OECD countries is even more striking in this regard – it is mostly the largest economies in that group that take off first, regardless of the fact that this requires a much larger RE sector in absolute terms. Thus, while comparing RE-based generation in absolute

[130] For example, in the US typical annual capacity factors for solar and wind energy (25% and 32–34% respectively) are approximately three times lower than the typical capacity factor for nuclear power plants (above 90%). See e.g. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b (accessed April 12, 2018).

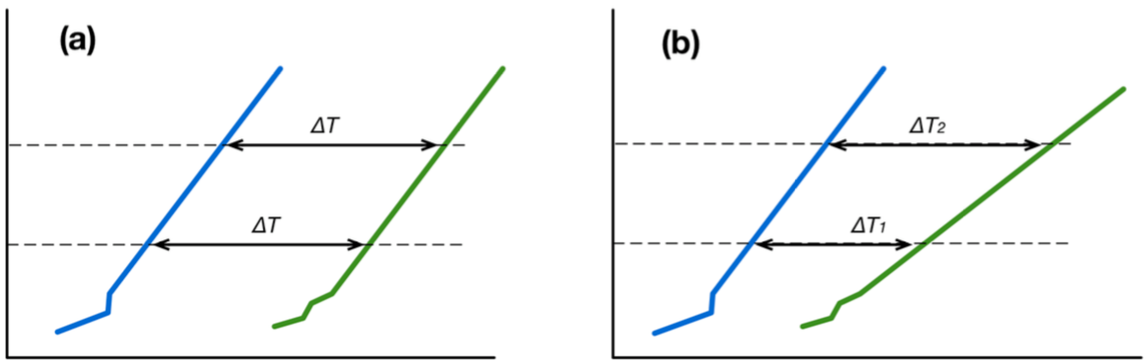
[131] Or installed capacity as in Gosens et al. (2017) who define the threshold for the beginning of the deployment phase as 100 MW.

terms can be used as an alternative method, using relative threshold for cross-country comparison is a meaningful approach, especially given the systemic focus of my analysis.

One limitation of using the relative threshold is the fact that this threshold can be easily crossed in smaller countries as a result of singular events (e.g. construction of a single wind farm by a foreign company) not reflecting mechanisms of the formative phase leading to the emergence of a domestic socio-technical system. I address this issue by limiting my sample to 60 largest countries in terms of electricity supply, as described in section 7.4.

The third element of my definition of takeoff is its quantitative threshold – 1% of the total electricity supply. Obviously, feedback loops driving sustained growth are unlikely to kick in momentarily, so takeoff, being a boundary between two time periods, may be a “fuzzy” moment or a period itself. So a single quantitative indicator is unlikely to capture the entire complexity of the transition between the two periods. Furthermore, for different countries sustained growth may start at different market shares. Nevertheless, I assume that a reasonable quantitative indicator of takeoff as a moment in time defined by a certain market share can be productive, making it possible to undertake a comparative analysis of a large sample of countries.

Figure 7.4. Measuring “time shift” between growth curves: a stylized illustration



Note: Y-axis is in log-scale.

There are two consideration relevant to choosing the timing of takeoff. First, it should be followed by exponential growth, so the respective market share should be high enough. If all the countries had the same growth rate, they would be represented by parallel lines on a graph with a log-scale Y-axis, so the shift in time between them could be measured at any level (Figure 7.4(a)), even if he specific dates would not reflect the end of the formative period. However, because different countries may have different growth rates, measuring the difference in time at a high level would mix effects of "takeoff timing" and "growth rate" (e.g. if a follower country grows at a slower rate, the difference in time measured at a high level would include effects of both a later start and a slower growth – see Figure 7.4 (b) for a stylized illustration). Furthermore, setting up too high a bar for takeoff would reduce the number of datapoints available for analysis, because fewer countries would make past this threshold. So the takeoff level should be located as early time in possible, but still after (or at) the beginning of sustained exponential growth.

Bento and Wilson (2016) identify a preferred indicator of the end of formative period in terms of market share (2.5% of the maximum potential market). When applying this indicator to wind power, they define maximum potential market as 100% of domestic electricity supply. This approach is based on Rogers' (2003) classification of adopter categories, where at the level of 2.5% innovation moves beyond the narrow circle of "innovators" to a broader group of "early adopters". Though I follow this general approach, for the purposes of my research I define the exact threshold at a lower level – 1%. There are several conceptual and empirical arguments justifying this choice.

First, sustained growth of renewables is triggered and supported not only by socio-technical and economic (as in case of more "neutral" technologies analyzed by Rogers), but also by political feedback loops (increasing returns). These mechanisms depend on the relative political strength of the renewables sector which is greater than its share in electricity supply. For example, in 2000 in Germany, the number of jobs in the wind sector that accounted for 1.6% of the national electricity supply was comparable to that in the nuclear sector, which accounted for 30% (Cherp et al. 2017, Table SM3). Renewables not only generated more employment and ownership per every unit of electricity produced, but also were disproportionally present in public and policy discourse. The 1% threshold as the level when the "change of gear" (Jacobsson and Bergek 2004) happens is also consistent with the evidence provided in case studies in Chapers 5 and 6. In several countries, crossing this threshold was associated with important events demonstrating the ability of the RE sector to sustain itself. In Germany (where the share of wind power stood at 1% in 1999) in 1999–2000 the pro-renewable coalition was able to defeat strong resistance, securing the adoption of a new feed-in tariff law based on technology-specific rates (Jacobsson and Lauber 2006). In Spain (1% of wind power in 1999), a mature feed-in tariff legislation was introduced in 1998. In the Netherlands, the introduction of a universally accessible feed-in tariff scheme in 2003 coincided with the takeoff. In these examples, the adoption of a mature support scheme is seen as another measure of the maturity of the entire socio-technical system associated with renewable energy, which roughly coincides with takeoff dates defined by the 1% threshold.

These examples also demonstrate the political strength of the sector already at the 1% level, going beyond what could be expected from a narrow group of "innovators".

Second, as demonstrated by Figure 7.1 and Figure 7.2, sustained growth close to exponential is observed already at the level of 1%, which signals the presence of positive feedback loops. Another evidence of stable growth already after 1% is presented in Table 7.1, which shown the quality of takeoff dates as a predictor of share of renewable energy (similarly to Figure 7.3, but for different takeoff thresholds). As seen in the table, the quality is relatively low for 0.125% and 0.25%, which signals erratic irregular growth. It noticeably improves when the threshold increases to 1%, but no further significant improvement is seen when the threshold changes to 2%.

Table 7.1. Quality of takeoff date as a predictor of share of renewable energy (wind and solar) in 2015, measured by R^2

Takeoff threshold	**R^2**
0.125%	0.68
0.25%	0.695
0.5%	0.765
1%	0.812
2%	0.82

Finally, I compare takeoff dates for countries in my sample using three different thresholds – 0.5%, 1%, and 2% – and look at the difference between these dates (Table 7.2).

Table 7.2. Country takeoff dates for the thresholds 0.5%, 1%, and 2%, and the difference between the dates

Country	Year (0.5%)	Year (1%)	Year (2%)	Diff. 0.5–1%	Diff. 1–2%
Denmark	1987	1989	1991	2	2
Germany	1997	1999	2002	2	3
Spain	1998	1999	2000	1	1
Netherlands	1998	2003	2006	5	3
Greece	2000	2001	2005	1	4
Portugal	2001	2003	2005	2	2
Austria	2003	2004	2005	1	1
India	2003	2006	2009	3	3
Egypt	2004	2010	–	6	–
Italy	2004	2007	2009	3	2
New Zealand	2004	2005	2007	1	2
Sweden	2004	2008	2010	4	2
United Kingdom	2005	2006	2009	1	3
Australia	2006	2007	2010	1	3
Norway	2006	2011	–	5	–
United States	2006	2008	2010	2	2
Belgium	2007	2009	2011	2	2
Canada	2007	2009	2012	2	3
France	2007	2008	2011	1	3
Poland	2008	2010	2011	2	1
Bulgaria	2009	2010	2011	1	1
China	2009	2010	2012	1	2
Czech Rep.	2009	2010	2011	1	1
Hungary	2009	2010	–	1	–
Japan	2009	2012	2014	3	2
Turkey	2009	2010	2011	1	1
Chile	2010	2014	2014	4	0
Romania	2010	2011	2011	1	0
Finland	2011	2014	2015	3	1
Mexico	2011	2012	2014	1	2
Brazil	2012	2013	2015	1	2
Switzerland	2012	2014	2016	2	2
Israel	2012	2014	2016	2	2
South Korea	2013	–	–	3	–
Thailand	2013	2015	–	2	–
Ukraine	2013	–	–	–	–
Peru	2014	2015	–	1	–
Pakistan	2014	–	–	–	–
South Africa	2014	2015	–	1	–
Philippines	2015	2015	–	0	–
Mean				**2.0**	**1.9**
St. dev.				**1.36**	**0.94**
No. of datapoints	**40**	**37**	**30**		

Notes: Blue – time interval between 0.5% and 1% or 1% and 2% more than three years. The last three rows show means and standard deviation for the respective columns, as well as the number of datapoints available for different definitions (number of countries having reached the respective threshold by 2015).

As seen from the table, for most countries the effect of doubling a threshold is a one to three year-long delay in takeoff (two on average), so the change in definition does not significantly alter the sequence of countries taking off – the main object of my statistical analysis. There are just a few countries with a relatively long delay (4 years or more), which are shaded with blue, so the first conclusion is that the change from 0.5% to 1% or from 1% to 2% does not change the overall picture much. To make a choice between 0.5% and 1%, I am looking at some countries with a significant delay in light of the available literary evidence. One of these countries is the Netherlands, which is one year behind Germany when using the 0.5% threshold and four years behind when using the 1% threshold. The larger difference between the two countries is in line with the comparative analysis by Bergek and Jacobsson (2003), according to whom the Netherlands, unlike Germany, struggled to initiate sustained marked growth until the early 2000s. Another country which takes off significantly later when using the 1% threshold is Egypt, where early deployment of wind energy was based on external resources (see section 6.2.9). With the 0.5% threshold, Egypt turns out to be an early starter among the global leaders in RE deployment, so its later takeoff is more logical. Thus, the two thresholds produce a broadly similar sequence of countries taking off, but the 1% threshold fits the available historical evidence somewhat better. The change from 1% to 2% also has the effect of shifting takeoff by two years on average, but it also leads to a significant loss of datapoints. Therefore I conclude that 1% is a sensible choice of takeoff threshold.

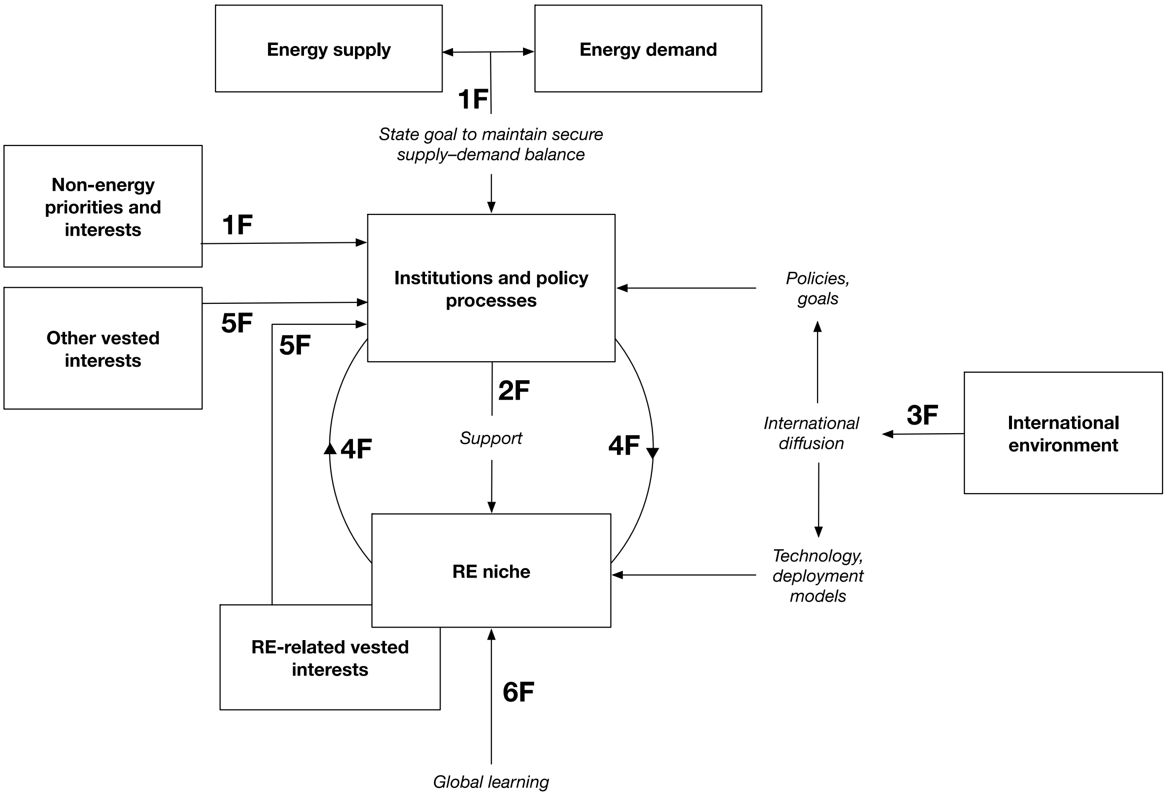
Finally, in Annex A I present an empirical analysis of growth rates that demonstrates that around 1% growth characteristics change from erratic to more stable and even converge across countries, which signals a transition to different growth mechanisms.

7.3 Independent variables

7.3.1 Mechanisms of the formative period

Renewable energy takeoff – a moment when sustained growth of wind and solar power is triggered – is an outcome of the formative phase. I identify independent variables for my analysis on the basis of mechanisms characteristic of that phase, which are presented in Figure 7.5. This chart builds upon Figure 3.3 presented as part of my conceptual framework, but incorporates modifications reflecting its focus on the formative phase of renewable energy deployment and/or based on the empirical analysis in Chapters 6. In particular, the chart does not include feedback loops supporting incumbent regimes (but still includes their role as vested interests influencing state decisions). Other differences are discussed in the context of specific mechanisms below. Mechanism numbers include the letter "F" to prevent confusion with the numbering of generic mechanisms introduced in Chapter 3.

Figure 7.5. Mechanisms at the formative stage of RE technology deployment



There are six mechanisms of the formative phase:

1F. **Formation of state energy goals in response to vulnerabilities of supply–demand balance and other priorities.** This mechanism corresponds to mechanism 1 of the generic energy transition mechanisms identified in Chapter 3 (Figure 3.3).

2F. **Provision of state support to the renewable energy sector.** This mechanism corresponds to mechanism 6 from Chapter 3.

3F. **International policy and technology diffusion** from the "core" countries to the "periphery". This mechanism combines mechanisms 3 and 7 from Chapter 3.

4F. **National policy and technology learning**, which involves adjustment of initial policies, innovation and experimentation until they become effective in bringing the deployment of renewables to the levels triggering cumulative causation. This mechanism generally corresponds to mechanism 8 from Chapter 3, but is defined more broadly, encompassing not only the technological renewable energy niche but also state institutions involved in its regulation and support. This reflects the finding of the case studies that these institutions are also actively involved in learning processes – policy learning, which is significant at the formative phase.

5F. **Vested interests** promoting or opposing renewable energy deployment. This mechanism associated with pro-renewable interests can still be very weak at the formative stage when the shares of renewable electricity are too low to generate significant political clout. Therefore, initially it was not included in the repertoire of mechanisms in Chapter 3, which assumed that pro-renewable interests become strong enough only when the sector reaches the regime level. Nevertheless, as demonstrated by the case studies, this mechanism cannot be wholly discounted. For example, German electric utilities challenged pro-renewable energy policies already in the 1990s when the shares of wind in power supply were far below 1%, whereas some industry associations and labor unions actively supported pro-renewable measures at that time (Jacobsson and Lauber 2006). As seen from this example, this mechanism also includes vested interests opposing renewable energy deployment.

6F. **Global technology learning** through which the core technology (e.g. wind turbines) is gradually improved in cost and efficiency. This mechanism is a highly aggregated representation of the outcome of diverse learning processes taking place in different countries and contributing to the global innovation system. However, given the concepts of learning as a result of accumulated experience and the close-to-exponential global growth of RE deployment, in the most general form the effect of this mechanism can be described as decline in cost of RE technology and growth of its availability over time. This reduces the barriers for the technology adoption, making it available for new countries and country groups with less capacity and/or motivation (as demonstrated by the discussion of global takeoff sequence in section 7.5 below). This mechanism was added to the scheme based on the observed sequence and statistical analysis of takeoff.

Given the hierarchical nature of causal mechanisms, these mechanisms can be further detailed and unpacked. For example, international policy and technology diffusion includes two more specific mechanisms – policy diffusion and technology diffusion respectively (as shown in Figure 3.3) – and the former may include top-down policy imposition by international bodies and horizontal policy learning (see section 2.7.2 for more details). However, the level of generality of this figure is consistent with the variables used in the event history analysis.

7.3.2 Identifying independent variables. Variables and mechanisms

I select independent variables to characterize the formative stage mechanisms described in the previous section. I aim to identify several variables characterizing each particular mechanism (see Table 7.3). Important intermediate concepts in this process are actors with their motivations, capacities, and interactions. As explained in section 3.3.3, the idea behind this approach is that most causal mechanisms involve actors and therefore their functioning and significance depend on motivations, capacities and interactions of this actors. For example, mechanism 1F is associated with the motivation of the state to achieve certain energy goals. The effectiveness of mechanism 2F depends on the capacity of the state to provide support to the renewable energy sectors, whereas the effectiveness of mechanism 4F depends on the learning capacity of various state and non-state actors. Interaction of actors from two or more nations is especially important for mechanism 3F, international policy and technology diffusion. Such interaction can be characterized by the presence of free movement of goods, people and capital, incentives for harmonization of policies, as well as geographic and cultural proximity.

The choice of variables for each particular mechanism took into account the results of case studies in Chapter 6, variables used in existing large-N studies (section 2.8), and data availability. In the process, I found that some variables characterize several mechanisms – for example, income per capita may characterize both the ability of the state to mobilize resources for supporting renewable energy (mechanism 2F) and learning and experimentation capacity of non-state economic actors (mechanism 4F). This is reflected in the table. The associations between mechanisms and variables presented in the table are tentative – more specific conclusions are made in the process of interpreting results of statistical analysis and case studies in Chapter 8.

Because a variable may be associated with several mechanisms, the discussion of variables below is organized not by mechanisms, but by broad categories such as "Energy system variables", "Political variables" etc.

Table 7.3. Mechanisms and variables used in the large-N analysis

Mechanism	Actors	Capacities, motivations, and interaction	Variables
1F. Formation of state energy goals in response to vulnerabilities of supply–demand balance and other priorities	States	**Positive motivation:** import dependence of energy supply, demand growth, high carbon emissions	Import dependence of electricity supply Share of fossils in electricity supply Cabinet composition (left–right) Proportional representation
		Negative motivation: availability of secure domestic sources of electricity	Major energy exporter status Share of nuclear power in electricity supply
2F. Provision of state support to renewable sector	States	**Economic capacity:** larger and wealthier economies	GDP per capita / High-income status (in combination with OECD in OECDHI) Size of GDP
		Institutional capacity: stable political systems with well-functioning institutions	OECD membership Major exporter status (likely lower capacity due to "resource curse") Democracy (POLITY IV)
3F. International technology and policy diffusion	Donors (supplier) and recipient (client) state and non-state actors; international organizations and corporations	**Motivation:** donor's intent to export and recipient's intent to adopt policies and practices; policies of international organizations **Capacity:** political and economic power of donors; institutionalized diffusion mechanisms **Interaction:** geographic location, political similarity, freedoms of movement of goods, capital, and people, incentives for policy harmonization, membership in international organizations	EU membership OECD membership
4F. National policy and technology learning	State and non-state niche actors	**Capacity:** technological and regulatory sophistication	Federalism GDP per capita / High-income status Size of GDP Major exporter status (likely lower capacity) Democracy (POLITY IV)

Mechanism	Actors	Capacities, motivations, and interaction	Variables
5F. Vested interests supporting or opposing RE	Non-state actors	Motivation and capacity: larger sectors would provide more resistance	High-technology exports as % of GDP Value added in manufacturing as % of GDP Electricity intensity of industry
6F. Global technology learning	Highly aggregated mechanism with multiple actors		Time

7.3.3 Economic variables

Income per capita. Several studies include hypotheses on the role of income per capita (usually measured as gross domestic product or GDP per capita) for RE deployment (Cheon and Urpelainen 2013; Gosens et al. 2017) or the adoption of RE support policies (Schaffer and Bernauer 2014). Summarizing the existing literature, Gosens et al. (2017) mention two mechanisms potentially facilitating earlier adoption of RE technology in countries with higher GDP per capita. Firstly, the governments of these countries have more resources to provide economic stimulus essential at the early stages of RE deployment – this makes GDP per capita an indicator of a state's economic capacity (mechanism 2F). Secondly, these countries have "better technological capabilities to develop and deploy modern renewables" (p. 270) – this reflects learning and innovation adoption capacity of other actors in the economy (mechanism 4F). While income per capita cannot capture all aspects of country development, according to the World Bank "it has proved to be a useful and easily available indicator that is closely correlated with other, non-monetary measures of the quality of life, such as life expectancy at birth, mortality rates of children, and enrollment rates in school" (World Bank 2017b). Thus, this indicator may reflect certain aspects of human capital, which also may be relevant to national learning capacity.

In my analysis, I use income per capita both as a continuous and a binary variable. The data source for the continuous variable is World Bank data (World Bank 2017d); in event history analysis I use log-transformed value of GDP per capita (logGdpPc). For the binary variable, I rely on the World Bank's country classification by income group. The World Bank classifies economies into low-income, lower-middle-income, upper-middle-income, and high-income ones based on their level of gross national income[132] (GNI) per capita (World Bank 2017c). To produce the value per capita, the country's GNI is converted from the local currency to US dollars using the World Bank Atlas method[133] and is divided by the country's midyear population. In my analysis, I am specifically interested in high-income countries, as I assume that their economic capacity may be high enough for relatively early deployment of renewable energy.

Economy size. The size of the national economy measured as the country's GDP is another economic variable used in my analysis. This variable is also associated with the mechanism of state support of RE deployment, the assumption being that a state with a relatively low

[132] Gross national income (GNI) is closely related to gross domestic product (GDP) per capita; the only difference is the handling of income produced in one country and received by residents of another (World Bank 2017a).
[133] The Atlas method uses exchange rates averaged over three years to reduce the effect of short-term rate fluctuations (World Bank 2017b).

income per capita but large overall GDP may still be able to accumulate and channel significant resources for RE support. Schaffer and Bernauer (2014) use this variable in their analysis of RE policies adoption in advanced industrialized countries. For my event history analysis, I use GDP in constant 2010 US dollars based on World Bank data (World Bank 2017d)). In defining groups for the analysis of takeoff sequence (section 7.5), I use a binary version of this variable, which takes a positive value when annual GDP exceeds 700 bln dollars.

7.3.4 Energy system variables

Import dependence of electricity supply. As discussed in Chapter 3, balancing demand with secure supply is a key imperative of state energy policy (Helm 2001; Cherp et al. 2017), and import independence is an important aspect of security of supply. In the electricity sector, import dependence usually takes the form of reliance on imported fossil fuels and, to a lesser extent, on imported electricity. Thus, states seeking to reduce their import dependence may seek to expand domestic fossil fuel production or to switch to non-fossil sources of electricity generation. The former option is usually unavailable to import-dependent high-income countries, which rarely had untapped fossil fuel resources by the 1990s or earlier 2000s. Usually, the potential for large-scale hydropower projects in high-income countries had also been exhausted by that time, and the only options for expanding domestic electricity supply available to such countries were nuclear energy and new renewables (including solar and wind). Therefore import dependence of electricity supply is a potential factor of *motivation* for renewable energy deployment, at least for countries not pursuing other ways to reduce import dependence (see the discussion of nuclear energy below in this section).

Although quantitative studies of RE deployment often include import dependence of energy supply as an explanatory variable (e.g. Cheon and Urpelainen 2013; Baldwin et al. 2016), they typically use import dependence of total energy supply, which may be not specific enough to reflect motivation for the transformation of the electricity sector. For example, a country may rely on imported oil for its transportation sector, but produce electricity from domestic coal and nuclear energy. Whatever energy independence problems this country may experience, they cannot be addressed by developing alternative sources of electricity. Import dependence of electricity supply defined in a way described below was used by Jewell (2011) as an indicator of national motivation for the adoption of nuclear energy.

In my analysis, import dependence of electricity supply is determined by import dependence of supply of individual generation sources, the proportion of these sources in the national generation mix, and also by net imports of electricity. Only fossil fuels (coal, oil, and natural gas) are taken into account when calculating import dependence – renewable energy sources are considered domestic, and nuclear energy is considered “quasi-domestic”. Import dependence of a fossil fuel represents the proportion of domestic supply of the fuel met with imports and is defined as a ratio of its net imports (imports minus exports) to its domestic supply (domestic production plus net imports):

$$D_f = \min(0, \frac{I_f - E_f}{P_f + I_f - E_f})$$

In this equation, D_f is import dependence of the fuel f, P_f is its domestic production, I_f – total imports of the fuel, and E_f – its exports. For example, if the country produces 60 mtoe of coal domestically and net imports amount to 40 mtoe, domestic supply is 100 mtoe and import dependence of coal supply is 0.4 or 40%. By definition, for a net exporter of the fuel (i.e. a country with negative net imports) import dependence is zero (meaning "full independence of supply").

