Diffusion, Development, and Directionality of Stationary Battery Energy Storage

by

Steffen S. Bettin

Submitted to

Central European University

Department of Environmental Sciences and Policy

In partial fulfillment of the requirements for the degree of Doctor of Philosophy

Supervisor: Michael C. LaBelle

Internal Committee Member: Michael Dorsch

External Committee Member: Michael Ornetzeder

Vienna, Austria

2021

I, the undersigned [Steffen S. Bettin], candidate for the degree of Doctor of Philosophy at the Central European University Environmental Sciences and Policy, declare herewith that the present thesis is exclusively my own work, based on my research and only such external information as properly credited in notes and bibliography. I declare that no unidentified and illegitimate use was made of work of others, and no part the thesis infringes on any person's or institution's copyright. I also declare that no part the thesis has been submitted in this form to any other institution of higher education for an academic degree.

Vienna, 6 September 2021

S. Bettin

Signature

Acknowledgments

A thesis only materializes with a lot of outside support, and this one is no exception. It was written during turbulent times and has gone through a forced relocation of the host university, a pandemic, and many political upheavals.

First of all, I would like to thank my supervisor at the Central European University (CEU), Michael LaBelle, for his continuous support, guidance, and trust in me. I would also like to thank my internal committee member, Michael Dorsch, for rekindling my enthusiasm for econometrics and providing advice, good ideas, and practical tips over the years. My thanks also go to my external committee member, Michael Ornetzeder, from the Institute of Technology Assessment (ITA) of the Austrian Academy of Sciences, who has taught me so much over the years and repeatedly opened up new intellectual perspectives for me.

I want to thank other colleagues at the Institute of Technology Assessment. First of all, to the members of my Ph.D. self-help group Titus Udrea, Daniela Fuchs, Leo Capari, Anna Pavlicek, and Gloria Rose, whose substantive feedback has always been enlightening and whose emotional support has kept me going. Then I would also like to thank Tanja Sinozic-Martinez for helping me find my way into technology assessment, Michael Nentwich for the institute's support even outside the projects, and Thomas Hans for the encouraging beer after a long day in the office.

I am thankful for the professors of the Department of Environmental Sciences and Policy Alex Antypas, Guntra Aistara, Tamara Steger, and Alan Watt, whose courses have challenged me and made me grow intellectually, Aleh Cherp, for the many insights into the world of energy, and László Pintér for being a constant source of support.

A big "thank you" also goes to the other Ph.D. students of the department who were there before me Sergi Moles-Grueso, Márta Vetier, Mariann Molnár, Vadim Vinichenko, Souran Chatterjee, Brian King, for all the help in finding my way and the emotional support during the great uncertainty of the research process. I thank my EPRG colleagues Ana Stojilovska, John Szabó, and Varvara Aleksić for much feedback on parts of the text that were still very rough (thanks, John!). I also thank my fellow newbies Attila Katona, Kyle Piispanen, Héctor Herrera, for making it easier to get involved in the Ph.D. adventure. Also, thanks to Masahiro Suzuki, Olea Morris, and Judit Boros for the zoom beers during the pandemic.

A special thanks go to Gyorgyi Puruczky and Tunde Szabolcs, without whom I would never have been able to keep track of the university bureaucracy and who were always there with advice and help. Without them, this Ph.D. would never have progressed so far.

I would also like to thank Manuel Scholz-Wäckerle, who, as my master thesis supervisor, opened up the intellectual space that led to this work, and Brigitte Gerger and Leora Courtney-Wolfman for their help with text and transcripts. Thanks also to Konstantin Geiger for your friendship and continual brainstorming of new ideas.

Many thanks go to Christoph Scheuch for the countless deep conversations, the joint rants about academia, the support with R problems, Mirko Lieber for the walks through the city and the R support, and Felix Pöge for the inspiring discussions about innovation.

Special thanks also go to Hendrik Theine, with whom I have been on an intellectual journey for over ten years and who always set me on new paths with insightful comments and wise words.

Many thanks also to Therese Guttmann, who has been with me for a long time on the adventure of writing our doctoral theses in the field of innovation and energy technologies and whose insightful feedback on chapters and our joint brainstorming session were critical for making this thesis possible.

Particular thanks go to my family. Not only that my brother Felix Bettin supported me with his technical knowledge on energy topics and his many tips on R programming and LaTeX, but he and my parents Marina and Andreas Bettin have also long supported, advised, and encouraged me in my intellectual endeavors. I am deeply grateful for your love!

My deepest gratitude goes to Christine Gerger. Your patience and love kept me going.

Abstract

This thesis set out to find *influencing factors on the dynamics of stationary battery storage systems' diffusion and development direction*. It entails an intensive literature review, a brief technical review on stationary battery storage, a qualitative country case study of the development and diffusion of all kinds of battery energy storage technologies in Austria, and a similar country case study in Germany. This thesis used a theoretical framework based on the technological innovation system (TIS), and policy mix (PM) approaches to identify development phases. In addition, it included a quantitative large-N chapter on the diffusion of large-scale battery storage (LSBS) in high-income countries. Therefore, it had a narrower object focus but covered more countries. In this thesis, three sub-research questions were examined more intensively around the topics of (1) context structures, (2) legitimation, and (3) policy. This section briefly summarizes the central aspects of these results.

One contribution of this thesis is to the understanding of the role of legitimation in the development direction of TISs. In particular, it showed how context structures could be indirectly relevant for legitimation by using salience issues and discourses as anchor points for legitimation attempts. Moreover, this thesis also adds to the areas of energy and innovation economics, particularly in the field of diffusion of technological innovation. It is unique in its approach by investigating the actual diffusion of large stationary battery storage projects. Applying a previously unused data set with data on new large-scale battery storage projects in high-income countries and using a Bass-model-based fixed-effect panel regression approach, the findings on the relationship between salient green issues and the diffusion rate of large-scale storage are unique. Also, this thesis includes a methodological discussion of the compatibility of ontological and epistemological foundations from critical realism in connection with the TIS approach. Thus, the comparisons drawn here may serve as a point of reference for further methodological work. Another academic contribution is the theoretical conceptualization of potential extensions for the TIS approach. This was done by proposing to add spatial factors such as physical nature as a fifth element. In addition, it argues for considering the impact of the broader capitalist relations in future TIS analyses. Moreover, it suggested connecting the social acceptance literature with the market function of the TIS literature.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Technologies are manifestations of social practice, power relations, and expressions of social values (Rip and Kemp, 1998). But they are also knowledge, skills, and processes that can be embedded in material artifacts such as machines. Technologies change society and help us to transform our physical surroundings providing many societal benefits. But as Julius Goldstein put it in a book intended to explain technology to the general public at the beginning of the 20th century: “New inventions always create new problems themselves”[1] (Goldstein, 1912, p. 12).

One area where technology is central is in the area of anthropogenic global climate change (Schmidt and Sewerin, 2017), where it is “a source of the problem, a possible solution, and an instrument of measurement and analysis” (Rip and Kemp, 1998, p. 328). Climate change poses a threat to humans and nature and is an amplifier of other natural and societal risks (IPCC, 2019). A substantial driver of anthropogenic climate change

---

[1] Translated by the author from the original German: “Neue Erfindungen sorgen selbst immer für neue Probleme“.

comes from the energy system and its use of fossil fuels. Now the major societal challenge is to accelerate an energy transition from fossil fuels to often variable renewable energies (VREs) such as wind and PV (IEA, 2020d).

However, many obstacles and mechanisms are blocking the diffusion of these renewables. These can be due to, e.g., incumbents' interests, entrenchment in the social system, large capital costs, and long infrastructure lifetimes (Seto et al., 2016). One technical obstacle in the electricity sector is the so-called "intermittence problem" (Zöphel et al., 2018). The challenge arises as electricity must be generated at the same time as its consumption. However, VREs are not always available, creating challenges for the power system. One possibility to reconcile this and provide flexibility to balance generation and consumption is storing the electricity through other forms to re-use later (Child et al., 2019; Crabtree, 2015; Gallo et al., 2016).

Electricity storage in the energy system up to now occurred mainly through mechanical storage in pumped hydro storage power plants (Sterner and Thema, 2019). However, rapidly decreasing costs of electrochemical battery cells due to economies of scale through their application in consumer electronics (BNEF, 2020), such as smartphones and laptops, make their application in stationary energy storage systems more profitable (Davies et al., 2019; IEA, 2020b). They are now increasingly used in households (Kairies et al., 2019), as community storage (Koirala et al., 2018), in industrial applications (Schriever and Halstrup, 2018), and as battery factories at higher grid levels (Davies et al., 2019). Their primary purpose is providing short-term storage to balance supply and demand, shift loads, and stabilize the electricity grid (Sterner et al., 2019a).

Battery energy storage is affected by many developments such as advances in cell technology, electrification, and decentralization (IEA, 2020b). It is related to the energy system, which is undergoing a fundamental transformation in social relations, power constellations, and material infrastructure change. Among these are different interests and agencies as well as drivers and barriers. With large-technical systems, such as the power grid (Hughes, 1983), which battery storage systems contribute to, there are many lock-ins (Seto et al., 2016). Policymakers and society need to understand battery storage's role in the energy transition to start an enlightened debate on their future use and possibly co-create the technical development. Of particular importance is that the future extent of the "intermittency problem" and the demand for flexibility are uncertain. It depends on various factors such as grid capacity, network congestion points, demand profile, weather and its forecast, and VREs in the energy mix (IEA, 2020d), all of which also depend on technological developments and political decisions. This thesis aims to contribute to the debates on these issues by looking at the development and diffusion of stationary battery storage systems.

Two major streams of literature concerned with sociotechnical transitions and innovation studies relate to this. One is predominantly quantitative and focuses on the diffusion of renewable technologies within countries but also between countries. This is either done by investigating the actually deployed technologies or by using patent data as a proxy for technological innovation. The other approach tends to be more holistic, including dynamics around technology development, production, and markets, predominantly based on qualitative methods. However, there is an increasing number of studies that also include quantitative and network methods.

The first literature stream focuses on the diffusion of energy renewable energy technologies. Based on innovation diffusion approaches (Rogers, 2003; Bass, 1969), it shows how wind and solar energies spread within countries and globally across countries (Vinichenko, 2018; Verdolini et al., 2018; Popp et al., 2011). Moreover, it found out that research expenditures and demand-pull policies such as guaranteed feed-in tariffs played a major role in accelerating diffusion (Popp, 2019; Carley et al., 2017; Alizada, 2018; Couture and Gagnon, 2010). While various models attempt to simulate the future diffusion of energy storage (Child et al., 2019; IEA, 2020d), only a few approaches attempt to identify factors influencing the diffusion of battery storage. One example is Kittner et al. (2017) who found that increased research reduces the costs for batteries using patent data as a proxy for innovation diffusion in a technology learning approach. This thesis also seeks to contribute to filling this research gap by studying influencing context factors that accelerate the diffusion and actual deployment of stationary battery storage systems. This quantitative diffusion dimension is also reflected in the first part of the title of the thesis.

The second research strand comes from studying sociotechnical systems, an approach at home in many disciplines such as innovation and sustainability research, STS, evolutionary economics, and political sciences (Köhler et al., 2019; Sovacool and Hess, 2017). The different varieties (Van Den Bergh et al., 2011) are in a fruitful dialogue (Köhler et al., 2019). Furthermore, they all have in common that they understand technology as sociotechnical, interwoven with society, and shaped by institutions. Recently, the technology diffusion's and development's directionality has received more attention in this research strand, as it stresses the societal purpose behind particular innovations (Lindner et al., 2016). Since markets are "blind" (Nelson and Winter, 1982), mission-driven innovation policies can steer diffusion and development processes (Mazzucato et al., 2020). A prominent approach from this research strand, the technological innovation system (TIS), is in an amended form the primary framework of this thesis because of its prominence and usefulness for identifying systemic features and drivers. The thesis heading also reflects this more qualitative dimension of the directionality of technology diffusion and development.

Overall, there is plenty of research on the development and diffusion of renewable energies, such as wind (van der Loos et al., 2020; Reichardt et al., 2016), solar (Quitzow, 2015), or biogas (Markard et al., 2016). These results have in common that they underline institutions' importance and social and physical contextual factors for diffusion and development. However, energy storage is conceptually different from other renewable energy technologies. It is an auxiliary technology and less an end than a means to provide more flexibility to integrate more renewables into the energy system. Many assume that its importance will increase in the next phase of the energy transition when renewables step out of their niche and become systemically relevant (e.g., Markard, 2018b). However, the question arises whether the diffusion and development and the role of the innovation system and policy on the directionality will be different from the aforementioned renewables.

One initial study on energy storage has researched fly-wheel storage (Wicki and Hansen, 2017), while another investigated knowledge development and diffusion of lithium batteries in Japan (Stephan et al., 2017). Moreover, there is initial research on the social acceptance of battery storage (Devine-Wright et al., 2017; Schriever and Halstrup, 2018). These early approaches showcase the importance of the topic, but further research is needed that integrates other dimensions and broadens the empirical base. This thesis tries to contribute to the filling of this research gap. The overarching research question is therefore as follows:

- What influenced the dynamics of development and diffusion of stationary battery energy storage, and how?

This research question contains the following three relevant sub-areas and sub-questions, which this thesis answers. The first question is about the influence of national contextual factors such as geography, infrastructure, and national economy, which is:

- How did context structures such as geography, infrastructure, and national economy influence the development and diffusion of stationary battery storage systems?

The second sub-question focuses on the social context and asks about the influence of public issue salience and how companies and developers legitimize their technology.

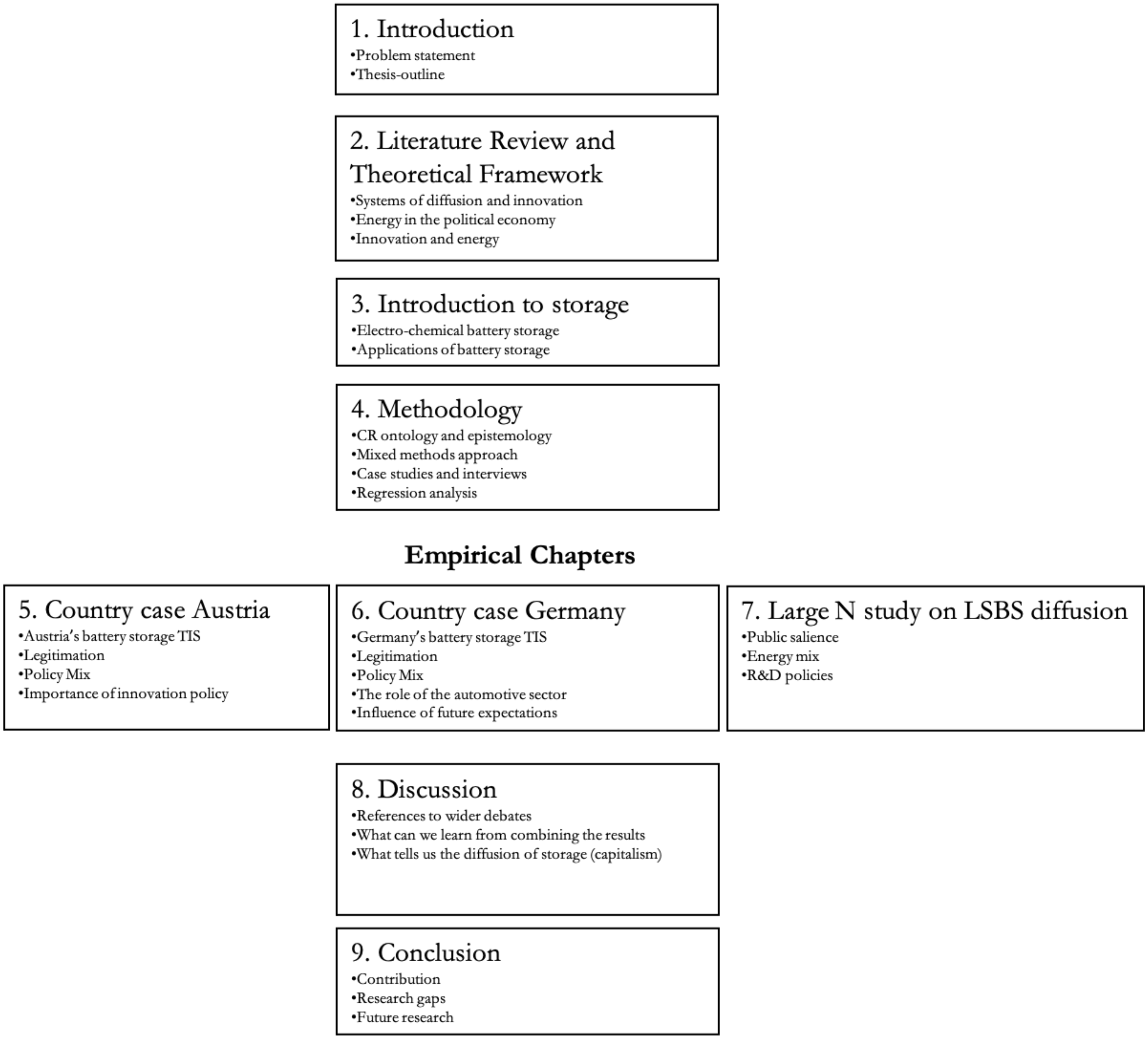
- How was the legitimacy for the development and use of stationary battery storage created, and how did it influence the innovation system's development?

The third research question is about the government's room for maneuver and the extent to which regulations and other policy initiatives influence development directionality and diffusion.

- How did energy and innovation policies influence the development and diffusion of stationary battery storage?

Answering these questions has an exploratory and interpretive dimension, which recommends qualitative methods and an explanatory, mechanism-focused side, implying quantitative methods. In the former instance, country case studies provide an excellent way of illustrating relationships with physical contexts, surrounding societal actors and institutions in the battery storage innovation system. Conversely, the latter recommends a regression analysis approach across countries that focuses, due to data availability, on larger-scale battery storage systems. A mixed-methods approach is applied based on a critical realist epistemology to offset both approaches' weaknesses while drawing on their strength (Bryman, 2006; Cresswell and Plano Clark, 2011). On account of the different scales of inquiry, the findings are not to be entirely corroborated. However, using theory as guidance, the thesis aligned the data on the content level. This juxtaposition of both methodological approaches also allows presenting the complexity of the research object, as chapter 3 explains in more detail.

This thesis is composed of nine chapters (Figure 1.1). Chapter two provides a focused literature review on renewable energy innovation and lays out the research's theoretical dimensions. It begins by reviewing innovation in industrialized societies, stressing national innovation systems, innovation diffusion, and technological innovation systems. This includes a section on the role of innovation policy. Afterward, a brief history of energy and electricity system follows. Building on that, the next section discusses the peculiarities of technological innovation systems of energy technologies, energy technology diffusion, and



1. Introduction
- Problem statement
- Thesis-outline

2. Literature Review and Theoretical Framework
- Systems of diffusion and innovation
- Energy in the political economy
- Innovation and energy

3. Introduction to storage
- Electro-chemical battery storage
- Applications of battery storage

4. Methodology
- CR ontology and epistemology
- Mixed methods approach
- Case studies and interviews
- Regression analysis

Empirical Chapters

5. Country case Austria
- Austria's battery storage TIS
- Legitimation
- Policy Mix
- Importance of innovation policy

6. Country case Germany
- Germany's battery storage TIS
- Legitimation
- Policy Mix
- The role of the automotive sector
- Influence of future expectations

7. Large N study on LSBS diffusion
- Public salience
- Energy mix
- R&D policies

8. Discussion
- References to wider debates
- What can we learn from combining the results
- What tells us the diffusion of storage (capitalism)

9. Conclusion
- Contribution
- Research gaps
- Future research

Figure 1.1: Overview of the thesis' chapters.

social acceptance. The last section closes with a tentative synthesis and proposes new emphases for the technological innovation system framework.

The third chapter is concerned with the methodology used for this study. It starts with the philosophy of science foundation and the ontological and epistemological commitments in critical realism upon which this thesis builds. A section on the operationalization of these ideas for this thesis through a mixed methods methodology follows. Afterward, one section on the qualitative case study approach also introduces the two country cases Austria and Germany, and one section on the quantitative regression approach follows. This section concludes with a description of the overall research process and how philosophical underpinnings, theoretical concepts, and empirical work align to answer the research questions.

The fourth chapter provides a brief overview of energy storage technologies in general and stationary battery storage in particular. It starts with a primer on electrochemical batteries and suggests a heuristic overview of typical sociotechnical applications for battery storage. It follows a descriptive summary of diffusion in the countries of Austria and Germany and globally.

The fifth chapter presents the empirical findings of the qualitative case study of the battery energy storage technological innovation system in Austria. It provides the context of its emergence and a timeline of its development based on actors, networks, and institutions. Moreover, it tracks the development of the policy mix around battery storage technologies. This chapter analyzes the Austrian technological innovation system's dynamics and innovation functions and identifies drivers of change. A particular focus is on how actors in the innovation system influence legitimacy for battery storage technologies by referring to societal debates such as regional decentralization, green security, and coolness.

The sixth chapter presents the empirical findings of the qualitative case study on Germany's battery energy storage technological innovation system. It summarizes the German battery technological innovation system's development and its emergence based on its central building blocks and influencing policy mix. Then, it follows an analysis of innovation functions, focusing on how actors affect the legitimacy of battery storage technologies by referring to societal issues such as green security and autonomy and electric vehicles. The section provides an overview of central divers of the German battery storage innovation system development. It shows how changes in the automotive sector create shifts in the battery storage innovation system.

The seventh chapter zooms out and focuses on the diffusion of large-scale battery storage systems in high-income countries with a quantitative econometric approach. It utilizes a fixed-effect panel regression model with controls designed based on the Bass diffusion model. This chapter analyzes the potential drivers and structural factors identified in the previous chapters and often discussed in academic literature. It examines how public salience of environmental issues influence the diffusion of large-scale battery storage using green voters' share as a proxy. Also, it provides an analysis of how the composition of the energy mix and structural factors in the energy sector influence the diffusion of large-scale battery storage. Moreover, this chapter analyzes the influence of spending on research, development, and demonstration for storage technologies. This chapter showed weak negative relationships between the diffusion of solar electricity and large-scale battery storage and a positive relationship between the spending for electricity storage in general and large-scale battery storage diffusion. However, the most robust relationship was between the public salience of green issues and the diffusion of large-scale battery storage, emphasizing its importance. The study includes robustness checks on alternative specifications and interpretations.

Chapter eight discusses the results from the preceding three empirical, analytical chapters and contrasts them with scientific literature and theoretical approach highlighted in chapter two. It discusses the two country case studies separately and compares the results.

Next, the particular case of large-scale battery storage is discussed following the insights from the two preceding qualitative case studies. Finally, the chapter concludes with a brief discussion of this thesis's three main themes, context structures, public salience and legitimacy, and policy.

The ninth chapter concludes by summarizing the fulfillment of the thesis objectives, the contributions to the literature, the limitations of this thesis, and a future research agenda based on the results.

Chapter 2

Theory[1]

2.1 Introduction

Few depictions of global capitalism are as emblematic as the double role that human-used energy plays—both as an enabler and stabilizer of contemporary global society and as a transformer of earth's ecosystems. Thus, socio-economic research should include the physical and material foundations of our human activities. The energy dimension is fundamental to academic research. Renewable energies become systemically essential and diffuse beyond their niche (Markard, 2018b); flexible supply-side options such as energy storage technologies require scholars' attention, as changes within the current energy system occur.

Sustainability transitions in, e.g., food or processing require the attention of socio-economic research; the current energy transition comprises issues such as heating, manufacturing, housing, and transportation of goods and services (Foxon, 2017). Against this

---

[1] An earlier version of this chapter was published under Bettin 2020 „Electricity infrastructure and innovation in the next phase of energy transition—amendments to the technology innovation system framework“. *Review of Evolutionary Political Economy* 1, Nr. 3.

backdrop, this chapter focuses on the role of electricity in the energy transition—a topic of increasing importance due to its centrality for many renewable energies, the electrification of key sectors like personal transport, and the growing use of computers and "smart" devices (IEA, 2020d).

In the past, much of evolutionary economics concentrated on the supply side while neglecting demand in innovation process research (Dopfer and Nelson, 2018). Entrenched in a pro-innovation bias, evolutionary economists and innovation researchers are increasingly adopting a transformation framework and seek to understand how (technological) innovation can benefit society, alleviate contemporary global challenges, and how policies can be framed accordingly (Schot and Steinmueller, 2018).

This chapter aims to conceptualize a research focus that incorporates elements of the next phase of energy transition where renewable energies are expected to replace fossil fuels, requiring more consideration of infrastructure, social and political power, and physical embeddedness. To do so, this chapter synthesizes selected approaches that bridge different fields of knowledge and concepts. There are contributions from economic geography, innovation economics, science and technology studies (STS), transition studies, political sciences, and business studies (Köhler et al., 2019; Rakas and Hain, 2019).

The chapter starts with a brief review of innovation in contemporary capitalist and industrialized societies, stressing national innovation systems, diffusion, and specific technological innovation systems. A section on innovation policy succeeds. A brief history of energy and electricity system development in capitalism emphasizing sociotechnical energy systems' biophysical embeddedness follows. The fourth section discusses the peculiarities of energy and technological innovation systems, diffusion of energy innovation, and social acceptance. Finally, the chapter closes in the fifth section with a tentative synthesis and proposes three amendments to the technological innovation system framework.

2.2 Systems of Diffusion and Innovation

Drawing on Schumpeter (1939), innovations refer to anything that is a recombination of existing things to perform a new function or have a novel aspect in the realm of economic life.

"Technological change in the production of commodities already in use, the opening up of new markets or of new sources of supply, Taylorization of work, improved handling of material, the setting up of new business organizations such as department stores—in short, any 'doing things differently' in the realm of economic life—all these are instances of what we shall refer to by the term Innovation." (Schumpeter, 1939, p. 84).

Schumpeter's definition of innovation exceeds the term 'invention'. While an invention can contribute to an innovation, such as developing a new technology, innovation can also include immaterial factors such as organization. More recent definitions put the use of a product or process at the center (Gault, 2018). Thus, an innovation is when "[n]ew or significantly changed processes are implemented when they are actual used in the operation of the institutional unit, including the making of product available to potential users."

In the following section, I briefly discuss the emergence and diffusion of technological innovations with the theoretical approach of diffusion of innovation, national innovation systems, and technological innovation systems.

2.2.1 Innovation Systems and Institutions

To answer Veblen's (1898) call for this specific economic field, innovation research must be an evolutionary science. Consequently, Schumpeterian and evolutionary economists like Nelson and Winter (1982, chap. 5) developed the theory of how innovation occurs in economic life and introduced a dynamic theory of innovation. Also, they stressed the historically contingent nature of economic change (Arthur, 1989) with path dependencies

(David, 1985). Technological change is context-dependent, i.e., circumstances of emergence are critical (Maréchal and Lazaric, 2010). Dosi (1982) introduced the idea of technological paradigms that—in reference to Thomas Kuhn's scientific paradigm shifts—limit the direction of technological change. Only within this paradigm are market dynamics of costs and benefits relevant.

From this perspective, heterogeneous agents (or entrepreneurs) innovate under uncertainty and have a vision to create something new (Nelson, 2018). Due to their bounded rationality (Cyert and March, 1963; Simon, 1991, 1955), they base decisions and evaluations on rules of thumb and routines heavily influenced by institutional settings and context (Shove, 2005) (Shove 2005). While daily practices help free-up resources from routine problems, their lock-in can foster unintended and unsustainable practices. Thus, the structure is both enabling and constraining (Giddens, 1984).

Based on this work by early evolutionary economists and guided by organizations such as the OECD (Godin, 2009), economists with different academic backgrounds have helped develop an approach to economic development that focuses on the role of knowledge infrastructures and on learning by both individuals and organizations (Lundvall, 1992; Nelson, 1993). Freeman would later label this approach as the study of innovation systems, which initially focused on innovation systems in countries (Freeman, 1989), i.e., national innovation systems (NIS) or national systems of innovation.

The innovation system approach builds on List's (1841) national economy doctrine, which he designed in opposition to Adam Smith's free-market approach. According to List (1841), bringing the German state's economy up to speed with England's would require government interventions and strengthening infrastructure, specifically, knowledge infrastructures and mental capital (Lundvall, 2016, chap. 9). However, knowledge can exist in tradeable commodities and is somewhat transferrable and embodied in the labor force (Lundvall, 2016). Accordingly, an innovation system is an analytical tool for understanding systemic properties that enable developing, diffusing, and utilizing new products and processes (Bergek et al., 2008a). Based on this reasoning, the importance of institutions that hinder or enable innovation assumes a key role alongside actor networks.

The NIS approach has a strong spatial dimension because knowledge in the labor force tends to be local and tacit. Physical infrastructure, e.g., roads, grids, ports, and factories can be replicated or moved to different regions—but only at high costs. Further, a few geographical factors are always present in certain regions (e.g., sunny days, mountains, natural resources).

Edquist (2006) added another dimension to innovation system research by focusing on activities or functions, their causes, and determinants. This emphasis on functions would later become one of the cornerstones for the technological innovation systems approach.

As in many innovation policies, innovation systems research tends towards a "deficit model" (Pfotenhauer et al., 2019) and deficit framing in its policy recommendations, with a clear pro-innovation bias that tends to marginalize other rationales. There is always a societal problem in this understanding that is missing a technological innovation as a solution. However, given the upcoming transformation, policy frameworks should tackle global challenges, rather than only the competitiveness of national innovation systems (Schot and Kanger, 2018). The technological innovation system approach can play a constructive role in steering transition and shifting the directionality of technology development.

2.2.2 Diffusion of Innovation

Diffusion of innovation is one of the most researched topics in social sciences and consists of many approaches (Bass, 1969; Rogers, 2003; Abrahamson, 1991; Comin and Mestieri, 2014). An essential extension of innovation theories arose from advancements in network sciences that combine knowledge from sociology, anthropology, mathematics, and physics. They could explain why seemingly useful innovations would not diffuse in society. These insights clarified that relatively effective top-down actors (such as the media or governments) did not influence innovation diffusion so much. Instead, communication amongst actors in different networks is central to how and if an innovation gets adopted on a larger scale (Rogers, 2003, chap. 8). Here, it became clear that, for example, missing links between actors—or weak ties—amongst different actors (Granovetter, 1973) influence the diffusion of innovation.

Rogers (Rogers, 2003, chaps. 1 & 8) devised a terminology for the different groups of actors, along with how and at what speed they adopt innovation. Accordingly, one group of actors takes the role of opinion leaders, who can be individuals or entire organizations, and are labeled innovators or early adopters. They are central to the adoption rate, as actors of their immediate surroundings who aim to follow and adapt their behavior trust them. As these groups' distribution follows a Gaussian bell curve, only a small group of actors lead in adopting an innovation. The majority follows later. A small group will always attempt to resist the adoption or is not informed about the innovation—the laggards. One way of capturing this diffusion process across an entire network is the S-shaped sigmoid curve that shows initial slow adoption, a sudden uptake, and a prolonged stabilization period (Geroski, 2000). Simplified, this curve can be represented by a logistic growth function (Figure 2.1) with L = maximum of adopted innovations, k = innovation growth rate, and x0 = turning point of the function.

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \tag{2.1}$$

More complex ways to capture diffusion dynamics were prominently modeled in the later-defined Bass model (Bass, 1969; Jiang et al., 2006; Mahajan et al., 1995).

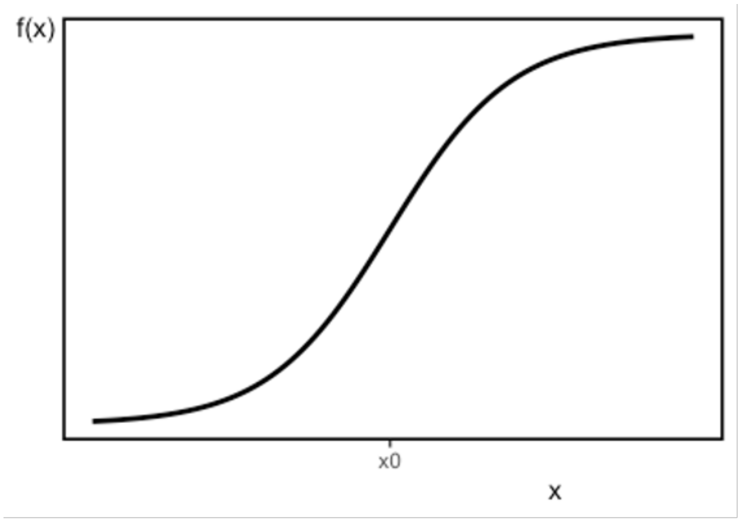


Figure 2.1: Logistic growth curve

2.2.3 Technological Innovation Systems

In recent years, research has investigated other innovation system types, including regions (Cooke et al., 1997; Doloreux and Parto, 2005; Mattes et al., 2015), sectors (Malerba, 2002; Squillace, 2012), and technologies (Bergek et al., 2008a). Because of the importance of flexibility options for the energy transition, this thesis focuses on technological innovation systems (TIS). Moreover, the TIS literature also increasingly incorporates the role of sectors, regions, and nations in their analysis.

A precursor for TIS was first discussed using the term technological system. Here, “[t]echnological systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services.” (Carlsson and Stankiewicz, 1991). Simultaneously, both Bergek et al. (2008a) and Hekkert et al. (2007) later developed this approach more coherently as TIS. This approach’s systemic perspective used to draw primarily attention to flaws or “failures” in the innovation system, hindering (or enabling) the rate or character of a specific technological development. These obstacles to development are typically identified when the system’s flow of information and knowledge is somehow blocked or interrupted.

Laterly, some author’s suggest abandoning the "failures approach", which tends to see

TIS structures as rather stable, and if unstable in need of a fix, and introduce a dynamic life-cycle perspective (Markard, 2020). According to this view, the structures around a technology emerge with it, formalize and become more stable when the technology matures, and weaken and break-up when the technology, and with it the TIS, decline.

Conceptually. TIS builds on four structural components: (1) The focal technology (2), actors (e.g., firms, universities, intermediaries, authorities) (Planko et al., 2017; Bergek et al., 2008a), (3) networks between those actors (e.g., firm networks (Musiolik et al., 2012) or learning or political networks (Markard et al., 2015)), and (4) formal and informal institutions (Bergek et al., 2008a; Kukk et al., 2016). Following the TIS approach, these structural components—such as the focal technology energy storage—are configured to enact innovation functions that fulfill central roles within the innovation system across the three other structural components (Planko et al., 2017).

Building on the notion of system functions, as mentioned above, several innovation functions (or processes) can be identified that enable sustaining the innovation system. To date, this group of functions is loosely developed, although they underwent re-interpretation and re-formulation.

Ultimately, in line with Myrdal (1957), the TIS approach stresses positive or negative feedbacks with cumulative causation between the different innovation functions, with the prospect of leading to virtuous or vicious cycles (Bergek et al., 2015; Haley, 2018). While a few authors (Bergek et al., 2015; Bergek, 2019) conceptualized this as positive external economies, others (Haley, 2018; Hekkert et al., 2007) conceptualize those as cumulative dynamics between functions or as positive effects from context factors. Different actors influence through actions innovation functions, e.g., government actors through policies, interest groups through lobbying, or universities through researching.

An essential innovation function that often starts the cycle at emerging TIS is legitimation (Bergek et al., 2008b; Markard et al., 2016; Markard, 2020). This involves presenting a particular technology as a desirable and realistic alternative to gain its acceptance. It serves to change expectations and, e.g., through lobbying and building networks and advocacy (Jacobsson and Lauber, 2006) and thus through institutional work (Kainiemi et al., 2020) to change institutions (Bergek et al., 2008b) but also to adapt to existing societal norms, values, beliefs and practices (Markard et al., 2016). Legitimacy is a prerequisite for the emergence of a new TIS and, e.g., visible from new actors' entry (Bergek et al., 2008b). Different actors interpret and frame broader calls for change to legitimize their ventures and technologies (Kainiemi et al., 2020; Markard et al., 2016) and "make meaning" by attaching themselves to discourses and making use of common narratives. While meaning underpins every practice and action (Van Leeuwen, 2017, 2007), it is especially true for unestablished ventures and entrepreneurs who need legitimacy (Aldrich and Fiol, 1994). It is therefore vital to establish trust for them because of the not yet widely diffused information and experience about the innovation, which needs all the more a convincing story and explanation (Van Leeuwen, 2007), to reduce the complexity in the eyes of others through trust (Luhmann, 1968). Legitimation is closely related to influencing the search direction, both determining the innovation process's directionality.

The emergence of legitimacy enables knowledge development and further entrepreneurial experimentation by public and private actors. It also facilitates access to various financial and human resources. In particular, knowledge development and diffusion are often central indicators for innovation processes (Stephan et al., 2017), especially for quantitative mainstream innovation economics (e.g., Jaffe and Trajtenberg, 2002). A TIS can emerge through this cumulative process, slowly becoming self-sustaining once a market emerges (Bergek et al., 2008b).

Following this general understanding, I conceptualize the following six innovation functions:

- Knowledge development and diffusion

- Resource mobilization (e.g., financial, human, infrastructure)
- Market formation
- Influence on the direction of search
- Private and public entrepreneurial experimentation
- Creation of legitimacy (interest groups and advocacy coalitions)

Although it was not designed initially with sustainability-relation issues solely in mind, the TIS-approach is often used to help or enable such matters like diffusing clean energy technologies (Markard et al., 2015). While it is useful in that regard, it is also applicable to other technologies (Kukk et al., 2016).