Import dependence of electricity supply is defined as:

$$D_{el} = \sum_f D_f F_f + \frac{I_{el} - E_{el}}{P_{el} + I_{el} - E_{el}}$$

where D_{el} is import dependence of electricity supply, D_f is import dependence of supply of fossil fuel f calculated as described above, and F_f is the share of this fuel in the generation mix (based on the amount of electricity generated from this fuel and not its primary thermal content). Thus, if import dependence of coal supply is 40% and the share of coal-generated electricity in domestic electricity production is 50%, coal contributes 20% to the total dependence of electricity supply; if the share of coal in the mix is 10%, it contributes 4%. This method is based on the overall national balances for individual fuels and does not purport to trace whether particular shipments of imported fuel are used for electricity generation or other purposes. The final term accounts for export and import of electricity. The logic of calculation is similar to the one for fossil fuels described above, but this term can be negative for a net electricity exporter. Thus, a country using imported fossil fuels for a fraction of its electricity generation and then exporting produced electricity may end up having zero import dependence of electricity supply. The source of all data used for calculating import dependence of electricity supply is IEA energy balances (IEA 2017d).

Electricity demand growth. Rapid demand growth threatens supply–demand balance making the state take action to maintain this balance. Furthermore, expanding market may provide more space for different energy sources, thus reducing regime resistance to newcomers. To measure this aspect of motivation, I use electricity consumption growth over 5 years expressed as a percentage of the total consumption in the base year. For example, the value for the year 2008 would be the consumption growth between 2003 and 2008 expressed as a percentage of the consumption in 2003. Similar indicators have been used in quantitative studies of RE deployment (e.g. Gosens et al. 2017); Jewell (2011) used it in her analysis of nuclear energy deployment. The data source for calculating this indicator is IEA energy balances (IEA 2017d).

Shares of other energy sources: nuclear and fossil fuels. Summarizing the existing literature, Gosens et al. (2017) mention three mechanisms through which other energy sources present in the generation mix may affect the deployment of RES: they may (1) be more or less prone to import dependence; (2) lead to environmental impacts; (3) make the integration of renewables into the electricity system easier or more difficult. Furthermore, a significant proportion of an energy source in the system may be a sign of the presence of an established regime capable of resistance to newcomers (Cherp et al. 2017). Shares of different energy sources are often used in quantitative studies of RE deployment (Schaffer and Bernauer 2014; Jenner et al. 2013; Gosens et al. 2017).

I use two variables representing shares of different energy sources in the generation mix – nuclear energy and fossil fuels. According to the case studies (Chapter 6), most early starters in terms of RE deployment went through a "nuclear reversal", giving up or scaling down previously considered plans for nuclear power development. Therefore it can be hypothesized that nuclear power is a major domestic supply option whose availability reduces state motivation for pursuing other options and vice versa. A significant proportion of fossil fuels may signal the presence of fossil fuel regime opposing RE deployment. The share of fossil fuels can also be seen as a rough proxy for carbon intensity of electricity generation,[134] and a positive effect of an increased share of fossils on RE deployment may reflect the state's environmental motivation. The data source for calculating both shares is IEA energy balances (IEA 2017d).

In my event history analysis, the share of nuclear energy is used as a binary variable which takes the positive value when the share of nuclear in domestic electricity supply exceeds 20% (NUC20). This provides for better model fit than a continuous variable; furthermore, given the shares of nuclear energy in various industrialized countries, this is a reasonable operationalization of the notion of "significant proportion of nuclear energy in electricity supply". The share of fossil fuels is used as a continuous variable.

Major energy exporter status. This binary variable defines the group of significant energy exporters – countries whose energy (effectively fossil fuel) exports are significant compared to their own energy consumption. It has a positive value for the countries whose net energy

[134] A more precise estimation of carbon intensity would require considering shares of different types of fossil fuels.

export exceeds 30% of their total primary energy supply (TPES). Unlike import dependence of electricity supply, this indicator characterizes the country's overall energy balance as opposed to its electricity system. The inclusion of this variable is motivated by the preliminary observation that no country meeting this criterion and not being an OECD member takes off by 2015 (see section 7.5). Mechanisms associated with this variable may involve a high level of energy independence reducing motivation for the development of additional domestic energy source, as well as political-economic effects on governance known as "resource curse" (Karl 1997). A more detailed discussion of these mechanisms is provided in Chapter 8. The indicator is calculated based on IEA energy balances (IEA 2017d).

7.3.5 Political variables

OECD membership. One of my political variables is OECD membership, which defines a group of countries that share important political and economic characteristics. The Organization for Economic Co-operation and Development (OECD) was created in 1960 to promote "the highest sustainable economic growth" and contribute to the expansion of international trade (OECD 1960). Its founding members included twenty industrialized countries, but then the membership expanded to other countries and regions, so that by 1973 it comprised "all democratic societies and significant players of the global market economy at that time" (Noboru 2004). The organization membership remained stable until the middle of the 1990s, when Korea, Mexico, and a number of European economies in transition joined the OECD; another group of countries was admitted between 2000 and 2016, bringing the total number of members to 35 (OECD 2018).

While, according to its convention, the OECD is able to make binding rules, it lacks the mechanisms to enforce compliance with its decisions and, unlike the International Monetary Fund or the World Bank, does not control substantial financial flows that could be used as a leverage. Instead, it acts mainly as a major hub in transnational knowledge networks on policy and governance, contributing to the construction and dissemination of research and policy ideas[135] (Mahon and McBride 2008). The key activities of the OECD include information collection and exchange, mutual surveillance of member countries in the form of peer reviews, expert and analytical work, as well as preparation of various guidelines and standards codifying "good policy" and "best practices", which have influence far beyond the OECD members. Porter and Webb (2008) emphasize the "identity-shaping" role of the OECD – by identifying "good policy and best practice" through its knowledge networks, the organization

[135] Mahon and McBride (2008) note that the role of the OECD in the transnational governance system is associated with ideas as opposed to interests or institutions.

helps to define "the identity of the ideal modern state" (p. 47), to which many governments aspire.

The influential OECD report "A strategy for enlargement and outreach" prepared in 2004 (so-called "Noboru report") defined the most important characteristic of current and prospective members as "like-mindedness", the key aspects of it being "market-based economy" and "democratic principles" (Noboru 2004). More specific "yardsticks" mentioned in the report include, among others, basic economic performance (reflected by per capita income levels), good governance and rule of law, as well as observance of human rights. This like-mindedness seen as an essential pre-requisite of mutual understanding necessary for the effective sharing of know-how and peer learning within the organization. Therefore, while seeking to maintain sustainable cooperation with all significant economies of the world, the OECD prefers to engage with countries like China, India, or Brazil as "key partners" rather than prospective members (OECD 2018).

Energy policy is not a primary focus of OECD work – it is dealt with by the International Energy Agency (IEA), an independent but closely related organization with significantly overlapping membership. However, the OECD addresses the issues of renewable energy and energy subsidies as part of its activities related to the environment and green growth. In particular, the OECD coordinated and facilitated peer reviews of inefficient fossil-fuel subsidies among G20 members, relying on the model of peer review developed within the organization.[136]

Thus, OECD membership of a country signals a combination of a certain economic and a certain political status, which can be broadly described as "economically developed democracy" and involves aspects of both economic and political (institutional) capacity.

Some quantitative studies of RE deployment use OECD membership (or significant subsets of OECD members) to define samples of comparable countries (Cheon and Urpelainen 2013; Schaffer and Bernauer 2014). In my analysis, OECD is used as a binary variable reflecting the country's OECD membership at the end of the given year. OECD membership, in combination with the high-income status and EU membership, is used in defining two major sub-samples of my sample. In the statistical analysis of all countries OECD membership in combination with the high-income status is used as a binary variable.

EU membership. Another significant group of countries overlapping with the OECD is defined by EU membership. The European Union (EU) evolved from the European Coal and Steel Community established by six Western European Countries in 1951. Since then, a number of

[136] See https://www.oecd.org/site/tadffss/publication/ (accessed December 15, 2017)..

treaties and decisions have transformed the organization into a full-fledged political and economic union having certain features of a federal state and currently comprising 28 member states (Pinder and Usherwood 2013). EU member states are required to meet both economic and political criteria. According to the Copenhagen Criteria, adopted in 1993, "[m]embership requires that the candidate country has achieved stability of institutions guaranteeing democracy, the rule of law, human rights and respect for and protection of minorities, the existence of a functioning market economy as well as the capacity to cope with competitive pressure and market forces within the Union" (European Council 1993). Thus, like OECD membership, EU membership signals that the country is a democracy based on the rule of law and a functioning market economy.

However, in addition to signaling a certain economic and political status, EU membership has more direct effects on a country's capacity and motivation for the deployment of renewable energy. EU members are required to comply with policies providing significant motivation for RE deployment. Unlike the OECD, the EU has in place a large body of legislation binding on its members (Pinder and Usherwood 2013). While specific provisions regarding common energy policy were incorporated in EU legislation only recently, with the signing of the Lisbon Treaty in 2009, the EU has been promoting renewable energy sources as part of its environmental policy, which has had a sound legal basis since 1987 and had climate change leadership among its priorities (Delbeke and Vis 2016). This includes both binding targets at the Union level and national targets based on the former. In 1997, EU members signed the Kyoto Protocol, agreeing to reduce their greenhouse gas emissions in 2008–2012 by 8% below 1990 levels. In 2001, the EU adopted its first directive on the promotion of electricity generation from renewable energy sources, which defined indicative targets for member states (EU 2001). In 2009, Directive 2009/28/EC was adopted, which defined the EU's renewable energy targets for 2020 and required all member states to establish national RE action plans (EU 2009).

Furthermore, by virtue of being an EU member, a country participates in a single market with free movement of goods, labor, services and capital (EU 1992) and therefore is more likely to attract necessary expertise and capital. Access to a wider European markets played a role in the development of wind turbine manufacturing industries in Denmark and other early starter countries (Gipe 1995). As demonstrated by the case study of Bulgaria in Chapter 6, accelerated RE deployment in new EU members that joined the Union in the 2000s was facilitated by both the targets established by EU policies and the countries' participation in the common economic and legal space.

Thus, EU membership creates, reinforces, or supports countries' motivation in the field of renewable energy, while improving their capacity due to enhanced access to necessary capital and expertise. In my analysis, EU membership is coded as a binary variable reflecting the country's membership at the end of a given year. In the analysis of takeoff sequence (section 7.5) I distinguish between "older" EU members (EU15) and "new" members – post-socialist countries that joined the EU in the 2000s.

Democracy and political ideology. Indicators of democracy and political ideology (measured on the left–right scale) are frequently used in the studies of energy transitions (see e.g. Schaffer and Bernauer 2014; Cadoret and Padovano 2016; Sequeira and Santos 2018). Böhmelt et al. (Böhmelt et al. 2015) argue that "democratic inclusiveness" is positively associated with climate policy outputs. Summarizing existing literature, Sequeira and Santos (2018) conclude that "more democratic and left-wing countries … tend to adopt renewable energy-friendly policies" (p. 560). According to Bayer and Urpelainen (2016), governments in a democratic system have more political incentives to adopt feed-in tariffs – a major policy instrument of RE promotion. They argue that a broader constituency of a democratic government makes it more likely to support clean energy as a public good with positive externalities. Furthermore, the competitive nature of democratic system makes government capture by incumbent interests less likely and easier to overcome, even if not completely impossible. Johnstone and Stirling (Johnstone and Stirling 2015) attribute the differences in nuclear trajectories of Germany and the UK to a better quality of democracy in the former country.

In my analysis, I use the Polity score produced by the Polity IV project (Marshall et al. 2017) as an indicator of democracy. The Polity score measures political regimes on the scale from +10 (strongly democratic) to –10 (strongly autocratic). As a measure of government ideology, I use an index of cabinet composition available as part of the Comparative Political Data Set or CPDS (Armingeon et al. 2017). This index measures cabinet ideological orientation on the scale from 1 (hegemony of right-wing parties) to 5 (hegemony of left-wing parties). This index was used by Schafer and Bernauer (2014) in there analysis of RE policy adoption. Whereas the Polity score is available for all countries, CPDS covers only OECD and/or EU member countries, so I use the cabinet orientation only for one of the two sub-samples – OECDHI/EU (see section 7.4).

Constitutional arrangements. I include in my analysis two variables representing constitutional arrangements of a country: federalism and proportional representation. A possible mechanism through which proportional representation may favor the adoption of pro-renewable policies is described by Lockwood et al. (2017) (see section 2.7.1). Summarizing the literature on the influence of federalism on environmental policies, Shaffer and Bernauer (2014) conclude that, according to most researchers, federalism "is presumed to provide more opportunities for policy experimentation by subnational units, and more room for policy diffusion processes driven by learning, competition, or other mechanisms" (p. 18). In their analysis of the adoption of RE policies in advanced industrialized countries, Shaffer and Bernauer (2014) use both these variables and find them statistically significant in most models. I use the Comparative Political Data Set (Armingeon et al. 2017) as a data source for both variables. Thus, data on proportional representation are used only for the OECDHI/EU sub-sample. For federalism, I use country constitutions and other sources to complement the data, so in my dataset federalism data are available for all countries and used for the entire sample and both sub-samples. The CPDS measures both variables on a three-level scale, the intermediate level being mixed (proportional/majority) system and "weak federalism" respectively. For my analysis, I convert these variables into binary ones, treating intermediate levels as positive values (a proportional system and federalism respectively). The CPDS treats Spain as a federal state, although officially it is a unitary one. This is in line with other available evidence (see section 6.2.3), and I accept this classification.

7.3.6 Industrial sector

On the one hand, industrial sectors actually or potentially involved in the manufacturing of RE equipment comprise a group interested in RE deployment. This may lead to a positive feedback loop, whereby the expansion of RE energy sector provides more resources to the respective manufacturing industry, increasing its ability to lobby for further support of RE (Cheon and Urpelainen 2013). National case studies presented in Chapter 6 demonstrate the role of the manufacturing sector in the early deployment of RES. Early takeoff in Denmark was made possible by the presence of a well-developed export-oriented manufacturing industry. In Germany, Spain, and also in China (Lewis 2007) industrial policy measures supported the growth of the RE sector and the associated manufacturing sector in the same time. In Germany, "general" industrial associations and labor unions joined the pro-renewable coalition relatively early, helping to overcome the resistance from other vested interests (Jacobsson and Lauber 2006). The access to foreign markets played a role in the development of RE manufacturing sectors in Denmark, Germany, and Spain, indirectly facilitating the expansion of RE in the electricity sectors of these countries. In Germany, early R&D spending on RE was motivated by the intent to develop off-grid solutions to be manufactured in Germany and exported to Third World countries (Jacobsson and Lauber 2006).

On the other hand, the broader manufacturing sector benefits from lower electricity prices and therefore, as an interest group, may oppose RE support schemes financed by increased prices for electricity customers. The strength of this resistance may grow with the share of energy-intensive industries in the national economy and the size of the RE sector (Cheon and Urpelainen 2013). Interestingly, Germany has been avoiding this problem by shifting the burden of increased electricity costs from industrial customers (Morey and Kirsch 2014).

In my analysis, I use several variables to represent the strength of vested interests associated with the industrial sector. Given the role of export-oriented industries in the early history of RE deployment, one of them is high-technology exports as a percentage of GDP (HTExp). Another one is value added in manufacturing as a percentage of GDP (ManVA), which is supposed to represent the size of manufacturing in a national economy. The source for both of these variables is World Bank data (World Bank 2017d). Finally, I use "electricity intensity of industrial production" (IndElGdp) calculated as industrial electricity consumption (based on IEA energy balances (IEA 2017d)) divided by the size of GDP in constant prices (World Bank 2017d). The assumption is that this indicator better represents the sensitivity of a country's manufacturing sector to electricity prices that the share of manufacturing in GDP calculated in monetary terms.

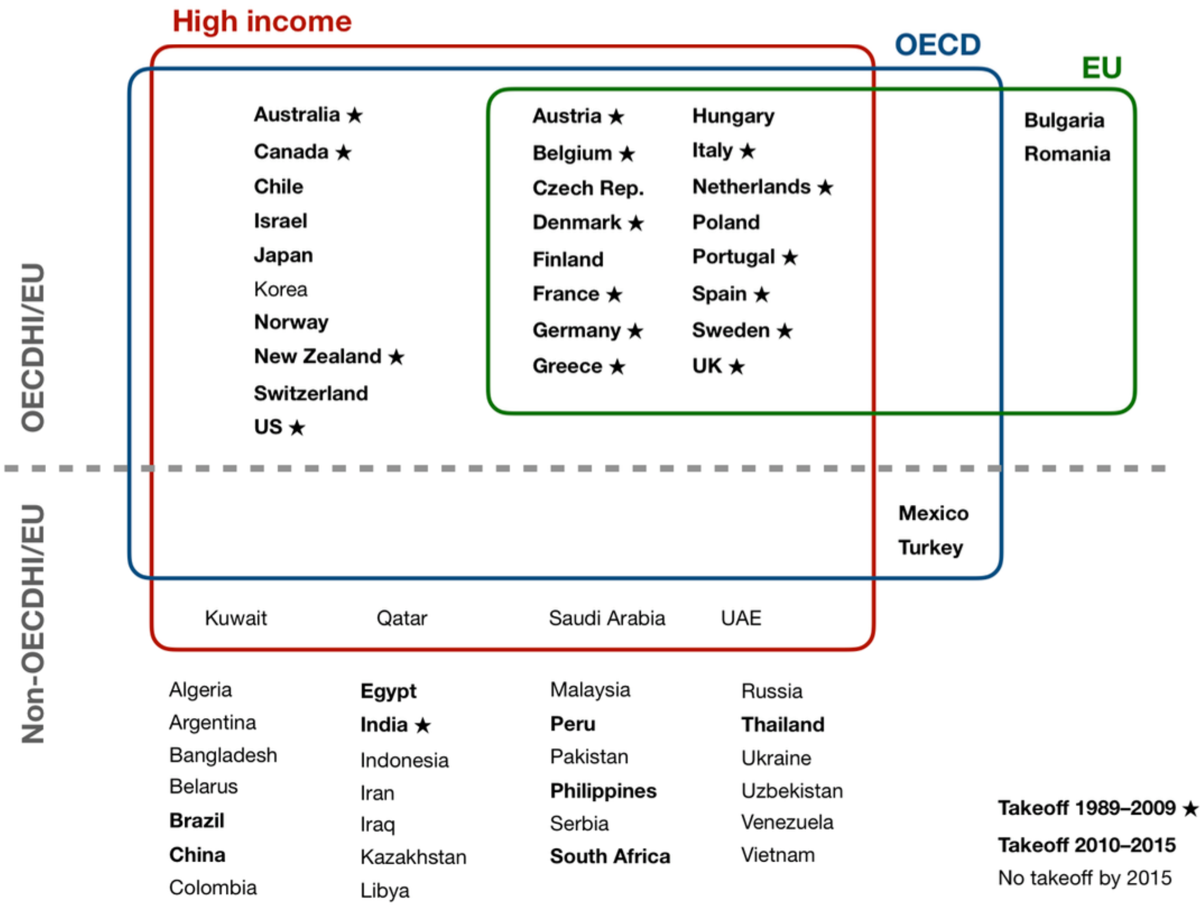
7.3.7 Time

Time is a variable associated with the mechanism of global learning, as explained in section 7.3.2 above. Time cannot be used as a variable in Cox regression due to the nature of this method, but I use it in my additional method of event history analysis – logistic regression with time variables.

7.4 Sample

My sample includes the world's sixty largest countries in terms of domestic electricity supply as of the year 2015. Singapore that would otherwise be in the sample is excluded because as a city-state with a small area it has a very limited RE potential. The entire set of countries in the sample together with their membership in several categories defined by binary variables is shown in Figure 7.6. Collectively, these countries accounted for 94.7% of the global electricity supply in 2015, representing almost the entire global electricity system. The reason for excluding smaller countries is that RE deployment in these countries may be dependent on singular events, sometimes resulting from external influence and not representing stable trends. A case in point is Morocco which, if included in the sample, would be one of the world's leaders in terms of RE deployment taking off in 2001 – just two years after Germany and Spain (see section 6.2.9). In fact, Morocco's takeoff resulted from the construction of a single wind farm financed by French investors, which produced enough electricity to account for 1% of the country's small electricity output at the time. After that, no significant activity in the country's RE electricity sector took place for several years until the next major project was implemented.

Figure 7.6. Countries included in the sample and their takeoff status (membership in categories as of 2015)



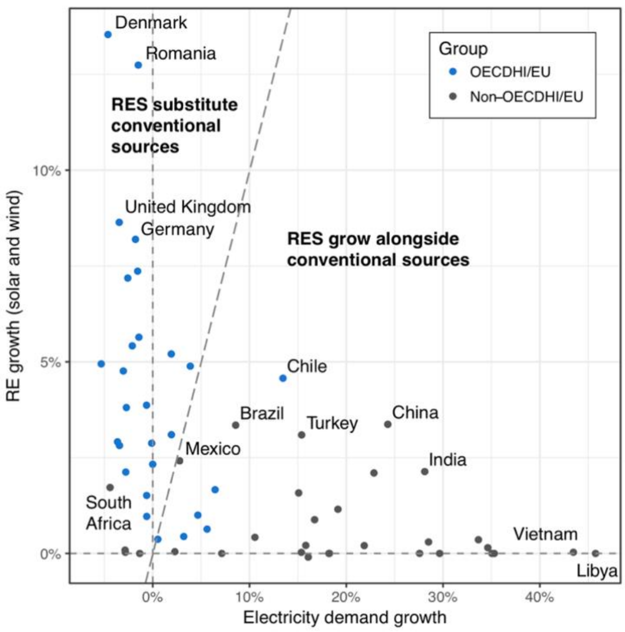
For the purpose of event history analysis, I divide the sample into two sub-samples or country groups. The first group includes high-income[137] OECD members (OECDHI) and also all EU member countries in the sample, regardless of their OECDHI status. I call this group "OECDHI/EU countries". This definition operationalizes the concept of "advanced industrialized countries" used in literature (e.g. Schaffer and Bernauer 2014). All other countries are referred to as non-OECDHI/EU countries. They include OECD members that are not high-income countries (Mexico and Turkey) and high-income countries that are not OECD members (like Kuwait or Saudi Arabia), among others. The membership in groups is not fixed and is defined by a country's characteristics in the given year: for example, the Czech Republic

[137] High-income countries are defined according to the World Bank classification.

becomes a member of OECDHI/EU when it joins the EU in 2004 (it is an OECD member but not a high-income country by the moment). The two sub-samples (with membership as of 2015) and categories defining them are shown in Figure 7.6. The assumption behind the identification of these two sub-samples is that RE deployment in them may be driven by different mechanisms. To test this assumption, I use event history analysis both for the entire sample of sixty countries and for each of the two groups separately. While the ultimate justification of this approach should be in the results of that analysis, below I provide several illustrations of differences between the two groups that may point to different transition mechanisms.

Figure 7.7 shows growth in total electricity demand (horizontal axis) and in RE-based electricity generation (wind and solar, vertical axis) from 2011 to 2015 for the sixty countries. Both values are expressed as percentages of the total electricity supply in 2011, and therefore they are directly comparable. If RE growth is greater than total demand growth, this means that RES substitute some other energy sources; it the opposite is true, RES grow alongside at least some other energy sources. Areas corresponding to these two growth regimes are separated by a 45-degree line,[138] where RES growth is exactly equal to demand growth. The two country groups are marked with different colors; selected countries are labelled.

Figure 7.7. Growth in total electricity demand and RE-based electricity generation from 2011 to 2015

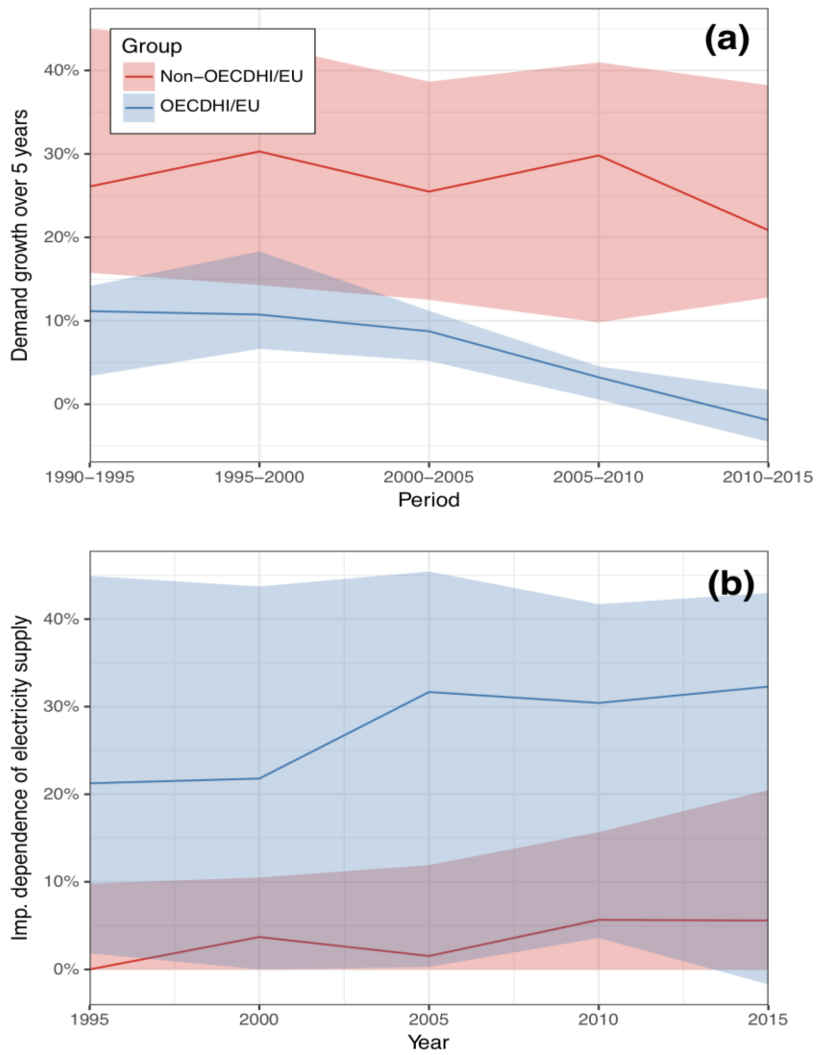


Source: Author's own calculations based on IEA (2017d).

[138] This slope of this line in the image is not 45 degrees due to differing scales of the axes.

The two country groups shown in the image demonstrate different dynamics of electricity transitions. Most non-OECDHI/EU countries have a very high electricity demand growth rate (above 10% over four years), whereas in OECDHI/EU countries demand is stagnating or even declining. The only OECDHI/EU country with a growth rate higher than 10% is Chile, which joined that group only recently (in 2012). Furthermore, in most OECDHI/EU countries growing RES substitute other energy sources, which is not the case for non-OECDHI/EU countries.[139]

Figure 7.8. Electricity demand growth (a) and import dependence of electricity supply (b) for the two sub-samples



Source: Author's own calculations based on IEA (2017d).

Note: Lines represents medians for the sub-samples and shaded bands represent inter-quartile ranges.

[139] The only exception is South Africa with its substantial demand decline uncharacteristic of this country group.

Figure 7.8 demonstrates differences in certain characteristics of two country groups and persistence of these differences over time. Figure 7.8(a) shows demand growth over five years expressed as a percentage of total demand in the respective base year. For example, value for the period 2000–2005 is the demand growth between 2000 and 2005 expressed as a percentage of total demand in 2000. Lines represent median values for the respective groups, whereas shaded bands represent interquartile ranges.[140] As seen in the figure, demand growth for non-OECDHI/EU countries has been much higher than for OECDHI/EU with a much larger spread; for example, in 2005–2010 its median value was 30% compared to less than 5% in OECDHI/EU. Based on this observation, one can hypothesize that mechanisms associated with demand growth have played a larger role in the transition dynamics in non-OECDHI/EU countries.

Figure 7.8(b) represents import dependence of electricity supply for the two country groups in a similar manner. As seen in the figure, OECDHI/EU countries as a group have a much higher median value and a much larger spread, which shows that this group has both import-independent and highly dependent countries. For non-OECDHI/EU countries, typical levels of import dependence are much lower. Thus, mechanisms related to import dependence may play a more significant role for some of OECDHI/EU countries.

Overall, these substantial differences in the patterns and potential drivers of energy transitions provide a preliminary justification for studying each group separately in addition to analyzing the entire sample of sixty countries.

7.5 Set-theoretical exploration

For the purpose of exploratory set-theoretical analysis of the sequence of renewable energy takeoff, I classify countries in my sample into several mutually exclusive groups based on some of the variables described in the previous section:

Group 1. Countries that were EU member states by the end of 1995 (EU15). Countries that joined the EU after 1995 (from 2004 and onward) are added not to this group, but to the Group 3 (see below).

Group 2. High-income OECD members (OECDHI), which are not EU member states.

Group 3. New EU members – former socialist economies of Central and Eastern Europe that joined the EU in 2004–2007.

[140] Interquartile range is a range between the first and the third quartiles; it contains 50% of the sample (Stata Corp 2017).

Group 4. Major economies that are not OECD high-income members and not major energy exporters (the definitions of major economies and major energy exporters are provided in section 7.3).

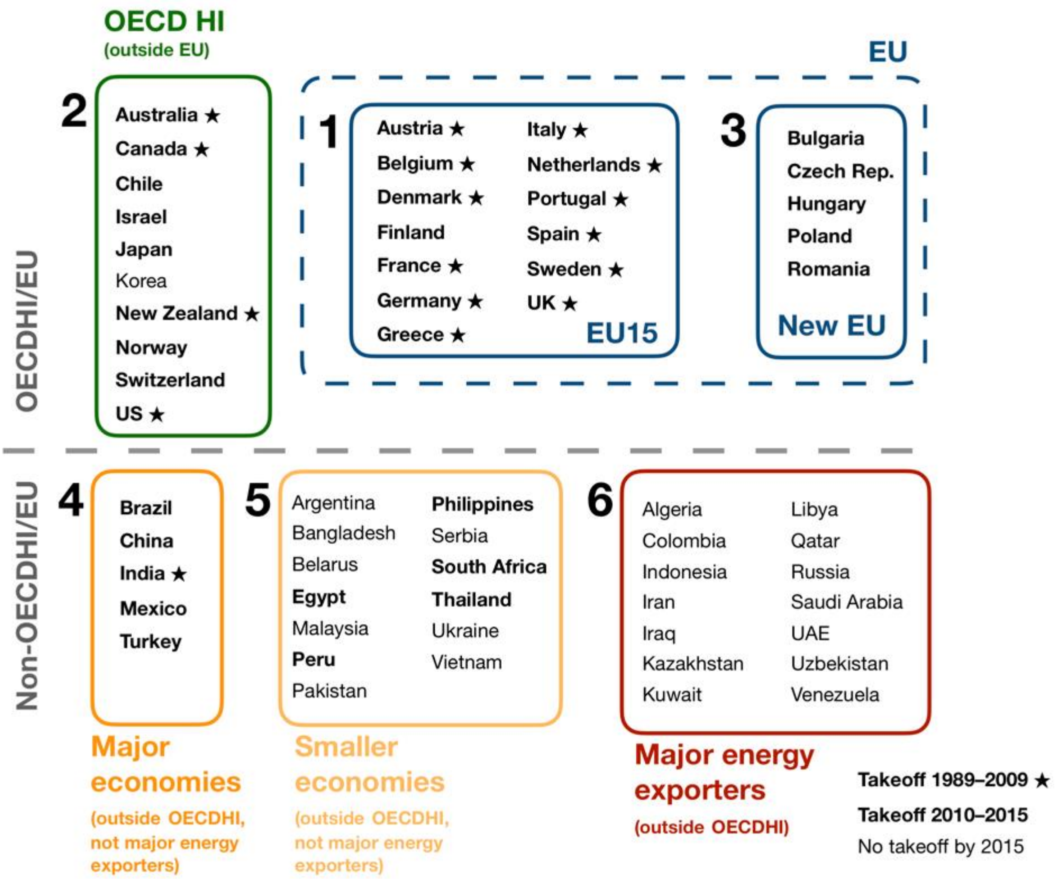
Group 5. Other countries outside OECDHI that are not major energy exporters.

Group 6. Major energy exporters outside OECDHI.

In terms of two main sub-samples identified in section 7.4, groups 1–3 are OECDHI/EU countries, and groups 4–6 are non-OECDHI/EU countries.

Figure 7.9 shows membership of all countries in my sample in these groups and their takeoff status in a manner similar to Figure 7.6. The group membership shown in the figure is based on country characteristics in 2015, but also correctly represents membership of each country at the moment of its takeoff.[141]

Figure 7.9. Country membership in the six groups (as of 2015)



[141] I.e. no country changes its status after the takeoff. For example, there is no country that would not be a high-income OECD member at the moment of its takeoff but would obtain this status afterwards.

While Figure 7.9 represents takeoff timing in very general terms, it already allows to make some conclusions, using group membership as an explanatory variable and takeoff status as an outcome.

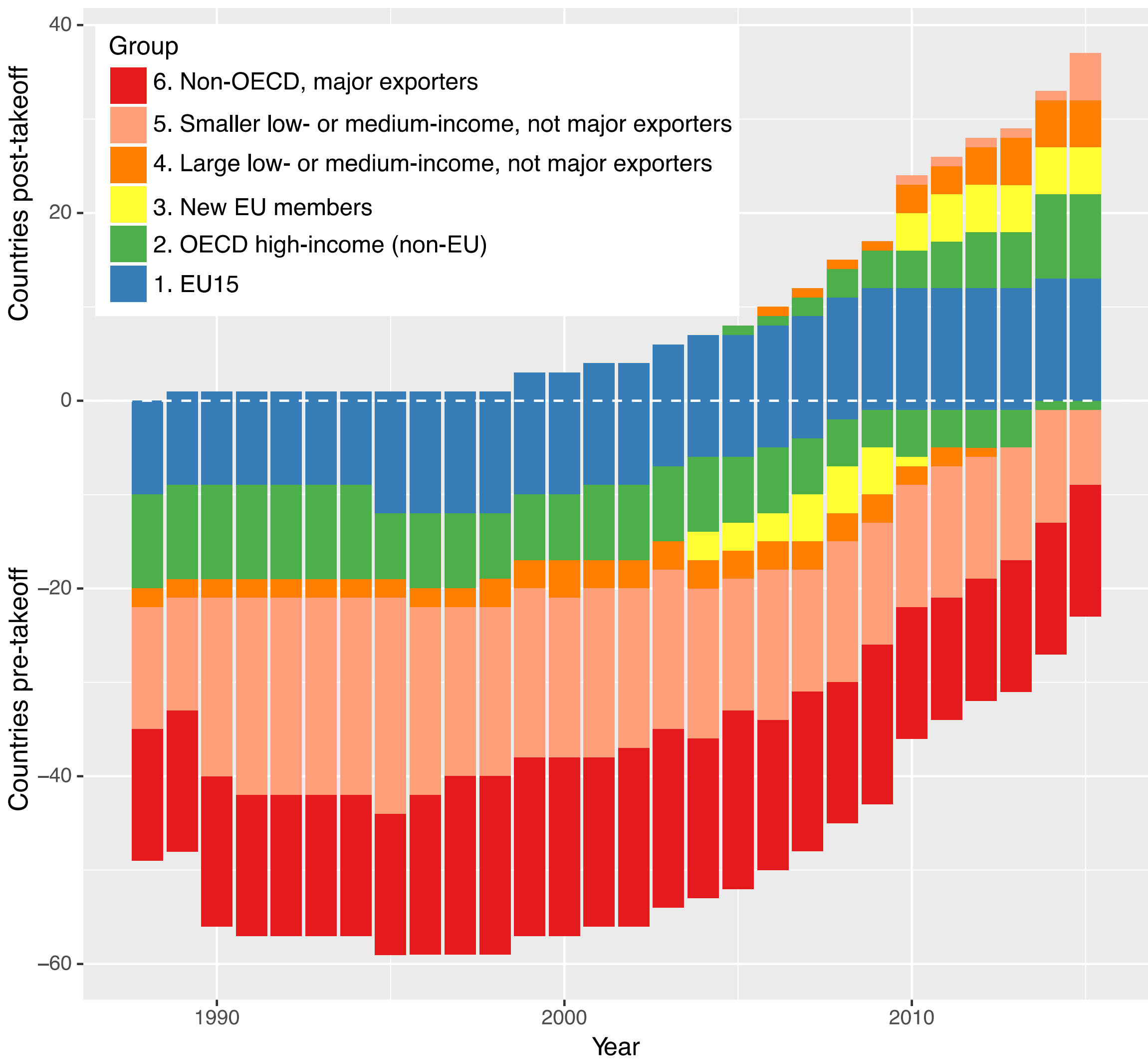
- All members of Group 1 (EU15 countries) take off by 2015, and all but one (Finland) take off by 2009. Thus, in terms of set-theoretical analysis, membership in this group is a perfect sufficient condition for takeoff by 2015 and an almost perfect sufficient condition for takeoff by 2009 (with the consistency 12/13 = 92%).[142]
- All members of Group 2 (non-EU OECDHI countries) take off by 2015 with the only exception – Korea (which takes off in 2016). Thus, Group 2 membership is an almost perfect sufficient condition for takeoff by 2015 (consistency 90%), but many countries in this group do not take off by 2009.
- All members of Group 3 (new EU members) take off between 2010 and 2015 – membership in this group is a perfect sufficient condition for taking off within this period.
- All members of Group groups 4 take off by 2015 (thus making membership in this group a sufficient condition of this outcome), but only one of them (India) takes off by 2009.
- No country in Group 5 takes off by 2009, and less than half (5 out of 13) takes off by 2015.
- Finally, no country in Group 6 takes off by 2015, which means that membership in this group is perfect sufficient condition for *not* taking off by 2015.

Figure 7.9 contains only limited information about the timing of takeoff. For example, it does not allow to see when countries in Group 1 start taking off. To present more detailed information about takeoff sequence between 1988 and 2015, I construct Figure 7.10, which I call "the takeoff chart." Stacked bars below the horizontal axis represent the number of countries that have not taken off by the given year, whereas bars above the axis represent the number of countries that took off before or in the given year. Therefore, as more countries take off, the bars below the axis become shorter, the bars above it become longer,

[142] Set-theoretical analysis allows for imperfect sufficient conditions, provided that the number of cases violating them is small. A measure of the quality of a sufficient condition is its consistency – a ratio of the number of cases meeting the condition and having the defined outcome to the number of all cases meeting the condition (Schneider and Wagemann 2012). A perfect sufficient condition has a consistency of 100%.

and the total number of countries remaining unchanged.[143] The sections of the bars are color-coded according to country membership in the six groups defined. The structure of bars *below the axis* represent country breakdown by the groups in the given year, so the composition of such bars may change due to change of countries' status. For example, new EU members are shown as Group 3 members from the year of their EU accession, and before that they are shown as non-OECDHI economies. As noted above, no country changes its status in terms of the six groups after its takeoff, so the structure of bars above the axis in any given year also represents the status of each country in its respective takeoff year.

Figure 7.10. Sequence of renewable energy takeoff by country group



[143] There are fewer than sixty countries in the early years covered by the chart, since post-Soviet and post-Yugoslav states did not exist as separate countries at that time, and relevant data for them is not available. This does not affect the logic of the chart, since no country takes off in those years.

Denmark (1989) is the first Group 1 (EU15) country and the world's first country to take off. It is followed by Germany and Spain in ten years (1999). All seven countries taking off before 2005 are EU15 members (all of them are discussed in Chapter 6). After the take-off of Belgium (2009), the last remaining country in this group is Finland taking off only in 2014. The first Group 2 (high-income OECD members outside EU) country to take off is New Zealand (2005). "Later starters" in this group (countries taking off after 2009) include Norway (2011), Japan (2012), Switzerland (2014), Israel (2014), Chile (2014), and Korea (2016). Israel and Chile joined the OECD high-income group only in the 2010s; the other late starters in this group are discussed in section 6.2.11. Interestingly, all G7 economies except for Germany (staring earlier) and Japan (starting later) take off between 2006 and 2009. The image shows new countries joining the EU in 2004 and 2007 (when the yellow area first emerges and then expands). All these countries (Group 3) take off in 2010–2011, a few years after their EU accession.

The first country in Group 4 (and in the larger non-OECDHI/EU group overall) to take off is India (2006). It remains the only non-OECD country above the takeoff threshold until 2010, when China and Egypt take off. All five countries comprising Group 4 and defined as the largest economies outside the OECDHI group not being major energy importers take off by 2013. Thus, with the exception of Egypt, it is the largest economies that are the first to start outside of the OECDHI group. This result is particularly significant, because a larger economy has to deploy more capacity in absolute terms to take off. Egypt, whose takeoff was fueled by external resources provided mainly by EU member countries (see section 6.2.9), remains the only Group 5 country above the takeoff threshold until 2015, when it is joined by several other countries. Finally, no country in Group 6 (major energy exporters outside the OECDHI group) takes off by 2015.

This exploratory analysis highlights the role of several variables associated with national capacity and motivation and related to certain transition mechanisms. Income level, explicitly used in defining the OECDHI group and also associated with EU membership, may characterize both state capacity to support RE deployment (mechanism 2F) and broader learning capacity of non-state actors (mechanism 4F). EU membership, which seems to be a particularly significant factor of early takeoff, is also associated with international policy and technology diffusion (mechanism 3F). For countries outside the OECDHI group, economy size seems to be a relevant characteristic of state capacity (mechanism 2F). Finally, the status of a major energy exporter characterizes is related to energy supply affecting state goals (mechanism 1F), although a more nuanced discussion of the role of this variable is provided in section 8.4.

Although this exploratory analysis provided some insights into factors determining the sequence of takeoff, not all significant variables can necessarily be captured this way. Therefore in the next section I present results of statistical analysis of renewable energy takeoff.

7.6 Event history analysis

7.6.1 Introduction

In this section, I use methods of event history (survival) analysis to explore mechanisms leading to renewable energy takeoff at the national level. These methods are described in Chapter 4, while here I provide details on their application to my research. I carry out event history analysis separately for the entire sample (sixty countries) and its two sub-samples: OECDHI/EU and non-OECDHI/EU. The main method of event history analysis that I use is Cox regression (CR) (Cleves et al. 2010), but I also use logistic regression (LR) with time variables (Carter and Signorino 2010) to validate the results. For each group, I go through a number of statistical models in order to identify best model specifications and statistically significant variables associated with the takeoff. Generally, I am moving from a full model containing all potentially relevant variables to a "reduced model", which ideally includes only statistically significant variables and variables substantially improving model fit. As described in section 4.4, in this process I use several techniques – the Akaike information criterion to evaluate model quality; the Wald test to compare full and reduced models; and proportional hazard criteria for Cox regression. Using these criteria, I look for a best-fit parsimonious model that would not lose much information compared to a full model, while meeting the proportional hazard assumption. In summarizing results for each of the three groups, I look not only at the variables significant in the selected best-fit model, but also at the variables significant in all (or a broad range of) estimated statistical models. I take this as a particularly strong evidence of significance of such variables.

For ease of reference, all statistical models reported in this section are numbered; the models for OECDHI/EU countries, non-OECDHI/EU countries, and all countries have prefixes 1, 2, and 3 respectively. Model 3.3a means a version of model 3.3 applied to a different (usually smaller) dataset. Model 3.3L means a model using the same variables as 3.3 but based on logistic regression with time variables instead of Cox regression.

7.6.2 Analysis for OECDHI/EU countries

This section provides event history analysis for the sub-sample of OECD high-income countries and/or EU member countries. The data set for this group covers the period 1989–

2015 for 28 countries (as shown in Figure 7.6) with each observation corresponding to a country-year combination. Countries are included in the data set only in the years when they have the OECDHI/EU status. For example, Bulgaria and Romania, which have never been OECD members, enter the dataset from 2007 – the year of their EU accession. Thus, the dataset is unbalanced. All countries in this sub-sample undergo RE takeoff during the period covered by the dataset except for Korea (which takes off in 2016). Overall, there are 621 country-year observations in the dataset, but only up to 411 are used for event history analysis because observations for countries after their takeoff are not used, and some variables may not be available for all observations.

Table 7.4. Variables used in RE takeoff analysis of OECDHI/EU countries

Name	Description	Mean (SD)	Transformation
Economic			
logGdp	GDP, constant 2010 US$, log10	11.83 (0.53)	SD = 1
logGdpPc	GDP/cap, constant 2010 US$, log10	4.54 (0.21)	SD = 1
Energy system			
Dep	Import dependence of electricity supply, %	26 (28)	SD = 1
DeltaDem	Change in electricity demand over 5 years (relative to the base year), %	9 (11)	SD = 1
NUC20*	> 20% of electricity supply from nuclear (0 – no, 1 – yes)	0.44 (0.50)	
FosShare	Share of fossil fuels in electricity production, %	51 (30)	SD = 1
MAJEXP*	Major energy exporter (total energy exports > 30% of TPES) (0 – no, 1 –yes)	0.14 (0.35)	
Political			
EU*	EU membership (0 – no, 1 – yes)	0.62 (0.48)	
Polity	Combined Polity IV score, autocracy–democracy (-10 – +10)	9.77 (0.65)	0 – 1
Gparty	Cabinet composition, average over 5 years (1 – 5; 1 – right-wing hegemony, 5 – left-wing hegemony)	2.51 (1.26)	0 – 1
FED*	Federalism (0 – no, 1 – yes)	0.34 (0.47)	
PROP*	Proportional representation (0 – no, 1 – yes)	1.53 (0.73)	
Vested interests			
HTExp	High-technology exports (% of GDP)	2.68 (2.69)	SD = 1
ManVA	Manufacturing, value added (% of GDP)	15.48 (4.58)	SD = 1

Note: * Binary variables.

Variables used in the analysis for the OECDHI/EU sub-sample are listed in Table 7.4 together with their means and standard deviations. Because coefficients in Cox regression represent the effect of a change by one in the respective variable, non-binary variables are linearly transformed so that their typical variance is close to one (see the last column of the table). Continuous variables are normalized to the standard deviation of one, so the respective coefficient represents the effect of a change by one standard deviation. Ordinal variables (e.g. coded as integers from –10 to +10, like Polity IV score) are mapped onto the range 0–1, so the coefficient represents the effect of a change from one extreme of the range to the other. Binary variables are left untransformed – for them the coefficient represent the effect of a change from one status to another.

At the first stage, I use only economic and energy system variables together with a single "diffusion" variable – EU membership. I start with the full model that includes all variables from these categories; then test a reduced model which contains only variables statistically significant in the full model; and then test models with dropped variables added individually. The results of this procedure are shown in Table 7.5 (not all intermediary statistical models are included).

Table 7.5. OECDHI/EU, economic and energy system plus EU membership

	1.1		1.2		1.3	
EU	7.440	(4.563)***	6.330	(2.877)***	7.170	(3.589)***
NUC20	0.222	(0.136)**	0.207	(0.093)***	0.213	(0.096)***
logGdpPc	1.495	(0.349)*	1.393	(0.229)**	1.340	(0.238)*
logGdp	1.240	(0.368)			1.291	(0.290)
Dep	0.789	(0.153)				
DeltaDem	0.928	(0.464)				
FosShare	1.218	(0.286)				
MAJEXP	0.863	(0.745)				
N	411		411		411	
pseudo R^2	0.155		0.139		0.147	
AIC	123.503		115.502		116.525	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Model 1.1 includes all economic and energy system variables, whereas model 1.2. retains only variables found statistically significant in model 1.1. The addition of dropped variables one-by-one does not improve model fit according to the AIC, and the added variables are not significant as demonstrated e.g. for logGdp by model 1.3. Thus, the best-fit model is 1.2 (shaded), which includes EU membership, high share of nuclear energy (NUC20), and GDP per capita (logGdpPc). All tables for CR in this section report exponentiated coefficients, which are easily interpreted as multipliers applied to hazard rate in case of a unit change in the respective variable. The EU membership is highly significant[144] at the 1% level and has a strong positive effect on RE takeoff – all other factors being equal, hazard rate (a probability for a

[144] I use the expression "highly significant" for variables statistically significant at the 1% level, "significant" for variables statistically significant at the 5% level, and "marginally significant" for variables significant at the 10% level.

country to experience takeoff in a given year, provided that it has not taken off earlier) for an EU member country is 6.3 times higher than for a non-member. High share of nuclear in the generation mix (above 20%) reduces hazard rate more than five times and is also highly significant. Income per capita is significant, and an increase by one standard deviation (1.6 times) leads to a moderate increase in hazard – 1.4 times. The comparison of model 1.2 (reduced model) to model 1.1 (full model) using the Wald test (Kleinbaum and Klein 2012) produces a p-value around 60%; this means that the variables being dropped from the full model are not *collectively* statistically significant. Model 1.2 also passes the proportional-hazard assumption test based on Schoenfeld residuals.

At the next stage, I add variables representing constitutional arrangements and ideology to the best-fit model identified at the previous stage (1.2). Similarly to the previous stage, first I add all variables, then drop insignificant ones and test the effect of adding dropped variables one-by-one. The results of the procedure are presented in Table 7.6 (not all intermediate models are shown).

Table 7.6. OECDHI/EU, adding constitutional and ideology variables

	1.4		1.5		1.6	
EU	9.814	(5.513)***	8.530	(3.776)***	10.114	(5.940)***
NUC20	0.168	(0.085)***	0.177	(0.082)***	0.177	(0.081)***
logGdpPc	1.348	(0.241)*	1.339	(0.236)*	1.360	(0.253)*
Polity	4.335	(9.422)				
FED	2.894	(1.196)**	2.612	(0.994)**	2.563	(0.961)**
PROP	0.624	(0.336)			0.646	(0.362)
Gparty	1.698	(1.256)				
N	411		411		411	
pseudo R^2	0.172		0.165		0.168	
AIC	119.315		114.231		115.882	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Model 1.4 is an extension of model 1.2 with all constitutional and ideology variables added to it. Of these variables, only federalism (FED) is significant. Model 1.5 is model 1.4 with all insignificant variables dropped. No other constitutional or ideological variables are significant, when added to model 1.4 individually (as illustrated by model 1.6 for PROP). Thus, model 1.5 is the best-fit model (in terms of AIC). Both EU membership and high share of nuclear energy are highly significant and have an approximately the same effect in the same direction as in model 1.2. GDP per capita is marginally significant, and increase by one standard deviation increases hazard rate 1.3 times (a much smaller effect than that of changes in EU or NUC20). Finally, federalism is significant, and, all other parameters being equal, the hazard rate for a federal state is 2.6 times higher than for a non-federal one. The Wald test used to compare model 1.6 to the full model, which includes all variables found in models 1.1. and 1.4, produces a p-value of 20%, which means that variables not included in model 1.5 are not collectively significant and can be omitted. Model 1.5 passes the PH assumption test based on Shoenfeld residuals.

Finally, I add two variables representing potential vested interests (Table 7.7) – value added in manufacturing as a percentage of GDP (ManVA) and high-technology exports as a percentage of GDP (HTExp). Because there are fewer observations available for these models (ManVA is missing for some observations, mostly in the 1990s, when no country takes off except for Germany in 1999), I also provide results for model 1.5 applied to this smaller dataset for comparability of the AIC.

Table 7.7. OECDHI/EU, adding variables representing vested interests

	1.5a		1.7		1.8		1.9	
EU	7.708	(3.211)***	11.836	(6.325)***	5.498	(1.778)***	10.153	(4.876)***
NUC20	0.186	(0.084)***	0.194	(0.099)***	0.245	(0.126)***	0.261	(0.106)***
logGdpPc	1.290	(0.219)						
FED	2.845	(1.140)***	4.209	(1.914)***	3.394	(1.215)***	4.287	(1.831)***
HTExp			1.321	(0.199)*	1.006	(0.171)		
ManVA			0.439	(0.100)***			0.499	(0.091)***
N	346		346		346		346	
pseudo R^2	0.168		0.225		0.154		0.214	
AIC	111.502		106.408		113.299		105.875	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Models 1.7 and 1.9 demonstrate that models with ManVA provide much better fit than model 1.5a. Although model 1.9 has slightly better AIC, I choose model 1.7 (shaded) which also includes marginally significant share of high-tech exports (HTExp). This model provides the best fit without punishment for extra variables (e.g. when using pseudo R^2 instead of AIC). In this model, ManVA is highly significant with an increase by one standard deviation (4.6 p.p.) reducing hazard rate by half. HTExp is marginally significant and has a substantially smaller effect in the opposite direction (an increase by one standard deviation – 2.7 p.p. – increases hazard rate only by one third). The remaining three variables are highly significant with the effects similar to those observed in the previous models (but somewhat stronger for EU and FED). In the absence of ManVA, HTExp is not significant (model 1.8), whereas ManVA is highly significant in the absence of HTExp. The Wald test does not reveal significant difference between model 1.7 and the full model that includes all variables introduced so far (p-value around 15%). Model 1.7 also passes the PH assumption test based on Shoenfeld residuals. In Annex B, I also report results of two graphical tests of the PH assumption for that model and demonstrate that they are satisfactory.