While TIS's internal dynamics are central to its development, increasingly, different kinds of contextual factors appear progressively important (Bergek et al., 2015). Thus, neighboring TISs may influence the focal TIS by competing for the same resources (Sandén and Hillman, 2011). However, it is also possible that, despite this competitive relationship, they benefit from each other by generating social legitimacy for the solution of their problem and run in in packs (Van de Ven and Garud, 1993), e.g., different renewable technologies. Furthermore, neighboring TIS benefit from each other through shared technologies (Bergek et al., 2015) and form a development block (Haley 2018). Moreover, a TIS is influenced by a specific sector or a particular national context with incumbent industries (Bergek et al., 2015) and global value chains (Binz et al., 2016; Hipp and Binz, 2020).

Besides, other social context factors such as policy and government and physical context factors such as geography and infrastructure are also likely relevant. The remainder of this chapter highlights their importance.

2.3 Innovation Policies

Policies were always a central topic for influencing the rate and directionality of diffusion and development of technological innovations (Weber and Rohracher, 2012). Thus, the following sections briefly introduce the role of innovation policies on technology diffusion by discussing policy mixes and government.

2.3.1 Policy Mix and TIS

Increasingly, a perspective concerned with the overall mix of policies gets attention in innovation and transition studies (Guerzoni and Raiteri, 2015; Kern et al., 2019; Kivimaa and Kern, 2016; Reichardt et al., 2016) and receives a bit of attention from international organizations such as the OECD and IEA (OECD, 2016; Meissner and Kergroach, 2019; IEA, 2017b). In other disciplines such as policy design (e.g., Oikonomou and Jepma, 2008) and environmental economics (e.g., Sorrell and Sijm, 2003), policy instruments' interacting roles are a long-standing research focus.

However, building on Flanagan et al. (2011), Reichhardt and Rogge (2016) reconceptualize policy mixes to include a dynamic perspective that considers the interaction between (TIS) actors and policy. A policy mix is composed of foundational elements such as strategies and the instrument mix, policy processes that capture the dynamics of political and social actors to derive policies, and overall characteristics of the whole policy mix (Rogge and Reichardt, 2016):

The combination of elements can be characterized according to their consistency. Amongst those elements, instruments are categorized into economic instruments such as taxes, feed-in tariffs, and infrastructure provision, regulation such as patent law, technological standards, and market design. Another element is information, such as types of training and public information campaigns. All of these policies can be either technology-push, demand-pull, or systemic (Rogge and Reichardt, 2016). Besides, policy strategies are central elements for different actors to align their actions as they serve as guiding principles.

The interactions between policy strategies and the coherence of policy process are also receiving particular attention for studying policy mixes as they influence outcomes (Edmondson et al., 2019; Schmidt and Sewerin, 2017). Central are thereby dynamics among the included actors that are involved in policymaking and policy implementation. Moreover, their interaction with the TIS actors—in turn—creates the policy mix and is shaped by prevalent power-relations. Also, instruments and strategies have developed incrementally over many years and constrain new policies while their original purpose might have already faded away (Kern et al., 2019; Kern and Howlett, 2009). Thus, it is useful to analyze the coherence of policy processes.

Sustainable transitions demand fundamental changes in the social practices, power structure, and physical infrastructure (Kern et al., 2019; Markard, 2018b; Schot and Steinmueller, 2018) that require solutions to how losing incumbents—i.e., those that are disadvantaged from a transition—can be compensated (Kivimaa and Kern, 2016; Markard, 2018a). For policy mixes to effectively foster transformative change, they have to be credible to other actors (Kern et al., 2019).

Policy mixes are particularly relevant when it comes to the fundamental and systemic challenges of our time. These are characterized by a high degree of complexity, different interests, and a high degree of uncertainty regarding possible futures (Kern et al., 2019). They have to be as holistic as possible and encompass many perspectives; therefore, comprehensiveness is a central characteristic of policy mixes (Rogge and Reichardt, 2016). As the policy mix perspective shows the importance of a bundle of instruments and strategies, it highlights that opposing social values and objectives can—and often do—exist.

2.3.2 Government and Policy

The government was always seen as a central actor for energy innovations, but the state's conceptualization sharpened recently. It moved from a night-watchman state that fixes "market failures" and provides public goods such as basic research towards a more enabling understanding of state where markets are social constructions, in a Polanyian (1944) sense, that provide and enforce rules (Callon and Muniesa, 2005; Mackenzie, 2006; Silvast, 2017).

Since innovation does not always happen where it is socially desirable (Foray, 2019; Mowery et al., 2010), search directionality is the qualitative dimension of innovation that can be steered through mission-oriented policies (Mazzucato, 2018, 2015). Here, the state provides, e.g., patient capital for research and experimentation to find solutions for pressing societal challenges through state investment banks (Mazzucato and Penna, 2016; Kattel and Mazzucato, 2018). Another way of steering development is through public procurement and driving aggregate demand (Edquist and Zabala-Iturriagagoitia, 2012) or by actively participating in research and development through government agencies such as the defense agency DARPA in the United States (Mazzucato, 2015). This mission-driven, active government engagement moves beyond previously favored approaches of mostly enabling experimentation in niches (as argued for by Maréchal and Lazaric, 2010).

Also, mission-oriented innovation policies pose a danger in that it is crowding out more critical research. If most research funds are allocated to finding (technological) fixes to selected societal challenges while providing economic growth—like in the current Horizon Europe program of the European Commission—critical reflections that question the mission itself are getting fewer resources. This innovation bias hinders tackling more structural challenges that might challenge current power structures.

Recent approaches by transition scholars consider the power perspective more explicitly and focus on incumbents' importance (Turnheim and Geels, 2013, 2012; Turnheim and Sovacool, 2019). Still, transition research received well-deserved criticism as capitalism and power-relations are mostly treated as a landscape factor. However, ".[c]apitalism permeates the workings and logics of sociotechnical systems in ways that are critical both in the elaboration of rigorous accounts of transition trajectories and for the capacity of [sustainability transition research] to support future societal sustainability transitions" (Feola, 2019). Thus, the state creates policies—also when they are mission-oriented—according to a 'general will'. "But, this 'general will' always neglects certain interests, while preferring others" (Jessop, 2008, p. 9).

When the inner workings of capitalism are articulated more explicitly in innovation research, new approaches such as degrowth and post-growth that are actively dealing with socio-economic relations outside of capitalism that aim to be more in line with nature can be better integrated into the study of transition (D'Alisa et al., 2015; Kallis, 2011).

2.4 A Brief History of Energy in the Political Economy

Every lifeform consumes various form of energy. Certain organisms, such as plants, transform electromagnetic waves caused by the gigantic fusion reactor our planet circles around —the sun—and transform it into organic matter via photosynthesis. Other lifeforms can feed upon these primary producers until we arrive at our human existence that is based, of course, on matter-energy as low entropy inputs (Georgescu-Roegen, 1971).

Vast amounts of organic matter have accumulated on earth over millions of years. This useable energy stored in this matter—fossil fuel, coal, and gas—was essential for the Industrial Revolution's emergence (Smil, 2017). Access to fossil energy resources enabled the centralization of factories and the increased control of workers via centralized workplaces—two cornerstones of industrial capitalism (Malm, 2016). In essence, the usage of these forms of energy resources enabled new social and power relations. After WWII, capital accumulation regimes became increasingly augmented with regulation regimes targeting economic growth. This growth-centrism was formulated and disseminated by international organizations such as the OECD (Schmelzer, 2016) and the World Bank (Allan, 2019). They established it with the theoretical support provided by neoclassical economics. Other possible policy objectives, such as those pertaining to social or environmental issues, were sidelined or treated as complements to the growth imperative (Allan, 2019).

The increased consumption and production of fossil fuels led to a series of unintended consequences. Due to increased energy-intensive activities, rising fossil fuel consumption is causing global warming and environmental degradation that harms human wellbeing (IEA, 2019c; IPCC, 2019). Meanwhile, the increased production of fossil fuel (Watts, 2006; Obi, 2014; Healy et al., 2019) is straining the environment and triggering many violent conflicts over land use and extraction rights (Mitchell 2011, chap. 10). It thus seems unsurprising that access to energy sources is a central objective of national defense sectors (Samaras et al., 2019).

Access to energy is a prerequisite for poverty alleviation and essential support for social provisioning and human wellbeing (GEA, 2012, chap. 2). Therefore, energy security—along different dimensions (see Cherp and Jewell, 2014)—becomes a central societal objective. This is why "access to affordable, reliable, sustainable, and modern energy" was set as the 7t̂h sustainable development goal (SDG) by the United Nations in 2015. In this context, the destructive impact of anthropogenic climate change—heavily driven by energy production—was globally acknowledged in the 2015 Paris agreement. While it is seen by many as a helpful call for action, others criticize our remainder within a green-growth approach (Spash, 2016).

With increased industrialization, energy has been applied in many ways to facilitate automation and encouraged the search for new ways of using and harnessing energies, such as using electricity, which is the focus of this thesis. However, electricity is by far not the only energy-form that transition scholars must consider (see Figure 3). Other forms such

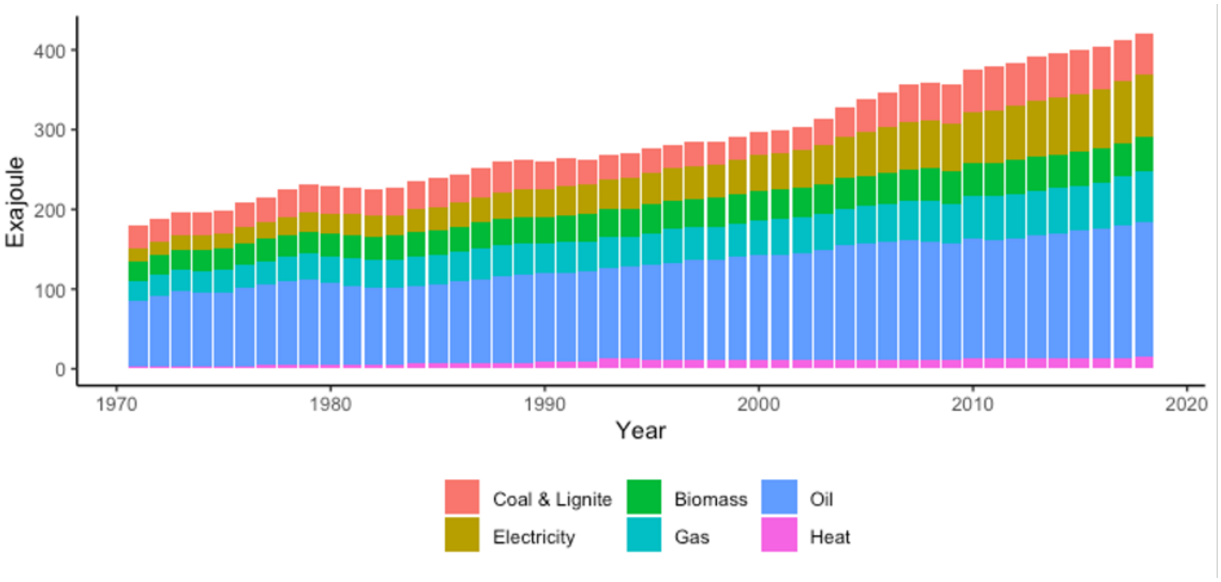


Figure 2.2: Global primary energy consumption in Exajoule. Data IEA 2020

as industrial energy use and transportation of people and goods—two systems that are still mostly dependent on fossil fuels, i.e., coal, oil, and gas—come with their own sets of challenges (see, e.g., Foxon, 2017).

The first commercial electric grid was switched on in New York by Thomas Edison in 1882 and financed by J.P. Morgan. Electricity grids evolved from small, decentralized projects for the few to all-encompassing interconnected grids run by natural monopolies used by all in industrialized countries (Bakke, 2016). Successor companies of their builders are still amongst the most influential in the world (e.g., General Electric and Siemens).

Notable advances include Nikola Tesla's alternating currents (AC) to overcome large distances and commercialization availability through the invention of the electricity meter (Yergin, 2012). Next to the consumption of fossil fuels, electricity especially "delivers a precision unmatched by any other form of energy; it is almost infinitely versatile in how it can be used" (Yergin, 2012, p. 347) and its usage is globally—mostly in the industrialized world—growing (figure 2.2). It provides constant access to light, allowing for a departure from pre-industrial cycles based on day-night changes and seasons. Also, it established the basis for using semi-conductors, computers, and the whole world of digitalization.

In his seminal work, Hughes (1983) defined electricity grids as large technical systems (LTS) composed of technological, institutional, and organizational elements. These sociotechnical systems can be considered the world's largest machines that transform enormous quantities of natural resources. Given their importance, electrical grids have for a long time been controlled or influenced by nation-states and therefore developed in parallel to them. Their historical roots and evolution from local to regional and to large, interconnected pan-national grids explain contemporary differences between infrastructure (e.g., 50 Hz frequency in Europe and Russia vs. 60 Hz frequency in many of the Americas).

The idea for developing a European electricity grid stems from the period between WWI and WWII, driven by techno-economic factors, such as the demand for increased grid stability, and by ideological views and visions held by grid planners, striving towards a unified Europe (Lagendijk, 2008). For many European countries, this development of interconnection goes hand in hand with the European Union's emergence from the European Coal and Steel Community and the policy alignment of member states through the Union for the Coordination of Transmission of Electricity (UCPTE) and its successor ENTSO-E.

Like in other policy areas, economic liberalization's continued dominance as a cultural ideology and political trend reaches the energy domain. Electricity, in particular, can also be a driver of this (Lagendijk, 2008). Following the Second Energy Package adoption in 2003 and the Third in 2009, the EU laid the foundation for an open energy market by unbundling grid operators and energy providers. This liberalization trend has been further sustained by establishing the European Energy Union and creating institutional mechanisms such as the Agency for the Cooperation of Energy Regulators (ACER). With the 2018 Clean Energy Package, the EU fosters liberalization in the internal energy market and lays the foundations for local energy communities and different companies to enter the market once controlled by the old monopolies. Nonetheless, policies support both the extensive, central infrastructure of an increasingly interconnected European grid and more decentralized solutions (energy communities, e.g., community storage). The latter are in Europe in general still grid-dependent.

Also, policies motivated by the mitigation of climate change and pollution such as the Paris Agreement 2015, the German *Energiewende*, or the EU taxonomy for green finance (European Commission, 2020b) have a structuring impact on technological innovation. While they provide legitimation for renewable energies and increasing investment in new infrastructures, the case of the German *Energiewende* exemplifies that energy innovation policy is a highly contested field. There, incumbents from the fossil fuel industry used the nuclear phase-out to replace nuclear with coal under the framing of renewable energy transition (Cherp et al., 2017). New zoning regulations recently bring wind energy diffusion to a halt (Renn and Marshall, 2020).

Historically, fossil fuels comprised a vast share of electricity production (e.g., gas, coal, and nuclear) and renewable hydroelectricity (e.g., pumped hydro or run-of-the-river). Both provided a relatively steady supply of electricity. This condition has been slowly changing since the 1990s, with the rise of wind power and solar photovoltaic. However, the unsteady supply of renewable energies requires additional flexibilities as a counterbalance (Sterner et al., 2017; IEA, 2019b; Ornetzeder et al., 2019). Simplified, one can say that the grid has to stay permanently in balance to prevent blackouts. The daily fluctuations of electricity supply by renewable energies are exemplified by the so-called duck-curve (Figure 2.3) that depicts the total load minus the variable renewable energies (VRE) solar and wind.

The growing importance of technologies such as energy storage, conversion, and transmission herald in a second phase of the global sustainability transition (Markard, 2018b). Following the first phase, the emergence of wind and solar technologies began transforming the energy system, making complementary technologies more critical. Conversely, incumbent generation technologies, such as coal power plants, are on the verge of decline, which

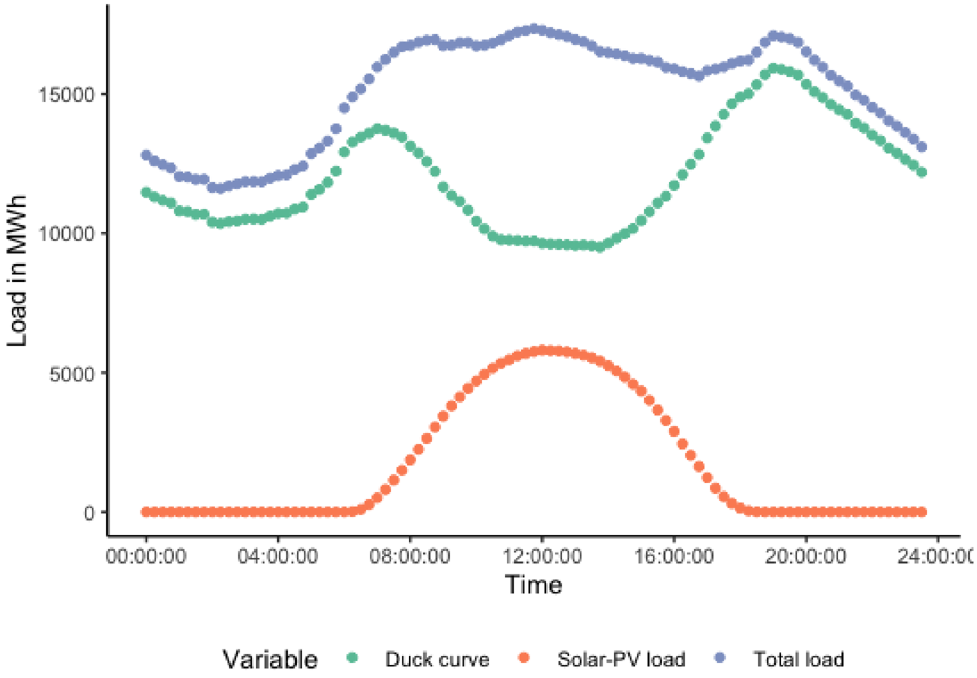


Figure 2.3: Author's depiction of the duck curve based on data by German Federal Grid Agency smard.de. The duck curve depicts the gap of electricity supply due to solar PV on March 31s, 2019. It consists of the total load minus the wind and solar load.

has led to institutional resistance as policymakers try to ease their demise through delays (e.g., of coal phase-out) (Cherp et al., 2017).

Of the different flexibility options that enable variable renewable energies (VRE), energy storage is the most discussed. Current transportation objectives, which depend on electric vehicles and electricity supply through micro-grids, are associated with energy storage—especially with batteries (Crabtree, 2015). From this perspective, the anticipated future has many decentral elements, such as local generation through renewables and local consumption, i.e., security through autarky (Kalkbrenner, 2019). By re-integrating energy-related activities into the daily praxis of users (or habits and routines), energy storage can be a driver for users to engage in the energy transition, help form new relationships amongst energy actors, and establish new practices (Christensen et al., 2020; Kloppenburg et al., 2019).

Currently, electricity storage solutions do not render profits for users based on arbitrage-trading and time-shifting (Anuta et al., 2014; Burlinson and Giulietti, 2017), as energy-only markets do not incentivize investing in energy storage (Gaudard and Madani, 2019). Making storage profitable would require other revenue streams beyond those offered by the spot market, such as ancillary service and capacity provision (Waterson, 2017), or new business models, such as virtual storage provided by aggregators (Castagneto Gissey et al., 2019). While virtual storage provision and other business models are increasingly established in a few countries, it remains questionable if alternatives, as well as social and environmental consequences, have been sufficiently considered (Ornetzeder et al., 2019).

The current changes in the energy system through a sustainable energy transition indicate that the nature of innovating and diffusion of new energy technologies will possibly be different from previous technologies due to the necessary accompanying institutional and infrastructural changes. Therefore, the following section will highlight a few current research avenues that stress energy innovation and transition complexities.

2.5 Innovation and Energy

Most of the approaches presented below aim to answer the precise questions asked by Unruh Unruh (2000, 2002) about how to escape situations where countries, or the whole world (Unruh and Carrillo-Hermosilla, 2006) are locked-in to using carbon-intensive energy technologies, such as coal and gas, seemingly incapable of substituting them with renewables. Therefore, carbon lock-in is a particular type of path dependency, including infrastructural and technological and institutional and behavioral lock-ins that mutually interact with each other (Seto et al., 2016). The technical superiority of new technologies is not the only requirement for an energy transition, but rather, interactions amongst different actors with technologies play a role.

Against this backdrop, investigating flexibility options such as electricity storage requires a political economy perspective, placing a greater emphasis on features like power, institutions, and physical infrastructure. This is because they are not only user technologies as, e.g., solar energy in the early stages, but are both user technologies and supporting infrastructure that require changes on multiple levels to diffuse. As exemplified in the brief historical account in section 4, physical/material constraints often precede socio-institutional changes and, therefore, techno-economic tipping points.

While energy systems and their transition were traditionally researched from engineering and economics perspectives, more research has recently emphasized energy's social dimension (Miller et al., 2015). From this approach, energy systems contribute to every aspect of contemporary society and allow for its functioning. Historical research shows a lengthy account of deeply connected and intermeshed relations between energy and society (Hirsh and Jones, 2014).

Adding to the brief history of energy in section 4, many energy issues are uniquely complex compared to other (consumer) products and technologies. Therefore, the following section gives particular focus to issues surrounding energy technologies. Notably, it unravels the subject of technological innovation systems and energy and their context. It also focuses on the diffusion of energy technologies with a focus on social acceptance.

2.5.1 Technological Innovation Systems and Energy in Context

Early investigations of inducement and blocking mechanisms for energy technology diffusion were the first studies from which the TIS-approach emerged (Jacobsson and Bergek, 2004; Jacobsson and Lauber, 2006).

In European countries, renewable technologies such as wind and PV often received their legitimacy in their early development stages depending on how they were understood as alternatives to conventional energy technologies such as nuclear or gas and oil (Jacobsson and Bergek, 2004). Creating legitimacy could be successful if it could connect to a societal value base (Jacobsson and Bergek, 2004). A lack of legitimacy prevailed, for example, if they were not seen as economically worthwhile (Dewald and Truffer, 2011). In addition, there have always been active de-legitimization attempts by incumbents, such as utilities, in the case of solar cells in Germany (Jacobsson and Bergek, 2004).

Ultimately, sustainability issues are becoming progressively crucial for employing the TIS-approach (Markard et al., 2015) and have an overlapping knowledge base with economic geography (Coenen et al., 2012; Hansen and Coenen, 2015). Increasingly, geographical circumstances play a fundamental role in understanding sustainable energy transition and are gaining more recognition in the literature (Bridge et al., 2013; Köhler et al., 2019; Lawhon and Murphy, 2012). Regarding flexibility options, conventional energy storage technologies like pumped hydroelectric storages (PHS) or compressed air energy storage (CAES) need geological formations such as mountains and underground caverns. Other renewable energies such as wind and solar technologies are also heavily dependent on physical contexts and influence other flexibility options such as energy storage (Gaudard and Madani, 2019).

Previous studies show the embeddedness of innovation processes in different institutional arrangements and interconnection with physical energy technology infrastructure. For example, the virtuous cycle of cumulative causation for natural gas as an automotive fuel can build on existing infrastructure as a driver (Suurs et al., 2010). Carbon lock-ins (Unruh, 2002) and an insufficient diffusion of renewable energy technologies are closely related to the innovation systems' lifecycle for fossil fuel technologies (Markard, 2018a). Thus, incumbents' resistance and push-back to protect their infrastructure and prevent stranding of assets are central for the development of an emerging TIS. Like technology diffusion processes, TIS also have lifespans and undergo a lifecycle that emerges, grows, is stable for a while, matures, and then declines (Markard, 2018a). This is important from a transition perspective, as certain technologies (e.g., coal) require phasing-out for a sustainable energy transition. Actors of incumbent fossil-fuel technologies also shape the context around the innovation system of renewable emerging technologies. An initial example that emphasizes the knowledge creation and diffusion processes already shows that sectoral configurations are essential for technologies such as batteries (Stephan et al., 2017). Haley's (2018) reintroduction of the notion of "structural tensions" as mismatches between a technological innovation and its broader sectoral system further conceptualizes this dynamic.

Regarding energy technologies, globalized knowledge flows are transnational (Binz et al., 2016). However, locality and localizing effects are still central to globalized innovation systems (Schmidt and Huenteler, 2016). Conversely, demand-side policies might even have adverse effects on local TIS in a global innovation system (GIS, see Hipp and Binz, 2020). Likewise, for multinationals, home or domestic markets are still critical for TIS (Crescenzi et al., 2015; Normann and Hanson, 2018). Also, context-dependent technologies that require local embedding diffuse slower than standardized technologies, which can be produced in series; for example, certain heat generation technologies tend to be more embedded than PV modules (Wesche et al., 2019). Additionally, technologies in very early development stages that are not ready to substitute the incumbents soon can still benefit from support networks (Musiolik and Markard, 2011). Nonetheless, these technologies remain heavily influenced by alternatives already in place (Wicki and Hansen, 2017). Thus, following Markard's (2018b) proposal for the next phase in the energy transition, comparing the development of PV technologies (Shubbak, 2019) is only likely to help with the first stages of a TIS, e.g., the TIS for energy storage technologies, and does not sufficiently explain successional diffusion dynamics.

Also, policy (mixes) can structure and "activate" innovation functions and "trigger structural change", innovation functions in turn influence policy; they mutually interact (Rogge and Reichardt, 2016). These policies are then publicly legitimated reactions to issues in the state's innovation systems (Rogge and Reichardt, 2016; Jessop, 2008). The legitimacy of technologies, in particular, as briefly touched upon above, is fundamental to their deployment (Markard et al., 2016) and is, therefore, one of the central and early researched central TIS functions (Bergek et al., 2008a). This appears to be particularly important for value-laden technologies such as VRE that require a vision for the future for diffusion.

The financial system is one central field that can radically change the economy through infrastructure investment (Naidoo, 2019). Currently, however, investment in a sustainable energy transition is insufficient (IEA, 2020c). While many are hoping for business to fill this gap, private investment remains low for reaching the 1.5° C-target as commercial initiatives mainly work when there is expectable profit. Often, no immediate profit comes from investment in energy innovations, which is why other short-term investments are more profitable (Malm, 2016, chap. 15). One way forward is to qualitatively change the financial rules to steer private finance into green infrastructure investment (Naidoo, 2019), e.g., by creating a common taxonomy for green finance in the European Commission (2020b). Moreover, private initiatives are often small-scale—a desirable feature to many advocates of an energy transition—but often, infrastructure is needed on a scale that only public capital can provide (Jaccard et al., 2012). Essential financiers of the transition are municipalities (Malm, 2016; Villaraigosa et al., 2013).

Besides finance, however, command and control are necessary to steer energy transitions (Malm, 2016, chap. 15). Otherwise, renewables remain merely an add-on rather than a substitute for fossil fuels (Vinichenko, 2018). Thus, governments remain the central actors able to block or enable renewable energy technology diffusion (Negro et al., 2012) and demand particular attention.

2.5.2 Energy Technology Diffusion

Historically, diffusion dynamics differ between technologies. The overall duration from product invention to widespread adoption can, according to one study, vary from 20 to 70 years for electricity supply or end-use technologies (Gross et al., 2018). For electricity generation technologies, Gross et al. (2018) found that adoption processes occur in a phase of invention-development-demonstration and a deployment-commercialization phase. The latter is the one that requires special attention in the second phase of the energy transition, where the diffusion of renewables is scaled up.

One explanation for the sluggishness of energy system transition is the long lifespan of energy generation technologies (Bento and Fontes, 2015; Gross et al., 2018). Economic viability and the expected lifetime of incumbent and alternative systems are highly relevant factors influencing technology substitution (Seto et al., 2016). Another explanation is that these products are not bought by end-users (households) but rather by firms. They tend to have a stricter cost-benefit rationale behind their innovation-adoption decision, thus less likely to contribute to diffusion dynamics resembling the S-curve (recall Figure 2.1) (Day and Herbig, 1990).

A counterpart to the legitimation-innovation function in TIS, which is about building trust and engaging in social discourse when it comes to diffusing technology innovation, is social acceptance. Social acceptance, a concept introduced to grasp possible resistance against new technologies and infrastructure, is an offspring of the public acceptance concept. Using pejoratives like NIMBY ("not-in-my-backyard"), local opposition to projects have been investigated to ideally help foster the acceptance of these new technologies (Friedl and Reichl, 2016; Wolsink, 2000). By parting from this NIMBY perspective, with its clear pro-innovation bias and taking societal concerns and the complex interaction of adopting new technologies more seriously, the concept of social acceptance formed. Stressing the social dimension of technological innovation, Wüstenhagen et al. (2007) propose that the social acceptance of energy technologies has three dimensions: (1) community (local stakeholders, residents, local authorities), (2) market (customer, investors, inter-firms), and (3) socio-political (public at large, key stakeholders) (see also Wolsink, 2018, for an updated version).

Local resistance to technologies is often the response of local actors (such as businesses and employees) to declining technologies threatened by a newcomer (Markard, 2018a). Studying social acceptance is becoming, therefore, more critical in the next phase of the energy transition. Up until now, social acceptance has been researched for different technologies including wind technologies (Khorsand et al., 2015; Liebe et al., 2017), infrastructure projects (Friedl and Reichl, 2016; Komendantova and Battaglini, 2016), and smart meters (Jegen and Philion, 2017).

It is not only crucial for implementing renewable energy innovation, but also for conventional ones like shale gas, as LaBelle (2017) shows for Poland. In addition, Devine-Wright et al. (2017) propose researching social acceptance of energy storage technologies as central technologies for the sustainable transition, which Thomas et al. (2019) tested in the United Kingdom with a deliberate approach.

Essentially, the social acceptance perspective is a demand-side perspective to investigate the diffusion of (energy) technologies. It provides a more precise differentiation of demand-side factors than the already extensive TIS literature, as it considers different dimensions of social acceptance. Also, it accounts for the often-complex interactions when it comes to the diffusion of “controversial” technologies. Thus, it should be seen as a step further than the diffusion of innovation literature (following Rogers as described in section 3) and used to amend technology diffusion systems. Moreover, it is as a first conceptualization attempt to answer Bergek’s (2019) call for considering technology diffusion systems alongside TIS.

However, social acceptance is likely to become relevant only when technologies diffuse more widely and receive public attention. Regarding energy storage, this is undoubtedly the case for PHSs that cause large landscape changes. It is currently more difficult to empirically grasp for smaller battery-driven storage at this time, as the emerging battery storage TIS is still in its formative phase and as the next phase of the energy transition just begins.

2.6 Synthesis of Theoretical Framework

As presented above, the vast body of literature on innovation identifies several mechanisms and phenomena of innovation development and diffusion. Both are related, as the previously given theoretical approaches show. Diffusion dynamics are context and innovation dependent but also dependent on how they are being developed. The technological innovation systems approach is one approach that successfully captures both these dynamics. It enables applied capitalism research under the premise that innovations are desirable. However, the approach tends to neglect the broader societal relations of power and dynamics within capitalism. While it considers the geographic dimensions and is not blind to history, it requires a stronger focus on the political context and support systems for capitalist production.

In particular, TIS provides a useful holistic perspective that captures both the emergence and directionality of innovations depending on types of technologies, involved actors, networks, institutions, and context factors. In particular, the centrality of creating legitimacy for emerging TIS in their formative stage is essential to consider. However, as shown above, the logics of capitalism and power-relations that permeate TIS's inner workings need to be stressed to strengthen the approach's explanatory capabilities for researching transitions.

The brief history has shown that the energy system is deeply embedded in physical infrastructures, strongly connected with the global political-economic system, and deeply structured by societal relations and culture. The upcoming changes in the electricity sector, in particular, show that social and political power relations are central for explaining its diffusion. Electricity grids as LTS are especially prone to inertia as they have a long history where power structures manifest themselves in the physical infrastructure's materiality.

Energy technology TIS and the diffusion of energy innovation is a particular case of innovation and diffusion. While the research of sociotechnical energy systems can profit from studying other non-energy technologies, the study of energy requires particular attention to several details: Although many elements are generalizable, the unique role of energy for society, its embeddedness into socio-institutional relations and physical infrastructure, make energy technologies unique. The new phase of the energy transition requires even more substantial consideration of these particularities. Thus, researching energy flexibility options such as energy storage—both as infrastructure and user-products—benefits from amending the TIS framework by including physical settings such as geography and infrastructure, the narrow and direct political economy context but also the broader political economy or landscape context, as well as the policy mix (Figure 2.4).

The shown analysis steps and considered elements and dimensions have already been applied in many studies and serve only as a different presentation form. However, the following three suggested amendments for future TIS related empirical work have not yet been made in this form and require further consideration:

Physical-Structure/Nature as Fifth Element of a TIS

Physical-structure/nature is foundational for the development of innovation systems. While this point receives considerable recognition in economic geography and ecological economics and is already getting implicit attention in current innovation system analyses, the TIS framework could explicitly include physical-structure/nature as the fifth system element. This is a way to embed the innovation dynamics within their physical system.

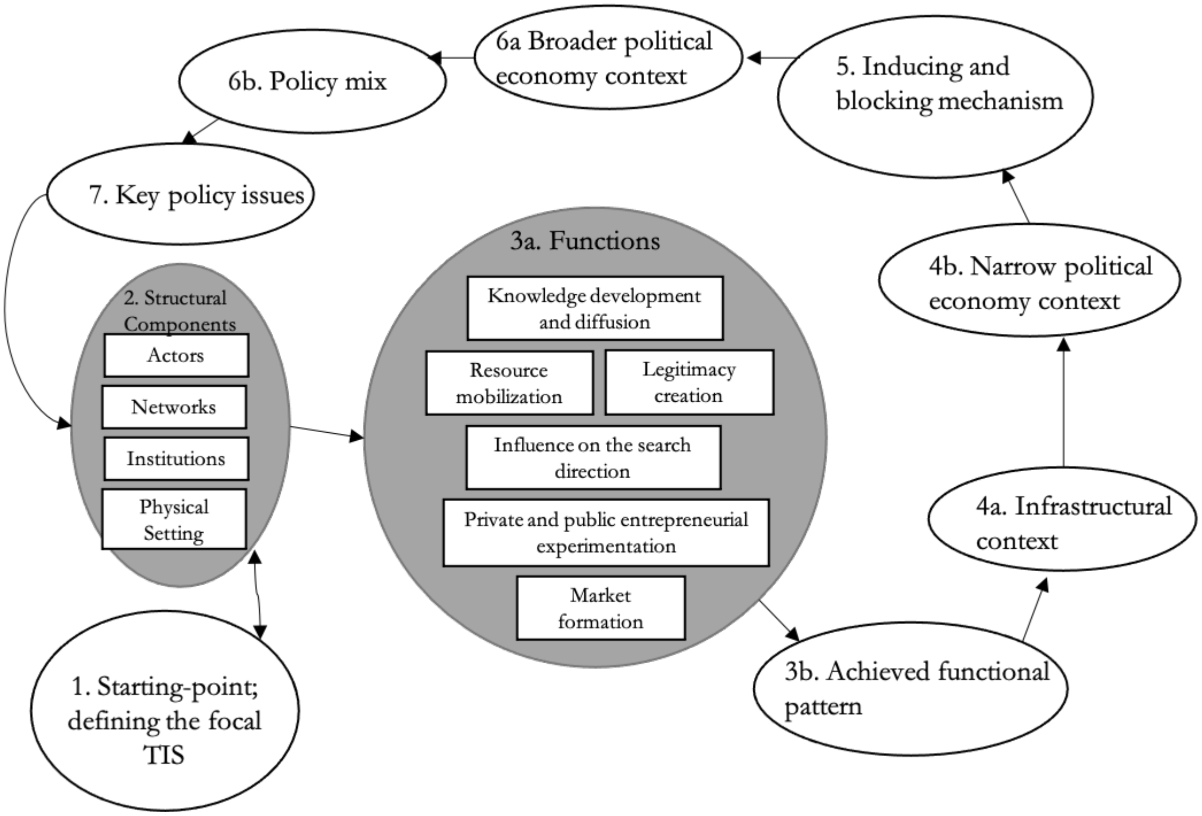


Figure 2.4: The updated analysis scheme (adapted from Bergek et al., 2008a)

For flexibility options such as energy storage, physical environments and spatial dimensions—such as mountainous areas—are likely to influence various TIS aspects. Also, human-made physical structures like grids as LTS are likely to influence the development. This includes the influence on apparent functions such as market dynamics, but also the direction of search and legitimation and, consequently, resources availability.

Strengthening the Societal Perspective of Market Diffusion Dynamics

Research should consider in a more nuanced and comprehensive way the social dimension of market dynamics. As noted above, in the TIS approach, this dimension is referenced in innovation functions such as the direction of search and legitimation. Also, it is closely related to the function of market diffusion. Thereby, firms create social legitimacy of their product by linking it to salient public issues such as climate change or technological progress that resonates in discourses and narratives. This then directly relates to how they market their product to consumers and regulators.

Conversely, diffusion of technological innovation is also heavily influenced by these salient public issues. In particular, when it comes to a widespread role out and scale-up of diffusion outside the niche, potentially controversial energy technologies such as energy storage require social acceptance on different levels (local, market, socio-political).

A social-acceptance-amended diffusion theory from energy social sciences presented above and the TIS framework from innovation studies form a conceptual duality whose combination appears beneficial for studying the next phase of the energy transition. This allows for a distinction between innovation development and diffusion, similar to the difference between supply and demand. They are two distinct sides that form a duality—dualities and not dualisms in the sense of Giddens (1984)—of the same co-evolutionary system; they are potentially spatially distinguishable, but always relative, since the local innovation system only overlaps with local social acceptance. In reality, these sides work as a co-evolutionary system and are one dynamic. In these, public salience is relevant for both sides. Salient issues provide the basis for search direction and reference points for firms legitimizing their product and technology. Conversely, public salience mutually affects the diffusion of technological innovation and social acceptance depending on whether the product appears to "solve" a problem or inflicting further controversies.

Incorporating the Broader Political Economy in TIS

The central role of state and policy in the conceptual TIS framework is receiving increasing attention. However, the broader political economy dimensions of policy intervention/state involvement require particular attention in the next phase of the energy transition. Therefore, power-relations—such as between incumbents and insurgents—receive increasing attention as they determine the choice-set of other actor groups (e.g., consumers but also regulators). While networks have conventionally been considered explicitly in TIS analyses—e.g., by emphasizing the vital role of lobbying organizations—it is important to stress that power-relations in networks rarely follow a top-down logic with states at the top. More broadly, capitalism as a system tends to structure the TIS's inner working (e.g., by defining worker-capitalist relations).

Including the broader, political-economy dimension for researching diffusion and innovation of new flexibility options can thus shed light on the importance of green growth rationales and other motives for actors to engage in the field that lie outside the direct VRE-specific drivers. It improves the research on why—in the long run—certain development trajectories did or did not materialize.

2.7 Conclusion

This chapter set out to identify the next research steps for the next phase of the energy transition. It is a phase in which renewable energies are about to scale-up beyond niches, incumbent (fossil-based) technologies demise, powerful industry and institutional actors will show resistance, and the development and diffusion of new infrastructure forms such as storage. These societal elements and structural factors and their dynamic interplay require a suitable theoretical and analytical framework.

Energy systems consisting of elements as the grid are deeply enrooted in physical infrastructure, dependent on geography and societal power relations and institutions. Past technological decisions matter for and foreshadow current and future energy system development paths. Unearthing those involves the study of fundamental regime changes on multiple spatial, societal, and technological levels. It is essential to account for the deep structures and prevailing path dependencies, trajectories, and power structures within contemporary global capitalism. Doing this requires a co-evolutionary understanding of the political economy. Thus, an analytical political economy perspective with a strong focus on historical materialism, physical structures, and power relations in society is essential for understanding the role of new technologies such as energy storage in the energy system.

Moreover, to provide policy guidance, a tangible approach, such as the presented technological innovation system approach, is necessary, illustrating how innovations and knowledge are created, diffused, and shaped to identify pressure points for a transition. The proposed amendments to said approach are useful to explain institutional change alongside diffusion pathways and dynamics. Three proposed amendments for future empirical TIS research on the next phase of the energy transition are (1) inclusion of physical-structure/ nature as the fifth element of TIS, next to actors, networks, institutions, and technologies. (2) Capturing complex social development and in TIS and diffusion dynamics in markets. (3) Incorporating the broader political economy of power-relations and capitalism in TIS.

The next chapter now presents how this broader TIS approach integrates into the research framework for this thesis. Moreover, it will give an overview of the research methodology used, the underlying scientific theoretical considerations, and the applied methods and empirical strategies.

Chapter 3

Methodology

3.1 Introduction

The next chapter describes the procedures and methods used in this thesis. This includes the philosophy of science foundations, the methodological concept, and the empirical methods used to address the research questions. Thus, it is about the conceptualization of the entire research process. The overall process includes the issues raised in the previous chapter and conceptualizations based on the scientific literature and applies them to the concrete empirical work. Moreover, it shapes how conclusions are drawn in the remaining part of the thesis. This chapter starts with ontological and epistemological dispositions. Then, it describes the overall methodology and the applied qualitative and quantitative methods. A summary of the research process concludes.

3.2 Ontological and Epistemological Dispositions

The following section describes the ontological and closely related epistemological foundations and commitments. This thesis relies on them for the use of methodology, the design of the overall research process, and methods. Ontology is the study of being, of what it is, and in the case of this thesis, in particular social ontology, thus “the study of the nature and properties of the social world (Epstein, 2018).” It is thereby concerned with the nature of societal entities. Building on this is the question of epistemology, which is the study of knowledge itself that poses the challenge of how and when we can say that a statement is true (Steup and Neta, 2020). This thesis uses a critical realist philosophy of science approach, as briefly explained in the following.

Foundation of Critical Realism

Critical realism, which goes back to Bhaskar (1975), integrates positivist/empiricist and social constructivist approaches (Danermark et al., 2002). It thus assumes that there is a real-world and that it is also a world of mechanisms but that this world is not congruent with the observable world. In this observable world, only actualized events of these mechanisms are observable, but the real objects that interest the researcher remain hidden.

Concepts and theories always mediate facts of what we can empirically perceive and grasp of this reality. Thus, “reality has an objective existence but that our knowledge of it is conceptually mediated: facts are theory-*dependent* but they are not theory-*determined*. This in turn means that all knowledge in fact is fallible and open to adjustment (Danermark et al., 2002, p. 20).” For this reason, our understanding of what the world is, our ontology, is particularly relevant to how our knowledge is gained (Sayer, 2010).

“[O]bjects have powers whether exercised or not, mechanisms exist whether triggered or not and the effects of the mechanisms are contingent – means we can say that a certain object tends to act or behave in a certain way. Whether it will actually act or behave in this way, however, is a completely different matter" (Danermark et al., 2002, p. 53). Thus, scientific laws and regularities are no definite description of constant processes but rather show directions and tendencies resulting from entities' structure (Ron, 2002).

While it is already challenging to infer the underlying real objects from natural regularities or mechanisms, this becomes even more so for social mechanisms and structures (Danermark et al., 2002). On the one hand, this is because social entities and, thus, the mechanisms are less stable than natural relationships (Ron 2002). On the other hand, they are first created by people's concepts and are also changed again by researchers' conceptualization, the so-called "double hermeneutics" (Danermark et al., 2002, p. 36). Thus, social structures exist because people make them by engaging with one another. Social structures arise from the interaction and relationship between individuals, mediated by material factors (Elder-Vass, 2010). But also, researchers' pre-conceptions and theories influence their scientific conclusions. In this thesis, the social objects in focus are organizations such as companies and non-governmental organizations, formal and informal networks between them but also structures such as states, governments, and regulatory agencies.

Critical Realism and Hermeneutics

This thesis combines the empirical of critical realism with the interpretative of hermeneutics. As shown in the following, mainly based on Durdovic's (2018) argument, the two make a fruitful combination for the kind of research carried out in this thesis.

A central justification for considering hermeneutics lies in the fact that "causal effects that impact real happening have at least some of their source in the understanding of actors and in how these understandings emergently converge in intersubjectively linked actions" (Durdovic, 2018). In turn, this means that reasons can also be cause (Sayer, 2010, chp. 1). So actors or groups of actors articulate their understanding of things and decide how they act, and it thus results in collective action.

Thus, understanding mediates social action. The tendencies mentioned above can take effect without fully manifesting themselves without the actors being aware of it. However, other groups' actions may prevent or block these tendencies, possibly because they have a different understanding. In the social world, therefore, language and understanding is a central element of *generative mechanisms.* „As a term for describing how the tendencies of social happening are born and interact, generative mechanisms encompass not just communication and action across social relations, but also (explicit, implicit, latent) social structures and semi-social structures such as the living environment, material resources and technology" (Durdovic, 2018).

Another argument for the consideration of hermeneutic methods in critical realism, according to Durdovic (2018), comes from Archer's (1995) *analytical dualism* and the so-called *morphogentic cycle.* These are based on a distinction between structures and actions, which implies that "structure necessarily pre-dates the action(s) leading to its reproduction or transformation" and that "structural elaboration necessarily post-dates the action sequences which gave rise to it" (Archer, 1995, p. 15). "Behind structures there are people, whose opinions, values, acts, and initiatives are not swallowed up by structures, but have the capacity in their own right to overflow into social relations and spread through them, and thereby, in some cases, to cause structures to change" (Durdovic, 2018).

Because "structures and social interactions exist with each other at all times like two factors in a process of social happening," it is impossible to analyze them separate of each other. Therefore, Durdovic proposes the concept of *generative hermeneutics.* This concept explores how „meaning articulated in speech emerges out of social relations and generates shifts in understanding that through their conversion into action bring about social change“ (Durdovic, 2018). Therefore, two analytical steps are proposed: First, capturing the emergence of real happening by *generative mechanisms*, and second, *generative hermeneutics* that grasps the emergence of the happening of meaning.

Because, unlike in the natural sciences, language allows insight into the interior of social life and thus also to understanding (Bhaskar, 2016, p. 57), it makes sense to investigate this hermeneutically. A consequence is that critical realist social sciences often employ qualitative methods that focus on meaning (Price and Martin, 2018).

Systems and Critical Realism

Following evolutionary critical realist conceptions (e.g., Sum and Jessop, 2014), this thesis aims to unravel social institutions and individual agencies that continuously interact in a system. While the term "system" is used by proponents of holism and individualism with competing meanings, a critical realist perspective provides a particular understanding (Fleetwood, 2017).

Bunge (2000, p. 149) defines systems "with a composition, an environment, a structure, and a mechanism". With this, systems are a suitable scientific-theoretical approach for many systems approach practices in general since phenomena such as emergence are central here (Mingers, 2011). Especially the innovation systems approach provides a suitable fit, which tries to uncover generalizable mechanisms in addition to case-specific regularities (De Oliveira et al., 2020; Vega and Chiasson, 2019). Although in the technological innovation system approach, the innovation functions are also used heuristically, they also provide a theoretical model that aims to identify and isolate said key mechanisms and their dynamics—primarily by conducting many case studies.

A systems-approach allows for an accounting of upward and downward causation (Gräbner and Kapeller, 2015; Elder-Vass, 2010). While this acknowledges individuals' role, it immediately stresses "the double role of emergent properties that constitute a joint interaction, and thus may carry mechanisms of downward causation" (Gräbner and Kapeller, 2015, p. 435). Therefore, this implies that society is a system comprised of many subordinate systems. Mechanisms bridge these different systems. Therefore, research that builds on this approach considers coherency between different system elements and sub-systems.

The understanding of a TIS fits an ontology with laminated levels. A laminated ontology means that there are different levels at work in the system (Price and Martin, 2018). For the TIS, these are focal technology, actors, networks, institutions, and physical structures, as I argue in 2.6. Moreover, innovation functions that have been identified so far in many case studies (e.g., Bergek, 2019) can be considered as the first indicators of some generative mechanisms that exist in many case studies. As mentioned above, social systems are particular and require a focus on meaning and understanding, which are often mediated by language. The TIS approach is also fitting in this regard as it entails two innovation functions—guidance of the search direction and legitimation —both focus on language and meaning. Both of these innovation functions are fitting to an *generative heuristic* approach, as mentioned above. In particular, the legitimation innovation function—upon which this thesis focuses specifically—entails the focus on "meaning-making" and language.

Similarly to innovation systems, an analysis of systems that influence innovation diffusion also harmonizes with a critical realism approach. Diffusion can also be regarded as a systemic phenomenon and is compatible with a laminated ontology. Additionally, the various theories of (energy) technology diffusion discussed in chapter 2 are also centered on actors that build relationships with each other and sometimes even form more fixed networks. The same goes for the social acceptance approach. In addition, using a critical realist perspective, language, culture, and other institutional processes are *generative heuristics*. Using this perspective, typical mechanisms for diffusion processes that would be focused upon in an analysis are supply and demand as well as mimicry and following trends.

Epistemology and Critical Realism

Epistemologically, the above mentioned ontological commitments imply the following: “According to critical realism, the scientific activity of explanation consists of three analytically different stages. During the first stage, a regularity is observed; during the second stage hypothetical causal mechanism is offered to explain the regularity; and during the third stage scientific activity is directed at isolating the mechanism itself“ (Ron, 2002, p. 133). Often this will not work, which does not suggest that no real underlying mechanism exists, but rather that our limited knowledge prevents us from recognizing it.

Another epistemological disposition follows that different kinds of sense data can be obtained and put in a context. However, language, pre-existing mental frames, limited measuring devices make this an ambiguous endeavor. Concepts and any kind of communication and exchange are always context-dependent and value-laden. These kinds of contexts change over time and place.

This thesis follows the approach by researchers that try to address this by combining methods that allow on the one hand to identify mental frames, social structures, and concepts, and on the other hand to add methods that allow determining mechanisms. “Thus, methods such as interviews and case studies that help to establish context-specific understanding further, by exploring the meaning and mechanisms of particular processes, need to be allied to other methods that begin to explore their generality in the sense that similar demi-regularities might be detected” (Downward and Mearman, 2002, p. 412).

3.3 Methodology

Having briefly discussed this thesis’s ontological and epistemological commitments, the next section moves on to the used methodology and methods. It follows a mixed-method methodology while utilizing both qualitative case study and quantitative methods.

3.3.1 Mixed Methods

This thesis applies methodological pluralism in a structured mixed-methods approach, which has become widespread in social sciences (Plano Clark and Ivankova, 2020). Mixed-method approaches are even titled as “the third research paradigm” (Johnson and Onwuegbuzie, 2004, p. 44), as they provide an “intuitive way of doing research” (Cresswell and Plano Clark, 2011, p. 1). In short, mixed-methods combine quantitative and qualitative data to illuminate societal trends. Thus, this thesis uses mixed-methods “procedures [...] in multiple phases of a program of study” (Cresswell and Plano Clark, 2011, p. 5) in a way that both forms of data (qualitative “word” data and quantitative “numbers” data) inform each other.

This thesis looks at the development of battery storage systems and the relationships to their environment quantitatively, focusing mainly on diffusion, and qualitatively, looking at the direction of development. The other chapters consider the relationships to surrounding societal actors and institutions in the innovation system. Further, the focus is on contextual structures of physical and social nature both qualitatively and quantitatively. This is consistent with the theoretical framework based on interdisciplinary innovation research, which are both (Köhler et al., 2019). Furthermore, a critical realist epistemology benefits from an interested methodological pluralism (Dobusch and Kapeller, 2012).

Research practice shows different forms of mixed-methods, just as human perceptions make sense of different kinds of information. The scientific method, however, requires the logical and comprehensible drawing of conclusions. Its exact form depends on the object of research and the research question (Cresswell and Plano Clark, 2011). Moreover, it also matters in which order questions are dealt with and which different priority aspects have.

All parts of the thesis have equal priority and timing is concurrent. This implies that both qualitative and quantitative research are implanted during the same phase in the research process. Following the theoretical assumptions, this thesis mixed the parts at the design level (Cresswell and Plano Clark, 2011, p. 68). Contrasting of the two strands happens according to content areas and according to timing. This way, both kinds of empirical data were related to theory. The alignment of the data was on the content level.

The level of interaction between the qualitative and the quantitative strand of the thesis is, in general, independent. For most parts, both sections were kept separate in the design but combined in the overall interpretation (Cresswell and Plano Clark, 2011, p. 64). However, as both thesis-parts' timing was simultaneous, there was selected interaction between the parts.

However, the goal was not to fully triangulate the qualitative and quantitative segments. The author expected that the findings could not be entirely corroborated due to the different scales of inquiry. Besides, the research object was defined more broadly in the qualitative part than in the quantitative part, and the study was designed accordingly. Instead, the goal was to offset both approaches' weaknesses while drawing on their strength (Bryman, 2006; Cresswell and Plano Clark, 2011), thereby allowing for a more comprehensive account of the inquiry area.

3.3.2 Qualitative and Case Study Methods

This thesis chose a case-study approach for the qualitative chapters as it "investigates a contemporary phenomenon within its real-life context, [. . .][where] the boundaries between phenomenon and context are not clearly evident" (Yin, 2009, p. 13). Thus, these chapters use a slightly extended TIS approach, as presented in chapter 2, which provided theoretical guidance. Due to the fuzziness of the system boundaries and the complexity of the interrelationships between different actors and material and social influences, different data sources are combined to "converge in a triangulating fashion" (Yin, 2009, p. 13), which again suggests a case study approach.

The next subsections describe the reasons for picking national boundaries as spatial frame for studying technological innovation systems, choice of the country cases picked for this thesis, the qualitative interview methods used, and step by step the research process process.

3.3.2.1 Spatiality and National Scope for TIS Case Studies

As indicated in section 2.6, spatial factors such as geography and physical infrastructure can be necessary for the development of TISs. For one thing, this suggests that it is also helpful for TIS research to have a clear spatial framework. A second reason for the inclusion of an explicit spatial boundary is practicability. For example, it is difficult for the research process, as it is dealt with in such a thesis, to grasp and analyze innovation systems in this depth internationally.

Most of the published TIS studies also choose a clear spatial focus, either national or based on specific regions (cf. subsection 2.2.3). A clear spatial framework within national borders is also helpful because it allows for easy incorporation of national regulatory conditions into the study. A critical insight from this research is that even in a smaller national context, developments occur within said TIS, which link to international and global dynamics. While research attempts to capture TIS in a genuinely international and complete way exist, these are now more commonly grouped under the terms such as global innovation systems (GIS, see, e.g., Binz and Truffer, 2017; Hipp and Binz, 2020).

For all these reasons, this thesis opted for national case studies. The selection of the countries Austria and Germany was based on access to interview partners, language and legal text, and further information. As mentioned above, this focus comes with the limitations that several significant developments and influencing factors could only be conceptualized as existing outside the focal (national) TIS. In the case studies, these were explicitly considered, e.g., concerning the development of the TIS of knowledge transfer or that pre-products are needed and concerning the diffusion dimension by exporting to foreign markets.

However, the two case studies are not intended to be classic comparative examples in the sense of a comparative political economy study. Although the comparison of dissimilar allows for many insights, the countries differ in population size by a factor of 10. However, they are very much intertwined through a common language, congresses, flow of information, and (business, but also political) exchange. Otherwise, the countries are very similar as already stated in 3.3.2.2. For these reasons, rather than a classical comparison, this discussion attempts a synthesis of the results.

3.3.2.2 Country Cases Austria and Germany

Regarding battery storage technology development and diffusion, many countries around the world are worthwhile studying in-depth. The obvious first choices are the large deploying countries such as China, the United States, Korea, or Germany (IEA, 2020b). In particular, China and Korea are among the large producers of battery cells and warrant a closer look (Transport and Environment, 2020).

Another relevant criterion for selecting country case studies is knowledge about the countries' cultural, political, and social dynamics. It is possible to acquire this while conducting a study. However, it is advantageous to understand the local language to pick out nuances and nuances in interviews and document analysis (Flick, 2009). The author of this thesis has German as his mother tongue, so country studies in the German-speaking area are apparent.

Finally, it is always helpful for a case study, which also works with qualitative interviews, to utilize different networks to access respondents. This is easier if one can fall back on already existing personal or professional networks. The author of this thesis comes from Germany but has been living and working in Austria for many years, so both countries are obvious choices for case studies for this thesis. In the following, a few general facts about the two countries will be presented. Besides the fact that Germany is ten times the size of Austria, with 82 million to 8.8 million inhabitants, the two neighboring nations share many common characteristics but are also distinct in essential aspects.

Austria and Germany are both parts of the global innovation system around battery energy storage technologies. Moreover, Chinese and Korean companies dominate the international (lithium-ion) cell production but hold factories in European countries (also Germany). Thus, both TISs are partially on the receiving end of the global innovation system. However, both have long-term knowledge and competencies in the battery storage area. There is theoretical research happening in domestic universities and research institutions. Various firms have competencies in electrical engineering in assembling complete battery packs and their integration with inverters and battery management systems into the entire system. They also have long-term competencies in using battery systems for conventional and electric vehicles. Both countries have a closely linked but different (technological) history with path dependencies and national peculiarities. Additionally, the two TISs are tied due to the same language and related within the European BES –TIS.

For both Austria and Germany, several structural factors are common: They are both members of the European Union (EU), Energy Union, OECD, share subsidiaries of the same transnational corporations, and are part of the same European and global supply chains. Within the EU, industrial actors from both countries coordinate their lobbying activities. Companies, universities, and research institutions experience a constant connection of knowledge flows through interaction and exchanging enabled employees through the shared language.

Economically, both countries have strong economies (Figures 3.1 & 3.2) that are among the most advanced worldwide. They tend to be export-oriented and heavily influenced by high-value industry products. Accordingly, both countries have a large share of around 25 % of the industry's real value-added as part of GDP (Figure 3.2).

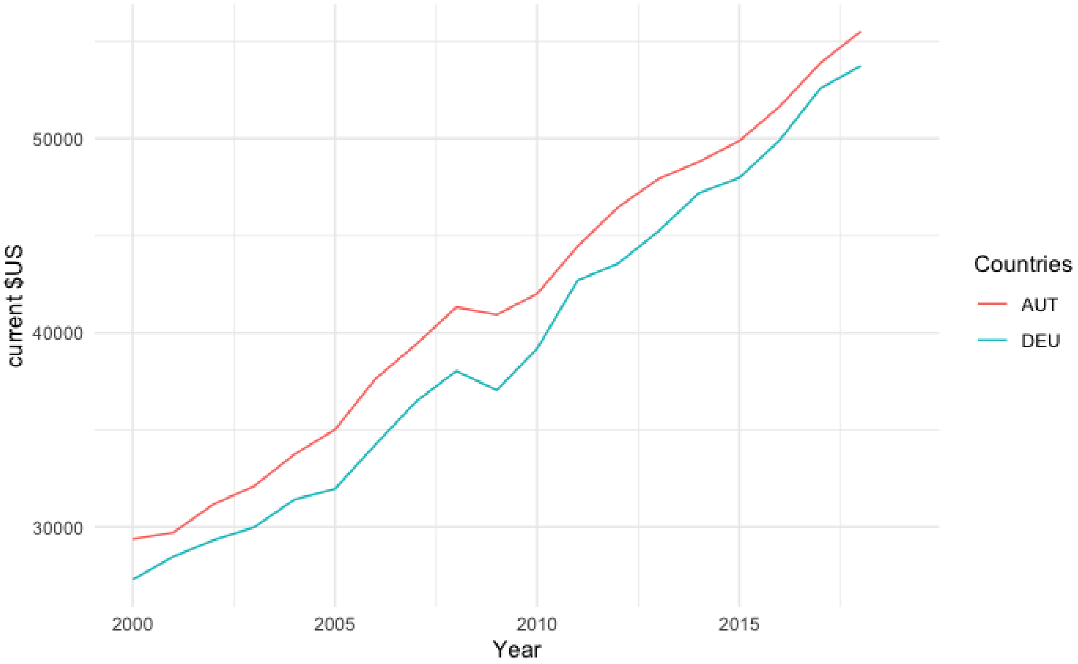


Figure 3.1: GDP per capita in current prices $US. Source: World Bank (2020b) WDI 2020 United Nations

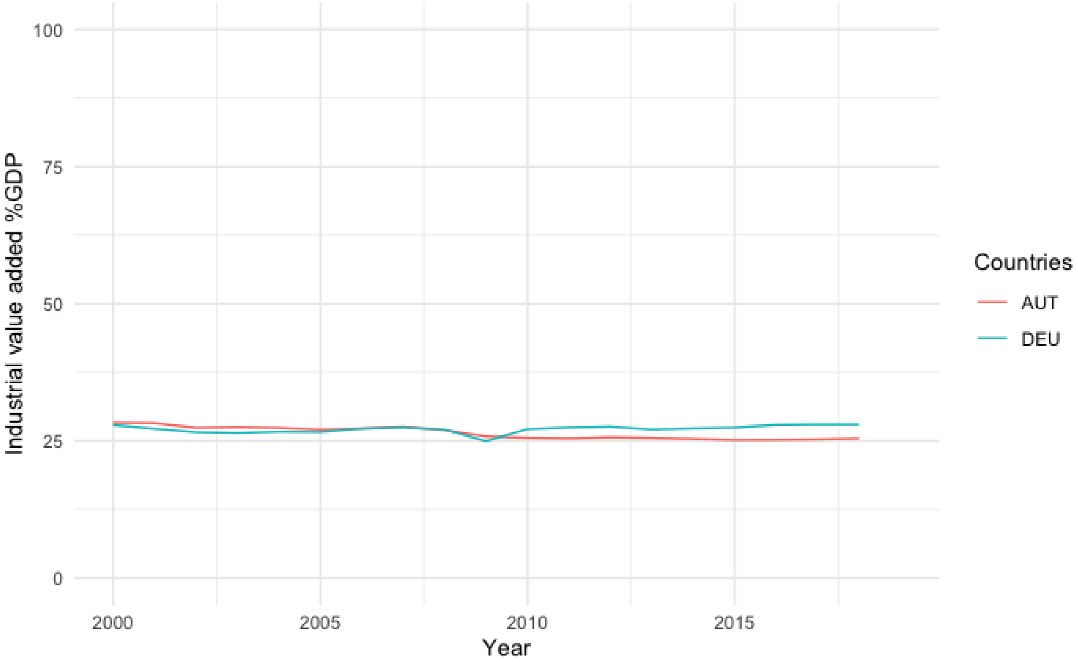


Figure 3.2: Importance of industry in the economy. Source: WDI 2020 United Nations

The capacity to innovate in high-tech industries is heavily dependent on education (Stromquist, 2002). Thus, a TIS around advanced battery storage technologies requires a large share of the population with advanced education. Both Austria and Germany have a share of around 75 % of the working-age population with advanced education (Figure 3.3).

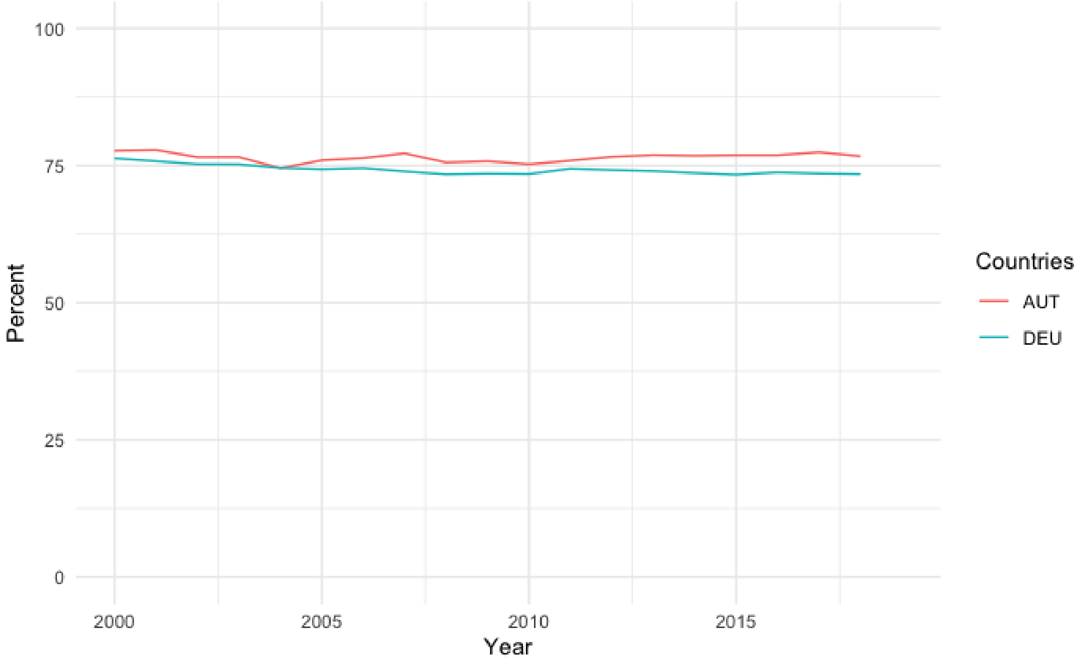


Figure 3.3: Working-age population with advanced educations levels. Source: World Bank (2020b) WDI 2020 United Nations

When it comes to the energy system between the two countries, both have, also due to geography, very different foci. While German wind parks, especially offshore in the North Sea, are well known, in comparison, Austria could advance the deployment of wind parks heavily in the last years and pull ahead (Figure 3.4). Also, pumped hydro storage, which requires mountainous areas, is much more important for the Austrian energy system then for the German one (Figure 3.5).

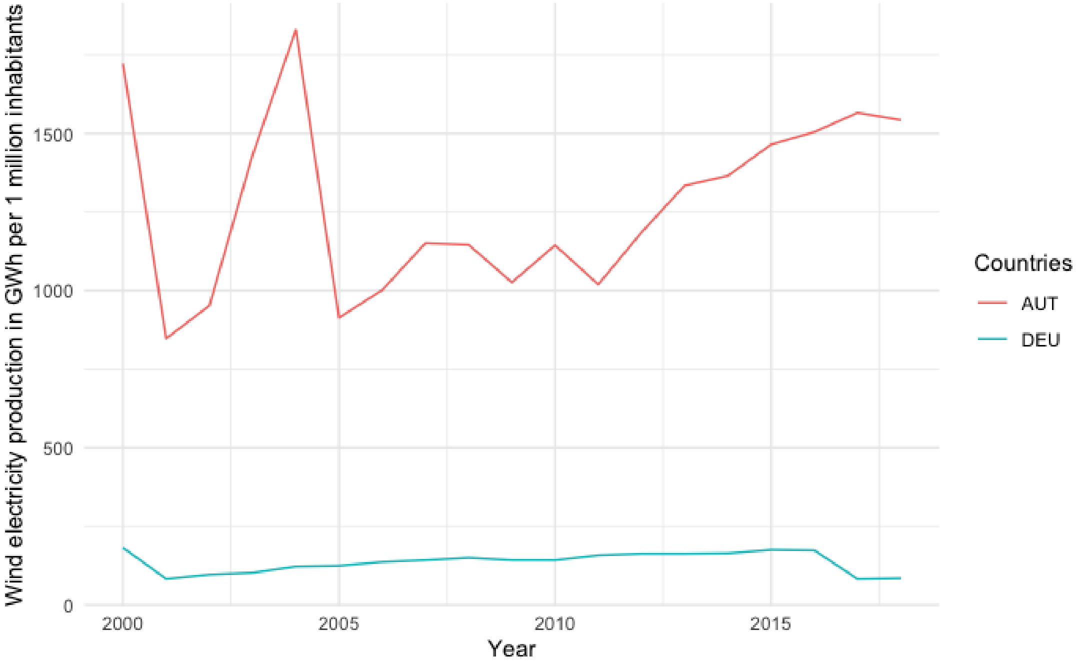


Figure 3.4: Wind electricity production in GWh per 1 million inhabitants in Austria and Germany. Source: IEA 2020

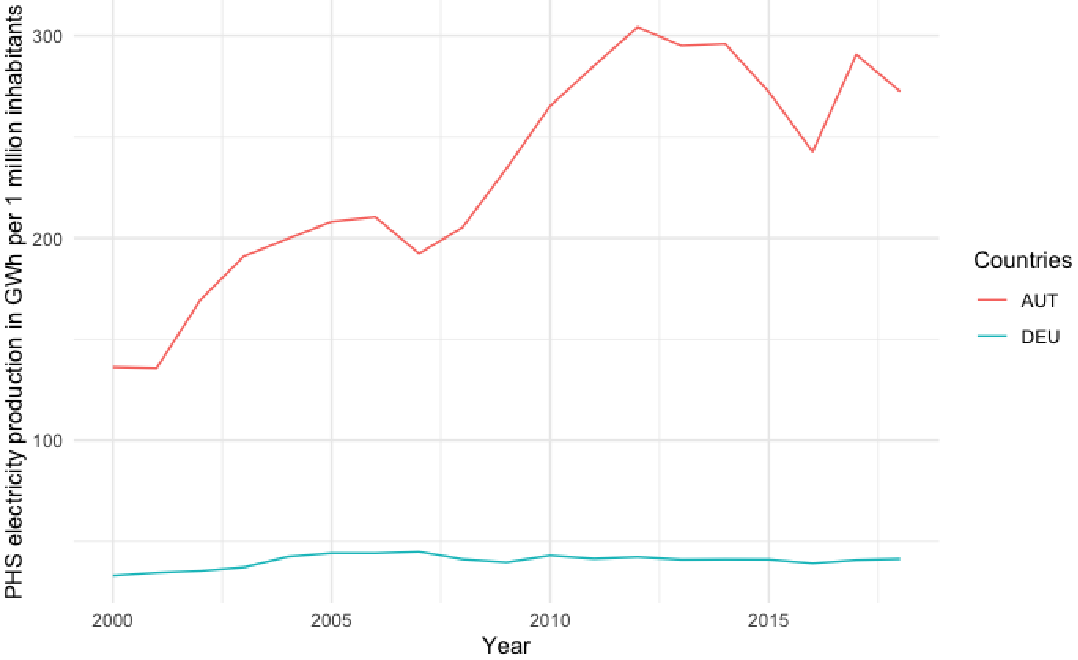


Figure 3.5: Pumped hydro storage electricity production in GWh per 1 million inhabitants in Austria and Germany. Source: IEA 2020

To sum it up, the two neighboring European countries Austria and Germany, are worthwhile examples for in-depth case studies on the development and diffusion of battery storage systems. They have similarities such as economic development, political environment, and language and differences such as geography, energy system, and size. However, both countries are so different that the two case studies can stand alone, and a comparative comparison is only an optional step after the primary analysis. Moreover, the border-crossing dynamics imply a joint rather than a side-by-side approach to the study.

As the next section discusses in more detail, the two country case of Austria and Germany chapters follow a case-study approach (Yin, 2009) based mainly on qualitative interviews, participation in workshops and events, document analysis, and descriptive statistics.

3.3.2.3 Qualitative Methods

For this purpose, this thesis uses a qualitative approach for the two chapters, thereby making it possible to combine the different and not yet standardized sources of evidence and capture the actors involved' different "lifeworlds" and experiences (Flick, 2009, p. 16). In this way, it is possible to arrive at an intersubjective understanding of the social process and capture its complexity. One primary data source comes from interviews with experts in the field.

Expert interviews have a strong tradition in German-speaking qualitative research and are distinct from elite interviews mostly found in the English-speaking qualitative methods literature (Bogner et al., 2017, p. 108). While there is an overlap between those considered elite and experts, the term expert stresses the meritocratic notion of knowledge. As Figure 3.6 shows, this knowledge makes experts part of an elite in which they exercise leadership positions in universities, company boards, or administrations (Bogner et al., 2017, p. 108). Elite, in contrast, is more associated with the social networks and habitus of well-connected people. Thus, one central assumption for focusing on experts is that they possess the

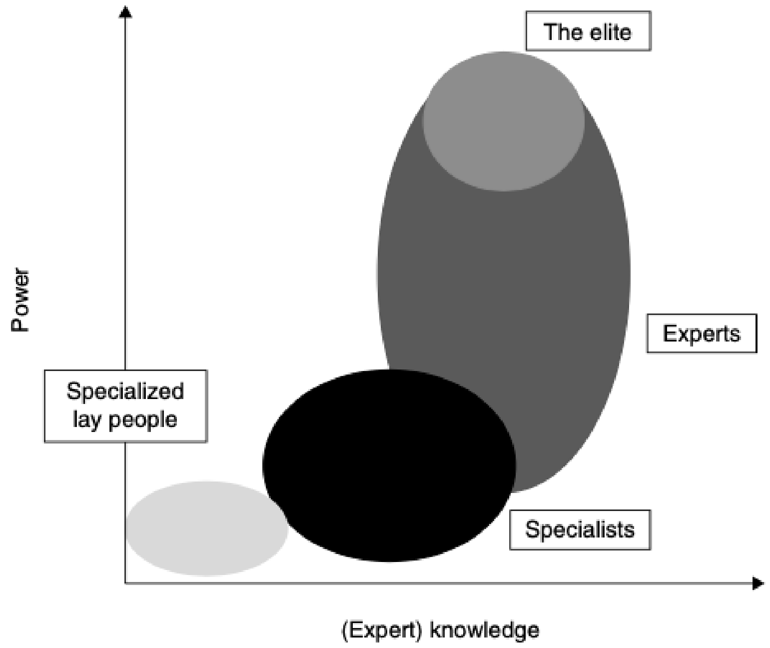


Figure 3.6: Differentiating between expert and elite. Source: (Bogner et al., 2017, p. 108)

specialized professional knowledge to exercise power. Therefore, experts are not solely fascinating as observers of situations but also as agents that generate practically relevant knowledge (Bogner et al., 2014, p. 14). The experts take the role of key informants (Onwuegbuzie and Leech, 2007).

One strength of expert interviews is that they allow capturing process knowledge. This is more than mere technical knowledge that experts also possess. Yet, it is better obtained by analyzing different materials such as statistics, documents, and scientific literature (Bogner et al., 2014, p. 18 f.). Process knowledge is experience and knowledge of practices, which are more locally and personally bound. Together with interpretative knowledge, which is strongly connected to experts' subjective views, these two forms of knowledge allow for explaining and theorizing current directionalities of BES-TIS development and BES diffusion.