To cross-validate the results of Cox regression, I use another method used for event history analysis – logistic regression with time dependence (see Chapter 4 for more details). As suggested by Carter and Signorino (Carter and Signorino 2010), I use t, t^2, and t^3 to represent time in my models. The results for models 1.6 and 1.8 are shown in Table 7.8. AIC values are not reported, because I am not comparing models in the table to each other.

Table 7.8. OECDHI/EU, logistic regression with time variables

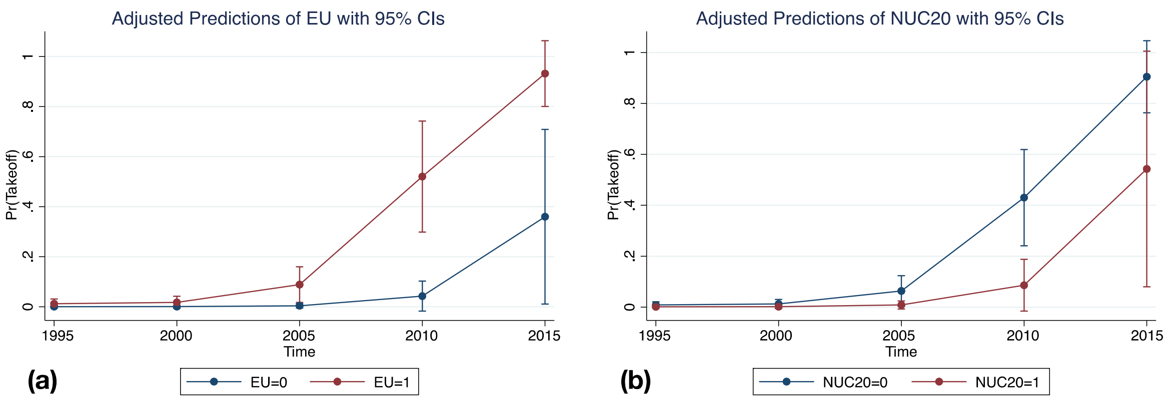
	1.5L		1.7L		1.10L	
t	-0.544	(0.557)	-0.746	(0.502)	-0.775	(0.543)
t^2	0.049	(0.041)	0.055	(0.036)	0.055	(0.040)
t^3	-0.001	(0.001)	-0.001	(0.001)	-0.001	(0.001)
EU	2.860	(0.714)***	3.194	(0.902)***	3.764	(1.243)***
NUC20	-2.158	(0.547)***	-2.083	(0.741)***	-2.142	(0.830)***
FED	1.221	(0.467)***	1.734	(0.626)***	1.685	(0.739)**
logGdpPc	0.321	(0.243)				
HTExp			0.321	(0.225)	0.400	(0.258)
ManVA			-0.963	(0.327)***	-1.002	(0.342)***
Dep					-0.167	(0.328)
DeltaDem					0.290	(0.704)
logGdp					0.442	(0.288)
_cons	-5.051	(1.949)***	-3.921	(1.857)**	-4.345	(2.251)*
N	411		346		346	
pseudo R^2	0.331		0.349		0.361	

Notes: Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
_cons is a constant term in the linear regression underlying the logistic regression model

As seen from the table, models 1.5L and 1.7L have the same statistically significant variables at the same significance levels as models 1.5 and 1.7 with the only exception – HTExp (high-tech exports as a percentage of GDP), marginally significant in model 1.5, is not significant when using logistic regression. Model 1.10L is one of the models I have tested to demonstrate that variables insignificant in Cox regression (CR) are also insignificant in logistic regression (LR). Due to differing structure of models used in the two approaches, coefficients produced by them are not directly comparable, and coefficients in LR do not lend themselves to a straightforward interpretation. However, the value of a coefficient and its sign in logistic regression are indicative of the size and direction of the effect. A negative value in LR means reduced probability and corresponds to a coefficient less than 1 in CR. As seen in Table 7.8, the effects of significant variables in LR have the same directions as in the CR. Models 1.5L and 1.7L are consistent with the link test – a test of model specification, which can be used for LR (Stata Corp 2017, pp.1313–1319). Thus, the two different approaches provide highly consistent results.

Although no individual term representing time is statistically significant, collectively they are highly significant, as shown by the Wald test. This demonstrates a critical role of time in determining the probability of RE takeoff. Unlike CR, LR estimates not only changes in probabilities (hazard rates) resulting from a change in a given independent variable, but the probabilities themselves. Figure 7.11 shows probabilities of takeoff in a given year (provided the country has not taken off earlier) for different values of binary variables (EU and NUC20) with all other variables taken at their mean values (so-called "predictive margins").

Figure 7.11. Predictive margins (with 95% confidence intervals) on the probability of RE takeoff in different years



Note: (a) for non-federal vs. federal states; (b) for states with a high share of nuclear energy vs. other states.

The figures show probabilities increasing over time as a result of growing availability of the technology and also differences in probabilities due to differences in some significant independent variables (EU membership and a high share of nuclear energy).

Table 7.9. OECDHI/EU, logistic regression with time variables. Testing for electricity intensity of industrial production

	1.11L		1.12L		1.13L	
t	-0.738	(0.499)	-0.646	(0.525)	-0.802	(0.481)*
t^2	0.055	(0.036)	0.054	(0.039)	0.061	(0.036)*
t^3	-0.001	(0.001)	-0.001	(0.001)	-0.001	(0.001)
EU	3.067	(0.845)***	2.533	(0.646)***	3.353	(0.990)***
NUC20	-1.732	(0.527)***	-1.768	(0.521)***	-1.732	(0.606)***
FED	1.729	(0.582)***	1.157	(0.489)**	1.560	(0.670)**
ManVA	-0.820	(0.258)***			-0.877	(0.298)***
IndElGdp			-0.635	(0.261)**	-0.689	(0.287)**
_cons	-4.058	(1.881)**	-4.276	(1.954)**	-4.527	(1.703)***
N	350		350		350	
pseudo R^2	0.343		0.328		0.368	
AIC	141.060		143.820		138.176	

Notes: Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7.9 presents results of logistical regression for statistical models including electricity intensity of national industrial production (industrial electricity consumption per unit of GDP, IndElGdp). These tests are reported only for logistical regression (and not included in summary tables), because models with IndElGdp do not meet proportionality tests for Cox regression. As seen from the table, IndElGdp when used instead of ManVA has a similar negative effect with a somewhat worse model fit. However, the addition of IndElGdp alongside ManVA improves the model fit, even in terms of AIC, which punishes additional variables.

The results from a range of models for OECDHI/EU countries are summarized in Table 7.10

Table 7.10. Summary of event history analysis for OECDHI/EU countries

Variable code	Variable description	Significance
EU	EU membership	Highly significant in all models, strong positive effect
NUC20	High share of nuclear in the generation mix (>20%)	Highly significant or significant in all models, strong negative effect
FED	Federal state	From significant to highly significant in all models, positive effect
ManVA	Value added in manufacturing as a percentage of GDP	Highly significant in all models, negative effect
HTExp	High-technology exports as a percentage of GDP	Marginally significant only in combination with ManVA in CR, moderate positive effect
logGdpPc	GDP per capita (logarithm)	From insignificant to highly significant, depending on model specification, moderate positive effect

7.6.3 Analysis for non-OECDHI/EU countries

In this section, I apply event history analysis to countries that are neither OECD high-income members nor EU members states (the non-OECDHI/EU subsample). The dataset covers years between 2006 (when the first country from this category – India – takes off) and 2015. It includes observations for 36 countries, but several countries – Bulgaria, Romania, Chile, and Israel – leave the dataset before takeoff due to becoming either EU members or high-income OECD members. Overall, 10 countries from this sub-sample take off by 2015. There are 332 observations in this dataset, but only up to 294 are used for event history analysis, because observations for countries after their takeoff are not used, and some variables are not available for all observations.

Table 7.11. Variables used in RE takeoff analysis of non-OECDHI/EU countries

Name	Description	Mean (SD)	Transformation
Economic			
logGdp	GDP, constant 2010 US$, log10	11.46 (0.51)	SD = 1
logGdpPc	GDP/cap, constant 2010 US$, log10	3.80 (0.45)	SD = 1
Energy system			
Dep	Import dependence of electricity supply, %	14 (22)	SD = 1
DeltaDem	Change in electricity demand over 5 years (relative to the base year), %	29 (22)	SD = 1
FosShare	Share of fossil fuels in electricity production, %	77 (24)	SD = 1
MAJEXP*	Major energy exporter (total energy exports > 30% of TPES) (0 – no, 1 –yes)	0.41 (0.49)	
Political			
Polity	Combined Polity IV score, autocracy–democracy (-10 – +10)	1.34 (7.01)	0 – 1
FED*	Federalism (0 – no, 1 – yes)	0.27 (0.45)	
Vested interests			
HTExp	High-technology exports (% of GDP)	2.53 (5.29)	SD = 1
ManVA	Manufacturing, value added (% of GDP)	15.21 (6.36)	SD = 1

Note: * Binary variables

Variables used in the analysis of non-OECDHI/EU countries are listed in Table 7.11 together with their means and standard deviations. Several variables used in the analysis of OECDHI/EU are not used for non-OECDHI/EU countries. NUC20 does not make sense for this sub-sample (the only country with the share of nuclear energy > 20% in this sub-sample is Ukraine which does not take off within the period in question), as well as EU membership. Political variables include Polity IV democracy score and federalism (systematic data on proportional representation and left–right orientation of the cabinet are unavailable for this sub-sample). Like with OECDHI/EU countries, continuous variables are normalized to the standard deviation of one, so the respective regression coefficient represents the effect of a change by one standard deviation.

Table 7.12. Non-OECDHI/EU, economic, energy system, and political variables

	2.1		2.2		2.3		2.4	
MAJEXP	0.000	(0.000)***	0.000	(0.000)***	0.000	(0.000)***	0.000	(0.000)***
logGdp	8.547	(8.402)**	3.466	(0.998)***	3.659	(1.144)***	3.690	(1.315)***
logGdpPc	0.486	(0.249)						
Dep	1.346	(0.752)						
DeltaDem	0.713	(0.454)					0.873	(0.233)
Polity	9.494	(23.842)						
FED	0.321	(0.262)			0.600	(0.377)		
FosShare	1.255	(0.408)						
N	294		294		294		294	
pseudo R^2	0.460		0.405		0.412		0.406	
AIC	49.717		41.361		44.861		43.230	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

I start with a full model (2.1) that includes all variables except for those representing vested interests (Table 7.12). Both the full model and the best-fit reduced model (2.2) have only two significant variables – MAJEXP and logGdp. Different significant variables from model 2.1 do not become significant and do not enhance model fit when added to the best-fit model individually (as demonstrated for selected variables by models 2.3 and 2.4). This is also true for the variables representing vested interests – see models in Table 7.13 (for a smaller dataset). The Wald test demonstrates that the variables dropped from both full models (with or without HTExp and ManVA) to produce the best-fist model 2.2 are not significant collectively (p-values around 80–90%).

Table 7.13. Non-OECDHI/EU, best-fit model with variables representing vested interests

	2.2a		2.5		2.6		2.7	
MAJEXP	0.000	(0.000)***	0.000	(0.000)***	0.000	(0.000)***	0.000	(0.000)***
logGdp	3.432	(1.005)***	3.328	(0.947)***	3.542	(1.030)***	3.483	(0.965)***
HTExp			0.682	(0.221)			0.763	(0.193)
ManVA			1.170	(0.296)	0.921	(0.206)		
N	249		249		249		249	
pseudo R^2	0.374		0.388		0.375		0.385	
AIC	41.309		46.463		45.245		42.592	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Thus, there are only two statistically significant variables for non-OECDHI/EU countries. One of them is the major energy exporter status, which suppresses the hazard rate to zero (reflecting the fact that no major energy exporter in the non-OECDHI/EU sub-sample undergoes takeoff within the study period). The second one is the overall size of the economy represented by logGdp. An increase in this variable by one standard deviation (corresponding to a three-fold increase in GDP) increases the hazard rate approximately 3.4 times.

Model 2.2 passes the test of PH assumption based on Schoenfeld residuals (no graphical tests are applicable to logGdp, because it is not a binary variable).

Table 7.14. Non-OECDHI/EU, logistic regression with time variables

	2.2L		2.3L		2.4L		2.5L	
t	0.236	(2.448)	0.207	(2.434)	0.185	(2.358)	0.211	(2.356)
t^2	-0.057	(0.429)	-0.051	(0.428)	-0.063	(0.407)	-0.051	(0.414)
t^3	0.008	(0.023)	0.007	(0.023)	0.008	(0.021)	0.007	(0.022)
logGdp	1.555	(0.397)***	1.615	(0.519)***	1.664	(0.507)***	1.524	(0.408)***
Dep			0.171	(0.475)				
DeltaDem					-0.232	(0.344)		
HTExp							-0.484	(0.377)
ManVA							0.138	(0.300)
_cons	-5.027	(3.960)	-5.081	(3.934)	-4.835	(3.770)	-5.026	(3.828)
N	167		167		167		157	
pseudo R^2	0.308		0.309		0.312		0.314	

Notes: standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7.14 demonstrates the application of logistic regression with time variables to the same data. In this method, coefficient for MAJEXP, which works in a "deterministic" manner, is not reported; other coefficients are estimated only for observations with MAJEXP = 0, hence a smaller number of reported observations. The results of LR and CR are in agreement with each other – setting aside MAJEXP, only logGdp is significant (model 2.2L) with a positive effect, and variables insignificant in CR remain insignificant in LR (as demonstrated for selected variables by other models in the table). Results of event history analysis are summarized in Table 7.15.

Table 7.15. Summary of event history analysis for non-OECDHI/EU countries

Variable code	Variable description	Significance
MAJEXP	Major energy exporter (total energy exports > 30% of TPES)	Highly significant in all models where it is estimated, reduces probability of takeoff to zero
logGdp	GDP (log)	Highly significant or significant in all models, positive effect

7.6.4 Analysis for the worldwide sample

Finally, I apply event history analysis to all sixty countries in my sample at once. The dataset covers years between 1989 (Denmark's takeoff) and 2015. It includes observations for 60 countries, of which 37 take off by 2015. There are 1620 observations in this dataset, but only up to 1285 are used for event history analysis, because observations for countries after their takeoff are not used, and some variables are not available for all observations.

Table 7.16. Variables used in RE takeoff analysis of all countries

Name	Description	Mean (SD)	Transformation
Economic			
logGdp	GDP, constant 2010 US$, log10	11.15 (0.58)	SD = 1
logGdpPc	GDP/cap, constant 2010 US$, log10	4.03 (0.57)	SD = 1
Energy system			
Dep	Import dependence of electricity supply, %	14 (22)	SD = 1
DeltaDem	Change in electricity demand over 5 years (relative to the base year), %	29 (22)	SD = 1
NUC20	> 20% of electricity supply from nuclear (0 – no, 1 – yes)	0.22 (0.41)	
FosShare	Share of fossil fuels in electricity production, %	66 (29)	SD = 1
MAJEXP*	Major energy exporter (total energy exports > 30% of TPES)	0.31 (0.46)	
Political			
EU*	EU membership (0 – no, 1 – yes)	0.24 (0.43)	
OECDHI*	OECD membership and high income (0 – no, 1 – yes)		
Polity	Combined Polity IV score, autocracy–democracy (-10 – +10)	4.81 (6.84)	0 – 1
FED*	Federalism (0 – no, 1 – yes)	0.28 (0.45)	
Vested interests			
HTExp	High-technology exports (% of GDP)	2.33 (4.05)	SD = 1
ManVA	Manufacturing, value added (% of GDP)	16.22 (6.22)	SD = 1

Note: * Binary variables

Variables used in the analysis of sixty countries are listed in Table 7.16 together with their means and standard deviations. They include all variables used in the analysis of OECDHI/EU and non-OECDHI/EU countries, except for the three detailed political variables (federalism, proportional representation, and left–right orientation of the executive), which are not available for non-OECDHI/EU. Additionally, the dataset incudes OECDHI (OECD membership and high income), a key variable used in delineating the two main country sub-samples for the analysis. Continuous variables are normalized to the standard deviation of one, so the respective regression coefficient represents the effect of a change by one standard deviation.

Table 7.17. All countries, economic, energy system, and political variables

	3.1		3.2		3.3		3.4	
EU	7.804	(3.365)***	6.987	(3.395)***	7.356	(3.079)***	8.429	(4.098)***
OECDHI	6.533	(3.738)***	6.007	(3.099)***	6.655	(2.957)***	6.751	(3.454)***
NUC20	0.137	(0.081)***	0.199	(0.089)***	0.119	(0.064)***	0.185	(0.079)***
MAJEXP	0.193	(0.131)**	0.249	(0.152)**	0.207	(0.109)***	0.231	(0.141)**
logGdp	2.141	(0.845)*	2.446	(0.923)**	2.501	(0.848)***	2.179	(0.859)**
logGdpPc	1.279	(0.937)						
Dep	0.487	(0.347)						
DeltaDem	1.680	(2.070)						
FosShare	0.546	(0.401)			0.280	(0.152)**		
Polity	1.035	(0.063)						
FED	1.479	(0.580)					1.998	(0.651)**
N	1280		1285		1285		1280	
pseudo R^2	0.308		0.288		0.299		0.298	
AIC	210.500		203.920		202.797		203.234	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A full model (without variables representing vested interests) is shown as model 3.1 in Table 7.17. Model 3.2 retains only variables statistically significant in the full model. However, further tests using dropped variables demonstrate that FosShare and FED are also significant, when added to the reduce model individually (models 3.3 and 3.4). When added together (the model not shown), neither of them is significant individually, but they are significant collectively, as demonstrated by the Wald test. The model using FosShare (3.3) has the best fit.

Table 7.18. All countries, best-fit model with variables representing vested interests

	3.3a		3.4		3.5		3.6	
EU	7.290	(3.020)***	7.161	(3.162)***	7.190	(3.050)***	7.067	(3.035)***
OECDHI	6.276	(2.715)***	5.645	(2.519)***	6.272	(2.712)***	5.680	(2.542)***
NUC20	0.125	(0.068)***	0.151	(0.089)***	0.129	(0.075)***	0.154	(0.087)***
MAJEXP	0.249	(0.134)***	0.203	(0.114)***	0.244	(0.135)**	0.201	(0.112)***
logGdp	2.522	(0.831)***	2.580	(0.907)***	2.501	(0.848)***	2.551	(0.873)***
FosShare	0.309	(0.167)**	0.374	(0.210)*	0.315	(0.178)**	0.377	(0.209)*
HTExp			2.274	(8.011)	0.499	(1.789)		
ManVA			0.954	(0.039)			0.956	(0.039)
N	1049		1049		1049		1049	
pseudo R^2	0.282		0.286		0.282		0.286	
AIC	199.385		202.294		201.359		200.328	

Notes: Exponentiated coefficients; standard errors in parentheses;
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7.18 demonstrates the effect of adding two variables representing vested interests (which produces a dataset with fewer observations). The two added variables (HTExp and ManVA) are significant neither collectively nor individually, but the addition of ManVA makes FosShare marginally significant (instead of significant). Thus, model 3.3 remains the best-fit model. According to the Wald test, variables dropped from the full model to produce model 3.3 are not collectively significant (p-value around 70%).

According to model 3.3, EU membership increases the hazard rate 7.3 times compared to a non-member country, and the OECDHI status additionally increases the hazard rate 6.7 times. A high share of nuclear energy (NUC20) reduces the hazard rate some 8 times, and the status of a major energy exporter reduces the hazard rate approximately 5 times. An increase in logGdp by one standard deviation (which corresponds to an increase in GDP 3.8 times) increase the hazard rate 2.5 times. Finally, an increase in FosShare by one standard deviation (29 percentage points) reduces the hazard rate approximately 3.6 times. All the variables in the model are highly significant (at the level 1%), except for FosShare, which is significant at the 5% level.

Model 3.3 passes the proportional hazard assumption test based on Schoenfeld residuals and graphical tests (see Annex B).

Table 7.19. All countries, logistic regression with time

	3.3L		3.4L		3.7L	
t	-0.563	(0.510)	-0.605	(0.508)	-0.564	(0.509)
t^2	0.054	(0.037)	0.058	(0.037)	0.054	(0.037)
t^3	-0.001	(0.001)	-0.001	(0.001)	-0.001	(0.001)
EU	2.599	(0.598)***	2.797	(0.633)***	2.606	(0.600)***
OECDHI	2.010	(0.519)***	2.115	(0.569)***	2.022	(0.529)***
NUC20	-2.445	(0.656)***	-2.181	(0.571)***	-2.446	(0.658)***
MAJEXP	-1.516	(0.555)***	-1.499	(0.617)**	-1.516	(0.556)***
logGdp	0.573	(0.224)**	0.491	(0.247)**	0.574	(0.226)**
FosShare	-0.305	(0.176)*			-0.307	(0.176)*
FED			0.761	(0.379)**		
DeltaDem					0.018	(0.275)
_cons	-6.709	(1.939)***	-7.127	(1.936)***	-6.720	(1.940)***
N	1285		1280		1285	
pseudo R^2	0.386		0.388		0.386	
AIC	226.076		225.144		228.073	

Note: Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7.19 shows the results of applying logistic regression to the same dataset. Model 3.3L has the same significant variables as model 3.3 with the same direction of effects. The only difference is the levels of significance – logGdp is significant at the 5% level in LR as opposed to highly significant (1%) in CR; FosShare is marginally significant in LR but significant at the

5% level in CR. Thus, CR and LR applied to all countries in the sample cross-validate each other. Unlike CR, a LR model with FED instead of FosShare (3.4L) has slightly better fit than model 3.3L, and FED remains significant at the 5% level. The variables insignificant in CR are also insignificant in LR, as illustrated by DeltaDem in model 3.7L. Thus, LR validates the results of CR. However, the two methods do not provide enough evidence for choosing between FosShare and FED (or using both at the same time). The fact that FED and not FosShare is significant for OECDHI/EU can be seen as an argument in favor of the former variable.

Table 7.20. Summary of event history analysis for all countries.

Variable code	Variable description	Significance
EU	EU membership	Highly significant in all models, strong positive effect
OECDHI	OECD membership and high income per capita	Highly significant in all models, strong positive effect
NUC20	High share of nuclear in the generation mix (>20%)	Highly significant in all models, strong negative effect
MAJEXP	Major energy exporter (total energy exports > 30% of TPES)	Highly significant in all models, negative effect
logGdp	GDP (log)	Highly significant or significant in all models, positive effect
FosShare	Share of fossil fuels in electricity production	From insignificant to significant, depending on model specification, negative effect (insignificant when FED is present)
FED	Federal state	From insignificant to significant, depending on model specification, positive effect (insignificant when FosShare is present)

Table 7.20 summarizes significant results of event history analysis for all countries.

Except for FosShare (share of fossil fuels in electricity generation mix), all variables significant for all countries are also significant either for OECDHI/EU or non-OECDHU/EU countries. At the same time, ManVA (value added in manufacturing) is significant for OECDHI/EU countries but not significant for all countries.

7.7 Summary

Table 7.21 presents a comparison of variables used in defining country groups for the takeoff chart and found significant in event history analysis for different country sub-samples. As seen from the table, all variables used in the chart are found significant at least for one of the sub-sample or are implied in sub-sample definitions for statistical analysis. A discussion and interpretation of the results is provided in the next chapter.

Table 7.21. Comparison of variables used in the takeoff chart and found significant in event history analysis

Variable	Takeoff chart	Event history analysis		
		Full sample	**OECDHI/EU**	**Non-OECDHI/EU**
High-income OECD member (OECDHI)	+	+	In the sub-sample definition	In the sub-sample definition
EU member (EU)	+	+	+	In the sub-sample definition
GDP (logGdp in regression)	+ (Only in comb. with non-OECDHI)	+	–	+
Major energy exporter (MAJEXP)	+ (Only in comb. with non-OECDHI)	+	–	+
Income per capita (logGdpPc in regression)	Implied in OECDHI	–	+/– (and implied in the sub-sample definition – OECDHI)	– (only implied in the sub-sample definition – OECDHI)
Significant share of nuclear energy (NUC20)	–	+	+	-
Federalism (FED)	–	+/–	+	–
Value added in manufacturing as % of GDP (ManVA)	–	–	+	–
High-technology exports as % of GDP	–	–	+/–	–
Share of fossil fuels in electricity generation mix (FosShare)	–	+/–	–	–

Notes: "+" – used in defining groups in the TC or significant in event history analysis; "–" – not used in defining groups in the TC or insignificant in event history analysis; "+/–" – significant in some model specifications in event history analysis.

8 Discussion

8.1 Introduction

This discussion is focused on the empirically-oriented objectives of this thesis: (3) empirical validation of the energy transition mechanisms and (4) using mechanisms for explaining cross-country variations in RE deployment and its global pattern. In section 8.2, I discuss how the comparative longitudinal analysis of the use of nuclear, wind and solar power in Germany and Japan validates the presence and demonstrates the explanatory power of the generic energy transition mechanisms. In section 8.3 I describe how the twelve national case studies of the introduction of new renewables validate and refine specific mechanisms of the formative phase. In section 8.4, I explain which of these formative phase mechanisms can explain cross-country variations in the timing of the introduction of wind and solar power. Section 8.5 formulates "causal recipes" for takeoff for different country groups, summarizing the results of my analysis. The chapter concludes with the discussion of the implications of my analysis for the global diffusion of RE technologies (section 8.6).

8.2 Energy transition mechanisms explaining contrasting energy paths of Germany and Japan

Chapter 5 has demonstrated the application of the mechanism-based approach to a comparative analysis of energy transitions in two countries covering over 30 years and different energy sources. The key results of the chapter with regard to transition mechanisms include the following.