3.3.2.4 Step by Step Outline

Based on this, the outline of the qualitative case study work to study the BES-TIS in Austria and Germany in the years 2000-2019 was the following: The first step was the analysis of technical and academic literature and further expert interviews with technical experts to grasp the technological phenomena stationary battery storage systems. Second, the author participated continuously in events such as talks and fairs for energy professionals. Third, further in-depth semi-structured interviews with experts and stakeholders were conducted in person or via telephone (Bogner et al., 2017, p. 108). Fourth, the gathered interview and secondary data were coded using a guide based on the TIS and policy mix (PM) approaches.

The interviewees sampled for this either work in leading positions in BES-producing, -developing, selling, or using companies in Austria or Germany or have profound knowledge on its decision making (e.g., industry experts in ministries, industry, and civil society organizations). Following Bogner et al. (2017), and as mentioned above, the first step for sampling was to conduct an extensive literature review, follow public media, and engage in dialogue with people with industry knowledge. A snowball sampling approach then followed this. The interviewees belonged to different subgroups and were chosen to reflect heterogeneity while allowing for initial generalization.

There were a few challenges in gathering the interview data. For example, many direct attempts to contact stakeholders via email initially came to naught. The author made progress through the press offices of companies, organizations, and institutions. Also, direct contact via the social media platform *LinkedIn* was successful. After the first interviews were successful, further interviews were gained through referrals and snowballing.

The latter interviews were guided by an interview guide around the interviewee's organizations, motives, and perceived influence on the development and diffusion of BES-technologies (see Appendix A.1). Following the theoretical starting point of the techno-

Table 3.1: Overview of innovation functions

Innovation function	Code
Knowledge development and diffusion	F1
Resource mobilization (e.g., financial, human, infrastructure)	F2
Market formation	F3
Influence on the search direction	F4
Private and public entrepreneurial experimentation	F5
Creation of legitimacy (interest groups and advocacy coalitions)	F6
Context factors	C1

logical innovation system (TIS) approach, the interviews touched upon all of the TIS's innovation functions and constituting elements. However, it contained guiding questions from which the interviewer can divert to allow the interviewees' free and associative speech. In the interviews, the experts were asked to locate their organizations between other actors to grasp larger parts of the regional network in their TIS. Moreover, the first results from previous interviews and the quantitative analysis were used to probe for additional topics. The goal was to probe for detailed stories concerning strategies and decision-making of BES selling companies, utilities, grid operators, regulators, and NGOs.

The general point is—applying the *generative hermeneutics* approach—to understand these experts' motives and expectations that can influence energy transitions through their companies' positions. Through their power, they also influence whose knowledge and practices might become dominant (Flick, 2009, p. 166). Another idea of this step is to show how companies construct the understanding of energy storage technology in the policy context of sustainable energy transitions, climate change, energy geopolitics, and their larger business environment. Concepts and terminology emerge from the interview data and are aligned and contrasted with theoretical definitions from established literature.

Table 3.2 now shows an overview of the information persons. An interview was conducted between 30-60 minutes, recorded, subsequently transcribed, and coded in vivo and theoretical codes. Due to the positions and the sensitive nature of the information, which sometimes touches upon trade secrets, the interviewees were promised anonymity. Therefore, they received pseudonyms.

Analytically, based on the gathered evidence, the author mapped key actors. Then, a historical timeline of the national BES-TIS was established following an event sequence approach that defines events as actions or decisions (Garud et al., 2017). Afterward, a summary of the development of the BES-TIS central building blocks and their influencing policies followed. For this, the process, as visualized in figure 2.4, was further followed, and the geographical and infrastructural context, as well as the "narrow" political economy context such as neighboring sectors, were analyzed. This led to a consideration of the broader political economy context, such as the role of renewable energy in capitalist society. Also, a policy mix analysis followed that categorized and analyzed policy strategies and instruments and their overall characteristics. The next step identified key dynamics and influences within the TIS development, the role of legitimation, the interaction of crucial innovation functions, and the dynamics between TIS and PM. Finally, the research cycle concluded by identifying key policy issues regarding the focal technology.

Table 3.2: Overview of interviewees

Position	Organization-Type	Code	Country
Press Officer	Medium-sized, specialized firm	MSF1	DE
CEO	Medium-sized, specialized firm	MSF2	DE
Manager	Large, diversified firm	LDF1	DE
CEO	Small, specialized firm	SSF1	DE
Press Officer	Medium-sized, specialized firm	MSF3	DE
Manager	Large, diversified firm	LDF2	DE
Manager	Large, diversified firm	LDF3	DE
Manager	Large, diversified firm	LDF4	DE
Unit Head	Federal regulatory grid agency	FRA1	DE
Consumer Expert	Consumer rights organization	CRO1	DE
Head Politics	Industry Advocacy Group	IAG1	DE
Industry Expert	Industry Advocacy Group	IAG2	DE
Professor/dep. Director	Public Research Organization	PRO1	DE
Grid Developer	Transmission System Operator	TSO1	DE
Partner	Business Consultancy	BC1	HU
Grid Developer	ESCO	ESCO1	HU
Ministry Official	Ministry of Infrastructure & Technology	MO1	AT
Department Head	Austrian Energy Agency	PA1	AT
Senior Executive	ESCO & University	ESCO2	AT
CEO	Industry Advocacy Group	IAG3	AT
Deputy Head	Federal Regulatory Agency	FRA2	AT
Senior Executive	ESCO	ESCO3	AT
Senior Researcher	Public Research Organization	PRO3	AT
Storage Expert	ESCO	ESCO4	AT
PR Head	Large, diversified firm	LDF5	AT
Senior Executive	Medium-sized, specialized firm	MSF4	AT
CEO	Small, specialized firm	SSF2	AT
Head of Process Technology	Large, specialized firm	LSF1	AT
Project Head	Financial Institute	FI1	AT
Senior Expert	TSO	TSO2	AT
Research Engineer Batteries	Public Research Organization	PRO4	AT
Senior Researcher	Public Research Organization	PRO5	AT
Professor	Technical University	TU1	AT
Energy Expert	Chamber of Labor	CRO2	AT
Energy Expert	Chamber of Labor	CRO3	AT
Energy and Climate Campaigner	NGO	NGO1	AT
Social Policy Campaigner	Labor Union	LU1	AT

3.3.3 Quantitative Methods and Econometrics

Turning now to the second methodological approach in this thesis, econometrics. According to a popular textbook is “econometrics [...] the science and art of using economic and statistical techniques to analyze economic data” (Stock and Watson, 2015, p. 47). This approach portrays sense-data in quantitative form, mostly as numbers. The overarching goal of this is finding common patterns and explanations in many countries at once.

This claim also fits well with a critical realist approach, as Ron (2002, p. 122) explains: “When a scientist offers a regression equation, she does not necessarily mean that the whole model or part of it approximates a universal general law. Instead, she argues, at least implicitly, that she was able to demonstrate the activity of a mechanism that could not be observed from the data alone. The gist of successful regression analysis is not to be able to offer a law-like statement, but to bring forth evidence of an otherwise hidden mechanism.”

The theoretical foundation for the basic regression model used in this thesis was provided by the theory of diffusion of innovations prominently formulated by Rogers (2003) and quantitatively specified by Bass (1969). The variables to be tested for their influence on the diffusion of storage technologies were taken from qualitative results of the country case studies and theoretically supported by further innovation studies literature.

Due to the presence of many countries' time-series, a panel approach was chosen. To control for heterogeneity between countries and between years in the data quality and exclude national contextual factors, time and entity fixed effects were included. For the estimation, heteroscedasticity corrected and robust standard error (HC 1 as conventionally used in *STATA*) and serial correlation corrected (Beck and Katz, 1995; Zeileis, 2004) was used estimated with the *R sandwich-package* (Zeileis, 2006).

The regressions were estimated in the R environment (R Core Team, 2020) in the R-Studio IDE (RStudio Team, 2015) using the *plm*-package (Croissant et al., 2020) by

Croissant and Millo (Croissant and Millo, 2018, 2008) and displayed in regression tables with the *stargazer*-package (Hlavac, 2018) and graphically via *ggplot2* (Wickham, 2016).

3.4 Summary of Research Process

The next concluding section briefly gives an overview of the concrete research process across the Ph.D. and its implementation. The challenge of this research process is to bring theory and concrete empirical work together. Moreover, it remains essential to align qualitative and quantitative methods, both with their particular paradigmatic background and language, to get deeper insights into the development and diffusion of battery energy storage. Due to the different methods, this process has its challenges. However, this interplay of methods is essential in order to do justice to the multi-faceted topic.

Figure 3.7 provides an overview of the overall process of the thesis showing three distinct but occasionally overlapping phases (1) empirical and theoretical scoping, (2) empirical basis, and last, the analysis leading up to the (3) analytical chapters. Starting from the research questions as set-up in chapter 1 and re-iterated in each of the analytical chapters (5,6, and 7), an extensive literature review along theoretical and empirical works built the foundation. Emerging from these early exercises, a theoretical conceptualization followed that guided the entire research process and was continuously adapted to reflect new insights.

After an intensive study of different kinds of theoretical and technical literature, this thesis profited heavily from a technology assessment study for the Austrian parliament on different types of electricity storage to which the author contributed. During the study's set-up, several technical experts were interviewed, workshops with experts organized, and the results were presented to members of parliament in an interactive setting. Together with further intensive literature study, these insights provided the basis for chapters 2 and 4 and contributed to the theoretical conceptualization that shaped the structure of the

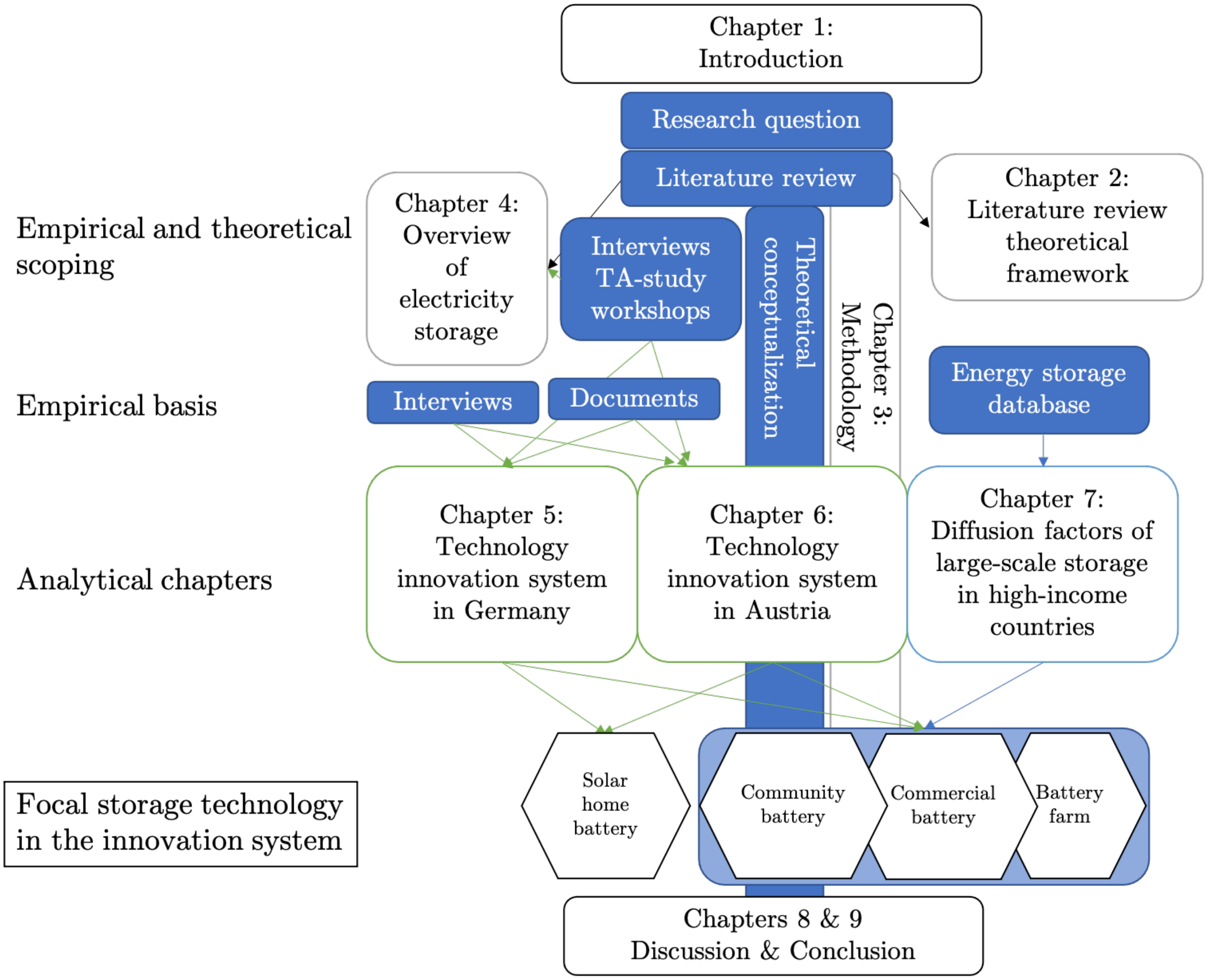


Figure 3.7: Schematic of central phases and building blocks of the mixed methods research process.

later empirical studies.

As already presented above, this empirical basis builds on expert interviews, document analysis, grey literature, and descriptive statics for the qualitative country case studies of Austria and Germany. For the quantitative study with a regression analysis including high-income countries according to the World Bank, as described in more detail in chapter 7, a database was merged out of several existing databases on energy storage projects.

This work led to three analytical, empirical chapters. Two containing qualitative and in-depth country case studies on the battery storage TIS in Austria and Germany. The third chapter contains the broad, international view using quantitative analysis of common patterns in high-income countries. It also contains its separate theoretical considerations and a more detailed methodological description of these considerations' consequences. As such, it is more comparable in structure and language to other econometric studies. Nevertheless, that chapter is firmly integrated into the thesis as a whole.

The entire research process is organized around stationary battery storage systems as a focal technology. However, a distinction is made between large-scale battery storage and small-scale battery storage. The two qualitative country case studies address both, and the quantitative international country study addressing only large-scale battery storage. While the storage systems are the focus, the research object is the TIS and the broader context around the storage systems.

Chapter 4

Overview of Electricity Energy Storage[1]

To distinguish the different electricity energy storage technologies this chapter will give an overview. This is necessary to distinguish battery storage technologies on which this thesis focuses from conventional energy storage technologies such as pumped hydro storage (PHS).

Especially the stationary batteries will be highlighted, as they are at the center of this thesis. It, therefore, starts with a brief explanation of electrochemical battery storage. Then, a heuristic description of four typical battery storage applications follows.

4.1 Storage as Flexibility Solution

As explained in chapter 2, a larger share of variable renewable energies (VRE) poses challenges to the electricity system. The challenges with this are threefold: the utilization of

---

[1] This chapter is partly based on the author's co-authored previous work in a technology assessment study on energy storage for the Austrian Parliament (see Ornetzeder et al., 2019).

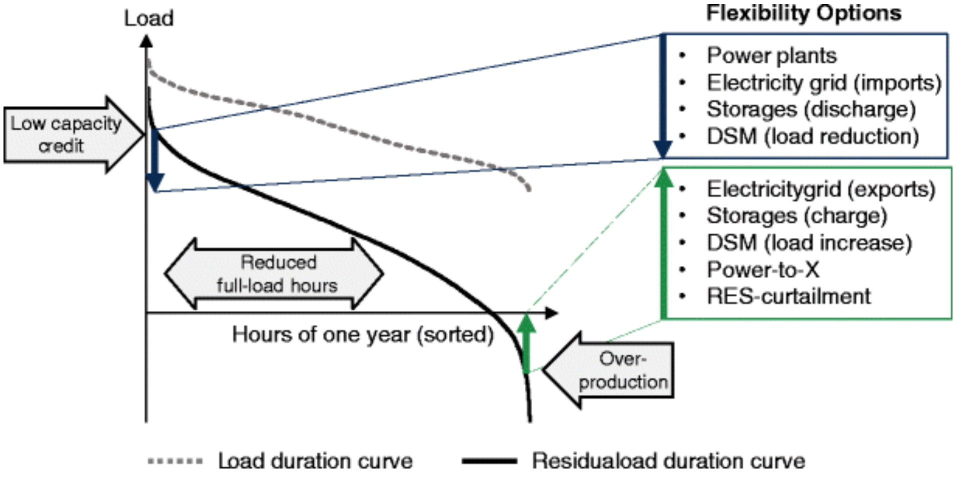


Figure 4.1: Residual load duration curve, challenges of RES integration (gray arrows), and flexibility options. Source: Zöphel et al. (2018).

conventional plants is reduced, VREs are not always available as a replacement, and plenty of renewably produced electricity cannot be utilized due to lack of demand (Ueckerdt et al., 2015).

There are two main levers to adjust to even out the difference between electricity generation and consumption to ensure a continuous supply: to take grid load or make it available as needed. Both can be made possible by flexible suppliers as well as demanders. As shown in Figure 4.1, storage facilities are exciting because they can do both (Zöphel et al., 2018). Further flexibility solutions are also networks, demand-side solutions, or curtailment.

4.2 Battery Storage Technologies

In electrochemical technologies to which the batteries belong, the stored energy is in the electrodes or electrolytes' chemical compounds, simultaneously acting as energy storage and energy converter (Sterner and Bauer, 2019). There are different types of storage. Primary batteries (single discharge) and secondary batteries (repeated charging and discharging), also known as accumulators, are widely used. The latter is relevant for this thesis since they can provide balancing energy, i.e., electrical energy that deviates from the predicted consumption; therefore, this thesis refers exclusively to this form. The following section briefly distinguishes the batteries according to the materials of the electrodes and electrolytes.

While lead-acid batteries are still widely used, e.g., in vehicles, they have poor economic and ecological performance despite low market prices (Davies et al., 2019). Although nickel batteries are still in many hybrid vehicles, lithium-ion batteries are increasingly replacing them (Harper et al., 2019). Developments in the ICT sector—especially in mobile computers and smartphones—have contributed significantly to the spread and use of lithium-ion cells (Kittner et al., 2017). For some years now, change in the automotive industry was a strong driver of the lithium-ion battery's development (Schmidt et al., 2019). The next generation of lithium-ion systems is still in basic research, and the first applications are unlikely to be commercially available in the near future (Zhang et al., 2018b). The form of batteries, such as metal-air batteries, magnesium-ion batteries, or solid-state technologies, promise high energy densities, increased safety, and longer service life, are mostly a topic in basic research and have a low degree of technological maturity (Sterner and Thema, 2019).

High-temperature batteries are electrochemical storage devices that contain solid electrolytes in the storage state that are inactive at average temperature (Stadler et al., 2019). Only at temperatures between 200 and 800°C the electrolytes melt, activating the battery. Examples are sodium-sulfur batteries used in large battery storage power plants or sodium-nickel chloride, some of which are used in the automotive industry but have now been replaced mainly by lithium-ion batteries (Stadler et al., 2019; Harper et al., 2019).

With the so-called redox flow batteries, the storage tank and the reaction cell are spatially separated (Stadler et al., 2019). Here, chemical compounds store the electrical energy, whereby the reaction partners are present in dissolved form in a solvent. Compared to other electrochemical storage systems, redox flow batteries have several advantages: they are suitable for large storage capacities, have a long service life, a short reaction time, low maintenance requirements, and good environmental compatibility. Disadvantages include relatively low energy and power density, problems in sealing cells and cell stacks, and maintaining the purity and concentration of redox pairs (Stadler et al., 2019).

4.3 Stationary Battery Storage Applications

The technological innovation system (TIS) for station battery energy storage consists of two (slightly) overlapping innovation systems. One revolves around residential housing, while the other focuses on industrial and commercial applications and utilities. They target different audiences (private customers, businesses in small dwellings, industry using TIS as a central element for their commercial actives, and large-scale power plants that provide various grid services). The following figure (figure 4.2) briefly depicts four socio-technical configurations of stationary battery storage.

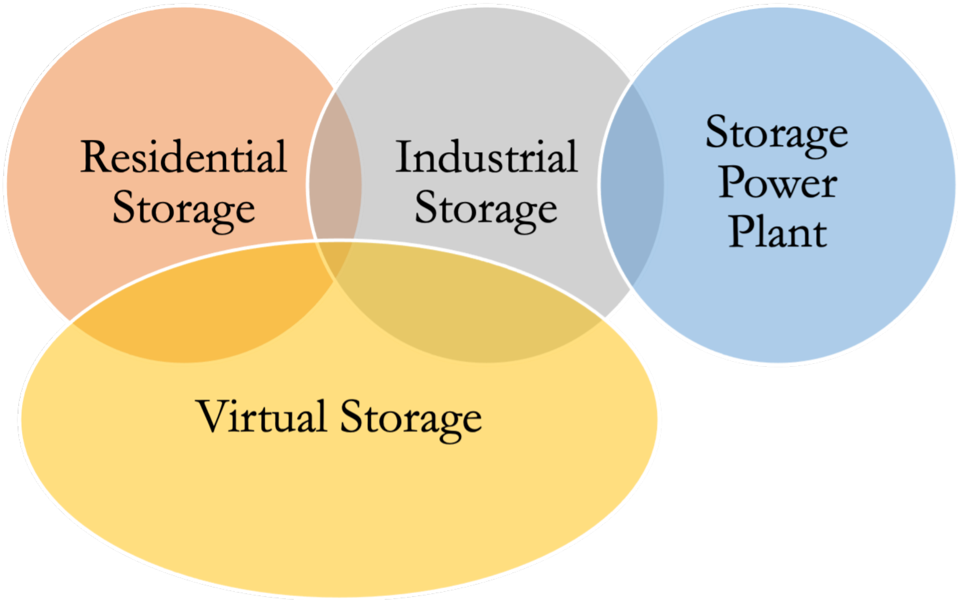


Figure 4.2: Typology of stationary battery storage.

Residential Storage

A battery (accumulator) installed in the building operates with a decentralized photovoltaic (PV) system in residential storage. First, battery storage helps to increase the proportion of self-consumed locally generated solar power. The solar power generated around midday—especially on sunny days—charges the battery. In the installed building, the energy is stored for later use (e.g., in the evening). Depending on the system-design and mode of operation, the system can increase the own consumption rate from 29 % to up to 69 % (Baumann and Baumgartner, 2017). Current data from Germany show that the average self-consumption rate over a given year is around 50 % (Kairies et al., 2019). The motivation is to improve PV system efficiency, resulting in a monetary gain through the difference between the feed-in tariff and the electricity price. House battery storage systems could also fulfill other functions such as emergency power supply. From a technical perspective, home battery storage systems can stabilize the electricity grid (Sterner et al., 2019c). This is the case, for example, if the systems reduce power peaks in PV feed-in (peak shaving) or charge the batteries on a forecast basis, i.e., in coordination with expected weather conditions. However, such network-related forms of operation do not occur automatically.

Virtual Storage

Virtual storage involves many decentralized storage systems (e.g., batteries and flywheels) combined to form a large virtual storage system (Sterner et al., 2019a; Cheng et al., 2017). This combination is also known as swarming or pooling. An important swarming or pooling feature is that a uniform ICT solution connects the decentralized storage units. It enables the coordinated loading and unloading of the spatially distributed storage units. In contrast to individual residential storage systems, swarm solutions are market-oriented and mostly grid-supporting (Grunwald, 2017). Swarm solution operators act as 'aggregators': If they fulfill specific requirements (pre-qualification), they can also offer system services (e.g., on the operating reserve market) (Sterner et al., 2019a). Pooling participants include residential storage systems, larger storage systems, and storage systems in mobile applications (e.g., batteries in electric vehicles). The aggregators generate revenues on the balancing energy market, which they pass on in part to the individual participants. Here, too, lithium-ion storage systems dominate the market.

Industrial or Commercial Storage Systems

Industrial battery storage systems are applications in which electrochemical storage systems primarily buffer time for commercial purpose (Schriever and Halstrup, 2018; Hartmann et al., 2018). They make the deliverance of high-power outputs at short notice possible while the grid load remains constant. One example is quick-charging stations for electric vehicles, which enable high-charging capacities without reinforcing the existing network connection. To increase the economic attractiveness of such products, they have several functions. Industrial battery storage systems can thus also offer network services as an element of a black-start solution or—in combination with local PV production—support the integration of renewable energies (Zhang et al., 2018a).

Another example is avoiding or provisioning peak loads in production (Sterner et al., 2019b). Lithium-ion storage systems have the most significant potential in these application forms, but flywheel storage systems are an alternative. Such industrial battery systems can also facilitate shifting the load over time through demand response. This load-shifting is particularly suitable for energy-intensive consumers from the cement, steel, and metal industries, who procure their electricity directly on the stock exchange or have contracts with time tariffs (Köhler et al., 2018, p. 38).

Battery Power Plants

Battery power plants are usually large systems that store electrical energy through accumulators and have power grid connections. Such battery power plants, or battery parks, have existed internationally for many years. They are used to maintain grid stability but also to balance out differences between consumption and generation. Battery power plants can thus support the integration of fluctuating renewable energies (Sterner et al., 2019a).

Large-scale battery plants use various electrochemical storage systems. Historically, until the 1990s, lead-acid batteries were the primary type of accumulators. Later, plants with other battery technologies were also built (Doughty et al., 2010). Since then, lithium-ion batteries have started to become the dominant battery technology in this application. Currently, planned plants have a lifespan of 20 years (Sterner et al., 2019a). Besides new lithium-ion cells, used batteries from electric vehicles are also increasingly being used (second life). For example, the German car manufacturer Daimler has been operating a grid-connected battery power plant with an output of 13 MW since 2016. For this, around 1000 used car batteries are bundled to form a stationary battery storage system.

4.4 Outlook

Electric stationary battery storage systems based on lithium-ion technology or other compounds will play an even more significant role in power grids in the future. The current calls of increased deployment in the United States following the 2021 Texas blackout are just one of many examples of this (Summer, March 8, 2021 6:38 PM ET). Behind-the-meter usage is also likely continuing to grow (IEA, 2020b). But, there will be other electricity storage technologies in the future. This is especially important to address seasonal storage issues, for which battery storage is not well suited due to its short storage time (Sterner et al., 2019a). Nevertheless, the growing use of battery-powered automobiles only intensifies the usage of stationary battery storage because of economies of scales, diffusion of fast chargers, and second-life use for e-vehicle batteries (IEA, 2020b).

Chapter 5

Battery Energy Storage Technological Innovation System in Austria

5.1 Introduction

Austria, an alpine republic with 8.9 million inhabitants, has one of the largest pumped hydro storage (PHS) shares in the world (IEA, 2020a). In 2018, the then minister for infrastructure declared Austria a center for energy storage in Europe, indicating a competence center for battery and PHS technology and a storage capacity provider foremost through PHS (Friedl and Kathan, 2018). Although this is not the only country in which policymakers have shown a particular interest in energy storage (e.g., the United Kingdom, Germany, Norway), this statement's emphasis stood out.

In Austria, next to PHS power plants, also battery storage facilities receive increasing attention. It saw massive investment in battery technology, culminating in the highest per capita expenditure in battery storage R&D among the OECD countries, besides the equally high expense for energy storage in general in 2017 (IEA, 2019a). Although falling behind countries like Denmark in 2018, Austria continues to invest substantially in this technology and its application.

Moreover, energy storage technologies have long been a topic of policy debates. An early prominent mentioning was in the Federal Government's energy research strategy in 2010 that promoted battery storage in the context of smart grids (BMWFJ and BMLFUW, 2010). Since then, many socio-political and economic processes organized around energy storage technologies. Central to Austria's approach is the *Storage Initiative* of the public funding agency *Climate and Energy Fund* launched in 2015, a platform for stakeholders to network and draft a shared understanding of Austria's storage development and implication requirements, which entered its second round in 2020 (Klimafonds, 2016). One particular policy response to this *Storage Initiative's first-round* included a storage technology roadmap in 2018 (Friedl et al., 2018).

By 2018, renewable energy generation had a share of 77 % of the Austrian electricity, whereof 60 % stems from hydropower (IEA, 2020a). So far, there is only a limited additional demand for storage in Austria, as 8.8 GW of PHS provide most of the required flexibility (E-Control 2020), and also provides it to neighboring countries such as Germany (Agora Energiewende, 2021). Nevertheless, the current government plans to achieve a 100 % renewable electricity supply by 2030. These changes require additional 22-27 terawatt-hours (TWh) of renewables by 2030, compared to the 73,46 TWh total energy generation in 2019 (E-Control, 2020; IEA, 2020a), and an expansion of wind and solar PV in particular. This is necessary because of forecasts of a 66 % increase in electricity consumption in 2050, compared to 2017 (IEA, 2020a).

As far as the diffusion of electricity storage in Austria is concerned, there are still few reliable figures. While a market survey from 2019 indicates strong growth in the diffusion of home storage in numbers (Figure 5.1), this is negligible in absolute numbers. Moreover, even these figures are only a first estimate, and their verification in further studies is missing

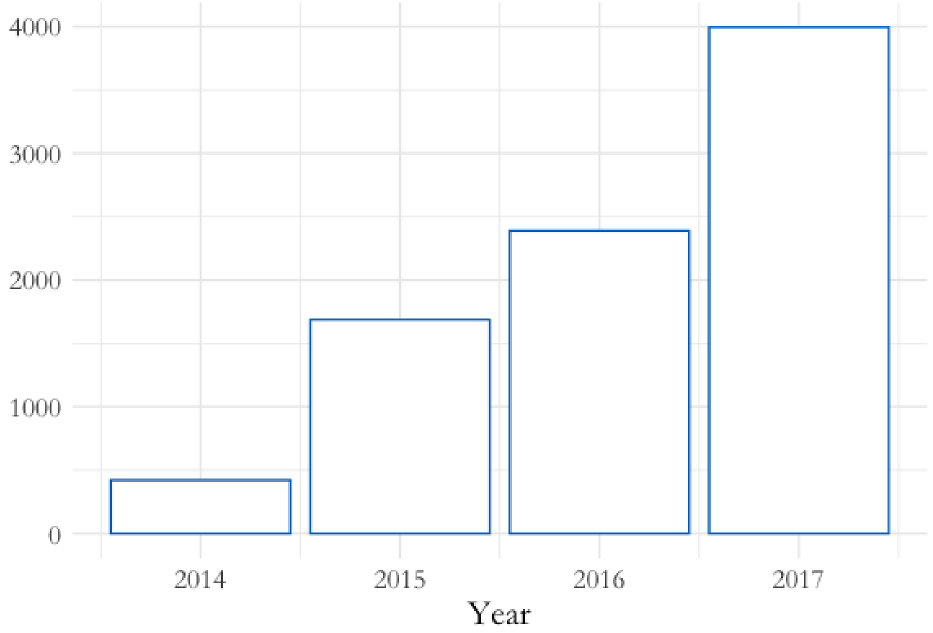


Figure 5.1: Estimate of installed small-scale stationary battery storage systems in Austria. Source: Fischer (2019)

so far (Biermayr et al., 2020).

At first sight, promoting battery storage in a mountainous country like Austria seems counterintuitive, as the many PHS facilities ensure that storage demand is well covered. Of course, this should not disregard that different storage technologies have various applications (see chapter 4). Therefore, one hypothesis investigated in this chapter is that storage diffusion in Austria to data remained primarily driven by innovation policy measures such as RD&D funding and subsidies.

This chapter uses a hybrid analytical framework combining (1) an extended technological innovation system (TIS) approach with its innovation functions and (2) a policy mix (PM) approach which distinguishes policy strategies and different policy instruments.

For new technologies and new innovation systems to emerge, multiple things must come together, as previous (TIS) research tells us (Bergek et al., 2008a; Hekkert et al., 2007). For example, there are internal dynamics between different actors, networks, and institutions from which the innovation system emerges and influences how innovative technology develops and diffuses. In an emergent TIS's early formative stages legitimacy is usually particularly important (Bergek et al., 2008b; Markard et al., 2016). This is why this chapter investigates the role of legitimacy in depth. Moreover, TIS research also shows that power and societal dynamics outside the focal-TIS substantially influence the development direction. Several authors conceptualized these external dynamics partly as part of TIS (Bergek et al., 2008b), recently emphasized their importance (Haley, 2018), and urged their increased consideration (Bergek, 2019).

Moreover, the used policy mix approach highlights the co-evolution of different policies with the battery energy storage (BES)-TIS (Rogge and Reichardt, 2016; Edmondson et al., 2019). It distinguishes between policy strategies and various instruments such as push-, pull-, or systemic instruments. The latter support function at a system level. In addition to the elements of the policy mix, it tries to consider the policy process. Also, it considers the possible impacts of single elements and the overall policy mix by analyzing characteristics such as comprehensiveness and coherence.

This chapter strives to capture relevant context factors, legitimation issues, and power dynamics in the wider political economy, as suggested in chapter 2, of the emerging BES-TIS in Austria to fill this research gap. Furthermore, it attempts to conceptually distinguish different phases in development by trying to differentiate between key developmental stages. This is done with the understanding that BES-TIS development is likely still in the formative stages of it's life-cycle and far from complete. Based on these considerations, the guiding research questions are:

1. What influenced the development dynamics of the Austrian technological innovation system of battery energy storage, and how?
2. How was the legitimacy for the development and use of stationary battery storage in

Austria created, and how did it influence the innovation system's development?

3. How did energy and innovation policies influence the development and early diffusion of stationary battery storage in Austria?

Using a hybrid of TIS and PM approach as the conceptual framework, data collection happened primarily through qualitative expert interviews, policy analysis, and desk research following a coding guide based on TIS and PM. Based on the gathered evidence, the first section 5.2 shows mapped key actors. It established a historical timeline of the Austrian BES-TIS following an event sequence approach that defines events as actions or decisions (Garud et al., 2017). Moreover, it summarizes the development of the BES-TIS central building blocks and its influencing policies in Austria. From this, in the next section 5.3 we identify key dynamics and influences within the TIS development, focusing on the role of legitimation, the interaction of crucial innovation functions, and the dynamics between TIS and PM.

5.2 Development of the Battery Energy Storage Innovation System in Austria

The following section presents Austria's BES-TIS's early emergence on the energy transition and innovation system background. It presents the empirical material by suggesting the central building blocks of Austria‘s BES-TIS. Following Bergek et al. (2008a), these consist of actors such as suppliers of storage solutions, consumers, civil society groups, the networks they form, and institutions. Formal institutions are depicted using a PM approach (Rogge and Reichardt, 2016). Based on the empirical material, this chapter identified two development stages of the Austrian BES-TIS's life-cycle. The first subsection describes the pre-phase up to 2012 in which central structures emerged and policy

Table 5.1: Overview of innovation functions

Innovation function	Code
Knowledge development and diffusion	F1
Resource mobilization (e.g., financial, human, infrastructure)	F2
Market formation	F3
Influence on the search direction	F4
Private and public entrepreneurial experimentation	F5
Creation of legitimacy (interest groups and advocacy coalitions)	F6
Context factors	C

decisions were made that enabled the subsequent formation of the BES-TIS. The second subsection then describes the still ongoing formation of the innovation system as of 2012.

Interview data is referenced by using a 4-digit code in paratheses. An overview of all the 21 interviews conducted in Austria is in Table 3.2. Moreover, 2-digit codes indicate innovation functions and a "C" context factors (Table 5.1) that are described in-depth in section 2.2.3. A more detailed summary of the methodological steps is in subsection 3.3.2.4.

5.2.1 Emergence of Structure in the Pre-Phase – 2002-2012

The emergence of the later BES-TIS was preceded by previous developments in Austria, which laid the foundation by creating several technological innovation system around various energy technologies, by building infrastructure, but also through previous political decisions. Many of these decisions had to do with industrial policy and the enforced energy transition towards even more renewable energy sources.

5.2.1.1 Actors and Networks in the Pre-Phase

Central to further emergence were medium-sized companies active in the environmental technology sector for several years (LSF1, IAG3, PRO4). These specialized in solutions for regional and decentralized energy supply and formed regional clusters (or innovation systems), such as in the environment that emerged out of suppliers and spin-offs of a large steel company in Upper Austria (Tödtling et al., 2014). Moreover, many regional universities of applied sciences, supra-regionally active research institutions such as technical universities, or the centrally operating Austrian Institute of Technology were involved in research and cooperation projects with said companies (LSF1, PRO4, SSF2). As a result, long-standing contacts and connections formed.

5.2.1.2 Policy Mix in the Pre-Phase

Some notable changes in the policy landscape during 2002-2012 emerged, which later suggested themselves to be significant for BES-TIS development (Figure 5.2). In 2002, this was a systemic regulatory approach through the Green Electricity Act (ÖGS), which established economic push policies such as feed-in tariffs for renewables like PV, created thereby incentives for small producers to invest in them. Furthermore, by establishing a dedicated fund for financing renewable energy research in 2007, the federal government created an intermediary actor to drive applied research. From the European level, the Third Energy Package from 2009 had significantly influenced Austria's development, as it changed its energy system fundamentally (Directive 2009/72/EC). The unbundling of energy suppliers and grid operators created the first theoretical possibility to have independent storage operators.

Another point that foreshadowed the later development and political handling was in a strategy document that was both energy and research strategy (BMWFJ and BMLFUW, 2010). In this strategy, battery storage was mentioned for the first time as potentially necessary for advancing the energy transition as the energy transition should not fail for lack of battery storage. Here, energy storage was seen as a crucial building block of smart grid systems, which had significant economic potential for the domestic industry. This approach, which provided the base for following policies, and the research funding based

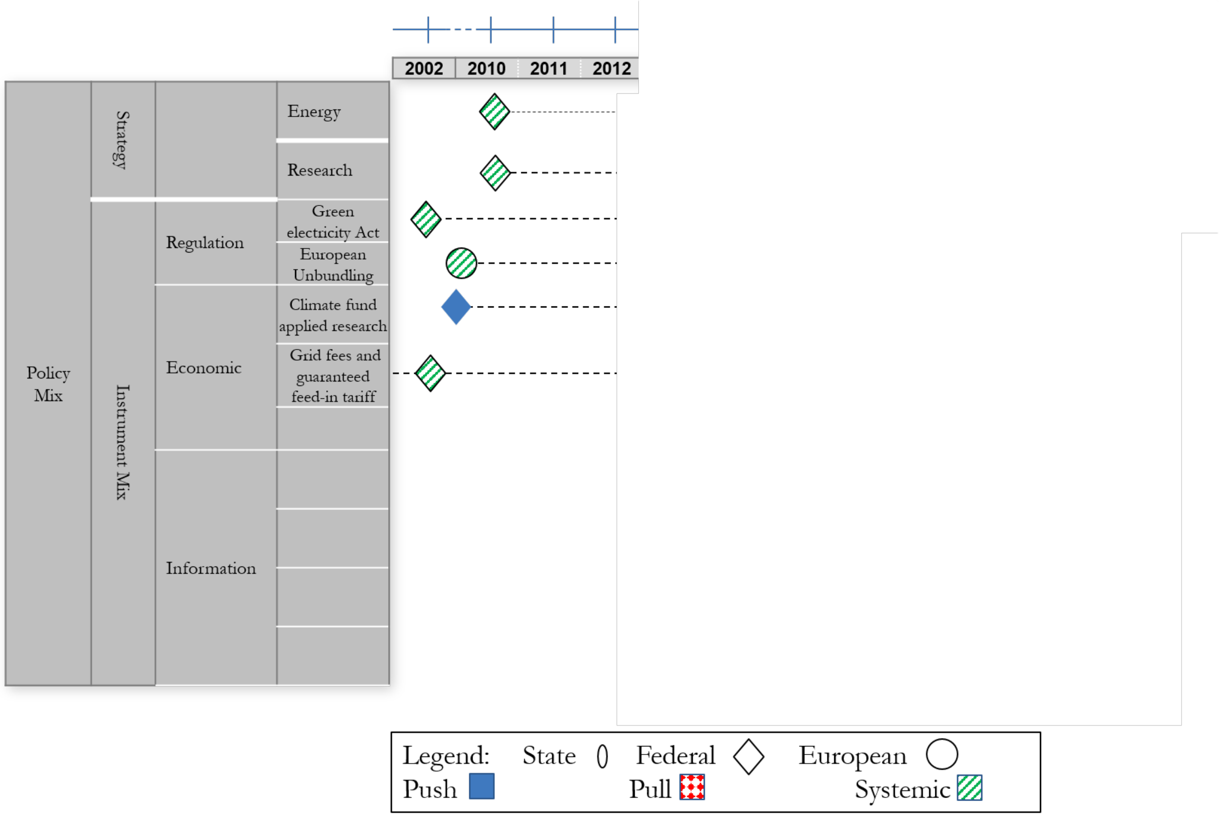


Figure 5.2: Policy mix of the pre-phase of the battery storage technological innovation system in Austria.

on it, was likely one of the foundations for developing the BES-TIS in Austria.

5.2.2 First Formative Phase Since 2012

Building on these foundations, a BES-TIS emerged in Austria, which, in the author's opinion, began to form in 2012. From this point on, the first companies included storage solutions, especially for households and small businesses, in their product range of prosumer solutions. Also, the importance of stationary battery storage solutions beyond the existing PHS approaches began to be promoted and pushed in research and innovation policy projects at the policy level. As the lack of contrary evidence suggests, this initial phase appears to have been ongoing in Austria.

5.2.2.1 Actors and Networks in the First Formative Phase

In addition to companies, the public sector, and research, other players such as interest groups and the first customers were now increasingly part of BES-TIS, which was in the process of being formed, entering into new constellations, and building networks among themselves.

Suppliers

Since 2012, the first companies started to produce or assemble stationary BES-systems to connect with PV systems. These companies were usually owner-managed SMEs (LSF1, MSF4), which fits the rest of the economy characterized by medium-sized, mostly owner-managed enterprises (OECD, 2019). Most of these companies had prior knowledge in the renewable energies sector and only recently shifted to include battery storage solutions in their product portfolio (F1) to increase PV self-consumption as a new business focus (F3, F5). One region with many other renewable energy firms systems was historically closely related through suppliers and spin-offs of a sizeable local metal processing company (Tödtling et al., 2014) and thus provided pre-existing infrastructure and context for the emerging development.

In addition to these suppliers of products that included BES-systems, Austria had various smaller engineering offices working on system integration and vehicle technology (PRO4, IAG3). Others stemmed from the automotive sector and specialized in car batteries (see, e.g., Banner, 2020). Moreover, several active companies were foreign but had subsidiaries in Austria (Die Presse, 2019b) (IAG3, LSF1).

Beyond these integrated BES-system solutions, startups and long-established firms began several entrepreneurial experiments to build up further business fields around electrochemical storage or experiment with other materials than lithium-ion (F5). Also, the recycling of large-scale electrochemical batteries received renewed attention, and incumbent recycling companies started to focus on it (Friedl and Kathan, 2018).

While a few of the companies were increasingly doing applied research in battery storage design (F1), one interviewee claimed that these companies were only able to develop BES-system products with the aid of specialized international technology consultants (F1) (SSF1). Other research also found that the primary focus and competence of Austrian companies lied in the packaging of storage modules, further processing already complex pre-products (Friedl et al., 2018). These were then integrated with other technologies (e.g., inverters).

Despite the claim regarding the supposedly missing competencies, another interviewee provided an economic explanation for this. He emphasized: "*Just generating [solar energy] is a dead-end. Anyone can do it. It is also no longer possible to stand out from the international competition from Asia, where products are becoming cheaper and cheaper*" (LSF1). Moreover, many interviewees agreed that the Austrian BES-TIS depended on other European suppliers for specialized parts but mostly on Asian suppliers from Korea, Japan, Taiwan, or China (IAG3, LSF1, PRO4). As national producers cannot compete on price with major international producers, this strategy ensured survival (LSF1). Consequently, Austrian companies had a relatively low added value part of the supply chain and mainly specialized in integrating storage systems. Thus, the combination of PV and stationary storage with other products like inverters could have been one strategy of Austrian companies to distinguish their products from international competition.

To sum up, most entrepreneurial experimentation was about integrating storage systems with renewables to produce comprehensive solutions that increase self-consumption. In this also lay the existing knowledge base of the firms. They intensified this specialization, which influenced the search direction and fostered applied knowledge creation. Besides, further knowledge diffused into the BES-TIS from abroad through consultants and pre-products. Lately, the companies began their business field development, and the BES-TIS is still in its formative stage. They have been, therefore, very engaged in legitimizing their activities. They refer to benefits of decentralization, security as well as positive effects on a green energy transition, and the "coolness" of these products. For example, they created legitimacy through public appearances and personal contacts and jointly network through interest organizations, as explained in the following section.

Interest Groups

Two major interest groups in Austria began to act as intermediary actors for the emerging BES-TIS and supported the firms' legitimation efforts, *PV-Austria*, and *Österreichs Energie*.

PV-Austria, a photovoltaic industry interest group, included electricity storage as their second main issue next to PV in 2015 to promote the two issues together—a fact that they even symbolized in a new logo (PV-Austria, 2021) (F6). They lobbied towards federal and provincial governments and the standardization institutes to promote stationary electricity storage in the building sector, and increasingly also larger communal, industrial, or municipal storage facilitates. They created legitimacy by pitching the idea of prosumer households that are regionally connected and more independent from the grid who also do something good for the environment (IAG3).

Österreichs Energie, in contrast, represented all Austrian energy companies (F6). Due to the dominance of PHS in Austria, they began to emphasize the importance of storage in general (ESCO2, ESCO3). Rhetorically, this included BES. However, they were primarily focused upon PHS, which presumably came from the fact that they conveyed the interests of all energy providers. As they became an influential actor in popularizing the overall energy storage topic, they helped create legitimacy of storage in general by highlighting its benefits to the energy transition by providing flexibility and stabilizing electricity supply.

Research and Demonstration

As mentioned in the introduction, research in battery technologies became more substantial in Austria (IEA, 2019a). Although there has been strong national growth in patents—particularly in the field of lithium-ion batteries—Austrian research activity has so far been classified as low by international standards (Friedl et al., 2018). Nevertheless, several Austrian research institutions, such as the Graz and Vienna Universities of Technology and the Austrian Institute of Technology (AIT), were beginning to do applied and theoretical research on electrochemical storage (F1) (LSF1, PRO5, PRO4).

A significant share of electricity storage research happened in publicly funded applied demonstration projects (F1, F5). These projects usually received public funding via the intermediary *Climate and Energy Fund* (F2) and involved utilities or energy service companies (ESCOs), research institutes, and distribution system operators (DSOs). An example is the *Leafs* project, where a central storage facility with 100 kW/100 kWh got integrated into the distribution network and the *Urban Storage Cluster South Burgenland* project that began testing storage facilities at the district level (Friedl and Kathan, 2018). Other projects were, e.g., Vienna-based *Wien Energie* that began building a community electricity storage in a new development area (Futurezone, 2019) and a flywheel storage system at Vienna airport (F1, F5) (ESCO4).

These kinds of demonstration projects are those few that currently use large grid-connected BES. Of particular note is the *EVN* test facility in Prottes, Lower Austria, which, with an output of 2.5 MW and a capacity of 2.2 MWh, has built a lithium-ion-based storage facility at the transformer station (F1, F5). The utility *Verbund* tested other projects, including large-scale batteries, to shape peak loads of electric vehicles' fast chargers (F5) (EVs). They announced integrating 16 MW BES into a river power plant to provide primary operating reserve, reducing the turbine's adjustment to prolong durability by the end of 2019 (Die Presse, 2019a) (ESCO3).

To sum up, a great deal of BES growth began taking place in applied research and development projects. Here, in particular, the public sector's financial resources were decisive for implementing the projects, which thus determined the BES-TIS's search direction. There was, therefore, private and public entrepreneurial experimentation. Research projects were also the place where larger energy storage systems were used. These have been mainly used for demonstration, to create legitimacy for other activities, and to learn for their future operations. Thus, it can be concluded that publicly funded applied research has become an important driver for the development and continuation of BES-TIS.

Consumers

While large storage systems have been mostly used on an experimental basis, smaller storage systems for residential houses or smaller dwellings were also sold. However, as mentioned in the introduction, only limited quantitative data is presently available on the diffusion of small to medium-sized storage facilities in Austria. Therefore, this analysis relies on qualitative data for capturing storage diffusion in Austria.

In many cases, when it comes to home storage and small industrial applications, the producers' direct customers were wholesalers, such as IBS Solar and Sonepar (F3). They were, in turn, the link to the installation technicians (LSF1). They sold products of both Austrian and international companies (IAG3). A few large energy providers were also selling third-party battery storage as part of their portfolio (F3) (ESCO4).

However, there is currently incomplete evidence of how many smaller storage systems are being sold in Austria (see again Figure 5.1). While they do not want to give sales figures, the company representatives offering such products indicated that it is still difficult to sell such systems on a larger scale (LSF1, SSF2, IAG3). They built their hopes for increasing sales figures on increased subsidies, simplified regulations for energy communities, participation in the standard market for small storage operators, and further legitimacy creation through awareness-raising for the supposedly positive contribution of storage systems to the energy transition (IAG3). While Austrian companies began already exporting abroad (LSF1), it becomes evident that there is no independent market dynamic in Austria that goes substantially beyond the public support measures, yet.

5.2.2.2 Policy Mix and Other Institutions in the First Formative Phase

This section analyses the policy mix for influencing the BES-TIS in Austria, which appears to be central to its emergence. Since 2012, the policy mix included several elements: systemic guiding strategies on the federal level, push policies such as development funds and subsidies, pull policies such as grid fees and feed-in tariffs, and various systemic policies with an informational character such as government papers, stakeholder initiatives, and participation in European and Global programs (Figure 5.3).

2012 not only marked—according to some interviewees (LSF1, PRO4)—the first beginning of the development of a BES-TIS in Austria, but it was also a turning point in the policy mix. Thus, the federal government announced a new energy strategy, which established energy technology research as a central response to climate change (BMLFUW, 2012). It also introduced the new Green Electricity Act (ÖSG 2012), a regulation with systemic character, which regulates the basis for PV electricity and smaller plants' feed-in. As a result, increased activity took place in the provinces. Carinthia, Salzburg, Upper Austria, and Vienna introduced subsidies for installing storage systems in 2013 as economic push policies (PV-Austria, 2019).

While this laid the foundation for later developments, in 2015, the *Storage Initiative*, a systemic and information policy element that used stakeholder participation, began to connect different actors around the storage topic. With the *Storage Initiative*, the *Climate and Energy Fund* has been working on the subject since autumn 2015 with extensive stakeholder participation, focusing not only on the storage of electrical energy but also on

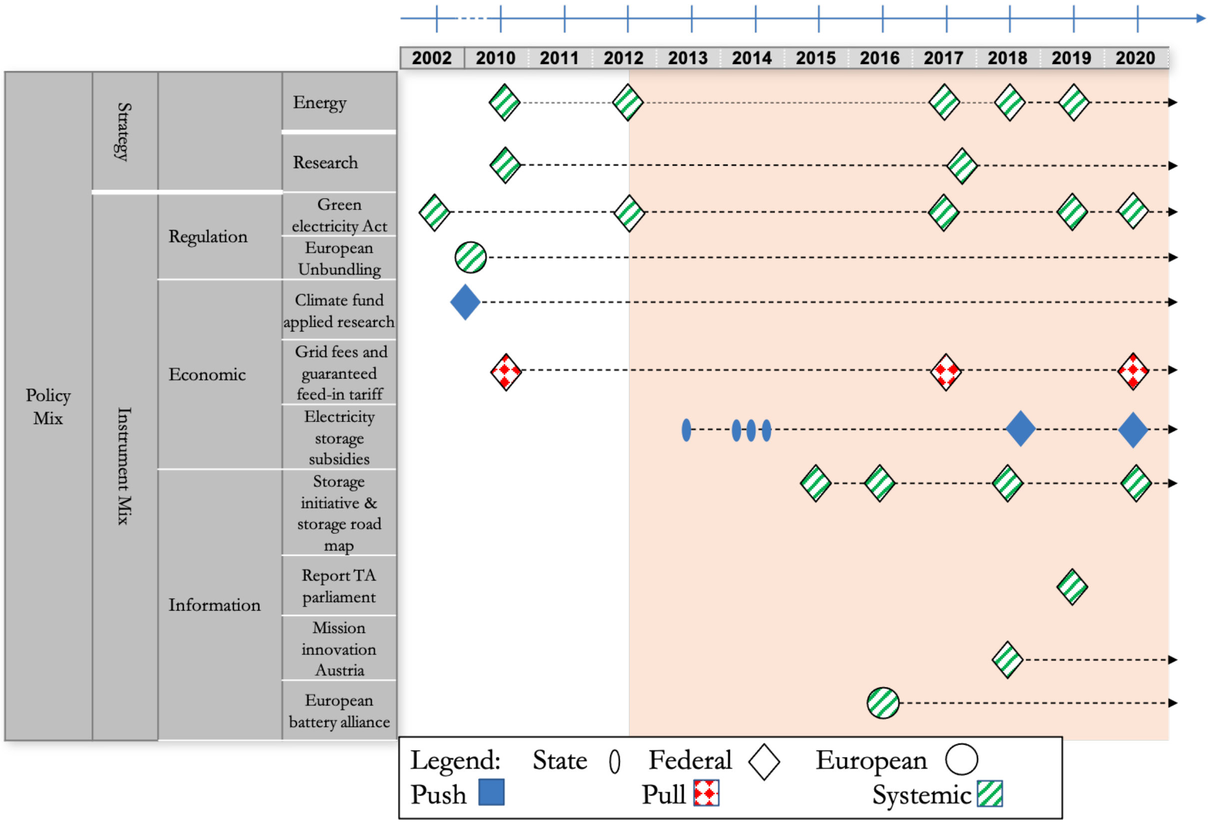


Figure 5.3: Policy mix for battery energy storage in Austria derived from policy documents and interviews.

heat and cold storage and the mobility sector (Klimafonds, 2016). These results translated into numerous technical RD&D projects funded by the *Climate and Energy Fund*. While staying vague in its recommendation beyond emphasizing a general need to promote every kind of storage approach, it helped create legitimacy by referring to a multitude of societal benefits, thereby making financial resources available to actors in the forming BES-TIS. As a follow-up, in March 2017, after a one-year dialogue process, the Federal Government published the Energy Research Strategy (BMVIT and Klimafonds, 2017), which addressed "conversion and storage technologies" as a topic area. Based on the participatory *Storage Initiative's* results, the technology roadmap "Energy storage systems in and from Austria" was developed by the AIT for the Infrastructure Ministry in 2018 (Friedl et al., 2018; Friedl and Kathan, 2018).

Simultaneously, the European Commission started a so-called "Battery Alliance" that was meant to connect producers along the battery value chain and providing them with additional financial resources to create a European battery industry (European Commission, 2018). We can consider this an attempt to create legitimacy by pointing to the industrial benefits, thus amplifying the perceived urgency for Austrian national policymakers to further engage with the issue.

In 2017 there were changes in systemic regulatory elements of the policy mix. For example, there were now a number of exemptions from grid charges for pumped storage and negative control reserve providers in the Energy Act (EIWOG), thereby incorporating the EU Third Energy Package into national law (European Commission, 2017). Otherwise, the 2010 regulation in the EIWOG continued to exist, which provided guaranteed feed-in tariffs for Green Electricity Producers and has no legal definition for energy storage and sees it either as a producer or consumer (as in Germany).

2018 saw an overhaul of the national energy strategy with the federal government issuing a target of 100 percent renewable electricity net consumption in 2030 (BMNT and BMVIT, 2018). In this strategy, supporting electricity storage was introduced to reach these targets for the first time.

Through the Green Electricity Act, in addition to photovoltaics, the purchase of intermediate electricity storage facilities is also financially supported on the federal level since 2018 (handled by *OeMAG*).[1] Electricity savings of between 0.5 kWh and 10 kWh of installed PV bottleneck capacity were subsidized with 500 €/kWh usable capacity of between 45-65 % of the costs (PV-Austria 2019). In the case of systems for self-sufficiency in

---

[1] § 27a Bundesgesetz über die Förderung der Elektrizitätserzeugung aus erneuerbaren Energieträgern (Ökostromgesetz 2012 – ÖSG 2012), BGBl I 75/2011 BGBl. I Nr. 75/2011 in the version BGBl I 108/2011.

insular locations, the subsidies also included 35 % of the electrical energy storage systems' costs for an investment of more than 10,000 €. In 2020, the levy on self-consumed PV electricity was abolished, making electricity storage more profitable (IAG3). The government continued amending the Green Electricity Act in 2019 and 2020 and will replace it with the new Renewable Expansion Law in 2021.

In the policy mix, the request for a technology assessment report of the Austrian Parliament in 2019 stands out among the government initiatives.[2] In this report (Ornetzeder et al., 2019), based on a workshop, several interviews, and extensive literature research the potential dangers and risks for the society, the economy, and the environment resulting from the use of storage systems—not only battery-based storage systems—were the main focus for the first time. One result was that other flexibility options besides storage should also receive political attention since storage systems are often the most expensive alternative. While the results did not show a direct impact on political decisions yet, there is evidence that it influenced the set-up of the second round of the Storage Initiative 2020 that considers societal and environmental impacts of storage systems more explicitly.

The involvement of different societal stakeholders in the design of innovation strategies shows the increased role of stakeholder participation in the policy mix's information elements. Especially the two waves of the Storage Initiative of 2016 and then again in 2020 build on extensive stakeholder processes. While research institutions have also participated in the working groups, mainly employees of engineering departments, a clear dominance of the Austrian innovation system's economic actors is evident (Klimafonds, 2016). The same goes for the storage technology roadmap from 2018 (Friedl et al., 2018). Both technology manufacturers and energy suppliers were the most represented in the process. The 2020 wave is still in progress at the time of writing this chapter and, therefore, cannot yet be

---

[2] The author of this thesis was also a co-author of this report commissioned by the Austrian Parliament.

conclusively assessed.

To sum up, public research and industrial policy appear to be important in the formative development of the Austrian BES-TIS so far. Affected by the early understanding in 2010 that the energy transition must not fail because of storage facilities, the public sector included them in the various energy research expenditures, which it emphasized in several strategy papers. For this purpose, stakeholder processes were organized to design new tenders for applied research and industry subsequently. Simultaneously, the government is making regulation for storage operators a little easier and grants extensive subsidies for purchasing smaller storage facilities.

5.3 Influences and Dynamics of the Technological Innovation System

The previous section presented the historical development of actors, networks, and institutions within the geographic boundaries of Austria with its unique infrastructure and physical context that can be described as an early emerging BES-TIS. Moreover, the previous section matched events to specific innovation functions and contexts.

The following section takes a step back and interprets the macro picture. For this purpose, the previously mentioned developments and events—derived from interviews, workshops, and policy documents—were evaluated and assigned to certain innovation functions depending on how the interviewees assessed them. As argued in chapter 2, the TIS literature emphasizes the importance of legitimacy for an emerging TIS. Legitimacy is an answer to the "why-question" to justify an activity (Van Leeuwen, 2007). In line with this, this section too places a particular emphasis on this innovation function.

Subsection 5.3.1 highlights how the role of legitimacy stands out and displays three common ways in which legitimacy for BES gets constructed in Austria. Subsection 5.3.2

summarizes TIS dynamics to identify initial patterns. For this purpose, this subsection arranges the innovation functions in a schematic overview to make first assumptions about possible supporting and blocking mechanisms that drive the BES-TIS and influence its development directionality. The next section 5.3.3 reflects on dynamics between the policy mix elements and the TIS functions.

5.3.1 Legitimation

This subsection presents three approaches that exemplify how producers and their interest groups establish storage solutions' legitimacy. The three emphasized strategies presented here do not show a representative and complete list of legitimation approaches, but first answers by actors to the "why-question": why do you do what you do? All these three attempts at legitimation emerged from the interviews and showed the distinct ways how some actors constructed legitimacy for BES. The three approaches are summarized as "regional decentralization", "green security", and the "coolness" of technologies—each pointing to a specific societal discourse.

Regional Decentralization

A pivotal anchor to establish legitimacy for battery storage, which most interviewed BES-promoting actors mentioned, was 'regional decentralization'. For example, one respondent from a storage solutions provider commented on his company's approach: "*We believe very strongly in this decentralized concept. We also believe that this can be well represented in the future at the community level or in the area of neighborhoods, which are now the talk of the town*" (LSF1). This interlinking between regional decentralized approaches was often highlighted by interviewees as increasing the regional resilience of the energy network and having a social component (SSF2). The regional and decentral focus fits with other approaches that emphasize a citizen-driven energy transition (Wiseman, 2018).

Therefore, the interviewed stakeholders also expressed great interest in further expanding and strengthening the EU Commission's energy community concept (Kalkbrenner, 2019; Koirala et al., 2018) to also include community storage projects (SSF2, IAG3).

While the strengthening of regional, decentralized solutions also links to regional autonomy concepts, the interviewees were all clear in pointing out that higher network levels were still needed. This emphasis is also made clear by the following quote from an entrepreneur who was planning regional solutions under the term "energy cells": *"I am not talking about energy autarky, in my opinion, total nonsense, but I am talking about regional energy cells"* (SSF2). This is particularly useful from a technical point of view for countries like Austria, where fewer island solutions are needed because a well-developed grid is already in place (Dallinger et al., 2019; IEA, 2020a).

Green Security

Closely related to the concept of regional decentralization but with a slightly different perspective is a legitimation approach subsequently called 'green security'. It highlights the fact that storage systems in combination with PV represent security and sustainability. Thus, users with their own residential houses supposedly desire to increase consumption of own PV electricity (IAG3, SSF2, ESCO4). The following quote from an industry stakeholder clarifies this legitimation approach as follows, describing PV and stationary storage as identical twins: "*Why are [PV and stationary storage] identical twins? Because the sun does not always shine, that is, somewhere it always shines, but if you want to use the electricity in Austria also at night, especially in winter, you need electricity storage so that the solar power can also fully use the sun produces*" (IAG3).

However, legitimation is not only generated via the residential sector; the commercial application of storage is also emphasized, as the following quote makes stresses: "*For companies that can use it to cap power peaks, when all machines are running at full load,* *they can use it to cap their power peaks, because companies pay for their electricity according to the peaks, if you have a lot of peaks, it is more expensive than if you have evenly. And that is interesting for companies. It is about saving grid fees*" (IAG3). This phenomenon has already been studied for Germany, where although companies are interested in such storage solutions in principle, they have little knowledge and motivation to actually install such solutions at present (Schriever and Halstrup, 2018).

Furthermore, BES-TIS stakeholders emphasized that storage PV systems fulfill other additional benefits. For instance, another aspect, which also falls under the green security legitimation approach and used by actors, is that storage facilities also enable security of supply during power failures and other catastrophic events. The alleged insecurity of power grids is increasingly attracting media attention in Austria, as illustrated by a near blackout in January 2021 (ORF, 2021). Building on these debates, the same representative commented as follows: „*there are also power storage systems that can ensure emergency power supply; if there was a storm somewhere and pylons were destroyed or blackout, the households can continue to supply themselves*" (IAG3). Thus, in this view, electric storage systems take over diesel generators' role or similar contingency measures and fulfill additional functions.

Coolness

While many advantages of storage systems were advertised to give them legitimacy, other attributes have nothing to do with how the storage system works. For instance, the technology is also presented as "cool," which has been a tradition for a long time, especially in the consumer technology sector (Kohlenberger, 2015). That emphasizing of novelty and coolness aspects is at least partially successful is shown by the following experience report of an employee at an interest group: "*A few years ago, when Elon Musk announced that he would release the electricity storage unit, people called us and asked, where can I get that?*

And when we asked them for their PV system, they said, no, I don't want a PV system. I want a storage unit." (IAG3). Another company also took this approach by using U.S. celebrity coolness to promote the use of energy storage. Thus, a regional company managed to generate attention by being publicly advertised by the former governor of California, Schwarzenegger (Die Presse, 2017).

However, from the companies that use storage systems, not every firm engaging with the BES-systems pursuits the topic because they believe in its potential. One manager of an utility noted after an interview that the primary reason for their exploration of BES-projects is because their CEO receives many questions regarding the issue at public events and wants to have convincing responses. This incident gives a hint that some of this entrepreneurial experimentation (F5) is partially an issue of mimicry and conformity to achieve social legitimacy by appearing innovative (F4) (see, e.g., Rodrigues and Child, 2008). A similar reason might explain why the Austrian transmission system operator (TSO) is also involved in a BES research project (F5). Meanwhile, the TSO's leading managers argue publicly in favor of grid expansion as an alternative for flexibility-provision to the role out of BES (TSO2).

Summary Legitimation

This case study findings illustrate the role of legitimacy in developing a new TIS in particular, as legitimacy is one essential factor in the early formative stages. The companies and other supporters promoting stationary battery storage seem to have done so by tying them to current societal discourses. It appears that this "generated" meaning for the firms' activity and their proposed products (Van Leeuwen, 2007), established trust in and reduced uncertainty of BES for consumers, investors, and regulators (Aldrich and Fiol, 1994). Consequently, we can infer that companies created legitimacy for themselves and their proposed technological (Markard et al., 2016; Bergek et al., 2008b). In the Austrian case study, the three observable forms of legitimation were related to discourses of regionalization (Suitner and Ecker, 2020; Späth and Rohracher, 2010), security (Scrase and Smith, 2009), and the “coolness” of (Silicon Valley) technology (Kohlenberger, 2015), which are also all permeated by the theme of energy transition (Buschmann and Oels, 2019). However, we cannot extrapolate these findings to all Austrian actors as they provided a qualitative perspective on the spectrum of views but cannot be taken as representative.

In addition to the directionality of development, legitimacy appears to be also one essential element for the diffusion of energy storage. This particularly applies since there is currently little evidence for substantial demand for BES in Austria. The evidence suggests hereby that one key reason for this was the high upfront cost of BES, making them not economically viable. Consequently, market demand for energy storage was not a primary cause for the Austrian BES-TIS development. Hence, till today, the development of the Austrian BES-TIS and the diffusion of BES in Austria seem to have been currently mostly independent. Thus, a strong advocacy coalition between companies, research institutions, and political actors that legitimizes a technology such as BES can be seen as being ever more important for its future success (Bergek et al., 2008b).

5.3.2 Innovation Function Dynamics

Taking a step back, the different events can be matched to different innovation functions and context factors and help to visualize possible inducing and blocking mechanisms in the Austrian BES-TIS (Table 5.2). Unsurprisingly, elements of all innovation functions existed in one way or another in Austria. Based on this overview and the interviews, this section derives initial assumptions about possibly influential innovation functions. While these are described separately below, many of the processes (or innovation engines) were active simultaneously.

Table 5.2: Overview of technological innovation system functions with inducing and blocking factors[4].

Innovation-Function	**Inducing Factors**	**Blocking Factors**
(1) Knowledge development and diffusion	• Automotive companies freeze BES production standard is plenty of previous experience from the solar and inverter sector as well as the automotive sector • Research is abundant: AIT and Graz, and FH OÖ. • Pre-existing innovation system of energy technology • Patent performance on the rise but internationally relatively limited • Application knowledge developed in demonstration projects	• Knowledge about cell production and battery design mostly available abroad
(2) Resource mobilization (e.g., financial, human, infrastructure)	• Companies have pre-existing business fields in solar etc. • Climate Fund • Private capital (banks) • Storage subsidies	• Compatibility of infrastructure protocols not given (plug and play necessary) • Too many funding agencies leads to confusion for applicants (e.g., KPC, Umweltförderung, FFG, Climate Fund)

(3) Market formation	**Export** • Limited small-scale BES exported in comprehensive products active by, e.g., Fronius. **Domestic market** • Regulation • Storage subsidies • Regionally different demand (countryside vs. city)	• A domestic market dominated by pumped hydro storage for many storage applications • Levy on own consumption until 2020 • Taxation on both feeding and discharging • Grid fees • Low electricity prices
(4) Influence on the direction of search	• Discursively pushed by the importance of PHS • Both are very different regarding technology and applications • Other actors (Utilities) need to show storage-activity to appear innovative and invest in BES • Technology assessment report for the Parliament strengthens considering the downsides of storage solutions to the intermittency problem	
(5) Private and public entrepreneurial experimentation	• Public experimentation via model region • smaller private (startups). • Fronius used to have an experimental area (therefore now PV and inverters). • Another area of experimentation is rural areas (e.g., Burgenland) • Large-scale battery storage experiments remain scarce • TSO and DSO but now forbidden due to EU regulation	• Small companies

(6) Creation of legitimacy (interest groups and advocacy coalitions)	• PV lobbies • AIT's public activities • Networking and coordination via technology roadmap drafting process, etc. • Public forums, e.g., Mission Innovation Week • Flagship projects • News media reporting • Technology assessment and subsequent "Storage Initiative" uptake shows serious consideration of possible storage downsides.	
Context	• Functioning global innovation system with various suppliers of pre-products • PHS in Austria • PV sector	

Interplay of Five Innovation Functions

This analysis concludes that part of the development began by public actors influencing the **search direction** by pointing out a perceived need for storage solutions in energy and research strategies. Here, it was possible to build rhetorically on the long-standing experience with PHS and the positively connoted importance of energy storage in Austria in general, **creating legitimacy**. Also, they engaged in **public entrepreneurial experimentation** by supporting applied research projects with **financial resources** at a relatively early stage. Thus, this pushed the practical **knowledge-development** for applying storage systems in industry and research institutions forward. Inspired by this, the firms **experimented** with storage systems by testing new applications and thereby **creating knowledge**. They could already build on much existing knowledge about renewable energy solutions and contacts and existing infrastructure as **context factors**.

The "Legitimation" Innovation Function

Particularly relevant for the further development, as already highlighted for other TIS (Bergek et al., 2008b; Markard et al., 2016), appeared to be the **creation of legitimacy**. This was done by docking to several salient issues in society with the topic of BES, thus "making meaning" (Van Leeuwen, 2007) for the use of storage. Also, various suppliers networked with each other, formed interest groups, and connected with other actors in the Austrian energy technology landscape. One of the **legitimacy** "anchors" that this study identified was the emphasis on regional networking through storage projects. Another closely related to that was the enabling of security through green energy use. A third anchor was to describe storage as cool, innovative, and future-oriented. The government has always supported the attempts to **create legitimacy** for storage solutions through systemic information elements in the policy mix.

Market Creation

So far, there was no "actual" **market** in Austria for BES. While a few companies were mostly export-oriented, their more domestic-oriented counterparts were still appearing to be amidst market build-up. Here, storage solutions were only in limited demand. A small part of it came from industrial firms or utilities that used BES themselves for learning or public relations. For the residential sector, sales to date within Austria remained limited, as far as can be said in the absence of reliable figures. Small-scale storage seemed to date rather not economically viable to users (LSF1, SSF2, IAG3), despite economic push-policies by the federal government, making the previous attempts to legitimize them all the more relevant to the supplier of storage solutions.

Guidance of Search Direction

Nevertheless, the **search direction** of the BES-TIS began moving in the direction of evermore "regional" networking of users as prosumers. According to such a view, storage systems are considered to be part of the overall energy solution. Besides, one focus was increasingly on larger storage units such as community or neighborhood storage.

Summary of Innovation Function Dynamics

To sum up, up until now, the emerging Austrian BES-TIS remained still in its formative stage. Moreover, the study suggests that the development has been mainly influenced by governmental applied energy technology research and subsidies based on the hope to build a new green industry. This result confirms the initial hypothesis for this chapter. To date, there is no evidence for a functioning market in Austria for storage products that exists independently without government support. Due to the unclear demand situation for the application of stationary BES in Austria, other flexibility options such as grid expansion, demand-side management, and the existence of many pumped storage power plants, the BES-TIS' continued development remains uncertain.

5.3.3 Policy Mix and Technological Innovation System Dynamics

The following subsection briefly describes the dynamics between the different elements of the policy mix with the innovation functions of the technological innovation system. As the first part describes policy mix elements and attempts to connect them to innovation functions, the second part considers the policy mix's characteristics holistically and makes some assumptions about their possible effect on key innovation functions.

Policy Mix Elements and Innovation Functions

The pre-phase of the emerging BES-TIS' development in 2002-2012 was characterized by economic push instruments such as research funding, which we assume to have laid the foundation for some of the later development by positively influencing the **resources** innovation function. Moreover, both the changes of regulatory policy instruments at the EU level and the new national energy and research strategies influenced the **search direction**—according to interviewees—thereby characterizing battery storage as a suitable solution for the "intermittency problem." They also prepared conditions for the later **context** structure relevant for **market** development. It thus prepared the ground for later **legitimation** approaches.

This study suggests that a set of relevant policies that we conceptualize as a PM for BES emerged in the first phase of the emerging BES-TIS' development in Austria from 2012 onward. Initially, it contained instruments that impacted the **search direction** and first attempts to pave the way to later **market creation** by including storage in systemic regulation and introducing subsidies as economic push policies on state and federal levels. Based on the results, we conclude that this influence on **search direction** was further fostered by a comprehensive information policy that brought various stakeholders together, helping **legitimize** storage solutions.

Then, direct federal economic push policy instruments that provided **financial resources** for RD&D projects potentially accelerated the **creation and diffusion of knowledge** within companies and allowed for **private** but also **public entrepreneurial experimentation**. In addition, systemic information policies set on the EU level that encouraged networking between different actors further aided **knowledge diffusion** and provided some **financial resources**. But foremost, they seem to have **created legitimacy** for energy storage issues at the national level.

Subsequently, new EU systemic regulatory policy elements in accord with national economic push policies (i.e., subsidies) continued to support potential future domestic **market creation**. Nonetheless, a new national energy strategy now entailed clear and ambitious renewable energy targets and mentioned the importance of solutions for reaching those. Also, there were new federal economic pull policies through tax levies, push policies through subsidies, and systemic market rules to incentivize domestic **market creation**. All of this presumably helped **legitimize** storage solutions, which suggests that they thereby reduced stakeholders' uncertainty and helped to make battery storage solutions more mainstream. Repeating the participative stakeholder process—a systemic information policy—encouraged mediating these different approaches of **legitimation**. In the future, the outcomes of this participative process are supposedly bound to inform policies, thus, aimed at influencing the **search direction** again.

Holistic Policy Mix Dimensions and Innovation Functions

This part will briefly analyze some dimensions that capture the entire policy mix holistically. These are policy fields, vertical and horizontal governance, policy consistency, coherence of the policy process, the credibility of the policy mix, comprehensiveness of the policy mix.

The policy mix included many interrelated policy fields such as energy, science, innovation, industrial, and transition and took place at all vertical governance levels EU, national, and state. In this context, the EU and national policies were sources of impulses for **search direction**, change of **market rules**, **financial resources**, and **legitimation**. Regarding horizontal governance levels, central national actors were the infrastructure and environmental ministries, as well as subsequent agencies, that lately fused to one single climate ministry.