1. The analysis has demonstrated the relevance of the repertoire of mechanisms introduced in Chapter 3 for the explanation of energy transitions spanning several decades and involving different energy sources. Chapter 5 demonstrates that mechanisms can be defined at different levels and specific mechanisms can be combined into more general ones. In particular it shows how generic transition mechanisms can combine into feedback loops. For example, feedback loop B (regime self-reproduction through vested interests – which can also be called a mechanism) is a combination of two mechanisms defined in Chapter 3: 2 (vested interests influencing the state) and 5 (state support of incumbent regimes).

2. Despite the relative complexity of the full scheme of mechanisms used in the analysis and the presence of numerous interacting mechanisms in each country at any given moment, key differences between energy trajectories of the two countries can be explained by differences between specific mechanisms in specific episodes. For example, much earlier and faster

adoption of wind energy in Germany is explained by mechanism 7 (technology diffusion). Germany borders Denmark, the country where wind energy first took off, and the two countries have similar natural conditions, which made Danish turbine designs suitable for coastal areas in Northern Germany.[145] The contrast between Germany's nuclear phase-out decision and nuclear expansion in Japan in the 2000s is explained mainly by the political strength of domestic coal mining industry in Germany compared to the country's relatively weak nuclear industry. An essential pre-requisite of using the causal mechanism approach to its full explanatory power was identifying "mini-cases" of transition using the comparative case logic. Such identification is summarized in Table 5.2 where the overall energy transition processes are broken by technologies and episodes.

3. The comparative analysis has demonstrated interaction between mechanisms characterized by different disciplinary perspectives. For example, stagnating electricity demand (a *techno-economic* factor) in Germany in the 1990s led to the weakening of the *socio-technical* regime associated with nuclear energy and the resulting *political* weakness of the nuclear interests in the early 2000s that resulted in the nuclear phaseout decision.

4. The analysis has also demonstrated the role of transition episodes in constructing mechanism-based explanations. In Germany and Japan different mechanisms were dominating different episodes. Furthermore, the analysis has demonstrated how outcomes of a certain episode become an important explanatory factor in a subsequent one. The chain of events cited as an example in the previous paragraph spans two episodes, and the weakness of the nuclear industry resulting from stagnating demand in the 1990s became important in the political battles of the early 2000s.

Thus, the comparative analysis in Chapter 5 has validated the mechanism-based approach described in Chapter 3 and demonstrated its applicability. The result of the application was "an analytical history" of two national energy transitions spanning more than three decades.

8.3 Formative phase mechanisms in twelve national case studies

Chapter 6 presented twelve national case studies of the formative phase of renewable energy deployment based on secondary literature. The case studies have demonstrated a number of mechanisms identified in Chapter 3, particularly those related to niches.

State motivation driven by supply–demand concerns (mechanism 1F) played a role in most early starter countries both in the OECDHI/EU and non-OECDHI/EU groups. In the former

[145] The theme of wind technology diffusion is further elaborated in the case study of Germany in section 6.2.2, where more detailed evidence of technology diffusion from Denmark is presented.

group, most early starters had a relatively high level of import dependence of electricity supply; in the latter group, early starters were seeking to meet rapidly growing electricity demand.

The case studies have demonstrated various ways in which the state, driven by energy supply concerns and other imperatives, supports emerging renewable energy niches (mechanism 6). These ways included, in particular, tax credits, feed-in tariffs, and direct participation of government as an investor. The cases of Germany, Spain, and India highlighted the role of regional authorities within a federal state in supporting renewable energy niches.

The case studies demonstrate many ways of international influence leading both to policy diffusion (3) and technology diffusion (7): interaction among EU members, particularly through support programmes targeting less-developed regions; wind turbine manufacturer countries financing the installation of that turbines in other countries (India, Egypt) through international development aid; Kyoto mechanisms helping to finance renewable early energy projects (Bulgaria); attempts at direct policy replication (Austrian parliamentarians trying to replicate German policies); as well as technology diffusion (e.g. from Denmark to Germany and later Spain).

In terms of niche innovation and learning (mechanism 8), case studies provide examples of both technology learning (e.g. in Denmark) and policy learning and experimentation (e.g. in Spain). However, the case studies also demonstrate learning processes leading to the formation of national renewable energy deployment systems (Strupeit and Palm 2016) that bring together technology users, providers of equipment, installation services, and financial resources, making use of the national policy context and instruments.

Thus, case studies have demonstrated the presence of mechanisms identified in Chapter 3, particularly those related to the niches, and also the interaction of these mechanisms (e.g. international aid eventually leading to a formation of a domestic deployment system in case of Greece).

Finally, in the conclusion to Chapter 6 I provided a comparative table summarizing the case studies (Table 6.6); the variables in the table were based on mechanisms described above – e.g. import dependence of energy supply, federal organization of the state, or EU membership. Thus, while Chapter 6 is not focused on systematic comparison of national cases, a repertoire of mechanisms has provided a framework for cross-case comparison. The concepts of state motivation and capacity related to some of the mechanisms (particularly 1 and 6 respectively) were extensively used in the analysis. Overall, Chapter 6 further validated the mechanism-based approach by demonstrating the presence of mechanisms identified in Chapter 3, and their use for analysis of case studies. It also demonstrated the variety of specific mechanisms and processes underlying more general mechanisms like technology diffusion or state support.

8.4 Formative phase mechanisms and the timing of introduction of solar and wind power worldwide

The third part of my empirical research aimed to explore whether and how the identified formative phase mechanisms can explain the differences in renewable electricity deployment across countries. I investigated six such mechanisms shown in Figure 7.4. The analysis was conducted by statistical methods (event history analysis) explained in sections 4.4 and 7.6 supported by a set-theoretical exploration (section 7.5) and observations from the case studies (chapter 6). In both statistical and set-theoretical analysis I used the takeoff year (the year when the combined share of wind and solar power reaches 1% of the electricity supply) as the dependent variable. The independent variables for the analysis are listed in Table 7.2 and explained in section 7.3. The following discussion is structured so that the role of each mechanism is defined and explained in terms of statistical significance of the variables linked to this mechanism as well as qualitative observations in the set-theoretical exploration and the case studies.

8.4.1 Mechanism 1F. Formation of state energy goals in response to vulnerabilities of supply-demand balance and domestic non-energy concerns

If this mechanism was important, then countries with higher import dependence, lack of domestic electricity supply options, and rapid demand growth would introduce renewable electricity sooner. Moreover, we could also expect earlier adopters to face stronger challenges of climate change mitigation and have more pronounced left-of-the-center orientation of their governments as well as proportional representation (that would enable environmental and generally more diverse interests to influence energy agenda-setting). However, the empirically observed importance of these variables is somewhat lower than I initially expected, especially for late adopters.

Case studies provide evidence that **electricity demand** growth and **dependence on imported energy** stimulated development of renewables among the pioneering countries. For example, Japan pioneered the development of solar power in the late 1970s as a response to rapidly growing demand for electricity and increasing instability of oil supplies (see Chapter 5). Denmark, the country which led the development of wind power, had one of the highest levels of import dependence of electricity supply and also experienced rapid demand growth

(IEA 2017d). More generally, early starters (see Table 6.6 in Chapter 6) on average tend to have a relatively high import dependence both globally and among OECD and EU countries.

However, **import dependence of electricity supply** has not been captured by the statistical analysis or the set-theoretical exploration as a significant variable in any of the tests. There can be several explanations for this:

1. According to the fundamental assumption of Cox regression, a variable should have the same effect on hazard rate throughout the entire period in question (Cleves et al. 2010). If import dependence plays a significant role for early starters, but then its influence decreases as the availability of RE technologies grows, then its effect may not be captured by Cox regression.

2. While early starters tend to have higher import dependence, this does not mean that all countries with high import dependence tend to start early. For example, Japan and Korea with their high levels of import dependence are among the latest starters in the OECDHI/EU group. In other words, a high level of import dependence may be a *necessary* condition for RE takeoff but not a *sufficient* one. Regression-type tests look for correlational (symmetrical) relations between variables and therefore may not identify asymmetrical ones (e.g. a necessary condition that is not a sufficient one) (Ragin 2008).

Thus, it is possible that import dependence of electricity supply plays a role at the early stages of global RE deployment, likely being a necessary condition for takeoff, but is less significant over the entire analyzed period. The same may apply to electricity demand growth.

The next consideration that may affect state's motivations to develop renewables is the availability of secure domestic alternatives to electricity supply. One variable that measures such availability is a **significant share of nuclear energy** in electricity generation. This variable has a statistically significant and strong negative effect on RE takeoff in all statistical models for OECDHI/EU countries.[146] This is consistent with the case-based evidence and data on individual countries. Out of the seven first countries to take off, six were either non-nuclear countries (Denmark, Greece, Portugal, Austria) that previously had considered nuclear energy deployment or nuclear countries that had scaled down their nuclear expansion plans (Spain, the Netherlands). Denmark, the first country to take off, had a legal ban on nuclear construction introduced in 1985 (Thurner et al. 2017). In Spain, the introduction of a moratorium on additional nuclear construction in 1984 led to an increased focus on the

[146] Other variables related to nuclear energy in the generation mix – percentage of nuclear energy in the mix (continuous variable) and a country's nuclear status (binary variable) – also have a statistically significant negative effect on RE takeoff, when included instead of NUC20 (these tests are not reported in this thesis.)

diversification of energy supply, including RE deployment. The seventh country among the early adopters, Germany, legally decided on nuclear phaseout only in 2001 (Thurner 2017), after the RE takeoff in 1999, but parliamentary discussions of this measure go back to 1980 (Jacobsson and Lauber 2006).

In contrast, three out of the last four longtime OECDHI/EU members to take off – Japan, Korea, and Finland – were not only prominent nuclear countries, but also building new reactor units in the 2000s (IAEA 2017). The fourth country in the later starter group, Switzerland, has a very high share of nuclear energy in its electricity generation mix – around 40% (IEA 2017d) – and also considered the construction of new reactors until the Fukushima incident (see section 6.12).

There is no similar negative effect of nuclear power deployment observed for non-OECDHI/EU countries. On the contrary, the early starters in this group – India and China – combined RE deployment with significant nuclear power expansion in order to meet rapidly growing energy demand.

The effect of high shares of nuclear energy may reflect two causal mechanisms: 1F (formation of state energy goals) and 5F (vested interests associated with nuclear power). Both mechanisms would result in delayed timing of introducing solar and wind power under larger shares of nuclear power and therefore it is statistically difficult to separate them. I further return to this discussion in section 8.4.4 dealing with mechanism 5F, where I argue that high shares of nuclear power are more relevant to state motivation rather than to vested interests.

Another variable potentially related to the availability of domestic electricity supply options is the presence of major energy exports, **"the major importer status"**. Although this variable is highly significant for non-OECDHI/EU countries, it does not necessarily reflect mechanism 1F. Indeed, if countries producing and exporting a lot of oil and gas would consistently have less electricity supply concerns, this variable would be significant for all countries. However, it is *not* significant among OECDHI/EU countries. For example, Australia, Canada, and Norway are all major energy exporters and yet introduced renewables earlier than highly import-dependent Finland, Japan and Korea (all with large shares of nuclear power). Furthermore, exported oil and gas are not necessarily used for domestic electricity production. Even when they are, countries may seek to replace them with renewables and thus increase export revenues. This is particularly important for countries like Russia, where major export revenues come from gas exports and yet a very large fraction of gas is used for domestic electricity generation. I argue that the reason for major exporters not to develop renewables is most likely relevant not to their motivations, but to their capacity for learning and innovation (mechanism 4F, see section 8.4.3).

Among non-energy concerns motivating the introduction of renewables, the most obvious would be climate change mitigation. If this was a significant driver, countries with **higher shares of fossil fuels** in electricity production would be more motivated to introduce renewables. However, statistical tests demonstrate the opposite: countries with higher shares of fossil fuels introduce wind and solar power *later*.

Finally, one could argue that state motivations to introduce renewable electricity for environmental or other similar reasons would be stronger in left-of-the-center governments with proportional representation. National cases provide some examples of the role of these factors in energy transitions: for example the role of Germany's proportional system in the emergence of the Red–Green coalition (Jacobsson and Lauber 2006) and the Socialist government in Spain scaling down the nuclear programme perceived as a legacy of the previous authoritarian regime (Chapter 6). However, there is not enough evidence to conclude that these observations are generalizable, and there are individual episodes demonstrating a positive role of right-wing politicians in the early development of renewable energy, for example the role of conservative politicians in the adoption of Germany's first feed-in tariff. Germany had a conservative government for 15 years leading to RE takeoff,[147] and Denmark had a conservative cabinet for most of the 1980s. Overall, the issue of RE deployment was not particularly politicized at the early stages of the global history of the technology. In all, **proportional representation** and **cabinet orientation** turn out to be statistically insignificant in the event history analysis for OECDHI/EU countries.[148]

Schaffer and Bernauer (2014) report that both proportional representation and left cabinet orientation have a significant effect on the adoption of RE support policies in advanced industrialized countries. The difference between these findings and my results likely reflects the difference between factors driving the adoption of policies and determining their effectiveness (this is discussed in more detail in section 8.5). The finding that certain political factors lead to the adoption of policies but not to the actual outcomes is not unusual. For example, Böhmelt et al. (Böhmelt et al. 2015) find that democratic inclusiveness is positively associated with climate policy output, but not necessarily with emission reductions.

In summary, potential vulnerabilities of supply-demand balance played a certain role in determining the timing of the introduction of wind and solar power. Specifically, high import dependence and demand growth motivated early takeoff in high-income countries which did not have large nuclear power. As global renewable technologies matured this strong

[147] The Red–Green government was formed only in October 1998, whereas Germany's takeoff took place in 1999 – obviously too soon to be affected by the policies of the new government.
[148] These variables were not systematically available for the entire sample.

motivation was no longer needed to overcome barriers and stopped being a differentiating factor. My analysis did not find any evidence that non-energy goals systematically affected the timing of RE takeoff.

8.4.2 Mechanism 2F. State action to support renewables

State goals formed as a result of mechanism 1F are translated into measures to facilitate the introduction of solar and wind power as a result of mechanism 2F. These measures are likely to be effective if the state has higher *capacity* to achieve its goals. Capacity can be measured through economic and institutional variables. Countries with higher capacities consistently introduced renewables earlier than countries with lower capacities.

The most commonly used measure of economic capacity is **income per capita** which I use both as a continuous and as a binary variable (high income status according to the World Bank classification). High income has clearly been an important factor in introducing renewables. For example, the first nine countries to take off between 1989 and 2005 are all high-income countries. The binary high-income status variable is statistically significant for the worldwide sample.[149] At the same time, *within* the sub-samples, the level of income is much less pronounced. Within the OECDHI/EU group, GDP/capita has only a marginally significant effect and only in some models.[150] This is confirmed by qualitative observations: Spain, Greece, and Portugal were among the earliest starters while having the lowest per capita GDP levels among high-income countries. This is generally in line with results of Shaffer and Bernauer (2014) that GDP per capita has marginal statistical significance in certain models explaining the adoption of RE support policies in advanced industrialized countries. This might mean that all countries with high income status had sufficient economic capacity to introduce RE irrespective of their exact level of GDP/capita.

For non-OECDHI/EU countries, per capita GDP has not been statistically significant. Relatively poor countries such as India introduced renewables significantly earlier than relatively richer countries such as Thailand, Malaysia, or Latin American countries. What differentiated non-OECDHI/EU countries was another measure of economic capacity: **the absolute size of GDP.**

Larger GDP allows the state to channel larger funds into RE support measures. Moreover, larger countries might have more diverse industries providing a better manufacturing base for renewable technologies equipment and they also have larger potential markets more attractive for both domestic and foreign investments and equipment manufacturers. The set-

[149] The results for the worldwide sample presented in the thesis include the OECD/OECDHI variable which acts as another proxy for high income and thus masks the importance of GDP/capita on its own.
[150] it is not significant in the models incorporating vested interests associated with manufacturing

theoretical exploration (Figures 7.9 and 7.10) shows that largest countries (India, China, Turkey, Mexico and Brazil) introduce renewables earlier that the rest of the low- and middle-income countries (Egypt being the only exception). The statistical analysis confirms that the economy size (measured by GDP) is highly significant with a positive effect for non-OECDHI/EU countries.

However, the absolute size of GDP is not statistically significant for OECDHI/EU countries. This is in line with the observed takeoff sequence: the early starters include both relatively small (Denmark, Greece, Portugal) and relatively large (Germany, Spain) economies. Shaffer and Bernauer (2014) also report that GDP does not have significant effect on the adoption of RE support policies in advanced industrialized countries.

The introduction of renewables was affected not only by economic, but also by *institutional* capacities. One proxy for such capacities is **OECD membership** that signals the presence of functioning politically stable democracies and market economies. In my analysis, this characteristic was expressed through OECDHI – a composite political and economic variable that combines OECD membership and high-income status according to the World Bank classification. OECDHI has been one of the most significant variables explaining the timing of the introduction of renewables. For example, out of 26 OECDHI countries, 25 have taken off by the end of 2015,[151] whereas only 12 out of 34 non-OECDHI countries have taken off by that date. In the statistical analysis, the OECDHI variable was also strongly significant with a positive effect.

The composite OECDHI variable explains the timing of takeoff better than separate variables of high-income status and OECD membership. This is illustrated by the fact that high-income non-OECD countries (Kuwait, Quatar, Saudi Arabia and UAE) have not taken off by 2015. The middle-income OECD members (Turkey and Mexico) take off relatively late only in 2010 and 2012. In the statistical analysis, the model with the composite variable OECDHI has somewhat better fit than the models with OECD and income per capita (either continuous GDP or binary high-income status) as two separate variables.

8.4.3 Mechanism 4F. National technology and policy learning

This mechanism involves adjustment of initial policies, innovation and experimentation until they become effective in bringing the deployment of renewables to the levels triggering cumulative causation. In parallel it involves experimentation of non-state actors with effective practices, business models and technologies to facilitate widespread deployment of

[151] Korea, the last country of this group, takes off in 2016.

renewables. For example, renewable energy policies have been significantly adjusted over years in Germany (Lauber and Jacobsson 2016), Spain (Dinica 2006) and the UK (Lipp 2007). Similar learning takes place with regard to technologies and "local deployment systems" bringing together various elements of the respective socio-technical systems (Strupeit 2017), and there are numerous actors involved in these processes.

National technology and policy learning depends on the capacities of state and non-state actors involved in this learning. The variables reflecting this capacity are similar to those characterizing state's capacity to introduce effective renewable energy support measures discussed in connection with mechanism 2F (section 8.4.2). In particular, they include economic capacities: **GDP per capita** and the **absolute size of GDP** and institutional capacities: **OECD membership**.

Additional variables reflect the capacities more specifically relevant to learning and innovation within mechanism 4F. The first is the **major energy exporter status**. Literature has been pointing out adverse effects of reliance on export of natural resources, especially oil and gas, on development of countries – the phenomenon known as "resource curse" (Karl 1997). One strain of literature links this to phenomenon to institutional weakness, especially in the institutions not serving leading export-oriented sectors, and underdevelopment of non-export sectors (Karl 1997; Shafer 1994). These factors likely lead to a reduced capability to learn and innovate, both in state authorities and non-leading sectors of the economy. The "resource curse" has been known to affect emerging and developing countries, but not wealthier industrialized countries where energy exports grow in the context of established democratic institutions.

In line with the resource curse theory, I demonstrate a strong negative effect of the major importer status on the timing of takeoff in non-OECD countries. Already at the level of set-theoretical exploration (section 7.5) I show that none of the major exporters outside of OECD takes off by 2015 despite their high per capita incomes. Statistical analysis shows high significance of this variable with strong negative effect for the non-OECDHI/EU subsample, but not for the OECDHI/EU sample. This is in line with the prediction of the resource curse theory that high exports do not impede capacities for governance learning and innovation in established democracies. This also shows that the major importer status variable is relevant to mechanism 4F (and potentially – mechanism 2F) rather than to mechanism 1F (formation of state goals) or mechanism 5F (vested interests), since if it reflected one of the latter mechanisms it would have an effect on both OECD and non-OECD countries.[152]

[152] This finding is in contrast to Baldwin et al. (2016) study which shows that fossil fuel rents (as share of GDP) negatively correlate with shares of renewables in high-income countries. The difference may be due to different

Another variable potentially relevant to national technology and policy learning is **federalism.** In my event history analysis, the federal structure of a state has a significant or highly significant positive effect on RE takeoff in all model specifications for OECDHI/EU countries (where the variable is present). Schaffer and Bernauer (2014) also find a significant positive effect of federalism on the adoption of RE support policies in advanced industrialized countries. Summarizing existing literature, they note that federalism may facilitate environmental policy-making by providing more opportunities for experimentation and policy diffusion within a country.

Indeed, a variety of natural and socio-economic conditions and differences in regional policy frameworks potentially create a diverse field for experimentation and generation of variety in terms of not only policies, but also local deployment systems, whereas the absence of "hard" economic and political boundaries between regions makes it easier for effective models to proliferate. Another aspect of federalism involves deliberate actions of regional governments adopting policies driven by their own imperatives like economic development or security of energy supply. There are two ways in which a combination of federal and regional policies can be more effective than central policies in a unitary state:

1. *More effective implementation of federal policies.* The federal government may adopt a general policy framework, leaving it to regions to determine specific modalities of its implementation (see the example of India's 2003 electricity law in Chapter 6). The regions may come up with solutions better suited to regional priorities and circumstances, and therefore more effective.
2. *Additional policies introduced by regions independently of the federal government.* Regions may also introduce additional RE support policies independent of federal requirements. Different regional policies may reflect regional priorities, and a combination of federal and regional policies may create particularly favorable "niches" for RE deployment. The regional policies in question can be financial incentives, as it was the case with the early "wind boom" in California, where the federal government and the state of California provided comparable amounts of subsidies for wind energy development (Gipe 1995). For example, in Germany and Spain industrial policy favoring RE manufacturers was defined and implemented at the level of individual regions (see Chapter 6).

definition of dependent or independent variable but in any case my observation is more in line with established "resource curse" theories.

Thus, at the formative stage federalism effectively creates spatially and politically delineated niches – regions within a federal state – facilitating national policy and technology learning. The role of certain regions as niches leading the way in RE deployment at the national level is demonstrated by the experience of Germany and India (see Chapter 6). In both countries, there were one or two leading regions at the early stage, and their share was decreasing as other regions were catching up, making the distribution of RE generation across regions more uniform (see Figures 6.1 and 6.3 In Chapter 6). While long-term distribution of RE generation across regions can be highly uneven due to a number of factors (e.g. RE potential, size of regional economy, energy demand), in both cases it was "particularly uneven" at an early stage.

Interestingly, federalism has rarely been included in quantitative studies of RE deployment as an explanatory variable. The study by Schaffer and Bernauer (2014) is the only example known to me. This may reflect a particularly significant role of federalism at the formative stage characterized by active learning and experimentation – the first adoption of RE support policies studied by Schaffer and Bernauer is usually associated with an early stage of national RE deployment. Consequently, federalism may be less relevant at a stage when mature socio-technical systems expand.

In general, the role of federalism is similar to the role of the EU described in section 8.4.5. Although in the country-centered view these factors are associated with different mechanisms (national learning and international diffusion respectively), specific processes behind these mechanisms are similar. While federal regions enjoy a lesser degree of autonomy than states, a federal state can also be thought of as a system of relatively autonomous but interconnected units[153].

The final variable reflecting the capacity for national learning is the **Polity IV democracy-autocracy score**. Functioning democracy enables transparent and accountable search through diverse approaches, identification and adoption of effective solutions, involvement of various state and non-state actors, and functioning feedback. The Polity IV scores are very different in the two subsamples. The mean value for the OECDHI/EU group is 9.8 with very little variation across countries. Within this group, the Polity IV score is statistically insignificant for the timing of takeoff, most likely because high levels of democracy allow for equally effective learning. The mean Polity IV score for non-OECDHI/EU countries is 1.1 with high variance across countries. Interestingly, this score is not statistically significant in this sub-sample as well. For example, the first non-OECD countries to take off are Egypt (Policy IV

[153] Scholars identify elements of federalism in the functioning of the EU, albeit with member states remaining central actors (Pinder and Usherwood 2013).

score –3 in the year of takeoff) India (score 9) and China (score –7). When measured across the worldwide sample of sixty countries this index is also not statistically significant in explaining the timing of takeoff, most likely because its effect is masked by the OECD membership. Therefore this particular measure of democracy does not reflect capacity for innovation and learning necessary for introducing renewables.

In summary, capacities for introducing effective RE support measures as well as for policy and technology innovation and learning are important in determining the timing of the takeoff. The most significant measures of economic capacities are the size of GDP for low- and middle-income countries or high-income status. The institutional capacity is most adequately captured in OECD membership and the absence of major energy exports for non-OECD countries. EU membership can also reflect economic and institutional capacity, but is more relevant to international diffusion and therefore discussed in section 8.4.5.

8.4.4 Mechanism 5F. Vested interests resisting or supporting the introduction of renewables

Economic sectors that can be harmed by the introduction of renewables include energy-intensive industries (due to potential increases in energy prices) and energy producers (due to potential competition or disruption of business models, e.g. for utilities). These industries may lobby against RE support measures. For example, German electric utilities challenged pro-renewable energy policies already in the 1990s when the shares of wind in power supply were far below 1%, whereas some industry associations and labor unions actively supported pro-renewable measures at that time (Jacobsson and Lauber 2006). On the other hand, potential manufacturers of RE equipment may support such policies and thus accelerate takeoff.

In event history analysis for the OECDHI/EU countries, **high-technology exports as a percentage of GDP** has a moderate and marginally significant positive effect on RE takeoff (increase in the hazard rate 1.3 times per increase by one standard deviation) only in some model specifications – when used together with **value added in manufacturing as a percentage of GDP**. The latter variable has a more pronounced negative effect (reducing the hazard rate approximately 2 times per increase by one standard deviation), highly significant in all model specifications. None of these variables is significant for non-OECDHI/EU countries or for the entire sample.