Concerning the consistency of policies, it should be noted that the alignment of policy objectives is only partial, especially between energy policy and innovation policy, which is also noticeable in the accompanying instruments. This slight mismatch has to do with the fact that particular policy objectives, such as energy security, potentially collided with an uncontrolled diffusion and support of BES. While strategies were able to align these different objectives rhetorically, they required balancing trade-offs in practice. However, state strategies increasingly emphasized the importance of storage and led to an uptake in supportive policy instruments.

There was some incoherence in the policy process due to the mentioned mismatch between different policy objectives. Increasingly, information policy initiatives, like the intensive stakeholder process in the "storage initiative," supported assembling knowledge from diverse actors and building networks between them. This alignment helped to mediate the **legitimacy** of BES solutions. Moreover, it informed research policy initiatives that combined various fields such as climate and energy policy with innovation policy.

Thus, some interviewees mentioned that they recognized the **search direction**—and deemed credible—that the research policy had a strong BES focus. However, they remained skeptical whether or not energy regulation will ease the use of BES for users.

Based on existing evidence, the comprehensiveness of the policy mix can only be speculated. While the strategies and the associated policy instruments seem to be very comprehensive, there has been no self-sustaining BES market in Austria so far. However, the author can only conjecture whether this is due to a lack of demand or other barriers and bottlenecks.

5.4 Summary

This chapter set out to capture key dynamics of the development directionality of the Austrian BES-TIS. Also, it tried to uncover potential drivers of these developments. Methodologically, this chapter used a hermeneutic TIS approach. Using expert interviews, policy documents analysis, and descriptive statistics, it identified key actors, networks, and institutions. Moreover, it established a timeline of events that showed the interaction and development of these elements and how they led to the emergence of an early BES-TIS still in its formative stage. Using innovation functions as a theoretical foundation, both as a heuristic device and an ontological anchor, it made first assumptions about possible supporting and blocking mechanisms. A particular emphasis was on creating legitimacy as a central mechanism in the innovation system's development. Also, this chapter adopted a policy mix approach to identify interactions between policy and innovation system holistically.

To date, Austria is a country that does not have a high demand for stationary battery storage because, due to its geographic location, pumped hydro storage has been providing flexibility for the electricity system. Nevertheless, there has also been a medium-sized energy technology sector in Austria. Apart from hydropower, this sector focused on decentralized renewable energy solutions and began integrating storage systems into their products alongside PV and "smart" control technology. The aforementioned sector has been receiving government support for a long time by innovation and research policies as well as subsidies for consumers. Additionally, new companies dedicated explicitly to battery storage have emerged.

Furthermore, there is a long history of research with battery storage technologies in Austrian research institutions. The search direction of the energy transition in Austria also included battery storage as an element for a long time. Financial resources that enable governmental and private entrepreneurial experiments and knowledge creation further support this search direction. These activities have been continuously legitimized with diverse legitimation approaches around themes like "regional decentralization", "green security", and "coolness" of technologies.

Cautiously interpreted, stationary battery energy storage in Austria has been predominantly a solution in search of a problem. While the topic of battery storage had strong links to discourses on the energy transition, national energy policy was not mainly concerned with battery storage but rather with the stability of the energy supply and increasingly with the decarbonization of energy production.

The market has presumably not yet been self-reinforcing without further government support for research projects and subsidies for end users. Unfortunately, no reliable figures are available for the diffusion, especially for small-scale storage systems. Therefore, the investigation in this chapter is limited to the qualitative dimensions. Because of regulation, but mainly because of the state of the energy system and the infrastructure, the market structures did not show an increased demand for battery storage.

The very different attempts to mediate legitimacy were just efforts to enable a self-sustaining market dynamic. This underlines once again the importance of legitimacy. The policy mix and the attempts to create legitimacy with information policies also show this. Even if this was not evident from the interviews, the interaction of innovation and industrial policy with energy policy taken together with the lack of demand and market development imply that a primary motive to support and legitimize stationary BES in Austria has been the intention to establish a new sector of the economy. This can be taken as first confirmation of this chapter's initial hypothesis.

Also, the results from this in-depth case study confirm the importance of various context factors for TIS development. In this case, an existing well-established energy technology sector that integrated battery storage systems into their product portfolio, while geographic and infrastructure context factors that shaped the energy system dampened demand for additional battery storage in the electricity system.

Chapter 6

Battery Energy Storage Technological Innovation System in Germany

Lummerland, Security and the Electric Car

Figure 6.1: The fictional island of Lummerland "An island with two mountains, And the deep, wide sea, With four tunnels and tracks" from the children's book by Ende (1963).[2]

"*On Lummerland, completely different questions arise when it comes to energy supply than in an interconnected Central European network. If I imagine a Pacific island [. . .] where 100 people live, if I seriously want to organize a renewable electricity supply, then I will probably not be able to avoid very, very large battery storage if I don't want the diesel generator to hum all night long. [. . .] That's absolutely right on Lummerland [. . .] but that is not where we are. We're in the middle of Central Europe, in an interconnected network that will be fossil-dominated and safe for decades to come.*"

A senior officer at the federal grid regulatory agency

"*Our product can completely replace the public grid in the event of a blackout, as long as the battery is large enough.*"

A manager from a mid-size producer of battery storage systems for households

6.1 Introduction

The future role of stationary battery storage systems for the electricity system and the industry in Germany—as in many other countries—remains uncertain and contested. As argued in chapter 2, there is an interplay of several possible influences like technical developments, energy system interrelationships, economic and political decisions, and public opinion formation. Moreover, geography, physical infrastructure, and international contextual factors are likely determinants of the development path. Regarding opinions about energy storage diffusion, as the two opposing quotes illustrate, central actors legitimize their dismissive or supportive positions differently. One of the issues at stake is how to achieve energy security by gaining autonomy while, at the same time, desirable renewable energies bring new uncertainties.

Against this background, as initial industry surveys indicate, the diffusion of various types of stationary battery storage systems increases in Germany. According to first estimates, the number of employees working in the sector has been also growing steadily from 11,100 in 2017 to 13,300 in 2019 (BVES, 2020). New companies' market entries and exits show a high dynamic (Figure 6.2).

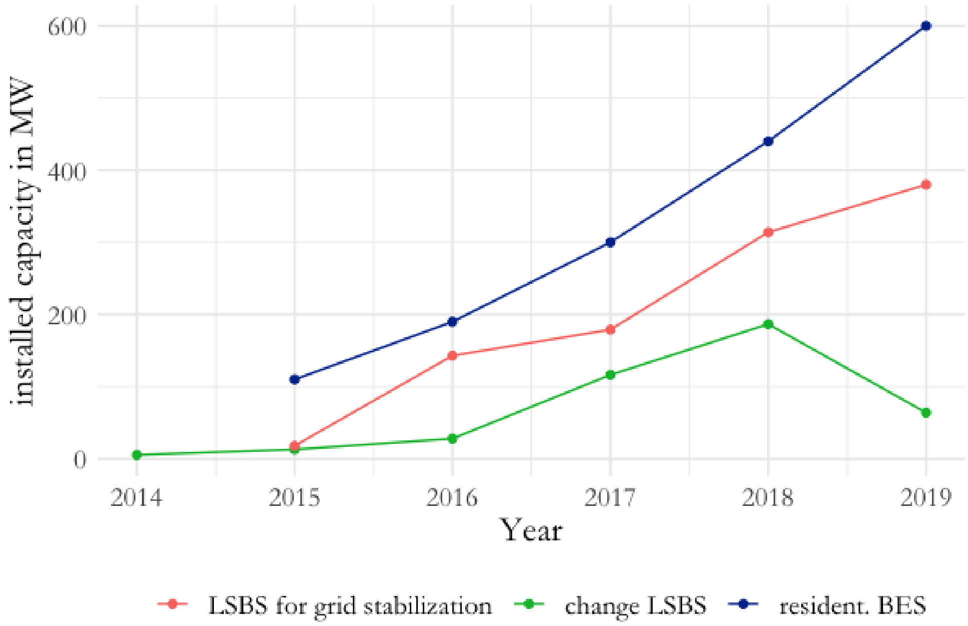


Figure 6.2: Battery Storage Diffusion in Germany. Source GTAI, BVES 2019. No data for large-scale batteries for grid stabilization and residential storage available before 2015.

Current energetic-systemic conditions in Germany illustrate the country's increased interest in energy storage. Here, the geographical asymmetries between generating new renewables through wind energy in the North Sea, the phasing-out of nuclear and coal, and consumption in the industrial areas in the southern and western parts create an imbalance between electricity consumption and production (Málek et al., 2018). While pumped hydro storage capacities in countries like Norway provide portions of the flexibility necessary for integrating renewables, the renewable electricity supplied by this remains insufficient for southern Germany's industrial centers. A possible way out of this situation lies in expanding the grid (Deutsche ÜNB, 2019; ENTSO-E, 2019). However, grid extension in Germany remains a cumbersome process where residents resist new projects in their immediate neighborhoods (Komendantova and Battaglini, 2016). A common characterization of these barriers is the “not in my backyard” NIMBY phenomenon. While it is an oversimplification, it remains influential as a derogatory term in political debates (Friedl and Reichl, 2016; Wolsink, 2018, 2000). Moreover, limited additional pumped hydro storage capacities due to scarce suitable geographic areas making battery storage appear a welcome alternative.

Besides the so-called "intermittency problem" in the energy system, another issue related to battery energy storage development in Germany is the automobile’s future. For the economically crucial automotive industry, its continuous survival in the light of the energy transition remains uncertain because of issues like the diesel scandal and competition from companies such as Tesla. Here, electric vehicles and battery technology appear to provide a solution, as the recent massive increase in investment in electric cars from Volkswagen (Transport and Environment, 2020) show. The launch of national experiments such as the “research factory storage” (BMBF, 2019a) exemplifies their industrial importance and entanglement of stationary battery storage and electric vehicles.

This chapter deals with all these dynamics and interrelationships. It shows how the German battery energy storage TIS emerged largely from the PV sector and how both the PV and automotive sectors influence its recent development. As previous research highlighted, legitimation is often essential in the formative phase of emerging technological innovation systems (Bergek et al., 2008b; Markard et al., 2016), which this chapter also emphasizes. Moreover, it tries to demonstrate how the German battery energy storage (BES) diffusion system develops against the backdrop of discourses around the future of the energy system and automotive sector. Therefore, it asks the following research questions:

1. What influenced the development dynamics of the German technological innovation system of battery energy storage, and how?
2. How was the legitimacy for the development and use of stationary battery storage in Germany created, and how did it influence the innovation system's development?
3. How did energy and innovation policies influence the development and early diffusion of stationary battery storage in Germany?

This chapter provides the results of an exploratory case study on stationary BES development and diffusion in Germany using a hybrid TIS and policy mix (PM) approach as the conceptual framework. Data collection happened primarily through qualitative expert interviews, policy analysis, and desk research following a coding guide based on TIS and PM. Based on the gathered evidence, the first section 6.2 shows mapped key actors. It established a historical timeline of the German BES-TIS following an event sequence approach that defines events as actions or decisions (Garud et al., 2017). Moreover, it summarizes the development of the BES-TIS central building blocks and its influencing policies in Germany. From this, in the next section 6.3 we identify key dynamics and influences within the TIS development, focusing on the role of legitimation, the interaction of crucial innovation functions, and the dynamics between TIS and PM.

6.2 Development of the Battery Energy Storage Innovation System in Germany

The following section entails a historical account of the German BES-TIS emergence on the energy transition background and establishes an event timeline (Garud et al., 2017). Following Bergek et al. (2008a), it outlines the unfolding TIS's development around important actors such as producers, consumers, civil society organizations, and the networks they form. Moreover, this chapter exemplifies formal institutions' role by sketching their development using a policy mix approach (Rogge and Reichardt, 2016).

In their comprehensive comparison of energy storage regulation across different countries, Winfield et al. (2018) identified certain key actors in the German innovation system. While their analysis applies more of a macroscopic lens, this chapter attempts to be finer-grained. It, therefore, includes more actors and focuses on the initial evolution of the German BES-TIS.

As in Chapter 5, once a piece of information comes from specific interviews, the interviewees are cited with a 4-digit code in parentheses. An overview of these interviewees is found in table 3.2. Also, 2-digit codes indicate innovation functions and a "C1" context factors (see table 3.1).

6.2.1 The Pre-Phase of the Technological Innovation System 2000–2008

In the pre-phase, crucial developments within the research and industrial landscape with the emergence of new actors and networks occurred that impacted the ensuing BES-TIS in one way or another. Also, the German government made major political decisions for the *Energiewende* and innovation policies.

6.2.1.1 Actors and Networks in the Pre-Phase

Pivotal for further development were the existing industrial structures and actors. Crucial among these were research universities and institutions that conducted research along the entire battery system value chain (F1) (MSF1, SSF3, PRO1). Such research included new kinds of electrochemical cell technology, the development of control algorithms or complete battery systems, and their real-world use cases (BMBF, 2019a). Within the German TIS, over 19 institutes (e.g., for solar energy, silicon-technology, integrated systems) from the publicly-funded Fraunhofer institute were central actors for applied battery RD&D

(Fraunhofer, 2020). They actively pushed the development of specific technologies and formed strategic partnerships with companies to steer technological development (F4, F5) (PRO1). These public research organizations focuds on active industrial policies that cab be subsumed under the umbrella of mission-oriented innovation (Mazzucato, 2018; Mazzucato and Semieniuk, 2017).

6.2.1.2 Policy Mix in the Pre-Phase

The policy mix also changed in the pre-phase, as this subsection describes. Relevant policies are summarized in Figure 6.3 below and grouped into four categories: strategies as well as regulatory, economic, and informing policy instruments. In the figure, the latter are, in turn, divided into push, pull, or systemic policies.

In 2000, Germany introduced the standard economic pull instrument of feed-in tariffs (FiT) with additional systemic regulatory changes in the Renewable Energy Sources Act (EEG (F3, F4, C1)). Although not officially considered a strategy, its far-reaching significance in discourses and role model effect justifies why it is also a strategy in this diagram. In 2004, the coalition between the Social Democratic Party of Germany and the Alliance' 90/The Greens revised the FiTs to increase renewable energy sources. In 2005, the Energy Industry Act (EnWG), which regulated grid-bound energy services, underwent its second revision to regulate natural monopolies to comply with EC regulations that unbundled grids and utilities. Here, it then defined storage explicitly as an energy consumer. Moreover, an essential element of the policy mix was the continuous promotion of applied research in universities and non-university research institutions.

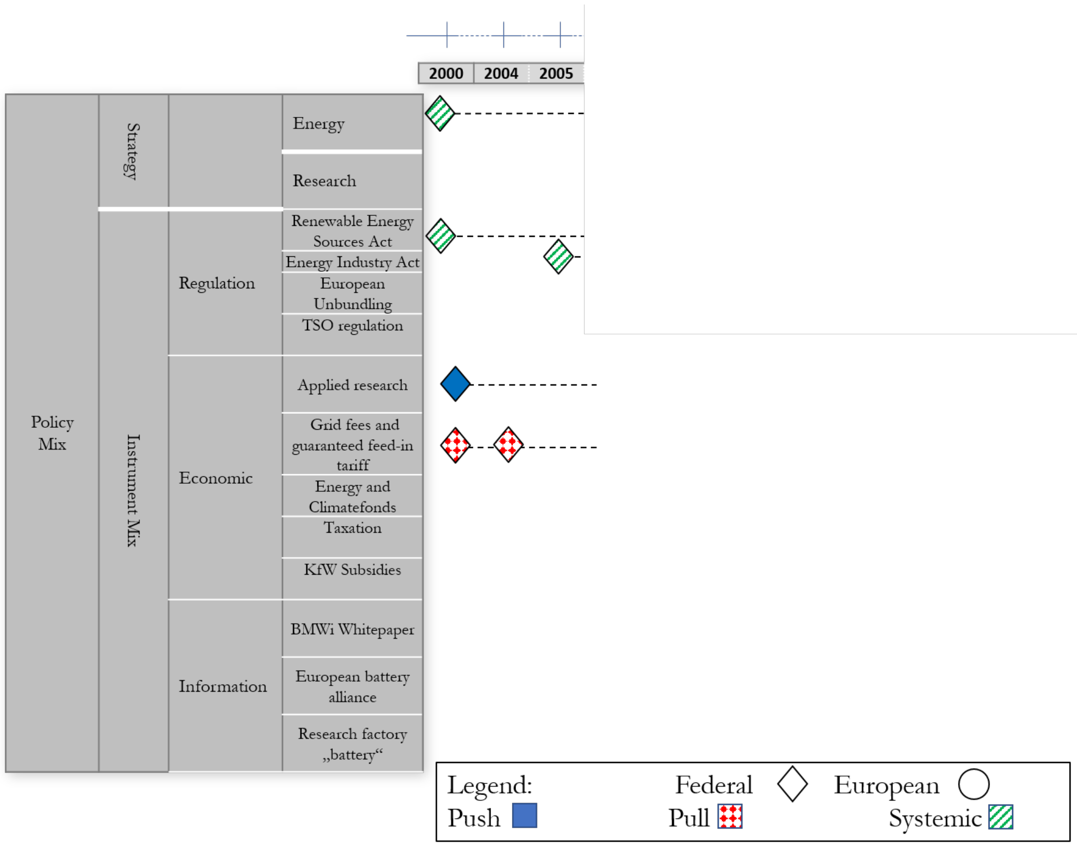


Figure 6.3: Policy mix of the pre-phase of the battery storage technological innovation system in Germany.

6.2.2 The First Formative Phase 2008–2016 – Company Formation and Government Innovation Policies

In 2008, according to the interviewees, the landscape changed. As solar energy increased its share in the electricity mix, strong concerns against renewables emerged due to their volatile production and their alleged inability to provide baseload for the electricity grid in Germany and other industrialized countries (FRA1, MSF1). The hitherto status quo was that nuclear power provided a baseload while additional flexibility was provided through coal and gas power plants and pumped hydro storage (Málek et al., 2018) (FRA1).

Policymaker and industry concerns related to technical and social challenges of the energy transition, increased demand for technological "quick fixes", such as decentral energy storage systems. These were supposed to render grid extension unnecessary for future integration of additional renewable energies (SSF1 and MSF1 below). Several interviewees expressed a suspicion that there was also the suspicion that the supposed storage demand and the intermittency problem were just a "red herring." Two of them described this time as follows:

"*2009 came this political turn on self-usage, [then] it was actually clear that someday soon these storage devices will gain a greater importance.*" (SSF1)

"*We have the advantage that, in all the discussions that have taken place in recent years about the energy transition, those who have been raving against all these things, whether they were right or wrong, have always said that there is not enough storage available. They have now maneuvered themselves into a corner from which they can no longer get out.*" (MSF1)

2008-2016 brought about changes to costs and prices conditions. There is evidence that falling lithium-ion cell prices due to massive economies of scale combined with their constant demand in many different applications (e.g., mobile devices, phones, computers, etc.) made them more and more affordable for stationary storage purposes (Davies et al., 2019; Kairies et al., 2019) (IAG1, MSF1, MSF3) (C1). Hence, various unprecedented projections of future price drops made (lithium-ion) battery storage a very appealing flexibility-option also for policymakers.

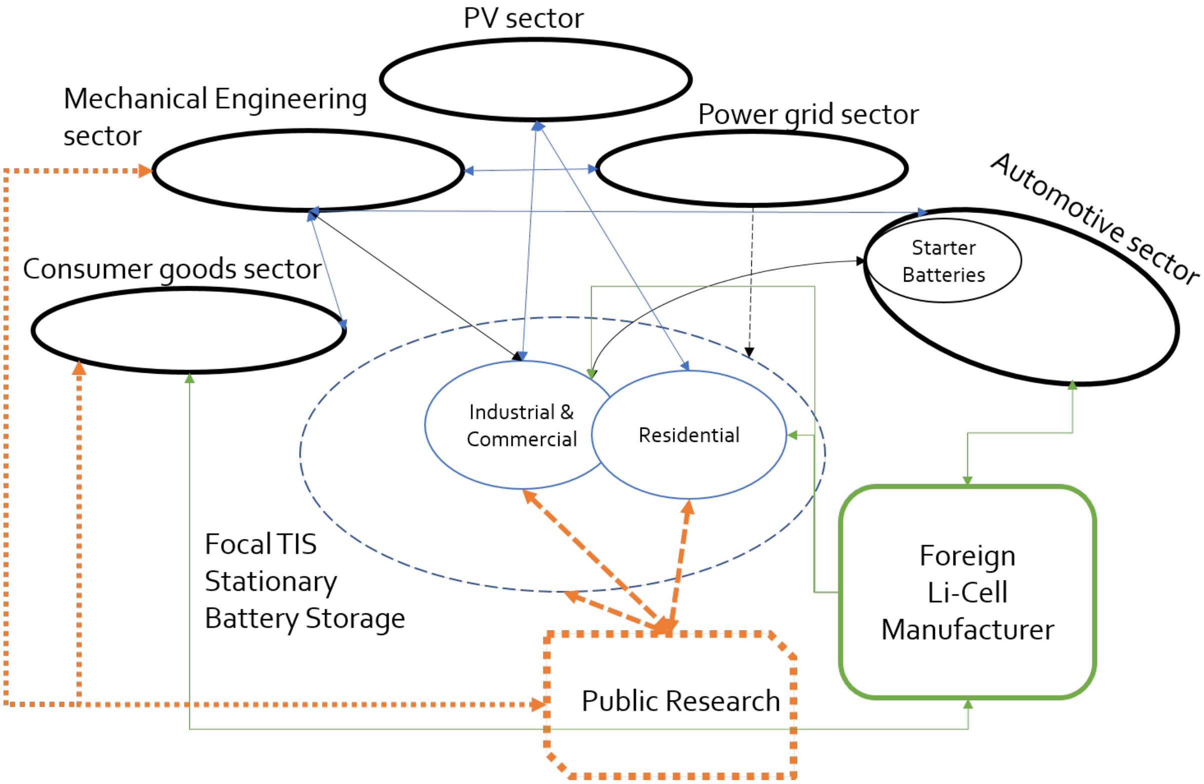


Figure 6.4: First-phase dynamics of focal TIS and neighboring sectors.

6.2.2.1 Actors and Networks in the First Formative Phase

Starting point for the first formative phase of the German BES-TIS is shown in Figure 6.4. It shows how the different private sectors impacted the two technologies in this thesis' focal TIS, commercial and residential stationary battery storage. A few of them were identified to have contributed directly to developing the technology, indicated by a solid arrow. Others influenced the technology or the whole focal TIS apparently only indirectly, marked by a dashed line. In addition to the private sectors, this schematic also includes the public research sector and foreign countries.

Based on several interviews, this thesis suggests that the first formative phase began in 2008 and likely ended in 2016, a phase during which a variety of battery storage companies emerged in Germany (MSF1, MSF3, SSD1) (F5). Many of these companies were small or medium-sized, originated from the PV industry (C1), were strongly regionally embedded, and had a background in electrical engineering (PRO1, MSF1). Moreover, most were smaller engineering firms, system integrators, and project financers rather than industrial companies. Still, they started to provide different end-products for private households and small companies and solutions for manufacturers. Also, automotive companies that used to focus on starter batteries began engaging with the BES-TIS (MSF3). Moreover, foreign producers also influenced the TIS development as producers of battery cells.

Producers

The primary type of German battery systems producer originated from the automotive industry (C1). These were, e.g., spinoffs like E3/DC, which engineers founded with a car battery and EV backgrounds in 2010 (E3/DC, 2019) (MSF3, MSF2) (F1). They used previous knowledge about car batteries and current automotive standards to build up development and production (F3); this knowledge also constituted the firm's philosophy, which they subsequently used as a marketing tool (MSF3). The market leader in home-storage system sales, Sonnen GmbH, also included founding members with a background in the automotive industry (MSF2). While large mechanical engineering companies, such as BMZ (MSF1), subsequently assembled the cell modules, there is evidence that German storage companies that functioned as original equipment manufacturers (OEM) developed mainly the final products (MSF1, MSF2, PRO1).

The increasing diffusion of electric vehicles in Germany (KBA, 2019) and the slow increase of electric vehicle production (LDF3) likely strengthened the connection between the automotive sector—including multinationals like Mercedes and Volkswagen—and the BES-TIS (PRO1). Consequently, providers of complete products that combined battery storage for photovoltaic and electric vehicle charging became typical, according to several interviewees from firms (MSF3, MSF1, SSF1, MSF2, LDF3).

Several domestic or foreign companies build battery production facilities in Germany and elsewhere in Europe, e.g., by the Swedish producer Northvolt (Milne, 2019). But some interviewees from firms claimed that German companies predominantly used cells originating from foreign-owned companies such as the Chinese BYD and CATL or the Korean LG and Samsung Group (MSF2, MSF1, SSF1). Regarding large-scale battery storage, a German-headquartered TNC—Siemens—put its capacities into a joint venture with the American AES called FLUENCE, which shifted most of its production and development activities to the USA (LDF2, PRO1) (F2, F5).

Interest Groups

The actors in the German BES-TIS formed multiple networks beyond primary producer-consumer relationships. Multiple new interest groups were starting to get involved in promoting energy storage technologies—notably, since 2012, the storage technologies lobby group BVES (IAG1, MSF1, MSF3). Additionally, other interest groups from the renewable and PV industries, such as the Federal Association of Renewable Energies (BEE), have started to include storage into their agenda (IAG2, SSF1). Moreover, mechanical engineering interest groups, such as the Mechanical Engineering Industry Association (VDMA) and the Automotive Industry Association (VDA), have also been actively lobbying for storage technologies.

Besides, the PV trade press started increasingly covering energy storage as a complement to PV, which helps contribute to a common language for vendors and knowledge sharing (F1). Also, specialized conferences on energy like Energy Storage Europe (ESS) have emerged and started to attract an increasing number of vendors each year that help networking, as attendance numbers suggest (F1).

Conversely, several environmental NGOs and consumer agencies began actively engaging in the public discourses on renewable engage with energy storage issues critically

(CRO1) (F6). They emphasized the drawbacks of battery storage, such as financial risks for consumers who buy a battery system and negative environmental and social impacts during raw material extraction.

Research, Development and Demonstration

Within Germany, several public actors began attempting to strengthening the BES-TIS. For example, the Federal Ministries for Economic Affairs and Energy (BMWi), Education and Research (BMBF), and the Environment, Nature Conservation, and Nuclear Safety (BMU) began to heavily fund the research institutes mentioned above since 2012, providing them with over 200 million € (BMBF, 2019a) (F1, F2, F5). Also, some projects received funds from the 2011 founded climate and energy fund financed through emission certificate sales.

While several large-scale companies in (mostly western) Germany began conducting their R&D activities that also included elements of basic research (F1), many small- and medium-sized battery systems providers started to focus their research on the final product and battery system management (PRO1, MSF1, SSF1). Most of the interviewed energy storage firms indicated a direct knowledge flow through recent graduates' employment from universities of applied sciences and research universities (MSF1, SSF1, MSF3) (F1).

6.2.2.2 Policy Mix in the First Formative Phase

The guiding plan for the German energy transition and, therefore, a guiding strategy for the policy mix (Figure 6.5) got passed by the Federal Government in 2010 (BMWi and BMU, 2010). It emphasized the further development of renewable energies and the phasing out of nuclear power.

At the European level, the EC established the Renewable Energy Directive (RED)[3] (2009/28/EC), which paved the way for own consumption of renewable energies from 2009 onwards. Further renewable energy- and energy storage-related regulations and government activities built on this (Papke and Kahles, 2018) (F3, F4). They materialized in the Energy Industry Act (EnWG 2011) as the regulatory foundation that adopted the EU's Third Energy Package and prepared later liberalization and restructuring of the energy market. The further unbundling of transmission system operators and storage system operators, new metering equipment and systems regulations, and advanced regulatory authorities' independence aided the emergence of flexibility markets.

Updates of the EEG legislation and its central instrument of feed-in tariffs (FiT) changed to include energy storage more explicitly. While the EEG defined storage as a producer[4], its amendment and the introduction of both a market-integration model and self-consumption bonus[5] in 2012 and 2014 continued to exempt storage from grid fees to avoid double taxation (F3). However, concerning storage, the 2014 EEG amendment introduced taxation for PV systems larger than 10 kW. Further, more industry sectors became exempt from the EEG FiT[6] to ensure international competition. Additionally, the Energy Saving Ordinance (EnEV 2014), based on the EEG, prescribed that self-produced electricity from PV can be stored and still offset[7].

---

[3] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

[4] §5 Nr. 1 EEG 2014/2017

[5] Photovoltaiksnovelle 2012

[6] §40 EEG 2014

[7] §5 EnEV 2014

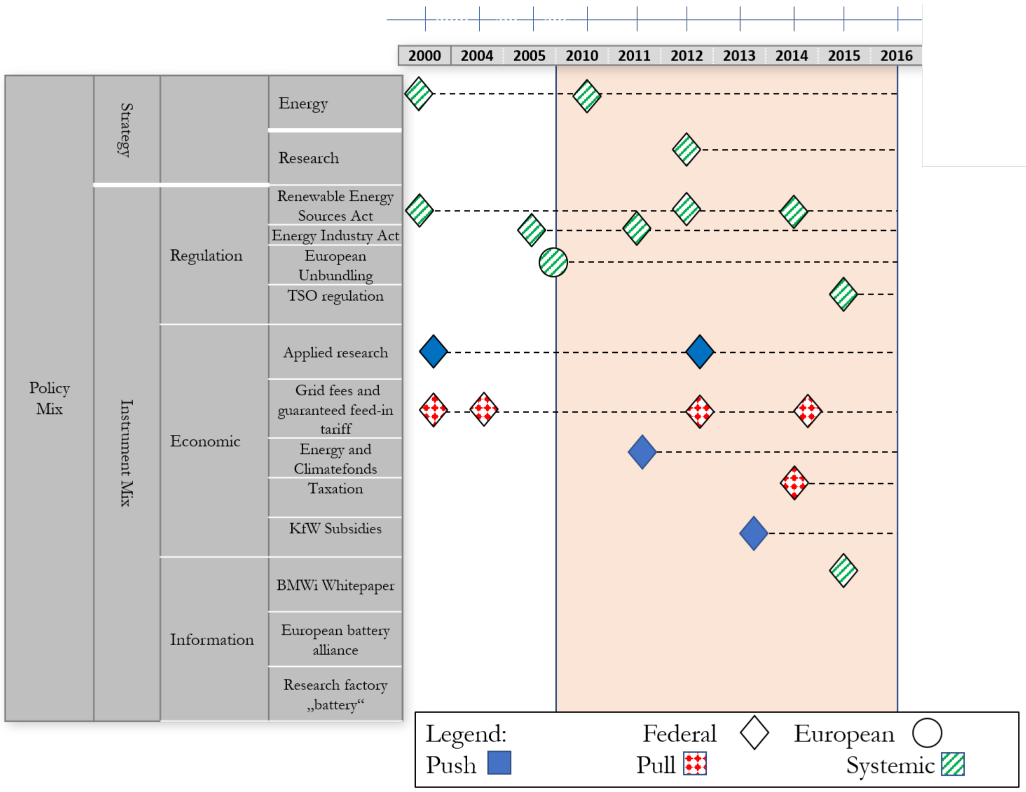


Figure 6.5: Policy mix of the first development phase of the battery storage technological innovation system in Germany.

To foster domestic demand, the government introduced the technology-push policy of subsidies. Therefore, the state-owned development bank (KfW) provided loans from May 2013 to December 2018 for home storage systems with a reduced rate and an up to 10 % discount on eligible cost repayment grants (Kairies et al., 2019) (F2).

Despite many storage interest groups' aim to foster domestic storage diffusion by establishing flexibility markets, public actors appeared to not always concur. In a 2015 white paper, the Federal Ministry for Economic Affairs and Energy announced that although electricity storage may play a role in the long-term future for lower voltage levels, grid extensions will be, in the short and medium run, the most crucial flexibility option (BMWi, 2015). In this understanding, storage will only assume a minor role (F4). The white paper also proposed strengthening the capacity reserve but did not advocate for increasing capacity markets.

In line with this, in 2015, the TSOs defined rules about battery storage conditions participating in capacity markets. They proclaimed that pre-qualifying batteries for operating reserve must either be large batteries or pool batteries (Deutsche ÜNB, 2015) (F4).

6.2.3 The Second Formative Phase Since 2016 – Company Consolidation and the Rise of EV

Interviews and policy documents suggest that in 2016 the focal TIS' development reached a tipping point. Arguably, this year marked the beginning of the TIS' second formative phase. Again, a dynamic interplay of various actors, the networks they form, and the policy mix that emerged in response became visible.

6.2.3.1 Actors and Networks in the Second Formative Phase

In the second phase of the German BES-TIS, there is some indication that more and larger producers such as large automotive companies began engaging with the focal TIS (Figure 6.6). Other foreign and domestic larger companies also became involved in the sector and consolidated and bought up many of the above-mentioned medium-sides storage producers. Also, foreign producers pushed more into the German domestic market. Besides, the motives of domestic consumers became increasingly crucial as domestic companies moved beyond their startup phase. Additionally, storage power plants and virtual storage started to gain the interest of potential large-scale domestic consumers.

Producers

Since 2016, many small startups have emerged, and other companies (like VARTA and Siemens) were re-joining the German battery storage TIS. Several became active in the market for residential storage in Germany because of the significant diffusion of PV and

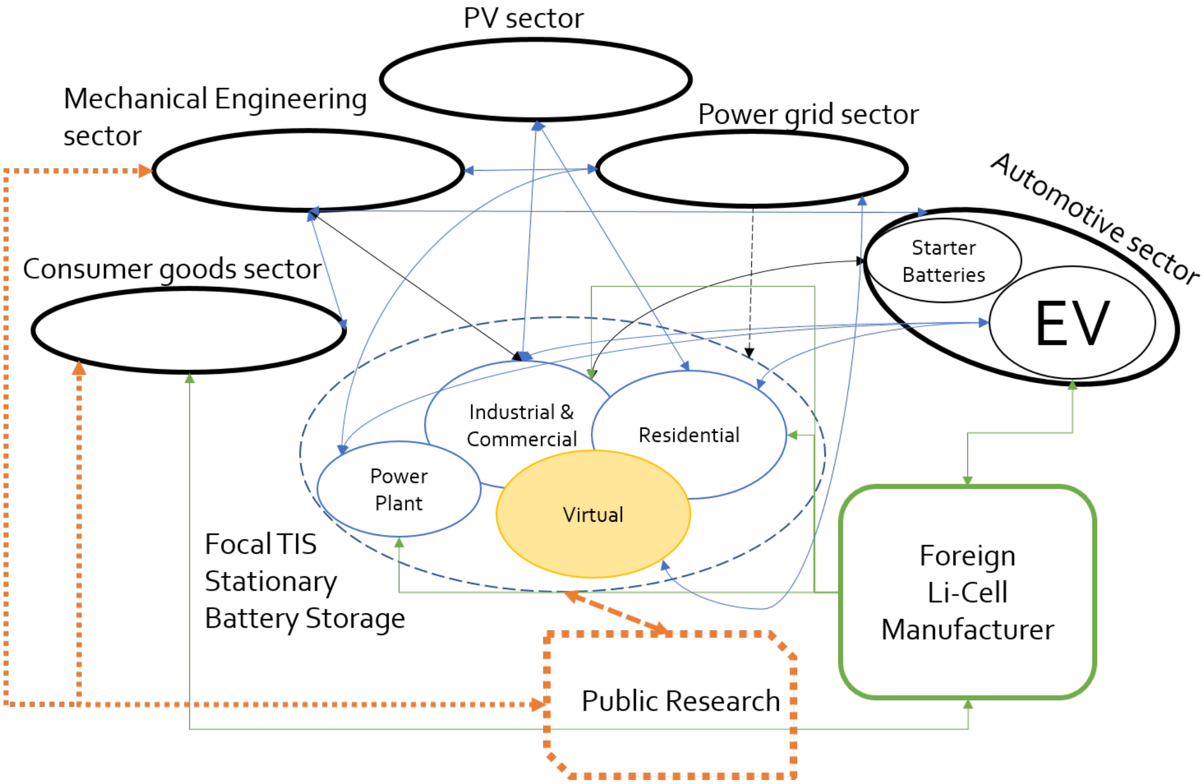


Figure 6.6: Second-phase dynamics of focal TIS and neighboring sectors.

its complementarity with battery storage (MSF1) (F3). Compared to the PV sector, consolidation and acquisitions by utilities (e.g., ENBW and Shell) and ICT companies (e.g., the Hager Group) occured relatively early in the TIS life cycle compared to the PV sector's development (F5).

A key interview finding is that central actors emphasized the strong influence of the automotive sector on the battery development process by setting production standards (MSF3, PRO1) (F1, F3). Accelerated by Volkswagen's diesel scandal, tightening EU regulation on fleet consumption, and rising competition from Asia, German car manufacturers began trying to ramp up their electric vehicle production. Since 2016, the automotive industry has focused on building cheaper batteries through economies of scale and avoiding research on other potential battery types (PRO1). Thus, developing commercial alternatives to lithium-ion batteries started to freeze on a larger scale likely as long as the new factories are not depreciated. Additionally, competition over battery cells (LDF3, PRO1) and employees (MSF3) with technological capabilities began taking place between the automotive industry and energy storage companies (F2).