Thus, the positive effect of export-oriented high-technology manufacturing (used as a proxy for RE equipment manufacturing) is less pronounced and less robust that the negative effect of “general” manufacturing potentially interested in lower electricity prices. While Cheon and

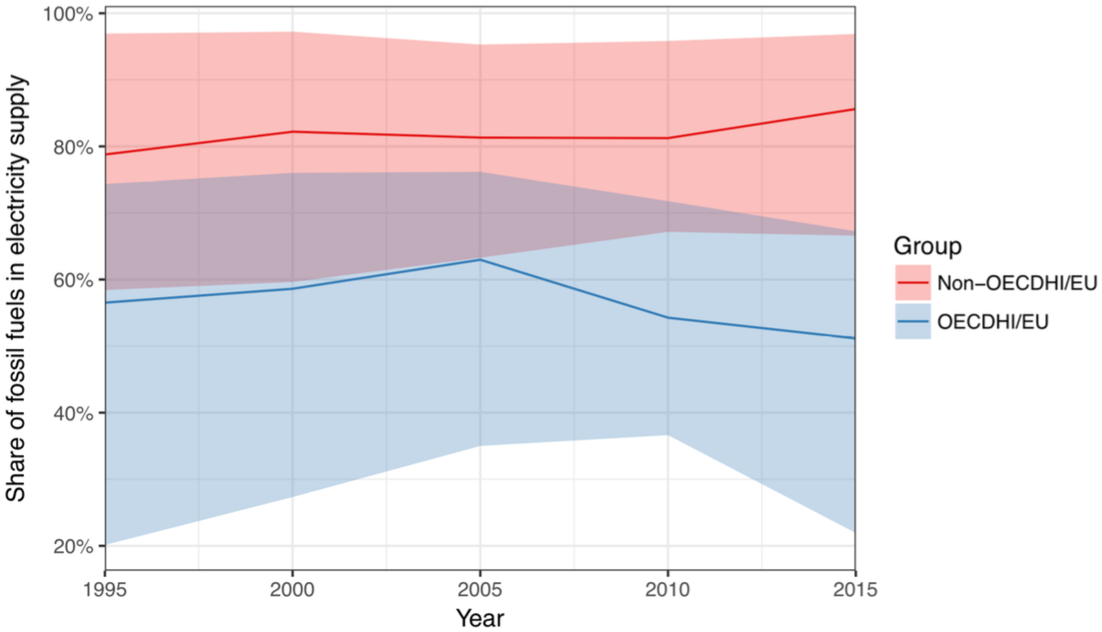
Urpelainen (2013) observed evidence of resistance of energy-intensive industries to RE deployment, they found that the resistance manifested itself as a “countervailing” effect increasing with the share of RES in electricity generation mix. I find that the share of manufacturing plays a significant negative role early enough to affect the time of RE takeoff. While the **electricity intensity of industrial production** cannot be used in Cox regression for technical reasons (it violates the proportionality assumption), in logistical regression it has a similar effect to manufacturing value added and is significant with improved model fit when used alongside manufacturing value added.

The positive role of export-oriented manufacturing observed in several case studies is less noticeable in my statistical analysis. A possible reason is that while this mechanism is clearly present in some early starter countries, these countries comprise a relatively small fraction of countries in the sample. High-income OECD countries that were able to develop an internationally significant wind equipment manufacturing sector include Denmark, Germany, Spain, the US, and, to a lesser extent, Japan (this observation is based on (The Wind Power 2018)). This is just five countries in a sample which, at its maximum, includes 28 countries. Among non-OECDHI/EU countries, significant manufacturing sector has developed only in India and China.

There is another mechanism of RE deployment associated with export-oriented manufacturing – exporter countries financing international aid programmes to facilitate RE deployment in receiving countries. This cross-national mechanism is not investigated in my statistical analysis, but can be observed in case studies for India and Egypt with Denmark, Germany, and later Spain being key donor countries.

Resistance to the introduction of renewable electricity may come not only from the nuclear power sector but also from fossil fuel-based power production. This should be captured by the effect of **the share of fossil fuels** in electricity generation on the timing of takeoff. In some model specifications for all countries, the share of fossil fuels has a strong negative effect (reducing hazard rate some 3.5 times per one standard deviation or 24 p.p.). However, this variable is not significant in either the OECDHI/EU subsample or the non-OECDHI/EU sub-sample. A possible explanation for this is that the share of fossil fuels simply reflects the difference between OECDHI/EU and non-OECDHI/EU countries. Indeed, as seen in Figure 8.1, non-OECDHI/EU countries as a group tend to have a higher share of fossils than the other group. In 2005, median values for OECDHI/EU and non-OECDHI/EU countries were 54% and 75% respectively, means – 63% and 81% respectively. Furthermore, the fact that the distribution for one group is shifted relative to the other one (also for 2005 data) is confirmed by the Wilcoxon test[154] with the p-value less than 1%.

Figure 8.1. Share of fossil fuels in electricity generation mix for OECDHI/EU and non-OECDHI/EU countries



Source: Author's own calculations based on IEA (2017d).

Note: lines represent medians and bands represent interquartile ranges (between the first and the third quartiles).

Thus, the negative effect of the share of fossil fuel may simply reflect the fact that countries with a higher share of fossils take off later; in a sense, acts as a proxy for OECDHI.

Another way of dealing with this problem is revisiting the choice between statistical models – effectively the choice between the share of fossil fuels and federalism as a significant variable. Although the model with FosShare (model 3.3 in section 7.5) has a slightly better fit than the model with federalism (model 3.4), the latter is better consistent with results for individual groups, namely the significance of federalism for OECDHI/EU countries. Furthermore, the alternative statistical method (logistical regression) provides a slightly better fit for a model with federalism. Therefore, a model with federalism is better consistent with other evidence.

[154] The two-sample Wilcoxon test can be used to check whether the distribution of one sample is shifted relative to the other one. Unlike the t-test, the Wilcoxon test makes no assumption about the shape of the distribution (Dalgaard 2008, pp.99-104).

In summary, interests of renewable energy equipment manufacturers may have played a role in a small group of countries, but do not have a systematic worldwide effect on the timing of takeoff. On the other hand, vested interests from electricity-intensive manufacturing may have played a role in delaying the introduction of renewables in OECD countries. Beyond this, there has been no evidence that vested interests systematically affected the timing of takeoff.

8.4.5 Mechanism 3F. International policy and technology diffusion

This is the mechanism of diffusion of policies, technologies, and associated socio-technical practices from the "core" to the "periphery" countries. It has been amply documented in the literature. For example, cross-national influences in the development of FIT as a policy instrument have been documented by Jacobs (2014). Technology diffusion is a similar process, through which technological knowledge, artifacts and practices developed in the core become introduced in the periphery.

My case studies show strong evidence of the role of international diffusion. For example, Germany adopted wind turbine designs from Denmark (Gipe 1995). The failure of such diffusion in Japan is an important factor in explaining the differences between the two countries. Spain, China, and India started the development of domestic turbine industries by licensing design from frontrunner countries (Lewis 2007; Gosens and Lu 2013).

The main variable reflecting international diffusion in the statistical analysis is **EU membership**. It has a strong positive effect on RE deployment in all model specifications used in event history analysis, both for OECDHI/EU countries and for the entire sample. This is corroborated by the fact that the first seven countries taking off were all EU members. They comprised almost half of EU members prior to the 2004 enlargement (so-called EU15). The first non-EU country to take off was New Zealand (2005). The significant role of the EU is in line with the findings of Schaffer and Bernauer (2014), who used event history analysis to explore the adoption of RE support policies in advanced industrialized countries.

There are several specific mechanisms made possible or facilitated by EU (or its predecessor EEC) membership. The common European market and the "four freedoms", including freedoms of movement of capital and goods, likely played a role in most cases, although in different ways for different groups of countries. For early starters that developed their own manufacturing this provided a wider market for the fledging industries. For later starters, particularly the countries that joined the EU in the 2000s, entering the common economic and legal space paved the road for the fast expansion of the RE sector driven by foreign investments from other EU countries.

Other diffusion mechanisms were relevant at different stages of EU-wide RE deployment. At the early stage, EU membership could be a proxy for spatial proximity between countries. This played particularly important role in case of Germany receiving wind technology from Denmark, as demonstrated by the experience of Schleswig-Holstein, a small German state immediately adjacent to Denmark, that was an early leader of wind technology deployment in the country. This is in line with the observation of Hansen and Coenen (2015) regarding the key role of spatial proximity at early stages of technology diffusion.

The next group of early starters were Southern European countries – Spain, Greece, and Portugal – that joined the EEC in 1981–1986 and were "new" members in the 1990s. These countries benefitted from a number of programmes that both provided resources and facilitated the creation of relevant networks. One example of a European programme that contributed to the expansion of RE in these countries is VALOREN (1986–1991), which was aimed at supporting the development of certain less-developed regions of the EEC by exploiting their local energy potential (European Commission 2014b). VALOREN was targeting regions mainly in Spain, Greece, Portugal, and also Ireland. The programme was seen as part of the EEC's regional development policy and did not have a particular environmental focus; while it made a reference to environmental policy and mentioned renewable energy sources, other eligible sources included local lignite and peat deposits (European Commission 2014b). The first feed-in tariff scheme in Europe was introduced in Portugal in 1988 (Jacobs 2012) to make it possible for local energy producers to participate in the programme. In Greece, VALOREN supported some early wind projects on Aegean islands (Kaldellis and Kodossakis 1999); in the late 1980s, many wind projects in Spain were financed by the programme, which was a "gold mine" for local developers (Gipe 1995, p.45).

Early development of wind energy in Portugal benefitted from European R&D programmes providing resources for specific projects, including the mapping of wind potential (Bento and Fontes 2015). These programmes facilitated the formation of national and international learning networks in the wind energy sector. Overall, while the effect of early support programmes was small in terms of installed capacity, they made essential contribution to the formation of national socio-technical systems at the early stages of RE deployment. As discussed in chapter 6, Greek engineering companies involved in EEC-financed wind projects later came to play a significant role in the national wind technology deployment systems.

New EU members in my sample – post-socialist countries that joined the EU in 2004–2007 – include Bulgaria, the Czech Republic, Hungary, Poland, and Romania. All these countries went through RE takeoff within a few years from their EU accession. These countries did not need to experiment with technology or support schemes, which were well-established by that time.

Their rapid RE growth leading to takeoff resulted from the adoption of indicative RE targets in line with the respective EU directive and the integration of their economies into the European common market. This created both motivation and capacity for RE deployment, helping to mobilize foreign capital for the deployment of the technology available at the time. In most cases this led to unsustainable growth characterized by the boom-and-bust pattern.

Another mechanism associated with EU membership is the diffusion of policies, specifically those dealing with RE support. As demonstrated in Chapter 6, development of FIT in Austria was driven by an attempt to replicate the respective German policy, although the resulting scheme turned out to be different. Jacobs (2012; 2014) describes how European countries learned from each other in the implementation of their feed-in tariff policies. He finds that top-down harmonization of policies driven by EU bodies played little role in this process – the EU was unable to codify a specific RE support scheme in its 2001 and 2009 directives – and the main mechanism behind RE support policy convergence in the EU was horizontal coordination between national policy-makers and industrial associations. Tosun (2013) discusses two main mechanisms through which the EU affects policies of its member states – harmonization and international cooperation; in the latter case “the EU merely serves as an instrument for enabling transnational communication” (p. 58), facilitating policy learning. It is international cooperation that played a key role in the diffusion of RE support policies in the EU. Furthermore, EU-sponsored research of the effectiveness of different policies facilitated policy learning through knowledge networks that included scholars, policy advisors and policy makers (Lipp 2007; Haas et al. 2011). While policy diffusion was not constrained by boundaries of the EU, the abundance of bilateral and multilateral ties and the broad similarity of national regulatory frameworks both facilitated information exchange and provided for cross-country applicability of approaches. The only non-EU country that features prominently in the history of experimentation leading to the formation of modern FIT schemes is the US with its PURPA act that guaranteed access of independent producers to the grid (Jacobs, 2012).

In principle, OECD membership can also be associated with the mechanism of international diffusion. However, as discussed in section 7.3.5, OECD does not make binding policies, and most of its publications codifying “good policy and best practice” are available to all states. OECD operates joint energy governance bodies such as the International Energy Agency (IEA), which may facilitate mutual learning not only within their primary focus (fossil fuels), but also in low-carbon energy technologies. OECD members are also more similar to each other in political and economic terms and involved in mutual trade, which may facilitate transfer of business practices, capital, and equipment. However, I assume that the strong effect of OECD membership primarily reflects capacity of its members, as discussed in sections 8.4.2 and 8.4.3.

8.4.6 Mechanism 6F. Global technology learning

This mechanism is a highly aggregated representation of the outcome of diverse learning processes taking place in different countries and contributing to the global innovation system and resulting in gradual improvement of cost-efficiency and peformance of the core technology (e.g. design and materials of wind turbines). In the most general form the effect of this mechanism can be described as decline in cost of RE technology and growth of its availability over time. This reduces the barriers for the technology adoption, making it available for new countries and country groups with less capacity and/or motivation (as demonstrated in the discussion of global takeoff sequence in section 7.5).

Due to the nature of Cox regression which seeks to identify the effects of variables on hazard rates independent of time (Cleves et al. 2010), time cannot be included into a statistical model as a standalone variable.[155] However, I am using **time** as an independent variable in the additional method of event history analysis – logistic regression (LR). All my statistical models for LR include time, time squared, and time cubed to account for possible non-linearity of time effects (Carter and Signorino 2010). In all these models time turns out highly significant, and the probability of takeoff increases with time (see Figure 7.10 for an illustration for one of the models). The role of time is also demonstrated by the global sequence of takeoff (see section 7.5), where new groups of countries start taking off with time, as economic and technological barriers for entry become lower. Overall, this clearly represents the mechanism of increasing availability of the technology due to global learning.

8.5 "Causal recipes" for takeoff in different country groups

This section goes beyond the effects of individual variables and discusses "causal recipes" (i.e. specific combinations of causal factors leading to a given outcome) for takeoff based on combinations of variables for different country groups. The event history analysis has produced two very different sets of explanatory factors for the two groups of countries – OECDHI/EU and non-OECDHI/EU respectively. For the **OECDHI/EU group**, early takeoff is determined by EU membership, absent or low share of nuclear energy in the generation mix, federal organization of the state, and a relatively low share of manufacturing in the national economy.[156] These variables point to the mechanisms of international policy and technology

[155] It still can be included as part of interaction terms.

[156] And/or electricity intensity of industrial production (demonstrated only in case of logistic regression).

diffusion (mechanism 3F), state motivation associated with energy supply challenges (1F), national learning and diffusion (4F), and vested interests (5F). As discussed above, both federalism and EU membership point to the same type of general diffusion and learning mechanism, associated with semi-autonomous but interacting units within a larger space. Economic capacity does not show up in a robust way as an explanatory factor, although GDP per capita is significant in some models. This does not mean that economic capacity is unimportant for RE deployment, but that the capacity associated with the membership in the OECDHI/EU group must be sufficient for an early RE takeoff. A result contrary to the initial expectations is statistical insignificance of import dependence of electricity supply in all models for OECDHI/EU countries. While the variable NUC20 points to the mechanism associated with security of supply, import dependence would demonstrate a stronger link to supply concerns. Furthermore, the cases of early starter countries demonstrate the role of import dependence in their histories of takeoff. Nevertheless, this role is not captured by the statistical analysis (possible reasons for that are discussed earlier in this chapter).

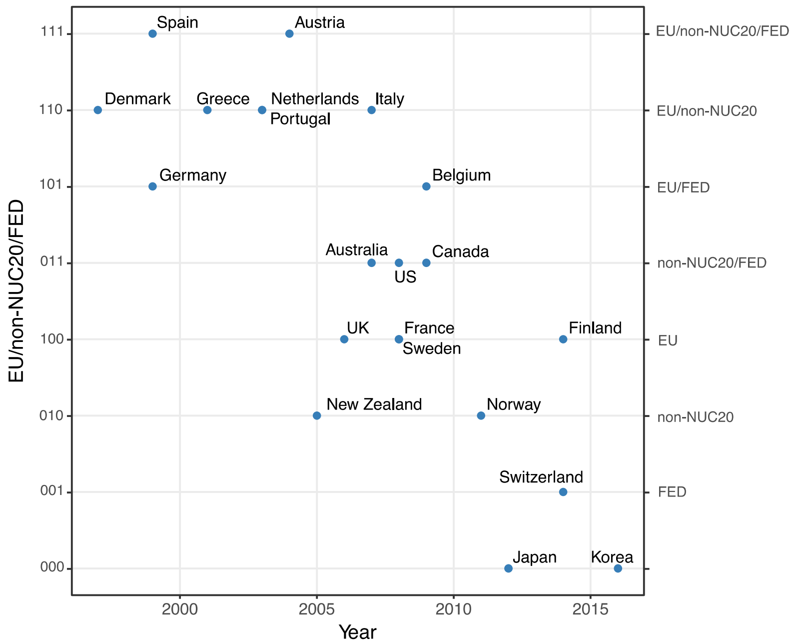
It is interesting to compare the results of my analysis with the results of Schaffer and Bernauer (2014), who used a similar approach – event history analysis based on logistic regression (my auxiliary method) – to study adoption of RE support policies in advanced industrialized countries. Both their method and their sample are close to my analysis for OECDHI/EU countries. While their dependent variable is different (first adoption of a renewable support policy in the country), it may be an element of the formative phase as I understand it and therefore may be related to takeoff. Of the political variables they found significant, EU membership and federalism are also significant in my analysis; the other two variables – proportional representation and ideological orientation of the government – are insignificant. A common feature of EU membership and federalism discussed above is that their effect is not limited to the impact on policymaking – they have serious implications for learning and diffusion, as discussed above. This puts them aside from the other two political variables that seem to lead to the adoption of policies but not their increasing effectiveness in promoting RE deployment. The role of economic variables – income per capita and size of the economy – in their analysis is generally similar to my results. The most significant difference between my results and theirs is in the role of energy system variables. In their analysis, increased shares of nuclear energy and fossil fuels in the electricity generation mix, as well as a higher carbon intensity of the economy all make the adoption of RE policies more likely. In my analysis, a high share of nuclear energy power makes takeoff less likely, whereas the share of fossil fuels (which also can be seen as a rough proxy of carbon intensity of electricity sector) is insignificant in my analysis of OECDHI/EU countries. Again, this difference may stem from the difference between the adoption of policies and their effect – in terms of section 2.8, Schaffer and Bernauer study the causal link 2 (from socio-economic and political context to policies), whereas I study the combined effect of links 1, 2, 3 (from socio-economic and political context to RE deployment, possibly but not necessarily through policies). For example, in Schaffer and Bernauer's dataset (Fig. 2 in their article), such countries with a significant proportion of nuclear energy as Switzerland and Hungary are among early adopters of RE support policies, but they are among late starters in terms of actual takeoff (the case of Switzerland taking off as late as in 2014 is particularly striking in this regard).

To relate the results of the event history analysis to the observed takeoff sequence, I am presenting a simple and highly stylized three-factor model. This model is applied to the countries that were members of OECDHI/EU by the early 2000s[157] – a set roughly coinciding with the one used to explore RE growth rates in Appendix A. The model includes three binary variables out of the four listed above – EU membership, a share of nuclear energy, and federalism. The share of manufacturing is not included, because incorporating a non-binary variable in such a model would be difficult. Possible combinations of three binary variables define eight country groups, and I am calculating a probability (hazard rate) for each group relative to a chosen baseline group. In doing so, I am using coefficients for the respective variables from the event history model (based on these three variables only). For example, if positive value of FED increases the hazard rate 4 times compared to the negative one, and the baseline group is "no EU membership/NUC20/no federalism", the hazard rate for the group "no EU membership/NUC20/federalism" is 4 times higher. Figure 8.2 present the countries with their levels and takeoff dates.[158] The order of levels is representative of the relative hazard rates, but the distance between them is not – they are spaced equally in the figure.

[157] Countries joining this group in the 2000s would be exposed to the factors for a shorter time, which would affect the timing of their takeoff in a way not consistent with this simple stylized model.

[158] Denmark taking off 10 years earlier than the next country is shifted in time closer to other countries to make the figure more compact.

Figure 8.2. Takeoff probability levels defined by three binary variables vs. actual takeoff sequence



Note: Ones and zeros at the y-axis designate the presence or absence of three explanatory factors – EU membership, absence of a high share of nuclear energy in the generation mix, and federal organization of the state (in this particular order).

If the three-factor model was perfect and deterministic, the takeoff order would follow a step function progressively descending from the upper left corner to the bottom right one – the countries at the topmost level were the first to take off and so on. Although the actual model is based on a statistical analysis implying a probabilistic process, one can see that the countries follow a general descending pattern in their takeoff sequence.

Most other countries in the OECDHI/EU group of the sample of sixty countries are **new EU members**. For them, the "causal recipe" for takeoff would be very simple – they take off soon after their EU accession as a result of their joining a single economic and regulatory space, which often leads to the "overheating" of the RE sector and the boom-and-bust cycle (see section 6.2.10 for further discussion).

The results of the analysis for **non-OECDHI/EU** are completely different – the statistical models for the two country groups do not share a single significant variable. According to the results of the event history analysis, there are only two significant variables for non-OECDHI/EU countries – the size of the economy measured by GDP (mechanism 2F associated with the state's capacity for RE support) and major energy exporter status (also predominantly related to mechanism 2F, as discussed above in this chapter). The latter variable works in a deterministic manner (no major energy exporter in the non-OECDHI/EU group had taken off by the end of 2015), so it effectively divides this country group into two further subgroups. Within the non-major exporter subgroup, the only variable determining takeoff sequence in my analysis is GDP. There is no need to build illustrative models to demonstrate the role of these variables – the role of these variable is immediately seen in the observed takeoff sequence. Two countries out of the three first non-OECDHI starters are the largest economies within this group (China and India).[159] All non-OECDHI countries taking off by 2013 (with the exception of Egypt) have their GDP above the certain level (700 bln 2010 US dollars), and all non-OECDHI countries having this GDP level take off by 2013. Thus, the combination of high GDP with the absence of the major importer status is the causal recipe for earlies takeoff for non-OECDHI/EU countries. In fact, this is a necessary and sufficient condition of takeoff by the year 2013 (Egypt being the only country violating the necessary condition). Presumably, this variable determines economic capacity for the countries below the World Bank's high-income threshold, although this takeoff pathway becomes available only later in the process of global learning leading to increased technology availability. As seen from the case studies and analysis of energy system data, growing electricity demand (mechanism 1F, formation of state goals in response to energy challenges) is a major driver of RE deployment for this group of countries that often seek do develop all energy sources available to them at once. However, rapid demand growth is a commons feature of most countries in this group (see section 7.4 on sample), so this is not a factor setting early starters aside from other countries in this group.

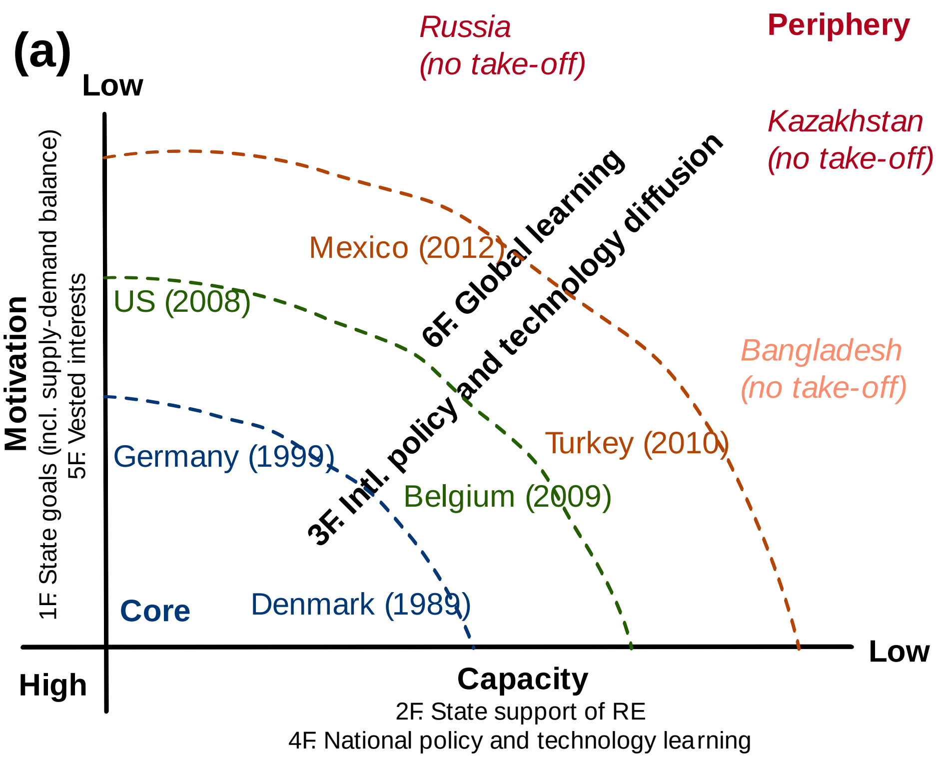
8.6 Global diffusion of renewable energy technologies

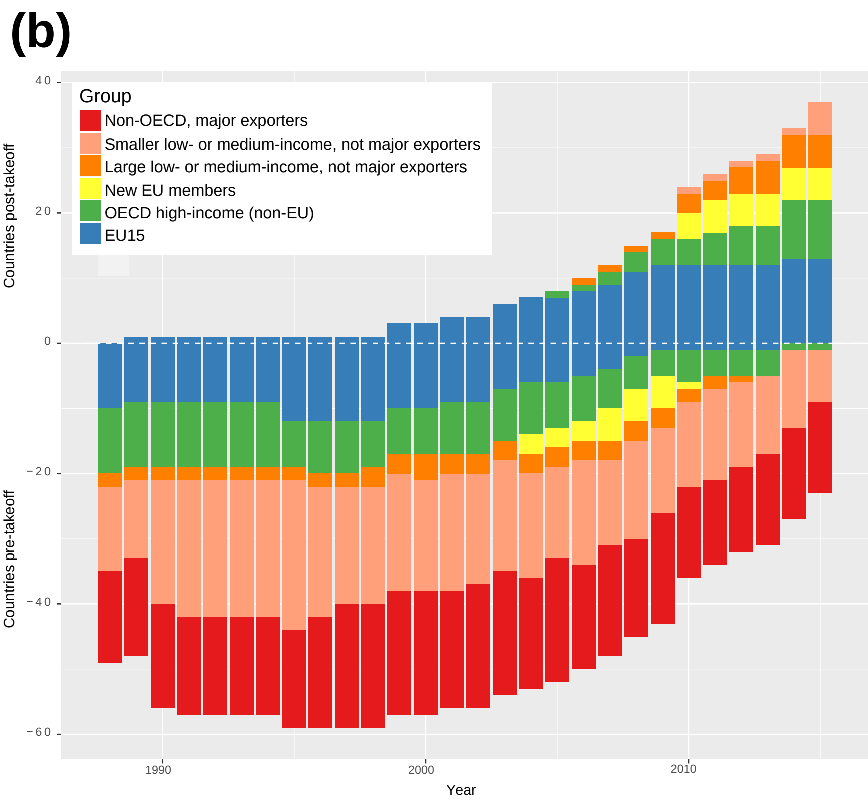
This section discusses some implications of the analysis in Chapters 5–7 for global technology diffusion. An important question in this regard is what places a country in the core or the periphery of the global diffusion process. First, the analysis demonstrates that the notions of core and periphery are relative. For example, Denmark effectively was the core for diffusion of wind technology in Western Europe (e.g. in Germany and Spain), but the leading European countries then became the core for the diffusion outside Europe, be it OECD members like New Zealand or major emerging economics like India and China. Later adopters that have been able to build their own RE equipment industries then act as secondary or tertiary centers of diffusion (e.g. Indian Suzlon providing turbines for projects in Australia and Brazil). In general, this process resembles the hierarchical process of spatial diffusion described by Hägerstrand (1967) (see section 2.3.4).