Based on this evidence, another innovation system around electric vehicles can assumed to be a main influencing factor for storage development, while by contrast, stationary energy storage is less important for development of electric vehicles (PRO1). The increasing importance of battery development for the German automotive sector is exemplified by the Chinese battery producer, CATL, which announced in 2019 that it will open a 20 GW car battery production facility near Erfurt to cater to the car manufacturers' needs (PRNewswire, 2019).

However, car manufacturers themselves also participated in the stationary energy storage market (F2). For example, to balance the battery production capacities of electric vehicles, Mercedes Benz Energy GmbH—a full subsidiary of the German car manufacturer—created comprehensive products for customers in 2017. This combined PV and a Mercedes Benz vehicle with a battery for residential or commercial dwellings (LDF3).

Nonetheless, due to the increasing demand for electric vehicle batteries and high competition in the storage market, Mercedes Benz decided to exit the home storage market after just one year (LDF3) (-F2). Nevertheless, they continue to provide large-scale battery storage for industrial and grid use out of second-life batteries (LDF3). Other car manufacturers showed similar engagement with secondary-life batteries (LDF5). Thus, second-life car batteries used for stationary storage applications likely began assuming a unique role (F3).

Consumers

Various consumer groups became relevant in the second phase of TIS development, depending on the type of battery storage application and its use context. Until the official monitoring of the German grid agency has become fully effective (Bundesnetzagentur, 2019), quantitative research on energy storage diffusion in Germany must rely on data from industry organizations (e.g., BVES) and one already-terminated monitoring program (Kairies et al., 2019; Figgener et al., 2020). Accordingly, by the end of 2018, there is data of 371 MW of installed power capacity through large-scale batteries available in Germany (see Figure 6.2), with around 314 MW qualified for primary operating reserve.

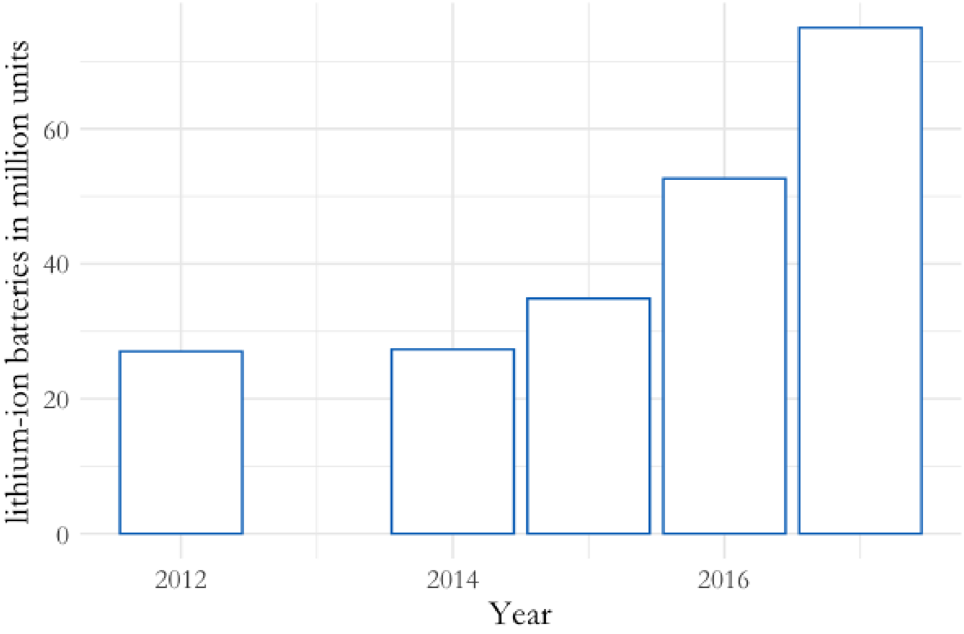


Figure 6.7: German export of lithium-ion batteries according to the UN COMTRADE database.

Additionally, the German BES-TIS became increasingly export-oriented (as Figure 6.7 suggests), while the local and home markets were still important, especially to small-scale startups. The interviews indicate, in this phase, export became the primary objective for companies in the German BES-TIS (PRO1, MSF2). For actors, other countries began to show a more considerable market potential for island solutions than the fully integrated German electricity system.

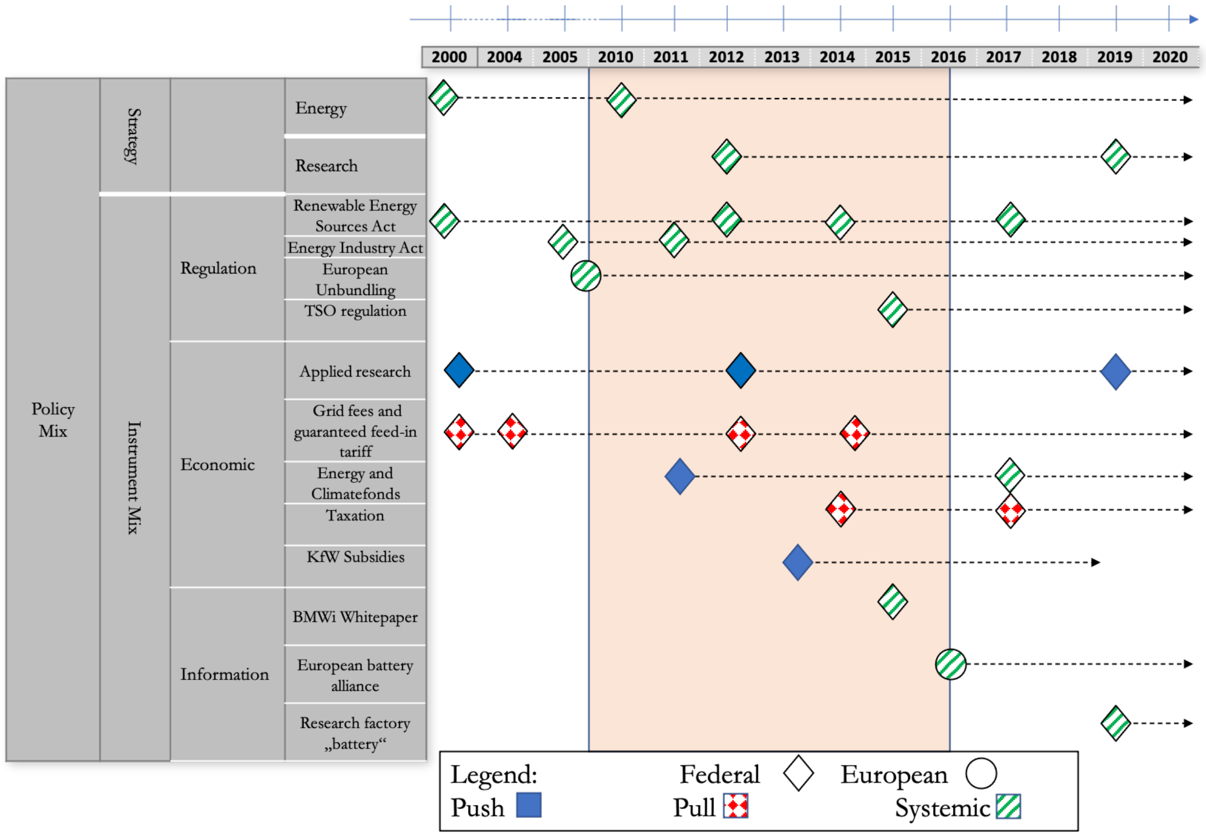


Figure 6.8: Policy mix of the second development phase of the battery storage technological innovation system in Germany.

6.2.3.2 Policy Mix in the Second Formative Phase

Since 2016, many policy mix elements surrounding energy and energy storage started going through changes or revisions (Figure 6.8). These mostly systemic policies were either already enacted at the European level and waiting to be adopted by national law or already in the federal legislative process. For example, with the EU's Clean Energy Package for All Europeans, the EC adopted a new Renewable Energy Directive (Directive 2009/28/EC). It will require member states to allow end-customer activity on the energy market (F3).

Interviewed stakeholders from industry interest groups were also expecting a simplification and merger of different laws (EnEV, EnEG, and EEWaermeG (Renewable Heating

Act)) to form the new Building Energy Act (GEG) (IAG1, IAG2). Thus, actors within the TIS—and the diffusion system—already act according to anticipated future regulation. Ultimately, regulation was not always clear to many actors and remained mostly in flux. This regulatory uncertainty was mirrored in the presence of legal research projects on battery storage in grids (see, e.g., Stiftung Umweltenergierecht, 2018) (F4).

Changes in energy policy also affected the BES-TIS policy mix. The 2017 revision of the Renewable Energy Sources Act (EEG) can be seen as a departure from ambitious renewable energy goals to a cap for further increases and a change in the remuneration system from FiT to a tender procedure. Furthermore, double taxation was further prohibited, and the new EEG heavily reduced fees for self-consumption of PV electricity (F3, F4). However, market actors continued to stress that double taxation still occurs in some instances and therefore lobby for storage to be the "fourth pillar" of the energy system, next to generation, consumption, and transmission (IAG1, IAG2, FRA1). Also, taxation of storage intended primarily for grid services and not for increasing self-consumption[8] existed.

Applying a mission-oriented approach to innovation policy, the German government introduced a series of push and systemic innovation policies. They started planning a national competence center called “battery factory” (BMBF, 2019a) to foster innovation along the value chain for battery systems. The University of Münster and the Helmholtz-Alliance institutes—another group of publicly funded research institutes—were about to integrate the core center (BMBF, 2019b) (F5).

Moreover, the need for national competencies for developing electric vehicles justified this promotion of battery-related policies according to actors (BMBF, 2019a) (PRO1) (F1). Examples included the development of energy-technology export initiatives (BMWi, 2019), regulatory sandboxes for development and demonstration for climate fund projects

---

[8] StromStg 2019

(BMWi, 2018)[9], and the overall objective to change national regulations, thereby fostering domestic market development (FRA1). Additional funding initiatives—that were not in the policy mix visualizations—came from state (Länder) ministries (SSF1) (F2).

6.3 Influences and Dynamics of the Technological Innovation System

The previous section presented the historical emergence of the emerging BES-TIS based on diverse actors, networks, and institutions. Also, it matched dynamics to specific innovation functions or contexts. The following section takes a step back and interprets the macro picture. As already explained in chapter 2, the TIS literature shows legitimacy as crucial for a new emerging TIS in its formative stage. This case study of BES in Germany suggests similar results.

Therefore, this section's first step is to highlight two two critical forms of legitimacy that emerged from the qualitative interviews. According to Van Leeuwen (2007), legitimation is the answer to a "why-question" to justify an activity. The purpose of legitimation is to establish trust. It is the basis and result of the other innovation functions (Bergek et al., 2008b). Next, identified innovation functions are arranged in a schematic and abstracted overview. This overview helps identify potentially supporting and blocking mechanisms.In a third step, a macro-perspective is taken to explore possible dynamics between the policy mix and the TIS.

---

[9] SINTEG-Directive - SINTEG-V SINTEG-directive from June 14th, 2017 (BGBl. I S. 1653)

6.3.1 Legitimation

In the following, two attempts of legitimizing stationary battery storage, which also link to other societal discourses, are shown. One form of legitimation is about autonomy and security through green energy. The other form of legitimation is about industrial policy and the future of the German automotive industry. The two forms of legitimation emerged from the qualitatively interviewed stakeholders and experts and where mentioned in most of the interviews.

Green Security

The first noteworthy motive used for legitimation has to do with a demand for autonomy and security while at the same time only relying on green technology. This salient sentiment is also apparent in the two quotes in the introduction. According to this, consumers who also want storage want to use green and sustainable technology and not rely on anybody.One interviewee pointedly called this the “Lummerland-perspective.”

Another interviewee explained the demand for self-reliance with a general mistrust between different actors. To him, this was also true for other actors, such as industrial companies, municipal utilities, and grid operators (MSF2), all of whom were trying to make their balancing zone smaller. This phenomenon appears to be in line with the first empirical studies for consumer preference for energy storage in Australia (Agnew and Dargusch, 2017).

This sense of self-reliance and community can be assumed to translate into new products, such as virtual cloud storage. It is a relatively recent trend, as described by a storage systems developer: “*. . . if you were talking about clouds [in 2014], you were talking about the weather forecast, not a technology*” (MSF2). While development towards products and services like IoT (Internet of Things) and other “smart” and connective technologies seemed to render virtual cloud storage a logical successor in product development, its promotion (and legitimation) through the motive of self-reliance remains puzzling; it appears initially contradictory, as virtual storage relies on an interconnected electricity grid and communication connection, i.e., the internet.

Nonetheless, the marketing pitch by companies involved in developing and selling such products still used the self-reliance motives from the "Lummerland perspective." As one company representative explained: "*if I feed in a lot, I can supply two more places in Germany. This is meant for holiday flats or the children in their shared flat in Berlin who moved out of the house. Then, I also consume less, and the children's shared flat is still supplied.*" (MSF1). The motive this company representative invokes contains the theme of "home-grown electricity" (Christensen et al., 2020) as users appear to show attachment and ownership to the energy they produce.

However, to various degrees, operators of industrial storage systems and large-scale storage plants seem to have followed a different logic than residential and small-scale commercial users. They could be assumed to follow a more "economic" rationale, with a stricter weighing of costs and benefits. However, many operators began using and building the plants to experiment and learn with the system rather than expecting direct profits. They also hoped that system services (e.g., frequency control, operating reserve, black start) require establishing flexibility markets (IAG1). Distribution system operators (DSO) would be the potential buyers of these flexibility services and would use those flexibilities as a substitute for grid re-enforcement (Nykamp et al., 2017).

Electric Vehicles

A second motive mentioned by storage solution providers, pertained to the expected market diffusion of electric vehicles (MSF2, MSF1, SSF1, LDF1). According to them, electric cars were drivers for the increasing use of stationary battery storage, which impacted on EV charging and the grid.

For EV charging, they believed that charging technology for electric vehicles requires using stationary battery storage devices. Then, batteries would be integrated into the charger buffer for fast charging or/and increasing the self-consumption of PV power and using it in cars. A few providers specifically targeted residential EV charging (MSF1), although this would require a large home battery (100 kW and larger) and might be too costly for many users (SSF1). Therefore, other providers focused on fast-charging stations for employees of bigger companies with large-scale storage facilities (SSF1), who aim to simulate the conventional refueling experience (Globisch et al., 2019).

For the grid, one likely implication of EVs might be that these storage companies began expecting a rising demand in storage at the grid level. This would come from the expected rising demand for electricity (MSF2), as electromobility and grid expansion will introduce new grid stability issues. However, given Germany's current EV and storage diffusion level, until today, the effect on the transmission system appears to have remained negligible (TSO1).

Summary Legitimation

In Germany, both young and long-existing firms involved in the BES-TIS seem to have "created meaning" for their activities and products by justifying their existence (Van Leeuwen, 2007) and thereby legitimacy. There is an indication that central to this was the influence of energy transition discourses. In particular, while the supposed shortage of energy storage was long considered an argument against renewables (see intermittency problem in, e.g., Zöphel et al., 2018), the political will to transition to renewables now likely provided a crucial basis for legitimacy creation of BES by BES firms. Next to the energy transition discourse that permeates many societal discourses (Buschmann and Oels, 2019), the study found that some firms and other proponents created legitimation in two distinct ways. First, by stressing “green security," which reference the issue of energy autonomy

(McKenna, 2018), and by stressing the importance of “electric vehicles” and referencing German discourses about the future of the automotive sector (Held et al., 2018; Mögele and Rau, 2020). However, these results need to be interpreted with caution as they are solely based on the interviews, and other forms to legitimize energy storage are likely to exist.

6.3.2 Innovation Function Dynamics

Taking a step back, the different events can be matched to different innovation functions and context structures and help to visualize possible inducing and blocking mechanisms in the German BES-TIS (Table 6.1). All innovation functions exist in one way or another, which is not surprising in a large industrial country like Germany. Based on this overview and the empirical data mentioned before, this section attempts to derive some assumptions about essential innovation functions.

Table 6.1: The German BES-TIS

	Phase	Inducing factors	Blocking factors
(1) Knowledge development and diffusion	2000–2008	• An established set of research facilities • Active PV trade press	
	2008–2016	• Knowledge diffusion through recent graduates • An influx of former automotive and PV sector workers	
	2016 –	• Strong basic research • Applied research declines • EV-storage research by the automotive sector	• Automotive companies freeze BES production standard
(2) Resource mobilization (e.g., financial, human, infrastructure)	2008–2016	• Large-scale private financial resources • Governmental research grants • Skilled workers from automotive and PV join	• Some car manufacturers withdrew investment in BES
	2016 –	• Human resources continue flowing between sectors • Buy-ups by larger companies	• Skilled labor is increasingly difficult to find in some regions item Rates of R&D spending start to fall

(3) Market formation	2000–2008	***Domestic Market***	• FiT for renewables established the foundation for BES	
	2008–2016		• Lithium-ion cell prices fell • Battery standards through the automotive sector • EU unbundling regulation opens the possibility for a third-party storage market • Federal government strategy for renewables • FiT adopted to include more exemption from taxation for storage • New pre-qualification definitions by TSOs for storage in reserve markets stress the importance of large-scale and virtual storage	• According to the storage industry still, double taxation
	2016 –		• The automotive sector sets production standards for battery systems • Further double taxation issues abolished • EU regulation moves towards the creation of flexibility markets	• Prices for flexibility do not show substantial demand for additional battery storage
	2016 –	Export	• Export becomes the primary objective for many companies	• For some actors, the different regulation in countries is a barrier

(4) Influence on the direction of search	2000–2008	• Mission-oriented innovation policies and applied research • Political and industry actors push for storage as the missing solution to the energy transition • Grid regulatory agencies favor other flexibility options (grid extension)	
	2008–2016	• Unbundling opened up space for new actors • Reduced effort but the government is still committed to *Energiewende* Grid extension is stressed as a flexibility	
	2016 –	• Experiences from diminishing PV sector becomes a guiding principle → increased willingness to buy up	
(5) Private and public entrepreneurial experimentation	2000–2008	• Public research institutions experiment	
	2008–2016	• Small startups for small scale BES form out of PV and automotive sector • First companies develop large-scale BES products • Automotive companies experiment with new BES with EV products and services	
	2016 –	• Public sector experimentation • Small companies experiment	• Large companies refrain from experimentation
(6) Creation of legitimacy (interest groups and advocacy coalitions)	2000–2008	• *Energiewende* becomes a reference frame • Advocacy groups highlight missing base load	
	2008–2016	• Actors portray energy storage as the apparent fix of the intermittency problem of renewables	
	2016 –	• Stationary storage loses in the debate about EV	

Relevant Context Structures Predating TIS

The evidence from the interviews indicates that the German BES-TIS originated primarily from two sectors: the PV and automotive sectors as relevant **context factors**. From them, there was also **private entrepreneurial experimentation** by relatively smaller players for the first time. They could build on a **knowledge base created** by applied and basic research in Germany. However, the evidence suggests that the BES-TIS was also heavily dependent on intermediate products and **knowledge diffusion** from abroad.

Interplay of Five Innovation Functions

The energy transition allowed to **build legitimacy** and influenced the **search direction**, which appears to have mobilized **financial resources** such as private investment and government grants. Moreover, it brought the sector **human resources** of qualified technical personnel who were ideologically motivated to work on the energy transition. This was a likely incentive that enabled **private entrepreneurial experimentation**. However, while regulatory obstacles also limited the **domestic market**, mainly by not yet given economic benefits for consumers, there was increased export to **markets abroad**.

Context Shift Leads to Legitimacy Shift and TIS Development Shift

This study argues that there was a turning point in the development that impacted the directionality, which came via the **legitimization** function. The sudden increase in demand from the automotive sector for battery storage from 2016 onwards in Germany due to the switch to EVs also increased attention for the BES-TIS players, who mainly focused on stationary applications. This sudden prominence—and shift in **context**—brought further **financial resources**, **private entrepreneurial experimentation**, and increased **public entrepreneurial experimentation** in application-related research institutions. Also, **knowledge creation** in public basic research intensified.

However, interviewees related to the sector claimed that those automotive companies that joined the BES were not particularly keen to experiment and were mainly interested in building up large industrial capacities for EVs as quickly as possible. For the original smaller players in the BES-TIS, most of whom also had an automotive background, this appears to have meant a new form of meaning-making and **legitimizing** their products. However, due to the importance of the automotive sector, this study's results suggest a substantial shift in the **search direction** from stationary storage for PV to the application of storage in the automotive sector.

6.3.3 Policy Mix and Technological Innovation System Dynamics

Policy Mix Elements and Innovation Functions

In what we consider the pre-phase in 2000-2007 that provided a background of **context** structures that enabled the later emerging BES-TIS in Germany, classical economic pull elements such as feed-in tariffs and systemic regulatory measures supported the expansion of renewables in Germany. These changes in the policy mix marked the beginning of the *Energiewende* and influenced the conditions for later **market formation**, influencing the **search direction** and creating a **context** for the BES-TIS consisting of different renewable energy sectors such as PV and solar. Furthermore, implementing the EU systemic unbundling policy into national law paved the way for future conditions in the **storage market**. This phase also included the continuous promotion of applied energy technology research.

In the first phase of the emerging BES-TIS in Germany in 2008-2016, a central national guiding strategy indicated the continuous support for the energy transition, which affected the **search direction**. Moreover, the systemic regulation policies at the European level liberalizing the electricity **market** emphasized the increased importance of electricity self-consumption influencing **search direction**, the shaping of storage **markets**, and **created legitimacy** for storage solutions.

Then, more changes in the national central energy market policies followed, both of a systemic and economic pull policy nature, which now more explicitly promoted energy storage use in Germany. There is indication that these changes contributed to the creation of something like an "infant" electricity storage **market** for private households and firms.

Afterwards, the federal government introduced economic push policies to support the domestic **market formation** for storage systems, providing loans and grants at reduced rates to buyers, helping **resource mobilization**. Conversely, a somewhat dampening signal for unfettered political support for storage use in Germany came from another central strategy paper of the Federal Government. It made clear that the grid expansion for the creation will be privileged and that storage will have a relatively minor role in this, indicating first possible conflicts with **context structures** and appear to have influenced **legitimation** attempts and **search direction**.

The second phase of the emerging BES-TIS in Germany, beginning in 2016, introduced a bundle of new systemic regulatory policies, mainly coming from the EU level. These policies aimed to influence the domestic **market formation** and foster prosumerism and other end-user activities in the energy market. Many firms of the BES-TIS, such as suppliers of storage products, expected additional demand and **legitimized** their products with said regulation. Conversely, other actors experience uncertainty due to the plethora of new policies, being a tad **de-legitimizing**.

Still, economic pull policies (feed-in tariffs) likely continuously supported domestic **market formation** by incentivizing self-consumption of electricity and the use of BES, thereby helping to **create legitimacy**. Also, a series of economic push policy elements and systemic innovation policies supporting applied research, following a mission-oriented innovation approach, provided additional **financial resources** and aim at **knowledge**

creation and **diffusion**.

Moreover, the shift in the **search direction** was mirrored in the policy mix that now contains information policy elements primarily targeted at promotion battery development for electric vehicles. This change also shifted the way battery producers **legitimized** their products, showing how they provide battery systems for the automotive industry rather than storage to deal with variable renewable energies.

Holistic Policy Mix Dimensions and Innovation Functions

This part will briefly analyze some dimensions that capture the entire policy mix holistically. These are policy fields, vertical and horizontal governance, policy consistency, coherence of the policy process, the credibility of the policy mix, and the comprehensiveness of the policy mix.

The policy mix included several interrelated policy fields such as energy security, innovation, technology, science, transition, and industrial policies, highlighting the cross-cutting nature of battery energy storage technologies. Moreover, it took place at all vertical governance levels EU, national, and state. Among many crucial actors regarding horizontal governance levels were the energy ministry, the research ministry, the grid agency, and the state-owned investment and development bank.

Concerning the policy consistency, there has been only a partial alignment regarding policy objectives that stemmed from the fact that energy storage remained for energy policy, not a goal in itself but an auxiliary technology—a means to an end. This interrelatedness is particularly visible when it comes, on the one hand, to energy policy that has been mainly concerned with stabilizing the grid while keeping down costs and, on the other hand, to industry and innovation policy that wanted to foster the growth of the domestic storage industry. Consequently, instruments sometimes contradicted each other. However, from the empirical evidence gathered in this thesis, the overall policy process could compromise these objectives by allowing regulatory sandboxes, providing applied research funding, and some financial incentives to customers while ensuring that grid stability remains a central priority.

This thesis remains speculative about the coherence of the policy processes as assessing this went beyond its scope. However, the author noticed no single mediating policy processes beyond parliamentary and ministerial deliberation. Thus, we cannot preclude that this showed incoherence in the process. Moreover, we can assume various private and public organizations with vast personal and financial resources have the required capacity to assemble relevant knowledge and engage with multiple stakeholders.

In the policy mix, innovation and research policy can be considered credible, this cannot with certainty be said for energy policy, which influenced domestic diffusion and thereby the entire BES-TIS. Regulation remained plentiful, and actors have been in doubt about future developments.

Based on the gathered evidence, the comprehensiveness of the policy mix remains unclear. The policy elements were comprehensive in that both the innovation policy elements and the energy policy elements aligned with decisive strategy documents. However, the inconsistencies in the policy mix also affected comprehensiveness. Thus, it is difficult to assess whether the overall policy process can be considered comprehensive, as thoroughness in this regard would require a better alignment of policy objectives.

6.4 Summary

This chapter set out to capture the main patterns of development directionality of the German BES-TIS. Moreover, it also attempted to identify potential drivers of these developments. This was done through a hermenutic TIS approach. Based on expert interviews, policy document analysis, and descriptive statistics, it identified central actors, networks, and institutions. It established a timeline of their interaction and development that led to the emerging of an early BES-TIS. Using innovation functions as a theoretical basis both as a heuristic device and as an ontological anchor allowed to make first assumptions about possible supporting and blocking mechanisms. A particular focus was on legitimacy-creation as a central function in innovation systems and how it was used to enable its emergence. In addition, this chapter adopted a policy mix approach to capture policy and innovation systems dynamics as holistically as possible.

This in-depth case study showed how the photovoltaic sector experiences were seen by many of the involved actors in companies that would later form the German BES-TIS as influential on their later decisions. While seen first as a future-proof sector, PV turned out to be a very scalable product. Thus, after the government faded out several supporting policies, most PV modules production moved to China, with larger economies of scale.

Besides few large-scale suppliers, most of Germany's first stationary battery storage producers were small or medium-sized companies—originating from either the automotive or PV industry—specializing in battery pack assembly and developing end-user products. They were mainly using battery cells from Chines or Korean electronics manufacturers. However, still influenced by the PV sector's experiences and still seeing Chinese competition as an external threat, interviewees claimed that the German TIS was affected by companies' early consolidation and their integration into larger energy or electronics companies. Most importantly, the energy transition and the consequential "intermittency problem" provided a way to create legitimacy for the emerging TIS, which likely provided the basis for experimentation, development, and diffusion of knowledge and resources.

This chapter identified a second still formative phase in the development of the German battery storage TIS that started around 2016 when German car markers started to engage with the field. The automotive sector—a cornerstone of the German economy—was in crisis due to the combustion engine running globally out of favor. Volkswagen's diesel scandal and increasing environmental regulation worldwide pushed automotive companies to invest substantially in electric vehicles. Although the German battery storage TIS was linked with the automotive sector before, after EV development and production capacities were ramped up, relevant attention from policy and industry shifted from stationary storage to EV. This shift in the public opinion provided another opportunity for the battery storage TIS to create legitimacy.

Taken together, the results from this chapter imply that previous contextual factors, such as historical industry composition, are of great importance. Moreover, they indicate the relevance of legitimacy for development in the formative stages of a TIS, thus agreeing with previous studies in this area. However, this chapter also shows that changing context structures, in turn, impacted legitimation, through which new meaning is made. The physical and infrastructural contextual factors initially assumed to be important appear mostly indirectly relevant to the development of the BES-TIS. For example, they seem to affect the economic potential for developing a domestic market. In turn, they can be seen as key guideposts for energy policy decisions, influencing BES diffusion. Furthermore, narratives about their state were used as anchors to provide legitimacy for or against the promotion and use of stationary battery storage.

The present study is one of the few empirical investigations specifically into battery energy storage in Germany with a TIS focus. While the results of this study provide first theoretical and practical insights, the short history of battery energy storage in Germany and the still volatile development make further research on this topic necessary. Although this chapter shows hermeneutically first connections, it cannot show stable causal relationships on its own. However, it allows first assumptions about these relationships in the sense of tendencies. Thus, it provides additional data points for the general TIS research and enables further research questions for future studies.

Chapter 7

Diffusion-Factors for Large-Scale Battery Storage

7.1 Introduction

The previous case studies of Germany and Austria show that (a) research and development expenditure, (b) public issue salience, and (c) policies are important influences on the diffusion of battery storage systems. Moreover, these case studies could already provide the first indication of potential mechanisms. However, the diffusion of new forms of electricity storage is global (IEA, 2019b). To do justice to these, many countries will now be examined together in a quantitative approach to identify common patterns there, irrespective of the local circumstances. Due to the data availability and to focus the analysis, this chapter focuses exclusively on large-scale battery storage (LSBS) in the following.

Generally, as a consequence of the accelerating diffusion of variable renewable energies (VRE) and other energy system changes, new flexibilities are needed to ensure a continuous and stable energy supply. There are currently various flexibility solutions available and under development (e.g., demand response, grid expansion (see Sterner and Thema, 2019; Ornetzeder et al., 2019). Among these flexibility providing technologies, energy storage is one of the most discussed solutions (Crabtree, 2015; Child et al., 2019).

Electricity storage promises security and decreasing electricity prices (Castagneto Gissey et al., 2019) and shows a whole range of possible applications in residential buildings, entire building blocks, industrial sites, utilities, or networks (Sterner et al., 2019c) with several potential business opportunities by decreasing volatility or aiding self-consumption of electricity (Mir Mohammadi Kooshknow and Davis, 2018; Castagneto Gissey et al., 2019). However, up until now, LSBS based on electrochemical batteries that are grid-connected and can potentially influence the energy system play no significant role for energy systems (IEA, 2019b).

In the industrial and large grid-side sectors, electricity storage systems provide grid stability, simplify use in production, and deliver high power at short notice while the system load remains constant (Schriever and Halstrup, 2018; Ornetzeder et al., 2019). Storage in residential houses also received significant attention in the consumer sector (Kairies et al., 2019), mainly because it is seen as a key enabler of a citizen-driven energy transition (Kloppenburg et al., 2019; Thomas et al., 2019; Koirala et al., 2018).

Besides, as national energy systems remain complex arrangements of various influencing factors, in-depth-country studies (as presented in chapters 5 and 6) remain central in designing policy mixes for managing energy transitions. However, while policy designs for specific country contexts are expected to be very effective (Magro and Wilson, 2019; Kern et al., 2019), they remain challenging to communicate across borders and make the setting of international standards a cumbersome process (see, e.g., van den Bergh et al., 2020, on carbon prices). Therefore, the following chapter will attempt to find commonalities about possible policies, drivers, and structural factors amongst several countries.

While first studies on diffusion within a national framework for small storage systems are published (e.g., Kairies et al., 2019), for the global diffusion of grid-connected storage technologies, this has only been descriptively empirically analyzed (see Buß et al., 2016) but—to the knowledge of the author—not yet using inference methods. Other studies, using patent-data, focused only on the innovation side (e.g., Fabrizio et al., 2017). Thus, there is a literature gap for studies on influencing factors on the diffusion of LSBS technologies.

Out of the country case studies of Austria (Chapter 5) and Germany (Chapter 6), two particular drivers for LSBS diffusion emerged. On the one hand, public issue salience and social factors as operators respond to public opinion and try to maintain their green and innovative image. On the other hand, some operators expect electricity storage to pay off economically in the future. In contrast, others remain skeptical, as the demand for flexibility at grid level—also due to the increasing VRE—will increase (e.g., shown by Schriever and Halstrup, 2018). The previous chapters also show that governments react with policy instruments such as increased RD&D spending to accelerate the diffusion of electricity storage.

Using econometric methods, in this chapter, I analyze potential drivers and structural factors affecting LSBS diffusion across countries, building on the preceding chapters. Public salience of environmental issues and public opinion towards innovative technologies influence LSBS diffusion is measured by a proxy using green voters' share. The results suggest that it is a driver for LSBS diffusion. Also, how structural factors in the energy mix influence LSBS diffusion is measured using shares of particular renewable technologies. The results show, surprisingly, some weak indication of a negative relation with LSBS diffusion. How increased RD&D spending on battery and energy storage technologies influences LSBS diffusion is also studied. Here, the results indicate a relationship between higher R&D expenditures for electricity storage and higher penetration of LSBS. This chapter's results suggest that LSBS diffusion is still in the early stages and not so much driven by current energy system demand but by further rationales of LSBS buying companies.

The chapter is structured as follows: after a few theoretical considerations on the nature of technology diffusion and technological innovation systems, the data are described, and preliminary descriptive results are presented. Then the results of the panel regression are described. First, the basic model and then the influence of social and structural factors and classical R&D measures are presented. Lastly, the results are compared with other studies and discussed within the broader question of the role of policy in the diffusion of LSBS.

7.2 Analytical Framework

Technology diffusion is the product of technological innovation and adoption (Comin and Mestieri, 2014). While both processes are heavily interlinked, they are still distinct as, e.g., even if innovation occurs in one country, it can be adopted in another and vice versa (further described in Chapter 2 and Bettin (2020)). There are differences in the diffusion process, depending on the type of technological innovation. For example, consumer products' diffusion shows different dynamics than for industrial goods (Day and Herbig, 1990; Herbig, 1991; Bianchi et al., 2017; Schiavone and Simoni, 2019). According to some studies, industrial products are considered to be less dependent on opinion leaders, as companies act more rationally and economically consciously (Day and Herbig, 1990).

Energy innovation and its diffusion is a particular case. Energy technologies take a long time to diffuse because they are particularly dependent on infrastructure and framework conditions (Verdolini et al., 2018; Gross et al., 2018; Popp et al., 2011). They are integrated into a socio-technical system, in which several factors must change for energy technologies to diffuse (Bettin, 2020). Renewable energy innovations, in particular, are considered especially societal beneficial and are supported by various policies. However, battery storage as an auxiliary technology for renewables is not unequivocally seen as such

(Ornetzeder et al., 2019).

The emergence of innovation and the changes in their technological trajectories can be studied by investigating technological innovation systems (TIS) that consist of networks of actors and institutions forming around a technology located at its center (Hekkert et al., 2007). They are self-reinforcing systems, in which processes reinforce each other in a cumulative causal process when a TIS develops (Bergek et al., 2008a). Moreover, diffusion processes differ between countries because of (if only slow changing) national and regional conditions (Fagerberg and Srholec, 2008). Due to the interconnectedness of the global innovation system, symmetrical global events such as a new iteration of an innovation affect the diffusion process in all countries equally. In this chapter, however, the aim is to go beyond these internal self-enforcing dynamics of innovation systems and investigate external factors that drive adoption.

7.2.1 Public Issue Salience

While utilities used some LSBS for technical reasons, the previous chapters suggest that decision-makers in companies are additionally influenced in their adoption decisions for LSBS by a green and innovative zeitgeist. Thus, the public salience of environmental issues possibly affects potential adopters' attitude towards new technology, as it also influences public opinion (Burstein, 2003), policy (Bromley-Trujillo and Poe, 2020), and increases the likelihood of an adoption-decision. As operator consortia of LSBS often have a partial involvement of the public sector, as typical for utilities (The World Bank, 2019), the importance of public opinions for decision-making is assumed to be particularly important.

However, this chapter must use proxies as there is currently insufficient data available—i.e., with many countries and longer time series to capture the public salience of green and innovation issues. One possible proxy—also used in this chapter—is the share of party votes in elections. In particular, research suggests that Green parties are generally congruent with their voters on environmental issues (Costello et al., 2021). Moreover, as other research notes (e.g., Vasseur, 2014; Carley and Miller, 2012), the presence of liberal politicians and environmental movement organizations is a driver for more renewable energy-friendly policies.

7.2.2 Energy Mix

Beyond societal factors, some structural factors are also currently transforming, such as the energy mix resulting from energy transition (IEA, 2019c). These changes lead to (i) more opportunities for the integration of new technologies such as LSBS and (ii) to potential larger demand for LSBS as they help reduce VRE risks and thereby provide security of energy provision (Child et al., 2019). These risks increase, in particular in the case of changes in the energy system because other market participants such as demanders and network operators have not yet been able to react adequately to the added VREs.

Overall, these risks are increasingly manifesting themselves in higher electricity prices (Davies et al., 2019; Hartner and Permoser, 2018; Castagneto Gissey et al., 2019) and higher spending on grid compensation measures (IEA, 2019b), although capacity markets still need to improve to accommodate storage better (Waterson, 2017). Two forms of VRE should be highlighted in particular, namely photovoltaic (PV) and wind energy. Wind energy is mainly organized in large projects and rarely on a small scale. Conversely, PV is found in large energy parks and small residential and commercial projects (IEA, 2019c). One can assume that energy systems with higher wind and PV energy shares show higher battery storage diffusion rates. However, some evidence suggests that wind electricity increases volatility on the macro scale, while solar electricity decreases volatility (Kyritsis et al., 2017).