[159] The third one is Egypt, whose early takeoff relied on resources provided by external donors.

Second, the analysis demonstrates the role of national capacity and motivation in defining whether a country is in the core or the periphery. In a stylized form, this role is demonstrated by Figure 8.3(a). Early starters have both high motivation and high capacity; a country with high motivation and lower motivation and a country with lower motivation and high capacity may take off at the same time; countries with low motivation may take off later than countries with high motivation but much lower capacity. Figure 8.3(b) shows the global sequence of takeoff and key factors determining it.

Figure 8.3. Global diffusion, national motivation, national capacity, and takeoff sequence





Note: (a) Global diffusion, national motivation and capacity. (b) Global sequence of takeoff and country groups (see discussion of Figure 7.10 in section 7.5 for the explanation).

The global diffusion can also be characterized in terms of country groups. Both the statistical analysis and the set-theoretical exploration have demonstrated major differences across these groups. In terms of the takeoff sequence, industrialized countries of Western Europe, particularly those with relatively high import dependence of electricity supply, are the first to achieve a significant share of RES in their generation mix. They are followed by other industrialized countries, and then by emerging and developing economies, starting with the largest ones. While these groups overlap in terms of takeoff times, this sequence is observed for the most countries in the groups. There are also more specific country groups not used in my large-N analysis but observed in case studies. One of them is three Southern European countries – Spain, Portugal, and Greece – which shared many political and economic similarities, generally followed similar trajectories, and had takeoff times close to each other. For global energy modeling, country groups delineated in terms of political and economic characteristics can provide a practical middle way between global modeling and resource-intensive modeling of each individual countries.

Several further observations deal with the nature of increased availability of RE technology due to global learning. As a result of this process, the barriers to adoption have become not only quantitatively "lower", but also less complex in qualitative terms. The design of my statistical study does not allow to explore the changing role of different factors over time. However, the difference between two groups – OECDHI/EU and non-OECDHI/EU – starting earlier and later in time respectively provides some insight into the nature of this change. The "takeoff recipe" for the former includes several factors – EU membership, federalism, share of nuclear energy, and share of manufacturing. The recipe for the latter group is simpler – it includes only the size of the economy (presumably a cruder form of the national capacity than those related to income per capita or federalism) and the major exporter status acting in a deterministic manner. This also demonstrated by case studies, where histories of early starters are usually longer, more complex, and include more factors than those of later starters (e.g. Bulgaria or Thailand).

8.7 Summary

This chapter relates the results of the empirical analysis presented in Chapters 5, 6, and 7 to the conceptual framework and objectives of the thesis. It explains how the comparative case study of Germany and Japan validates the generic mechanisms of national energy transitions and identifies new mechanisms. It re-visits the findings of the twelve national case studies identifying more specific mechanisms of the formative stage of renewable electricity adoption. It summarizes the results of case studies and the large-N analysis to show how some of these mechanisms can be used to explain differences in the timing of introduction of wind and solar power across countries (Table 8.1).

Table 8.1. Importance of formative phase mechanisms in explaining the difference in the takeoff timing

Mechanism	**The role and importance in determining the timing of takeoff**
1F. Formation of state goals	**Somewhat important for early adopters** **High import dependence** motivates early takeoff in OECDHI countries **without large nuclear power**. This mechanism stops being a differentiating factor as technology matures No evidence that non-energy goals systematically affect the timing of RE takeoff.
2F. State support to renewables 4F. National policy and technology learning	**Important for all groups and periods** **High income status** in combination with **OECD membership** significantly accelerate takeoff. **Large GDP** accelerates whereas major energy exports impede takeoff in non-OECD countries. **Federalism** facilitates national learning in OECDHI/EU countries, particularly at the early stages of global deployment. No evidence for importance of democracy or other institutional values (beyond OECD and possibly EU membership). GDP per capita is not important beyond designation of high import status.
5F. Vested interests	**Marginally important for early adopters** **Energy intensive manufacturing** slows down takeoff. Little evidence for other vested interests
3F. International diffusion	**Critically important** **EU membership** dramatically accelerates takeoff.
6F. Global learning	**Critically important** Takeoff becomes increasingly likely with the passage of **time**

9 Conclusion

This thesis was inspired by the need to develop more realistic scenarios of global long-term energy transitions which are important for climate change mitigation. Such scenarios would require an improved understanding of energy transitions which is nationally differentiated, empirically grounded, and goes beyond only technical and economic factors, integrating insights from relevant social sciences. The aim of this thesis was to contribute to the development of such an understanding. This Conclusion starts with explaining how this aim was achieved through fulfilling the four objectives formulated in Chapter 1. Then it outlines contributions of this thesis to various bodies of literature discussed in Literature Review (Chapter 2) and Conceptual Framework (Chapter 3) and the use of these literatures in my research. Subsequently it describes the limitations of the thesis and outlines further research agenda.

9.1 Fulfillment of the thesis objectives

The first objective of this thesis was *to develop a conceptual approach to integrating different bodies of knowledge explaining energy transitions*. The approach that I propose is based on two pillars. The first pillar is three disciplinary perspectives on energy transitions: techno-economic, socio-technical, and political. On the one hand, the three perspectives are associated with three distinct types of co-evolving systems involved in national energy transitions: energy flows and markets, energy technologies as socially embedded phenomena, and energy policy systems. On the other hand, they are associated with three disciplines: energy economics, socio-technical transition studies, and political science (see Table 9.1).

Table 9.1. Three perspectives on energy transitions with associated systems and disciplinary roots

Perspective	**System**	**Disciplinary roots**
Techno-economic	Energy flows and markets	Neoclassical economics, energy economics, energy systems analysis
Socio-technical	Energy technologies embedded in socio-technical systems	Sociology and history of technology, socio-technical transition studies, evolutionary economics
Political	Political actions and energy policies	Political science, political economy, policy studies

Although other scholars have pointed either to several bodies of knowledge dealing with energy transitions (e.g. Grubb 2014; Geels et al. 2016) or to several co-evolving systems involved in sustainable or technological transitions (e.g. Freeman & Louçã 2001; Foxon 2011), the conceptualization of the three perspectives based on the idea of three co-evolving system is a contribution of this thesis. Furthermore, it proposes the first framework of this kind which explicitly includes both political science and energy economics.

The second pillar of my approach is the idea of causal mechanisms of energy transitions. This constitutes a conceptual innovation because mechanism-based approaches (Tilly 2001; Little 2015) have not been applied to energy transitions. The mechanism-based explanations have several advantages:

- They are particularly well-suited for analyzing such complex social phenomena as energy transitions because it allows both for a degree of regularity at the level of individual mechanisms and for diversity of outcomes due to different combinations of mechanisms.
- Furthermore, the causal mechanism approach allows integrating heterogenous bodies of knowledge comprising the three perspectives, another conceptual contribution of the thesis. The methods for bridging different analytical approaches suggested before (Turnheim et al. 2015; Geels et al. 2016) were based a case-by-case approach, whereas the mechanism-based approach allows a more general integration allowing for the accumulation of knowledge (Little 2015).

The two pillars of my approach are related to each other. Causal mechanisms operate both within individual systems and connect different systems, leading to their co-evolution. Different types of systems are studied within different disciplinary perspectives. Specific lower-level mechanisms are usually theorized within a particular perspective – even if the explanatory factors and outcomes they connect belong to different systems, the mechanism itself is explained within one of the perspectives. However, the analysis of more complex mechanisms, such as the high-level mechanism of "increasing returns", may require contributions from several perspectives.

The second objective of my thesis was t*o identify generic mechanisms of national electricity transitions*. These mechanisms were first presented in Chapter 3 (Figure 3.3), then refined and supplemented through case studies in Chapter 5 (Figure 5.10) and Chapter 6, in the latter case focusing particularly on the formative phase.

Each of the individual mechanisms has been theorized in different bodies of literature. The contribution of my thesis is that I present a comprehensive repertoire of mechanisms bringing together different disciplinary knowledge. As I demonstrate in the thesis, additional energy transition mechanisms can be added to the framework. In this sense the mechanism-based framework is an "open" one, allowing for cumulation of knowledge when new insights can be added without wiping out the existing constructs.

My third objective was to *validate and refine the identified mechanisms using national case studies.* The first case study was a comparison of long-term dynamics of nuclear, wind, and solar power in Germany and Japan (Chapter 5). It confirmed the applicability of the proposed conceptual and methodological approach by demonstrating its explanatory power. It validated and provided additional details of seven generic mechanisms of national electricity transitions and identified two additional (lower-level) mechanisms. It also demonstrated that different mechanisms play roles at different periods (episodes) of a transition. Finally, it produced novel insights on the difference in electricity transitions between the two countries, rejecting single-factor explanations of this difference dominating the existing literature.

Subsequently, the thesis analyzed twelve cases of adoption of wind and solar (PV) energy in their initial ("formative") phases (Chapter 6). The cases included both early and later adopters representing different country groups. Once again, the mechanisms of transition at this stage were identified and discussed. My contribution was to show that such mechanisms are similar across a wide range of countries. At the same time the analysis demonstrated that learning mechanisms are more pronounced and diverse in early adopter countries. It also paid particular attention to cross-national interaction, identifying mechanisms underlying international technology diffusion and roles of individual countries in the global uptake of technology.

The fourth objective was *to explain the timing of deployment of wind and solar power across a global sample of countries in terms of the transition mechanisms.* This analysis was conducted through a combination of a set-theoretical exploratory analysis and formal statistical methods supported by the twelve case studies analyzed in the previous step.

To explore the beginning of sustained growth of renewable energy, I developed an analytical model combining the concepts of a logistic curve (S-curve) and the formative stage of technology deployment. Though the concept of S-curve was used to compare growth rates of different technologies (e.g. Wilson 2012), it has not been previously used for structuring cross-country comparisons, especially with respect to the timing, rather than speed, of technology adoption. Using this model, I demonstrated that it was analytically possible to disentangle two parameters: the time of the beginning of sustained growth and the rate of this growth.

This model allowed me to introduce a novel variable, which I call "the takeoff year" (the year when the combined share of solar and wind power for the first time exceeds a given threshold, in my case 1% of the total electricity supply) and which was used in the subsequent statistical analysis and set-theoretical exploration as a dependent variable. Such a variable has never been used in a cross-country analysis of renewable energy adoption. This methodological innovation allowed me to study the formative phase mechanisms separately from mechanisms of the growth and saturation phases.

Through my analysis of the worldwide sample of countries, I have demonstrated how mechanism-based understanding of transitions can be instrumental in explaining national differences in deployment of renewable energy. This demonstration was based on the assumptions that similar mechanisms support the introduction of renewables in all countries, but that their relative strength and importance differ from one country to another. These differences stem from differing motivations, capacities and interactions of actors involved in each mechanism. My next methodological innovation has been identifying, using case studies, accessible characteristics of the countries which reflect capacity, motivation and interaction of actors in transition mechanisms. These characteristics were used as independent variables in my analysis.

Using the takeoff year as the dependent variable, I carried out a set-theoretical exploratory analysis of the timing of deployment of wind and solar energy. I have been able to divide the 60 countries of my sample into 6 distinct groups which were different both in the timing of takeoff and in the independent variables characterizing the formative phase mechanisms. These groups are presented in Figures 7.9 and 7.10, which visualize a clear sequence of adoption of renewables in different groups of countries.

Additionally, I conducted a statistical study of the relationship between the takeoff timing and the characteristics of the formative phase mechanisms using event history (survival) analysis. This was my methodological innovation because such statistical techniques have never been previously applied to the deployment of renewables, in part because such deployment has always been seen as a continuous process, not as a discrete event. Another innovation was to use Cox regression supplemented by logistic regression to ensure robustness of my findings.

The case studies, the set-theoretical exploration, and the event history analysis consistently highlighted the role of specific causal mechanisms in the timing of takeoff across countries. The differences in the timing across countries were primarily shaped by the mechanisms of international policy and technology diffusion, state action to support renewables, and national policy and technology learning.

My research highlights an exceptional role of the European Union in facilitating the mechanism of **international diffusion** of renewables. Effectively, the EU has functioned as a giant "innovation machine" allowing experimentation and innovation in relatively protected national niches and rapid spread of successful policy, technology and business innovations across a large market. This argument resonates with the theories of economic historians Jones (2003) and Mokyr (2017) explaining the leading role of Europe in the industrial revolution and the origins of modern economic growth. They point out a unique combination of fragmentation and unity historically characterizing Europe. While being politically fragmented as a "system of states" (Jones 2003), the region featured a great deal of cultural and intellectual unity. Furthermore, to a large extent it functioned as unified market area for goods and factors of production. Although in Jones' and Mokyr's theories the main driving force of innovation was geopolitical competition between states, the idea of relatively autonomous but interconnected units as a favorable environment for experimentation, learning, and diffusion of innovations can be productive without this assumption. Autonomous units provide a variety of conditions – effectively a set of "niches" – where a successful innovation may emerge and then spread across the larger system, and different elements of a socio-technical system (e.g. technology design and policy design) may emerge in different units.

While international diffusion convincingly explains the earlier takeoff among EU members, beyond the European Union the difference between countries is primarily due to the capacities of state and non-state actors involved in two domestic mechanisms: the **state action to promote renewables** and **national policy and technology learning**. According to my findings, this capacity is predictably higher among high-income OECD members. Among non-OECD countries, major energy exports impede, and large economy sizes boost these capacities. Somewhat surprisingly I find that the size of GDP per capita or the level of democracy do not play a significant role either within the richer or the poorer countries. Finally, I identify and explain the role of federalism in facilitating learning among earlier adopters. Both EU membership and federalism point to the role of a certain "network configuration" (cf. Rogers 2003) – a system of autonomous but connecting units – for learning, experimentation, and diffusion of innovations in policy, business, and technology domains.

Two more mechanisms play a relatively smaller role in explaining the difference across countries. One of them is **the formation of state goals** in response to import dependence of supply, which motivated early takeoff in high-income countries which did not use a lot of nuclear power. As global renewable energy technologies matured, this strong motivation was no longer needed to overcome barriers and stopped being a differentiating factor. Nevertheless, the last high-income OECD countries to take off were the countries that expanded their nuclear sector in the 2000s or seriously considered such an option. My analysis did not find any evidence that climate protection or other non-energy goals systematically affected the differences in the timing of RE takeoff. Neither did I find evidence that constitutional arrangements such as proportional representation or government's ideology affected the timing of takeoff.

The fifth mechanism that I investigated was the **action of vested interests to support or slow down** the deployment of renewable energy. Through the case studies I have found that interests of renewable energy equipment manufacturers may have played a role in a small group of early starter countries, but my statistical analysis did not identify a systematic worldwide effect of this factor on the timing of takeoff. On the other hand, vested interests associated with electricity-intensive manufacturing may have played a role in *delaying* the introduction of renewables in OECD countries. Beyond this, there has been no evidence that vested interests systematically affected the timing of takeoff.

Finally, the overarching mechanism that affected the deployment of renewables in all countries was **global learning** leading to the improvement of core wind and solar power technologies and reduction of their costs at the global level, making them more accessible even in countries with weaker motivations and capacities. This was manifested in the increasing probability of takeoff over time, but also in the changing nature of factors impacting the timing of takeoff among earlier and later adopters. I have illustrated the latter phenomenon by conducting the event history analysis for two distinct sub-samples: high-income OECD members and/or EU members (OECDHI/EU counties) and all other countries in my sample (non-OECDHI/EU countries).

The countries within the first, **OECDHI/EU** group introduced renewables earlier due to their higher incomes and effective governance. Within this group, countries were differentiated by the conditions for technology and policy diffusion (EU membership), state goals (related e.g. to import dependence or a larger share of nuclear power), vested interests (e.g. electricity-intensive manufacturing), and the presence of federalism. As renewable energy technologies matured, high income and effective governance stopped being the limiting factors for their introduction and all the above-listed characteristics (except EU membership) stopped being differentiating factors.

At the same time, as renewables became accessible to countries outside the first group of the most advanced economies, they were differentiated by two less "sophisticated" **capacity** factors, which my study has identified through a separate analysis of the second sub-sample (countries which are neither EU nor high-income OECD members). The first capacity factor relates to the size of the economy: the early adopted among low- and middle-income countries were the largest economies, most likely because they were capable to mobilize sufficient resources (public funds, domestic and international investments) to support protected niches for renewables at early stages of their development. The second capacity factor relates to "resource curse", institutional weakness in resource-rich energy exporters leading to the lack of effective governance for innovation. I show that none of major energy exporters, despite their relatively high income, have managed to cross the takeoff threshold by 2015.

9.2 Contributions to literature

Through achieving its objectives, the thesis contributes to several bodies of literature summarized in Table 9.2.

The literature explaining various types of transitions through the interaction of several co-evolving systems (section 3.1) has provided one of the two pillars of my conceptual framework. My contribution to this literature is the identification of the three systems involved in national energy transitions – energy flows and markets, energy technologies, and policy systems - and the three disciplinary perspectives focusing on each system – techno-economic, socio-technical, and political.

Table 9.2. Use of literature in this thesis and its contribution to different bodies of literature

Literature/section	Main uses	Key contributions	Secondary contributions
3.1. Co-evolving systems	A pillar of conceptual framework	Identifying three systems involved in national energy transitions and associated disciplinary perspectives	
3.2. Causal mechanisms	A pillar of the conceptual framework	Applying a mechanism-based framework to energy transitions Identifying generic mechanisms of transitions in national electricity systems	Cross-country comparison of mechanisms based on capacities, motivations and interactions of actors
2.2. Models of energy transitions and neoclassical economics	General motivation for understanding global technology diffusion Foundation of the techno-economic perspective (conceptual framework) Elucidating specific mechanisms (e.g. demand growth and convergence)		Stylized facts about global takeoff sequence (in terms of country groups)
2.3. Technology diffusion	Component of the socio-technical perspective (conceptual framework) Logistic curve as a technology diffusion model Concepts of formative and sustained growth phases The concept of core-periphery diffusion underpinning cross-country analysis	Identifying factors defining the core and periphery of the global diffusion Demonstrating the global diffusion mechanism underpinned by national-level mechanisms	Operationalizing the boundary between the formative phase and sustained growth phase for the purpose of cross-country analysis of renewables
2.4. Innovation systems and local deployment systems	Component of the socio-technical perspective (conceptual framework) Concepts of learning and experimentation Concepts of formative and sustained growth phases Secondary sources for case studies (Chapter 6)		A mechanisms-based method for cross-country comparison of innovation and local deployment systems

Literature/section	Main uses	Key contributions	Secondary contributions
2.5. Regime–niche studies, lock-in and increasing returns	Component of the socio-technical perspective (conceptual framework) Concepts of niche and regime Focus on niche-level developments in case studies (Chapter 6) Increasing returns mechanisms		A mechanisms-based method for structured comparative analysis of niche-regime transitions through analysis of capacities, motivations and interactions of relevant actors Investigating support of niches and incumbent regimes as different avenues for state actions aimed at the same goals
2.6. Spatial perspective	Concept of proximity Use in case studies (especially early starters)		Highlighting importance of semi-fragmented polities (EU and federal states) for spatial technology diffusion
2.7. Policy and politics in energy transitions	Foundation of the political perspective (conceptual framework) Concepts of state goals and vested interests, advocacy coalitions, increasing returns, policy diffusion Identification of variables for case-studies and large-N analysis	Demonstrating that policy innovation and learning occurs as a part of transition in a broader socio-economic system	Highlighting the role of policy diffusion and policy learning in energy transitions.
2.8. Multi-country comparisons	Methodological insights, independent variables and data sources, initial hypotheses for the large-N analysis	Using the takeoff year as the dependent variable in the analysis of RE deployment Applying event history analysis to RE deployment Developing a method for selecting variables on the basis of mechanisms (through motivation, capacity, and interaction)	Identifying factors accelerating or slowing down the uptake of renewables (GDP size, EU membership, presence of major imports)

The literature on causal mechanisms in social sciences (section 3.2) is the source of the second pillar of my conceptual framework – causal mechanisms as a mode of explaining energy transitions. My contribution to this literature is the identification of the generic mechanisms of national energy transitions and the incorporation of mechanism-based approaches into different research methods, both qualitative (case studies) and quantitative (statistical analysis). The entire conceptual framework contributes to the tradition of detailed qualitative case studies of energy transitions by proposing a method to structure such case studies according to (a) causal mechanisms of energy transitions; (b) three disciplinary perspectives on energy transitions; and (c) specific transition episodes. This approach allows for the cumulation of heterogeneous knowledge, i.e. adding additional incremental insights from different disciplines to the already existing explanatory schemes. This approach can complement other ways of structuring analyses of energy transitions as in the multi-level perspective (MLP) literature. The mechanisms of energy transition can be instrumental in explaining phenomena at the niche-, regime- and landscape- levels as well as interaction between levels as demonstrated by the comparative analysis of Germany and Japan (Chapter 5).

The idea of substantive difference between the formative phase of technology deployment and the sustained growth phase, central to my approach, is based on several bodies of literature – on technology diffusion (section 2.3), innovation systems (section 2.4), and regime and niche (section 2.5). Eventually, this distinction helped me to disentangle two questions – how early does sustained growth of renewable energy start and how fast is that growth – and to treat them as two relatively independent problems, focusing on the former. It also has led to the idea of "takeoff" seen as an outcome of the formative phase and an event in time, which is essential to my research (see below for more detail). These bodies of literature also provided a foundation for the socio-technical perspective on transitions and helped to identify the respective mechanisms involving diffusion and learning. A secondary contribution to the innovation systems literature is tracing numerous linkages between national innovation and deployment systems (Chapter 6) collectively underpinning the global innovation system.

The literature on policy and politics in energy transitions (section 2.7) provided a basis for the political perspective on energy transitions and, consequently, for the identification of certain generic mechanisms (related to the formation of state goals and vested interests). My secondary contribution to this literature is demonstrating the role of policy learning and diffusion in the early deployment of renewable energy. However, contrary to the assumption typical of many cross-country studies (section 2.8), I do not view policies as the key driver of

RE deployment. Instead, I demonstrate how policy innovation, learning, and diffusion take place in a broader socio-technical system in parallel to technology learning and diffusion. The literatures on technology diffusion (section 2.3) and policy innovation and diffusion (section 2.7.2) were instrumental to establishing this parallelism.

The literature on Integrated Assessment Models (section 2.2) was a source of initial motivation for my research project, as explained in the Introduction (Chapter 1). Furthermore, the principles of neoclassical economics and resource economics embodied in such models have provided a foundation for the techno-economic perspective and helped to identify a number of transition mechanisms (e.g. related to resource depletion, costs of technologies or energy demand convergence).

The literature on technology diffusion (section 2.3) supplied the concept of the logistic curve underpinning my conceptual model relating diffusion stages and mechanisms. My contributions to the diffusion literature include the identification of factors defining the core and the periphery of global diffusion and a method of characterizing global diffusion in terms of differential takeoff times and visualizing it (the "takeoff chart", Figure 7.10). My analysis of the worldwide sample of largest electricity producers not only explains the difference between countries, but also identifies a global pattern based on the understanding of national mechanisms. The thesis shows that by identifying recurring mechanisms at the national level it is possible to both explain national specifics and uncover global regularities in technology adoption and diffusion. In essence, it demonstrates how a global-scale mechanism (technology diffusion) emerges as a sum of national-level mechanisms (e.g. state action, policy and technology learning) and interactions between countries. Although this thesis is primarily focused on the national level, its contributions can facilitate better understanding of global climate and energy futures, which was its initial inspiration.

The analysis of cross-country studies (section 2.8) helped me to identify gaps in existing studies and provided insights into methodological approaches and hypotheses typically used in such studies. My thesis makes several important methodological and empirical contributions to this literature. The first contribution is proposing a more coherent set of hypotheses based on causal mechanisms and rooted in socio-technical and energy systems in addition to political analysis. Secondly, having defined "takeoff" as an event and its year as the dependent variable, I for the first time apply event history analysis to renewable energy deployment (and not policy adoption). Empirically, I show the importance of some of the factors identified in the previous literature such as the EU membership, but I also show that many other variables previously used (e.g. ideological orientation of the government or the quality of democracy, beyond the basic distinction associated with OECD or EU membership) do not explain the difference in the timing of renewable electricity takeoff. I also show the importance of variables (such as the size of the economy) not identified in earlier studies. The thesis also goes beyond the traditional methodology associated with the causal mechanism framework, which is primarily focused on case studies (Little 2015) and is cautious about large-N analysis. The concepts of actors' capacity, motivation, and interaction characterizing mechanisms of energy transitions is both a conceptual contribution to the literature on mechanisms and a methodological contribution to cross-country studies (where these concepts can be used to relate mechanisms to specific variables).

The spatial perspective on transitions (section 2.6) made my analysis sensitive to spatial aspects of diffusion and regional patterns of diffusion within federal states. This has led to a number of observations regarding the role of spatial proximity at the early stages of global diffusion and specifics of technology diffusion in semi-fragmented policies (both the EU and federal states).

9.3 Limitations

The research presented in this thesis has several limitations resulting from its methodological choices. The first two limitations relate to sampling. To begin with, the qualitative case studies were dominated by early adopters and wealthy democracies. The detailed case study of Germany and Japan was naturally limited to two large wealthy democracies. Although the twelve case studies analyzed at the second stage of my empirical research expanded the circle of countries, it was still largely limited to high income democracies and primarily relied on secondary English-language sources. The omission of latecomers (e.g. major energy exporters and low-income countries beyond India) might have contributed to less accurate account of transition mechanisms in these societies. For example, my tentative conclusion that late adoption of renewables in major exporters is primarily due to their low institutional capacity could be either confirmed or rejected by qualitative studies of those countries.

The sample for the large-N analysis included both developed and developing countries, both pioneers and laggards in solar and wind power adoption. However, it focused on 60 largest electricity producers. This was because the marker of the end of the formative period used in this thesis ("takeoff date") cannot be used for smaller countries, where the crossing of the 1% threshold may result from singular events (e.g. intervention of an international aid agency) and therefore may not be representative of the ability of the renewable energy sector to sustain itself. Although these countries collectively account for some 5% of the global electricity supply, the analysis of the formative phase and its outcome in these countries is an important and interesting research enterprise not least for analyzing the future of renewable energy, where many of these presently small systems (such as the ones in Africa) may dramatically grow.

The next two limitations related to the choice of the dependent variable for the large-N analysis: the year in which the combined share of wind and solar power first reaches 1% of domestic electricity supply. Choosing the combination of wind and solar power rather than studying these technologies separately was a deliberate analytical choice explained in Chapter 4. It has reduced uncertainties arising from the geographic conditions of wind and solar deployment as well as the interaction between these technologies in policy processes. However, it has introduced a potential problem resulting from the different timing of global maturity of solar and wind power. In particular, it makes it difficult to interpret takeoff dates in countries where solar power has taken off before wind power (Switzerland, Japan, Korea, Israel, Thailand among others). In my regression analysis the later takeoff in these countries may over-emphasize the role of the EU membership (none of them are EU members) or large nuclear power deployment (in Switzerland, Japan and Korea) where it may simply reflect poor geographic conditions for wind and the later global maturity of solar power. Much more extensive statistical analysis would be required to disentangle these variables.

More broadly, inclusion of other new renewables such as modern biomass, geothermal and tidal power could provide more refined insights. For example, Finland – a relative late-comer in terms of wind power – uses a large amount of biomass for electricity generation, which may explain its lower interest in other renewables. However, such an inclusion would require much more sophisticated analysis of geographic preconditions for deploying various kinds of renewable energy. Nevertheless it could be attempted in further studies.

The methodological choice of choosing 1% of solar and wind share as the takeoff threshold is also a simplification potentially limiting my study. Cumulative causation and self-sustaining regimes might emerge at both lower and higher levels of deployment depending on the specific country's conditions and other factors. (I already mentioned this issue with respect to smaller countries). It is possible to imagine a more sophisticated research that would use different takeoff thresholds (based on qualitative case analysis) for different groups of countries and thus provide more granular findings about the end of the formative stage. The final two limitations relate to the choice of independent variables and interpreting the results of the large-N analysis. The independent variable used in the event history analysis are in some cases not sufficiently refined. For example, the index of democracy (Polity IV score) used in the thesis does not have much variance among OECDHU/EU countries, but there exist more specific indices of the quality of governance, e.g. those compiled by the Quality of

Government Institute (Dahlberg et al. 2018), which have much larger variance across this group.

In interpreting the results of the large-N analysis it was difficult to separate some transition mechanisms at the level of statistical analysis, because they were characterized by the same variables. For example, the mechanisms of state support and national learning were characterized largely by the same variables of capacity of national actors. The mechanisms of state goal formation and vested interests could be characterized by the same variables or energy resource endowments (exports) and availability of domestic supply sources (nuclear power). A more detailed qualitative analysis or more sophisticated independent variables would be necessary to distinguish between these mechanisms.

9.4 Further research agenda

The thesis opens several avenues for further research. Some of them would focus on overcoming the limitations listed above (e.g. analysis of smaller countries or wind and solar power as separate technologies). Another avenue is continuing investigation of wind and solar power beyond the formative period. In section 7.2 and Annex A I demonstrate at the exploratory level that the formative period is followed by exponential growth driven by "cumulative causation" or "increasing returns". This is in line with the large body of scholarship pointing to the generally similar rates of growth of similar technologies after their formative stage. The logical next step would be to understand the growth phase, particularly factors that determine the different rates of growth in different countries and in different time periods.[160]

Exponential growth of renewables in a particular country is going to eventually reach a qualitatively different phase of energy transition which I call "substitution". More specifically, when the constantly accelerating absolute rates of renewable energy growth exceed the rate of growth of electricity demand, renewables will start not only *supplementing* but also *substituting* other energy sources, forcing their gradual decline or phase-out. This process is likely to trigger an additional mechanism of political resistance from conventional energy sectors that will be directly exposed to competition with renewables.

So far, substitution has been observed in a limited number of early starter countries (high-income OECD countries) against the backdrop of stagnating electricity demand (see Figure 7.6). But it will likely spread to other regions as the growth of solar and wind power there accelerates to catch up with demand growth. This gives rise to several research questions.

[160] This would extend the work of Gosens et al. (2017).

First, does substitution trigger much stronger resistance and thus slows down the growth of RE? Second, which of the incumbent sectors are likely to be forced into phase-out first (e.g. low-carbon nuclear or high-carbon coal)?

Another question deals with the timing and nature of the inevitable slowdown of the exponential growth, which can result from economic and technical constraints, resistance of vested interests, market saturation, and other factors. The history of solar and wind energy deployment so far has provided numerous examples of such slowdowns, one example being the bust phase of the boom-and-bust cycles in new EU member countries (see section 6.2.10). These processes deserve further analysis, both qualitative and quantitative.

Another direction of future research is to go beyond solar and wind to other energy technologies essential for saving the climate. Beside the expansion of wind and solar and power in the electricity sector, these may include, for example:

- other low-carbon electricity technologies such as nuclear, ocean, geothermal and biomass;
- electrification of transport;
- expanded use of biofuels in transport, heating and other sectors;
- energy efficiency and other demand-constraining technologies and interventions in the end-use sectors (buildings, transport, industry);
- reduction of greenhouse gas emissions in agriculture;
- contraction of carbon-intensive sectors such as coal;
- carbon capture and storage;
- electricity storage; and
- carbon dioxide removal (CDR) technologies including through land use and forestry.

Each of these components might feature mechanisms different from those identified in this thesis, but even when the mechanisms are similar, their combinations and therefore outcomes may be different. Future research would be necessary to identify these mechanisms and explore how they unfold in time defining the temporary and spatially different patterns of transition.

The final and more ambitious direction of future research is to improve the current analysis of global energy and climate futures. This analysis would differentiate regions and countries not only by their energy demand and available energy resources as in current IAMs, but also by whether they are likely to be earlier or later adopters of new technologies taking into account not only technical and economic but also social and political factors. For example, country groups similar to those identified in my thesis can offer a practical middle way between reliance on global macro-regions and incorporation of individual countries in the building of global scenarios. In this way understanding mechanisms of energy transitions and the interaction of techno-economic, socio-technical and political factors would eventually result in more realistic scenarios of reducing the risks of climate change.

Annex A. An exploration of the growth rates of wind and solar power deployment to contribute to the identification of the takeoff threshold

The purpose of this analysis was to contribute to identification of the takeoff threshold. The concept of renewable energy takeoff explained in Chapter 3 defines it as the boundary between the formative and the sustained growth phases of renewable energy deployment. These phases are characterized by different patterns of growth rates: the formative phase has unstable and erratic growth while the sustained growth phase has exponential growth. Thus by measuring growth rates we can point to the time of takeoff.

The analysis was conducted on 20 countries which were high-income members of OECD in 1995. These include 13 out of 15 "old" EU member states as well as Australia, Canada, Japan, New Zealand, Norway, Switzerland and the United States[161]. This relatively homogenous group was selected to separate the characteristics of technological growth from the political and economic characteristics of countries. Yet countries in the group possessed sufficiently diverse features (e.g. geography and structure of energy systems) so that they included such pioneers in RE as Denmark and such relative laggards as Japan and Switzerland. The time period of the analysis was 35 years between 1981 (the year immediately following the historically first year the IEA recorded a non-zero wind power generation in the first country – Denmark) and 2016, the latest year with data available.

The growth in the deployment of wind and solar power was measured as the ratio in generation in a given year to the generation in the previous year minus 1. This measure could be zero (if the generation from SW power remained the same), positive, or negative. For example, the growth rate in Greece in 1993 was 4.88 and in 1994 it was –0.21. If no wind and solar energy was deployed in the previous year, the data point was discarded from the analysis since the relative growth would not be possible to calculate.

Subsequently, the data for each country were separated into three periods:

- when the deployment of solar and wind (SW) power was below 0.125%;
- when the deployment of SW power was above 0.125% but below 1%; and
- when the deployment of SW power was above 1%.

[161] Iceland and Luxembourg were excluded from the general sample because of their small size.

For each period and each country, a variety of statistical indicators were calculated (Table A1). The analysis demonstrated several differences in the statistical properties of the growth rates between the three periods.

The first of these differences is in the temporal volatility of growth rates in individual countries. This volatility can be explored by calculating standard deviations (SD), which shows how much the growth rates vary from one year to another, and relative standard deviations (RSD, the ratio of SD to the median value) across years for each country. Table shows that both values significantly decline between the first and the second period and experience a further (albeit less pronounced) decline in the last period. The average SD declines by almost four times from 1.21 when SW shares are less than 0.125% to 0.34 in the 0.125–1% period and drops by further one-third to 0.24 in the period when SW shares exceed 1%. The RSD declines from almost 2, on average in the first period, to around 1 in the last two periods. Thus, **the growth rates in individual countries are more volatile** when the SW shares are under 0.125%.

The lower part of Table A1 illustrates another important observation, namely convergence of median growth rates across countries from earlier to the later periods. The range of median growth rates narrows about two-fold (from 0.00–1.88 to 0.15–1.13) from the first period to the second one. It narrows further four-fold (to 0.10–0.37) in the last period. The standard deviation of median growth rates calculated across countries drops about five-fold from **0.43** when SW share is less than 0.125% to **0.26** when SW share is between 0.125% and 1% to **0.09** when SW share is above 1%. Thus, after the SW share exceeds 1%, its growth rate shows less temporal volatility and **becomes more similar across countries**.

Table A1. Volatility across years and variation across countries of SW growth rates in OECD countries in 1981-2016

Share of solar and wind		< 0.125%	between 0.125 and 1.00%	> 1.00%
Volatility across years				
Growth rates	Min	-0.21 (GR in 1994)	-0.08 (Finland in 2006)	-0.16 (Norway in 2016)
	Max	7.17 (US in 1983)	2.08 (Norway in 2000)	1.78 (Greece in 2000)
Standard deviation across years	Min	0.21 (Switzerland)	0.10 (Japan)	0.12 (Switzerland)
	Max	4.53 (Japan)	0.96 (N.Zealand)	0.43 (Greece)
	Average	1.21	0.34	0.24
Relative standard deviation (standard deviation divided by the mean)	Min	0.50 (Germany)	0.19 (Switzerland)	0.49 (Austria)
	Max	22.42 (US)	6.07 (N.Zealand)	2.82 (Greece)
	Average	1.94	1.10	1.05
Variation across countries				
Median growth rates	Min	0.00 (Greece)	0.15 (Belgium)	0.10 (N.Zealand)
	Max	1.88 (Germany)	1.13 (Greece)	0.37 (Sweden)
	Median	0.36	0.43	0.25
Standard deviation of median growth across countries		0.43	0.26	0.09

Source: Author's own calculations based on IEA (2017d).

In summary, this analysis shows that with respect to high-income OECD countries:

- **The temporary volatility of growth rates declines** with time stabilizing when the SW share exceeds 0.125%;
- **The variation of median growth rates across countries decreases** significantly after the SW share exceeds 1%, falling in the corridor of 10-40% per year.

Annex B. Graphical tests of the proportional hazard assumption

This annex presents tests of the proportional hazards assumptions for selected statistical models estimated in section 7.6 using Cox regression – model 1.7 for the OECDHI/EU sub-sample and model 3.3 for the entire sample.

Model 1.7

Figure B1. Graphical tests of the PH assumption: log-log plots for model 1.7

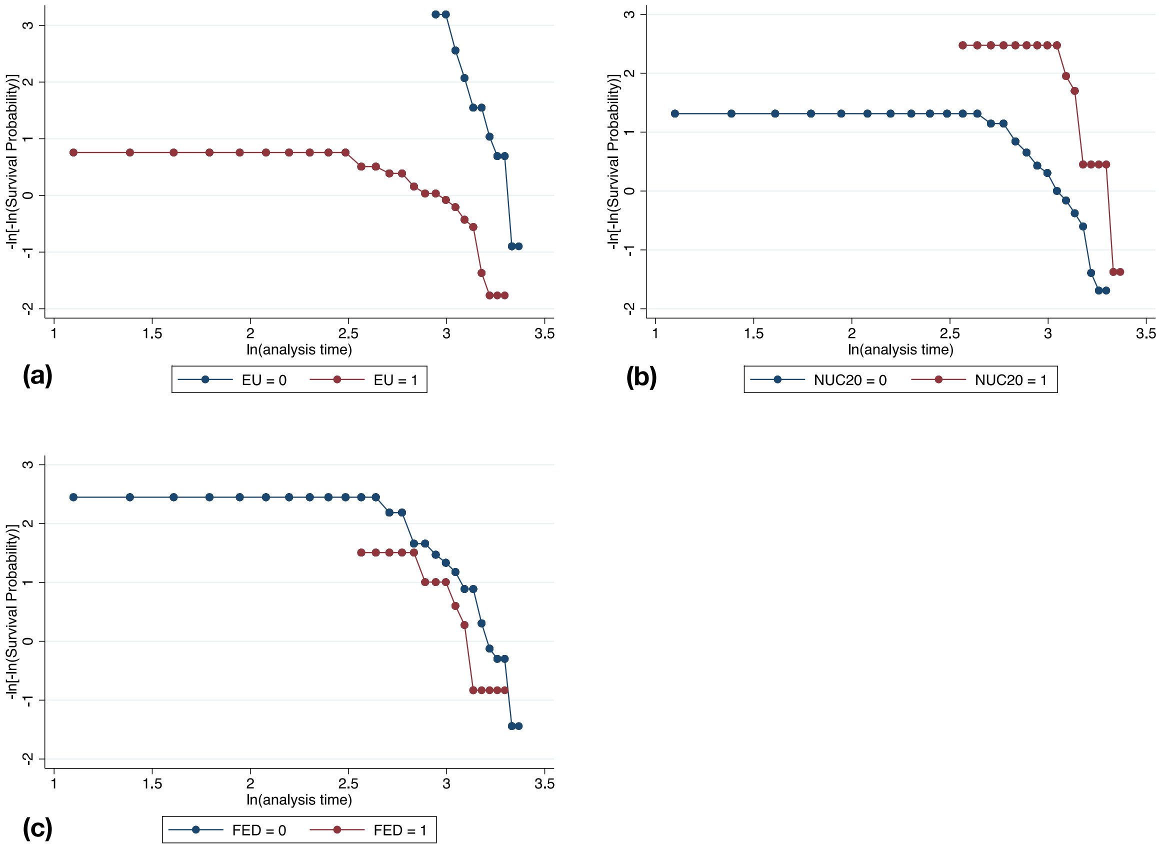


Figure B2. Graphical tests of the PH assumption: Kaplan-Meier and predicted survival plots for model 1.7

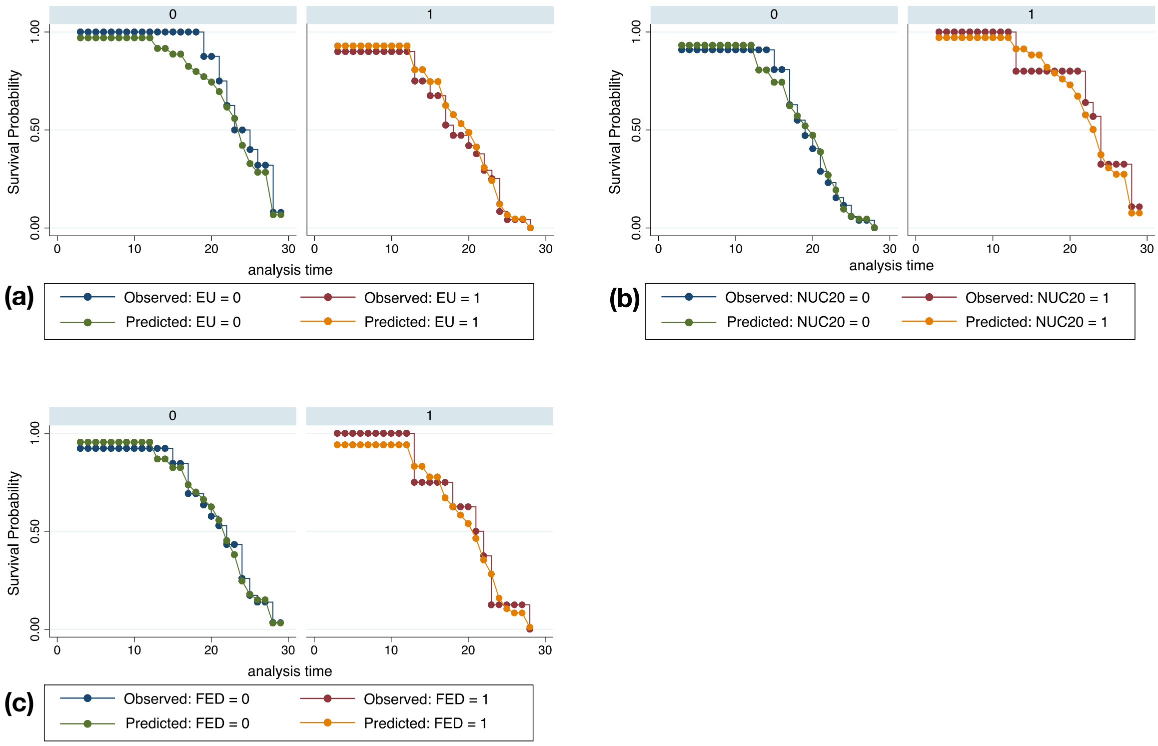


Figure B1 presents tests based on log-log plots for the three binary variables included in model 1.7 (the graphical tests cannot be applied to continuous variables). Ideally, the curves corresponding to two values of a variable (0 and 1) should be parallel; crossing curves signal a severe violation of the PH assumption (Cleves et al. 2010). While curves for EU (a) an NUC20 (b) are not perfectly parallel and somewhat converging, they clearly do not cross. The curves for FED (c) are close to each other, but generally parallel.

Figure B2 shows tests based on Kaplan-Meier curves and predicted survival plots. If the PH assumption holds (Cleves et al. 2010), the Kaplan-Meier curve representing empirically observed events and the plot of predicted events should be close to each other; this is generally true for all three variables. This, given positive results of the test based on Schoenfeld residuals, model 1.7 is generally consistent with the PH assumption.

Model 3.3

Figure B3. Graphical tests of the PH assumption: log-log plots for model 3.3.

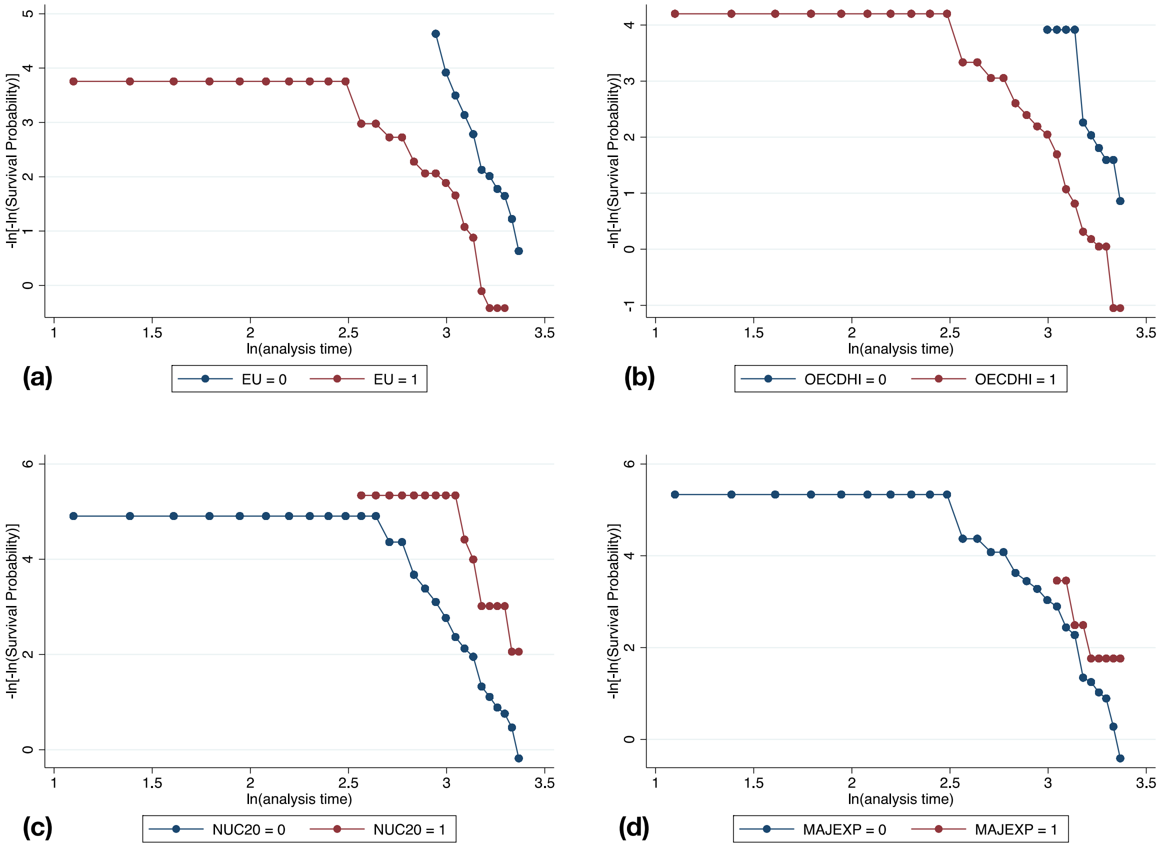
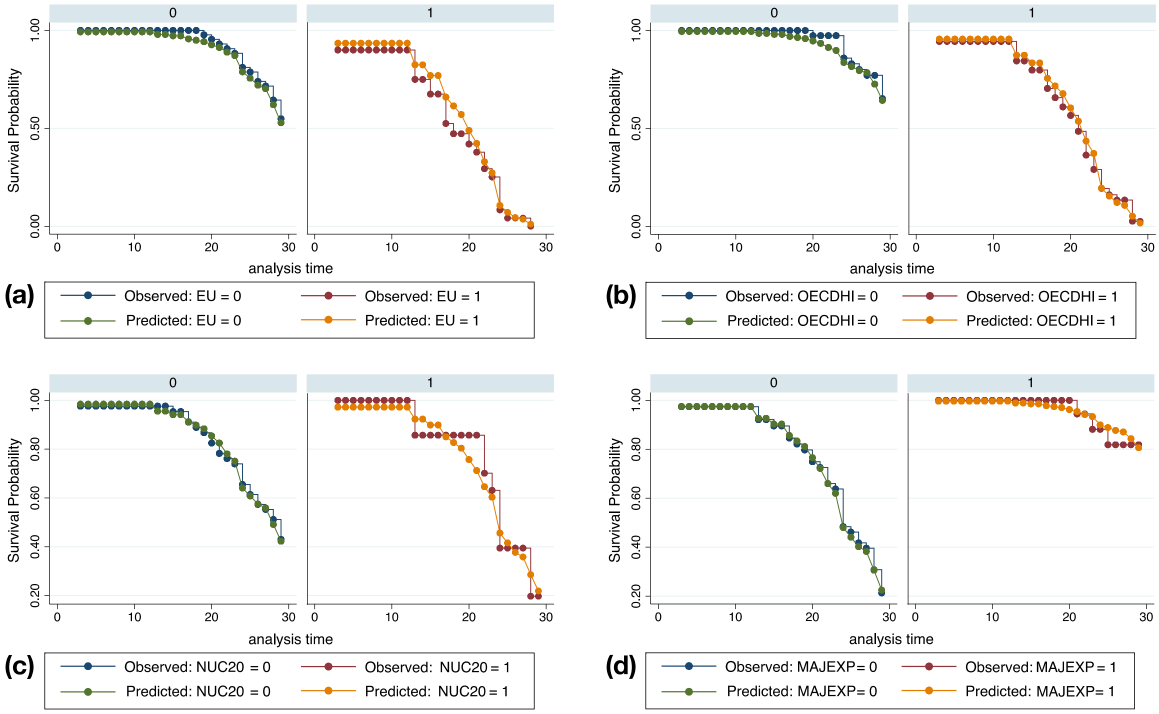


Figure B4. Graphical tests of the PH assumption: Kaplan-Meier and predicted survival plots for model 3.3



The curves for the four binary variables in the model are not perfectly parallel in log-log plots (Figure B3), but never cross. The Kaplan-Meier plots and predicted survival plots (Figure B4) are reasonably close to each other. In combination with the test based on Schoenfeld residuals, these tests allow to conclude that model 3.3 is generally consistent with the PH assumption.

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