7.2.3 Investment in Research, Development, and Demonstration

Investment in research, development, and demonstration (RD&D) is also an essential factor for innovation (Aghion et al., 2016; Acemoglu et al., 2016) and subsequent growth (Comin and Mestieri, 2014). Moreover, the salience of issues, public opinion, and structural factors drive investment decisions, and vice versa (Masini and Menichetti, 2013; Dasgupta and De Cian, 2018).

For energy storage, public R&D on innovation still has to be determined as the potential benefits have spillover effects to multiple sectors (Popp, 2019) as first evidence suggests that energy storage can bolster both renewable and conventional electricity (Lazkano et al., 2017). But first studies suggest that innovation policy can increase domestic innovation for energy storage (Fabrizio et al., 2017), which makes it potentially more competitive in the future (Kittner et al., 2017).

However, only a few countries focus a substantial amount of global R&D expenditures (Keller, 2004). As typically measured with patent data, changes in innovation do not automatically translate into increased diffusion of technological innovations (e.g., Lanjouw et al., 1998; Negro et al., 2012). Thus, the link between RD&D investment and the self-reinforcing technological innovation system and diffusion is only indirect.

7.2.4 Opposing Influences

To investigate possible opposing influences on LSBS diffusion, this chapter tests potentially explanatory variables for all three mentioned dimensions. This approach follows a political economy understanding that there are always winners and losers with every new development, such as due to technical innovations (Turnheim and Sovacool, 2019). These losers may likely be among incumbents who provide alternatives to the proposed LSBS. Many of these incumbents might have an interest in locking the development into the current status quo (see Seto et al. 2016 and also section 2.5). Examples include operators of gas-fired power plants, pumped hydro storage plants, and distribution grids (Gallo et al., 2016). Although they do not possess precisely the same technological properties and provide the same services as LSBS, e.g., because of slower reaction time (Sterner and Thema, 2019), this chapter will examine the influence of these technological alternatives on LSBS diffusion.

Other opponents may be found in political groups opposed to an energy transition that would require more storage. Votes, shares of parliament seats, or cabinet composition cabinets are therefore used as indicators to measure those.

7.3 Description of Data

For this chapter, I merged data on energy storage projects from three sources: first, from the globalstorageexchange, which is managed by Sandia National Laboratories on behalf of the United States Department of Energy (DoE, 2017; Hernández et al., 2016) and downloaded in 2020; second, data used in a recent report by the European Commission (2020a); third, data for Germany provided by the German Association of Energy Storage (BVES 2019). I checked all these entries for plausibility, adjusted them by desk research, and excluded redundancies. Every country-year pair with no new storage projects listed in the database was coded as zero. Treating for missing data, in the regression model, we introduce fixed effects to control for systematic gaps.

All storage projects built with electrochemical storage of kW >= 50 were aggregated on year and country-level from this new database. For the individual projects, partly different information was available for the construction. While only the announcement day was registered in some cases, in others, only the commissioning or the start of construction was noted. For many projects, however, all data was available. To standardize the entries,

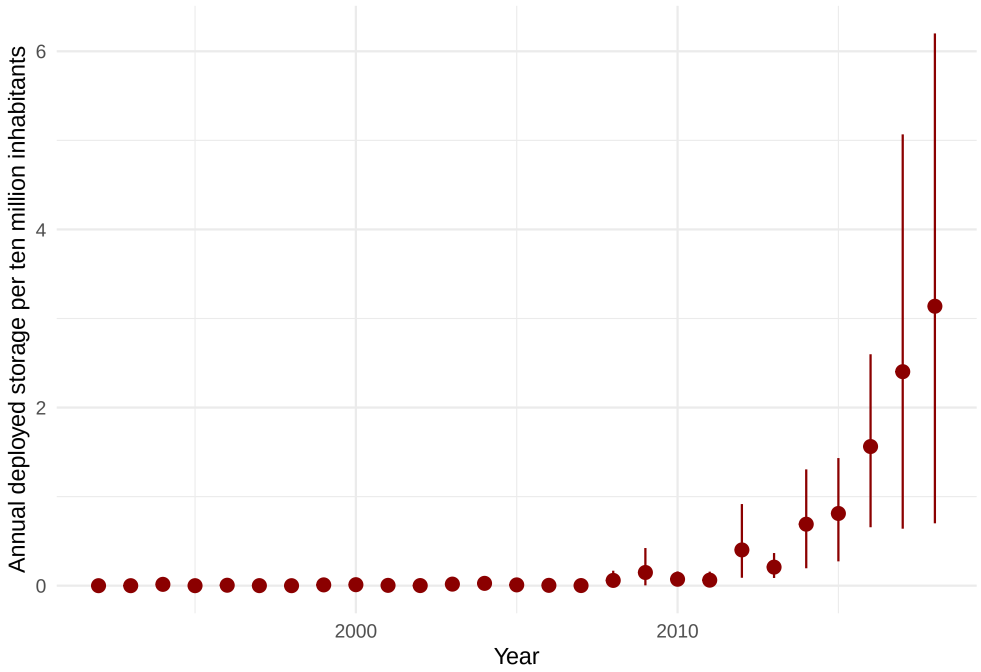


Figure 7.1: Heterogeneity of LSBS diffusion

commissioning was set as the decisive date for the energy stores. Using a linear regression with kW size as an independent variable, the missing date was estimated and imputed.

The index for new storage in the year-country panel was normalized to ten million inhabitants per country to ensure comparability. This standardization meant that some smaller countries had to be excluded from the analysis. These countries had very few and very small projects installed but were no longer comparable due to their small population. Only high-income countries (HIC) after the World Bank definition (World Bank, 2020a) were considered for this analysis. One notable exclusion of the focus on HICs is the Peoples Republic of China, which has several storage projects listed. Still, it only plays a minor role in the global country comparison due to its large population and the subsequently low standardized LSBS score. A complete list of countries is in the appendix.

Overall, the overview of LSBS diffusion in high-income countries (Figure 7.1) shows that the development has picked up speed globally, especially since the 2010s. This acceleration comes from the improvements in battery technological developments and falling prices for

Table 7.1: Descriptive statistics of used variables

	N	Mean	Std. dev.	Min.	25 %	Median	75 %	Max.
Delta LSBS	1,423	0.36	2.98	0.00	0.00	0.00	0.00	58.75
LSBS stock	1,188	1.17	6.20	0.00	0.00	0.00	0.00	123.15
Share of green voters	855	21.09	25.84	1.00	1.00	1.00	43.00	80.00
Battery storage RD&D	233	11.73	22.34	0.00	0.00	0.00	12.03	114.69
Electricity storage RD&D	244	16.74	29.62	0.00	0.00	0.00	24.11	145.46
Energy storage RD&D	575	26.47	39.94	0.00	0.33	10.24	35.35	230.32
Grid RD&D	579	78.71	314.05	0.00	1.29	27.06	74.43	3,873.19
Produced wind electricity	893	1,814.10	4,746.54	0.06	5.66	331.39	1,565.88	43,885.77
Produced solar electricity	891	1,375.92	3,984.81	0.05	1.42	145.99	996.42	33,566.79

lithium-ion cells (Davies et al., 2019). However, there is heterogeneity in diffusion patterns across years but also a clear upward trend.

Table 1 presents the variables I use in this chapter. Next to the change in LSBS normalized per million inhabitants with the use of World Bank (2020b) data (Delta LSBS) and the cumulated LSBS normalized per million inhabitants that makes the stock of LSBS (LSBS stock), I used several independent variables. First, I used election data from the CPDS (Armingeon et al., 2019) for the share of green voters. Second, I used IEA (2019a) data on investment expenditure in research, development, and demonstration (RD&D) for battery storage, electricity storage, and energy storage, as well as the share of grid RD&D investment of the overall energy technology RD&D expenditures. Third, I applied global data on the production of electricity from wind and PV (IEA, 2019d).

7.4 Panel Regression Results

7.4.1 Baseline Regression Analysis

The following section presents the base model for the analysis in this chapter. According to technological innovation system (TIS) literature, as described above, various endogenous dynamics occur along the lines of so-called innovation functions (Hekkert et al., 2007; Bergek et al., 2008a). Here, 'virtuous cycles' of cumulative causation drive the innovation system to develop evolutionarily around specific products and technologies.

This chapter aims to unravel factors where policy and structural factors can influence (e.g., accelerate or dampen) these dynamics beyond the endogenous cycles. Therefore, the following models control for these endogenous activities. This builds on the so-called Bass diffusion model (Bass, 1969) that attempts to forecast and estimate future diffusion of (end-user) technologies (see also Mahajan et al., 1995). It is one of the most cited works in business economics and marketing and got further developed for various specific cases (Kim and Hong, 2015).

However, for this chapter, a simple baseline Bass model suffices as the regression models applied in this chapter are not for future diffusion curves but rather an analytic tool to uncover dynamics of the past diffusion of LSBS. The starting point is the Bass model that estimates the magnitude of effects of innovation and network effects of imitation. Equation 7.1 shows a Bass-model for which an S-curve is assumed that displays an initial slow uptake of an innovation until it reaches a turning point after which a faster diffusion is assumed.

$$y_t = pm + (q - p)\, Y_{i,t} - \frac{q}{m}(Y_{i,t})^2 \tag{7.1}$$

Here y is the change in LSBS diffusion, q is the coefficient of internal influence (innovation), p is the coefficient of external influence (imitation), m the market potential, Y the cumulated diffusion of the technology, and Y^2 the cumulated diffusion of the technology squared.

For this chapter, I omit the detailed imitation and innovation coefficients and reduce the model to equation 7.2. As the information on newly connected LSBS projects is aggregated to a yearly level, I take Y as $StockLSBS$ and Y^2 as $StockLSBS^2$ with a lag of one year.

$$DeltaLSBS_t = a + b * StockLSBS_{i,t-1} + c * {StockSBS_{i,t-1}}^2 \tag{7.2}$$

In this chapter, I am interested in variables that vary over time. Thus, stable country characteristics are excluded. I assume a correlation between the country error term and predictor variables. This is why I control for entity effects by keeping them fixed only to assess the predictor variables' net effect on the outcome variables. Also, we are not concerned with time effects when special events coincide across all countries. Therefore, I control for time-effects that introduce unexpected variations. I am using a two-way fixed effects (FE) regression model 7.3, i.e., with time and entity fixed effects to eliminate omitted variable bias from unobserved variables that are constant over time and unobserved variables across countries (Stock and Watson, 2015, p. 369ff.). In equation 7.3, β is the predictor variable and $u_{i,t}$ is the error term.

$$y_{it} = \beta x_{i,t} + CountryEffect_i + TimeEffect_t + u_{i,t} \tag{7.3}$$

This equation 7.2 is extended to the base model to control for the endogenous dynamics within the innovation system. We omit the a from 7.2 as an intercept will not be used in an FE regression model. The final base model 7.4 is a Bass-model-inspired two-way FE panel regression model to capture policies and structural changes on a global scale on the diffusion of LSBS technologies beyond country-specific technological innovation systems dynamics.

$$DeltaLSBS_{it} = b{*}StockLSBS_{i,t-1} + c{*}StockLSBS^2_{i,t-1} + \beta x_{i,t} + CountryEffect_i + TimeEffect_t + u_{i,t} \tag{7.4}$$

For the estimation, heteroscedasticity corrected and robust standard error (HC 1 as conventionally used in STATA) and serial correlation corrected (following Beck and Katz, 1995; Zeileis, 2004) was used.

Table 7.2: Base panel regression model (FE)

	1992-2018
$StockLSBS_{t-1}$	0.074
	$(-0.188, 0.336)$
${StockLSBS_{t-1}}^2$	0.009^{***}
	(0.003, 0.015)
Years	24-27
Countries	53
Time FE	YES
Country FE	YES
N	1,423
R^2	0.258
Adjusted R^2	0.214
F Statistic	233.188^{***} (df = 2; 1342)

$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$

Table 7.2 shows the basic model. The presented basic structure shows that with an adjusted $R^2 = .214$, the influence factor $StockLSBS_{t-1}$ is not but the ${StockLSBS_{t-1}}^2$ predictive for the adoption of LSBS. Although exhaustive lag structures were analyzed for this chapter, the presented models show only two types of time lags of the tested β. First, no lag—with $t = 0$—where it is assumed that this independent variable's outcome was already known beforehand. Second, β with a lag of $t - 2$, which is the point in time we are assuming the decision to adopt LSBS took place.

7.4.2 Public Issue Salience

The results in table 7.3 show how the impacts of the public salience of environmental issues by the proxy share of green voters on LSBS diffusion. The more people vote for green parties the more LSBS projects are adopted. For 33 countries, this influence on the dissemination can be modeled. The model shows (Table 7.3) that an adjusted $R^2 = .282$ shows a positive effect of the share of green voters at the time of decision with $p < .05$.

Table 7.3: Share of green voters and green party seats in parliament on LSBS diffusion

	Delta LSBS	
$StockLSBS_{t-1}$	0.297	0.307
	(−0.123, 0.717)	(−0.124, 0.738)
${StockLSBS_{t-1}}^2$	0.007*	0.007*
	(−0.0004, 0.015)	(−0.001, 0.015)
$VoteGreen_{t-2}$	0.023***	
	(0.006, 0.039)	
$SeatsGreen_{t-2}$		0.008
		(−0.132, 0.147)
Years	24-25	24-25
Countries	33	33
Time FE	YES	YES
Country FE	YES	YES
N	822	822
R^2	0.333	0.322
Adjusted R^2	0.282	0.269
F Statistic (df = 3; 762)	127.092***	120.366***

*p < .1; **p < .05; ***p < .01

This relationship suggests that decisionmakers in LSBS-adopting organizations are influenced at the time of the decision $t - 2$ by salient issues in the population. One possible motivation for decisionmakers to adhere to these salient themes is to make an innovative and sustainable impression on employees and funding agencies. Moreover, through the often-given direct involvement of the public sector in the projects, it is also likely that influence on decisionmakers is exercised of this route.

Indeed, another possible explanation for the correlation found above is that it is not so much the salience of green issues in the population but much more the political influence of green parties crucial for more LSBS diffusion. Moreover, there is a presumption that this influence is more considerable in state systems with proportional representation. Thus, it is possible that “governments set stricter environmental policies under proportional, as opposed to majoritarian, systems” (Fredriksson and Millimet, 2004).

Table 7.4: Share of green party seats in parliament and type of electoral system on LSBS diffusion

	New Storage	
	Green Seats	Interaction
Y_{t-1}	0.307	0.320
	(−0.124, 0.738)	(−0.110, 0.750)
${Y_{t-1}}^2$	0.007*	0.007*
	(−0.001, 0.015)	(−0.001, 0.014)
$SeatsGreen_{t-2}$	0.008	1.173
	(−0.132, 0.147)	(−1.281, 3.628)
$ElectoralSystem$		−1.625
		(−3.664, 0.413)
$InteractionMajoritarian$		−1.125**
		(−2.245, −0.005)
$InteractionProportional$		−1.209
		(−3.665, 1.247)
$InteractionMixed$		−1.052
		(−3.517, 1.414)
T	24-25	23-25
Countries	33	33
Time FE	YES	YES
Country FE	YES	YES
N	822	821
R^2	0.322	0.327
Adjusted R^2	0.269	0.271
F Statistic	120.366*** (df = 3; 762)	52.562*** (df = 7; 757)

*p < .1; **p < .05; ***p < .01

Here, to check for this alternative explanation is a control for green votes’ influence in the following figure (Table 7.4). However, the results show that the relationship cannot be represented by the direct political influence of green parliamentarians. There is no significant relationship between the seats of green politicians in parliament and LSBS-diffusion, regardless of the political system. These results strengthen the above results with green votes as a proxy for the public salience of green issues. Thus, the present results support the initial findings of qualitative studies for Austria and Germany (Chapters 5 and 6), stressing the importance of salient green issues.

7.4.3 Energy Mix

I also investigate structural factors in the energy system that potentially explain the demand for LSBS. One goal is to see if there is, at present, demand for energy storage from the energy market due to a demand for flexibility. Therefore, the levels of both PV and wind electricity are investigated. Also, I consider potential alternative flexibility measures in the energy system. Due to the highly skewed nature of the data, I log-transform the data on wind and PV production levels normalized for inhabitant via $log(1 + x)$. Because I assume that the amount of planned electricity generation, which will be available when the project is finished, the independent variable are $t = 0$ in this section.

Table 7.5 shows an overview of the estimated impact of electricity generation changes from both PV and wind to the baseline on the diffusion of LSBS. At the same time, the endogenous effects of the technological innovation systems are controlled for. As can be seen, in the estimated model, wind electricity shows no significant positive effect on LSBS diffusion. Surprisingly, a significant negative effect of $p < 0.05$ with an adjusted $R^2 = .192$ could be found. Nevertheless, in a robustness check with an alternative specification considering only LSBS with a capacity $> 500kW$, this result could not be confirmed (Appendix, Table A.2). Using growth-rates of wind or solar-PV electricity, no effect on LSBS diffusion could be measured (Appendix A)

While technology-wise LSBS does not provide the same technologic services for the grid as other flexibility measures such as pumped hydro storage (PHS) and electricity out of gas,

Table 7.5: Influence of log(1+x) wind and solar electricity at adoption point on LSBS diffusion

	Delta LSBS	
	Prod Wind	Prod Solar
$StockLSBS_{t-1}$	0.063	0.044
	(−0.236, 0.363)	(−0.254, 0.341)
${StockLSBS_{t-1}}^2$	0.009***	0.009***
	(0.003, 0.015)	(0.003, 0.015)
$ProdWind_t$	−0.076	
	(−0.300, 0.149)	
$ProdSolar_t$		−0.171**
		(−0.317, −0.025)
Years	18	17-18
Countries	47	47
Time FE	YES	YES
Country FE	YES	YES
N	893	891
R^2	0.246	0.253
Adjusted R^2	0.185	0.192
F Statistic	89.870*** (df = 3; 825)	92.739*** (df = 3; 823)

*p < .1; **p < .05; ***p < .01

they are nonetheless considered in public debates as potential substitutes for each other. Therefore, the impact of these technologies on the diffusion of LSBS was modeled (Table 7.6). The results show that-controlling for the LSBS-technological innovation system-and applying again HC1 robust estimates, no significant effect on LSBS diffusion could be found. Those results confirm the hypothesis that these flexibility measures fulfill different functions within the energy systems.

7.4.4 Investment in Research, Development, and Demonstration

The following section sheds light on the question of how policies promote the diffusion of LSBS projects. Here, the first sets of analyses examine the impact of RD&D expenditure in capita on storage and battery technologies on LSBS diffusion. Due to the right-skewed

Table 7.6: Influence of log(1+x) potential flexibility alternatives at adoption time on LSBS diffusion

	Delta LSBS	
	PHS decision	Gas decision
$StockLSBS_{t-1}$	0.188	0.064
	$(-0.265, 0.640)$	$(-0.247, 0.376)$
${StockLSBS_{t-1}}^2$	0.008^{*}	0.009^{***}
	$(-0.0004, 0.016)$	$(0.002, 0.015)$
$PumpedHydro_t$	-0.041	
	$(-0.845, 0.764)$	
Gas_t		0.031
		$(-0.616, 0.679)$
Years	19	18-19
Countries	30	47
Time FE	YES	YES
Country FE	YES	YES
N	570	887
R^2	0.280	0.241
Adjusted R^2	0.211	0.179
F Statistic	67.303^{***} (df = 3; 519)	86.793^{***} (df = 3; 819)

$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$

nature of the expenditure distributions and because relative changes are of main interest, I log-transform the variable via $log(1 + x)$. Again, the analysis focuses on RD&D expenditure's impacts at the time of the investment decision for the new LSBS at (t-2).

We test for three different RD&D investment measures that potentially influence LSBS diffusion directly. (A) investments in battery technology in general, (B) investments in electricity storage technologies, and (C) investment in all energy storage technologies.

The results show (Table 7.7), with an adjusted $R^2 = 0.155$, more RD&D investment in electricity storage correlate with an increase of LSBS at $p < 0.05$ and show an estimated percentage change of .023 from baseline.

While the causal relationship between RD&D expenditure for electricity storage and LSBS diffusion may seem obvious, results must be taken with caution as it is also likely that parts of the expenditure will be for other storage technologies (e.g., small-scale residential

Table 7.7: Influence of different kinds of research and development expenditures log(x+1) on LSBS diffusion

		Delta LSBS	
	Battery RDD	El. Storage RDD	Energy Storage RDD
$StockLSBS_{t-1}$	1.237^{***}	1.209^{***}	0.101
	(0.447, 2.027)	(0.505, 1.913)	(−0.314, 0.516)
${StockLSBS_{t-1}}^2$	-0.009^{*}	-0.009^{*}	0.009^{***}
	(−0.020, 0.002)	(−0.019, 0.001)	(0.003, 0.015)
$BatteryRDD_{t-2}$	0.828		
	(−0.286, 1.943)		
$ElstoRDD_{t-2}$		1.023^{**}	
		(0.166, 1.880)	
$EnstoRDD_{t-2}$			0.101
			(−0.291, 0.492)
Years	1-23	2-23	2-25
Countries	24	25	28
Time FE	YES	YES	YES
Country FE	YES	YES	YES
N	212	222	535
R^2	0.333	0.350	0.261
Adjusted R^2	0.125	0.155	0.178
F Statistic	26.744^{***} (df = 3; 161)	30.463^{***} (df = 3; 170)	56.475^{***} (df = 3; 480)

$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$

storage). However, as there are several other applications for batteries, e.g., in cars, or several other forms of energy storage, e.g., heat storage, the insignificant results for battery RD&D and energy storage RD&D investment are not surprising as their impact on LSBS is not necessarily direct.

Also, for this chapter, typical incentives for renewables such as guaranteed feed-in tariffs were tested. Neither their height nor their guaranteed length had any impact on LSBS diffusion (see Appendix A).

7.4.5 Comparison of Influencing Factors

To compare the effect size of the analyzed factors in this chapter, Table 7.8 presents selected policies and structural demand factors, for which this chapter could establish significant relations. Here, I standardize the variables and make the strength of the effect and thus the relative importance of the factors β on different dimensions tentatively comparable. Their unit is standard deviations.

Table 7.8: Comparison of influencing factors with standardized betas

	Delta LSBS			
	Public Salience	Energy Mix	RDD Invest	All
$StockLSBS_{t-1}$	0.538	0.081	2.019***	1.989***
	$(-0.228, 1.304)$	$(-0.471, 0.632)$	$(0.522, 3.515)$	$(0.624, 3.355)$
$StockLSBS_{t-1}{}^2$	1.108*	1.419***	-0.928	-0.761
	$(-0.033, 2.249)$	$(0.475, 2.364)$	$(-2.617, 0.761)$	$(-2.300, 0.779)$
$VoteGreen_{t-2}$	0.190***			0.666**
	$(0.050, 0.329)$			$(0.035, 1.297)$
$SolarProd_t$		-0.176^{**}		-0.149
		$(-0.327, -0.026)$		$(-0.838, 0.540)$
$ElstoRDD_{t-2}$			0.133	0.452*
			$(-0.395, 0.661)$	$(-0.087, 0.990)$
Years	24-27	18-19	2-23	2-18
Countries	33	47	25	24
Time FE	YES	YES	YES	YES
Country FE	YES	YES	YES	YES
N	875	891	244	188
R^2	0.334	0.253	0.347	0.375
Adjusted R^2	0.285	0.192	0.165	0.172
F Statistic	136.201***	92.739***	33.665***	16.948***
	(df = 3; 813)	(df = 3; 823)	(df = 3; 190)	(df = 5; 141)

$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$

While the different included populations n make comparison difficult, the comparison shows that the effect size of public issue salience, with green votes as a proxy, is .19 standard deviations. In comparison, this is slightly larger than the estimated effect size of .13 standard deviations for the percentage changes in RD&D expenditure to the baseline.

Both are reasonably effective. In contrast, the negative effect of percentage changes in PV-levels from the baseline with an effect size of $-.176$ standard deviations shows the comparable impact of the energy mix on LSBS diffusion.

However, the overview with the standardized betas teaches more about the goodness of fit of the results. For example, no significant relationship could be found between the standardized research expenditures on electric storage and the standardized LSBS spread without resorting to untrustworthy measures. This suggests that the variance in either is too large that the standardized beta becomes imprecise.

However, informative results are the other results in the model "all" in which the three subject areas and their relationship with LSBS diffusion are considered together. These results show $p < 0.05$ significant relation to the public issue salience proxy green votes and electricity storage RD&D investment with $p < 0.1$. However, the energy system through PV electricity is not significant. The overall model now confirms the strength of the influence of the green votes proxy on the diffusion of LSBS so far.

7.5 Discussion of Results

This section discusses the several influencing factors on LSBS diffusion. From previous qualitative in-depth case studies from Austria and Germany (chapters 5 and 6), we suspected two main influences: the public appearance of the adopting organizations and economic viability due to the energy system. Also, in some countries, governments introduced innovation policies to accelerate storage diffusion. This section argues that this chapter's results using quantitative methods for a larger sample of countries support the qualitative in-depth case studies' results for Austria and Germany.

The comparison of significant influences indicates that economic drivers that have to do with the energy system and, thus, the operators' core business are equally crucial to other social factors. Their importance can be explained by mimicry behavior (Rodrigues and Child, 2008; Greenwood et al., 2002) and band-wagon effects (Abrahamson, 1991; Abrahamson and Rosenkopf, 1993) in the economic decision making.

7.5.1 Public Issue Salience

Public issue salience is an essential driver for policy adoption (Bromley-Trujillo and Poe, 2020; Burstein, 2003). One of the aims this chapter set out with was assessing the importance of the salient environmental issues on the diffusion of LSBS. As the previous qualitative studies for single countries have shown (see Chapters 5 and 6), there is the first indication that this has been a crucial driver for LSBS diffusion and a primary motive for adopters. This reasoning aligns with the classic technology diffusion theory of Rogers (2003).

The presented results demonstrate a relationship between the share of green voters—which was used as a proxy for a general attitude towards as green perceived technologies following Costello et al. (2021)—and the adoption of LSBS. However, this analysis works under the assumption that environmentally concerned people tend to see energy storage as an environmentally beneficial technology. In discourses, these perceptions of energy storage tend to be constructed as innovative and green in media outlets (Ganowski and Rowlands, 2020; Bakaki et al., 2019) and by intermediary actors in polycentric arrangements (Devine-Wright et al., 2017).

Previous studies did not find a systematic relationship between policies and citizens' preference for renewable energy policies (Stadelmann-Steffen and Eder, 2020), which is justified with negligible literacy of the broad public of energy issues (Brounen et al., 2013; Stadelmann-Steffen and Dermont, 2018). However, based on this chapter's results, there is the first indication that adopters of LSBS react to public opinion and use their adoption to appear innovative and green publicly and follow the zeitgeist.

7.5.2 Energy Mix

Energy storage in general and LSBS, in particular, were often publicly considered as a possible solution towards an increasing demand due to increasing VRE in the overall energy mix, which destabilizes the energy system (Crabtree, 2015; IEA, 2017a). Thus, there is potentially an economic demand for storage due to increasing renewables and their demand for flexibility measures (Child et al., 2019). Before 2010 it was mostly lead-acid, nickel/cadmium, sodium/sulfur, and vanadium-redox flow batteries that dominated the market (Doughty et al., 2010), but recently lithium-ion batteries began taking over. Consequently, at least in the future, battery storage is expected to yield economic benefits (Davies et al., 2019).

Besides, the types of energy storage systems studied in this chapter were medium and large projects. Therefore, it could be assumed that the diffusion of wind energy has a more extensive influence on the diffusion of LSBS than PV. In contrast to the results of Hartner and Permose (2018), I could not establish a positive relation between PV diffusion and storage. Nonetheless, the evidence of this chapter that shows a negative relationship between changes in the level of PV and LSBS diffusion is in line with Kyritsis et al. (2017) who suggest solar electricity decreases volatility and therefore reduces the need for storage.

For the overall energy system, Zerrahn et al. (2018) show that electricity storage is vital for renewable energy transition but that other measures such as curtailment still play a role and that even in high renewable diffusion scenarios, storage demand is limited. The results of this chapter, empirically, tentatively suggest a relationship between changes in the levels of PV and LSBS diffusion, but a negative one.

7.5.3 Investment in Research, Development, and Demonstration

Commonly quantifiable measures for policies such as technology-push policies (R&D expenditure) and technology demand policies such as feed-in tariffs do not seem to influence the diffusion of LSBS yet overall. While technology demand policies seem to influence renewables' diffusion in general (Carley et al., 2017), the relationship with auxiliary technologies such as LSBS is not clear. However, as technology-push policies such as R&D expenditure are only drivers in a few countries (see Keller, 2004), their influence is not yet wholly determined in this analysis and needs to be further researched.

Moreover, this study was able to establish a relationship between additional RD&D expenditure in electricity storage technologies and LSBS diffusion. The results are not surprising since higher research expenditures tend to increase the probability of demonstration projects. However, as the comparison made clear, the results are of lower quality than for public issue salience. Therefore, more far-reaching implications for policy, in general, can only be determined to a limited extent.

Overall, policies are still quite heterogeneous and difficult to compare across many countries. Thus, singling out one measure for a policy, e.g. RD&D expenditure, can only capture part of the picture. Moreover, the policy mix literature indicates that bundles of policies usually influence a particular objective, such as diffusing renewable energies (Rogge and Reichardt, 2016). Therefore, grasping the overall policy mix quantitatively to test LSBS diffusion's impact remains an open task.

7.5.4 Opposing Influences

Besides the influences that are likely to induce diffusion, this chapter considered further factors. In all three dimensions, (1) public issue salience, (2) energy mix, and (3) investment in RD&D, this chapter examined opposing factors, which represented incumbent technological alternatives or presumably opposing political groupings, in addition to the more likely diffusion-promoting influences.

Nevertheless, the results in 7.4 did not show any influence of these alternatives and opposing factors. Thus, for (1) voting results, parliamentary seats, and cabinet composition from other political parties, we could not find any influence on LSBS diffusion. The same was true for (2) energy mix. Moreover, there was no evidence that changes in alternative flexibility technologies such as gas and pumped hydro storage power plants impacted LSBS diffusion. Investments in flexibility alternatives such as energy grids (3) were also not found to be related to LSBS diffusion.

Based on these results, we cannot conclude that these factors do not influence LSBS diffusion. This is due to the nature of the statistical modeling in this chapter. As soon as these explanatory variables do not contain significant changes, the influences are absorbed by fixed effects. However, these fixed effects are necessary to explain this data set adequately. Therefore, the chapter falls short of making any causal statements about opposing factors. While we found no effect for them, the findings cannot exclude them either.

7.6 Summary of Appendix

The appendix (section A.2) provides an overview of the included countries and the total diffused kW of large-scale battery storage. In addition, there are robust checks of an alternative specification of the dependent variable in which only storage systems $>= 500kW$ were considered. The results of this alternative specification show the robustness of the public issue salience and RD&D expenditure results. However, in the alternative specification, it is clear that the energy system results, i.e., PV electricity is negatively related to LSBS penetration, are no longer significant.

7.7 Summary

In this chapter, a Bass (1969) inspired panel regression model with time and country fixed effects was formulated to analyze on a global scale how social factors such as salient environmental issues, structural factors in the energy system, and R&D policies influence the diffusion of large-scale battery storage.

First, it finds that public salience of environmental issues positively affects the diffusion of large-scale battery storage technologies. These results align with the previous chapters' other results in which identified appearing green and innovative as a driving force current adoption of battery storage technologies. Second, it also finds that the state and changes towards a sustainable energy transition do not positively influence the diffusion of large-scale battery projects. While wind-electricity showed no effect at all, PV electricity even had a negative effect. It could also not establish any systematic relationship between potential substitute flexibility options such as pumped hydro storage or electricity from gas. Third, classical innovation policies such as expenditures in RD&D as technology-push policies showed some positive effect on large-scale battery storage diffusion. Conversely, commonly used technology pull policies for renewable energies such as guaranteed feed-in tariffs had no effect.

The presented results highlight the importance of social factors such as public issue salience and indicate that public perceptions and possibly bandwagon effects play an essential role in diffusing early-stage experimental technologies such as large-scale battery storage. Moreover, at this point, these technologies do not play a substantial role in the overall energy system, implying that in most countries, no feedback effects from battery storage on the energy sector are observable.

Chapter 8

Discussion

In this discussion chapter, the various topical threads that ran through this dissertation on diffusion and development directionality of battery energy storage (BES) technologies are now considered together. The central results, which emerged from the three empirical Chapters 5 & 6 and 7, are discussed jointly. These results are reviewed considering the scientific literature and theoretical approaches highlighted in Chapter 2. This chapter starts with synthesizing the two case studies of the BES-technological innovation systems (BES-TIS) in Austria and Germany. Next, the special case of large-scale storage diffusion analyzed quantitatively and on a global scale in preceding chapters is discussed in light of the findings from the two (qualitative) country case studies. The chapter concludes with a brief discussion on implications for policy design and directionality and closes with some concluding remarks.

8.1 Case Studies of Technological Innovation System Development

This section discusses the two case studies on the BES-TIS development in Austria and Germany together. It starts with a brief reflection on the used methodological approach in Subsection 8.1.1. Then, in Subsection 8.1.2 it attempts to explain what influenced the BES-TIS development in these cases and how. Following, in Section 8.1.3, it discusses the dynamics between BES-TIS and policy mix. Last, in Subsection 8.1.4 it compares these results to other TIS literature.

8.1.1 Methodological Approach

The following subsection briefly reviews the methodological approach on which the conclusions from the two case studies are based. Thus, the first part briefly discusses the ontological and epistemological foundations and their application. Following, the second part briefly discusses how this thesis dealt with the spatial limitations that arose from the use of national case studies, even though technological innovation systems in principle do not have to be restricted to such boundaries.

The main research question in this thesis asks *what influenced dynamics of development and diffusion of stationary battery energy storage, and how.* Dynamics are first of all defined as "the way in which people or things behave and react to each other in a particular situation" (Def, according to Oxford's dictionary). In this definition alone, causality is implied. The second part of the main research question asks even more specifically about causality, namely "how" (unnamed) factors influenced these dynamics.

As illustrated in section 3.2, this thesis assumes, based on critical realism, that there is a real-world in which mechanisms prevail that we regard as tendencies. These mechanisms stem from less stable relationships between social (and natural) entities. However, we as researchers can never see the mechanisms directly. We only see the actualized results of these mechanisms in our observable world. While we are particularly interested in these mechanisms that reveal causalities, we can only reason about them theoretically based on observed regularities and then try to isolate these mechanisms. Especially when we are dealing with the social world, isolation is usually not possible.

Furthermore, language plays a central role and can even directly influence a particular dynamic, which is why we place *generative hermeneutics* next to *generative mechanisms*. Combining both makes it possible to try to identify tendencies of social happening based on social structures, which are partly based on opinions, values, and acts. Nevertheless, the conclusions that result from analyses like the one used in this thesis have to be taken with more caution than from other analyses that can isolate causality more clearly. For this reason, the results obtained in the case studies, which rely heavily on hermeneutic methods, are not written in a causal language.

Another caveat regarding the usefulness and generalizability of the case study results is that they use national borders as spatial and system boundaries. These boundaries also constrain the ability to look at the entire TIS. As explained in subsection 3.3.2.1, these limitations are common in current TIS research. Thus, only parts of a system are analyzed that usually connect to other systems, e.g., a global innovation system. Since TISs are open systems, other levels in the sense of a laminated ontology are always to be considered in an analysis anyway.

8.1.2 Technological Innovation System Dynamics

It is helpful to describe the development of a TIS based on different phases, which the following stylized synthesis of the observed TIS dynamics in both countries also does. Dynamics and mechanisms are highlighted, which the case studies of both countries particularly emphasize. The findings result from a hermeneutic process, which also drew on theory, and represent initial assumptions about actualized tendencies that may also be found in other TIS. The phases are, firstly, a pre-phase that established the background, secondly, an initial development phase, and, thirdly, changes in context. A graphical overview is in Figure 8.1

8.1.2.1 Pre-Phase Background

The results of the case studies suggest that the background in both countries was critical for later BES-TIS development. It consisted of several firms with already available **knowledge** and capabilities, such as companies that supplied integrated renewable energy technologies or home automation products. Moreover other **context structures** already emerged. Vital were neighboring sectors such as the PV or automotive sectors and perexisting (scientific) knowledge in research institutes. In addition, infrastructure set-ups and geography that shaped the outline of the electricity system already existed.

8.1.2.2 Initial Phase of BES-TIS Development

In the first initial phase of the TIS development, some firms with pre-existing **knowledge** and capabilities began moving with some of their activities into the emerging BES-TIS. Moreover, qualified individuals from the PV and automotive sectors founded new storage-related companies by themselves or joined spin-offs from established companies of these neighboring sectors (**human resources**).

The evidence from the case studies suggests that these firms now engaged in the TIS began **legitimizing** their **entrepreneurial experimentation** to receive primarily public but also private **financial resources**. One way how **legitimation** occurred was by portraying battery storage as a solution to the so-called "intermittency problem," which was considered publicly to be a significant roadblock for the energy transition. This focus on balancing electricity supply and demand also influenced the **search direction**. In ad-

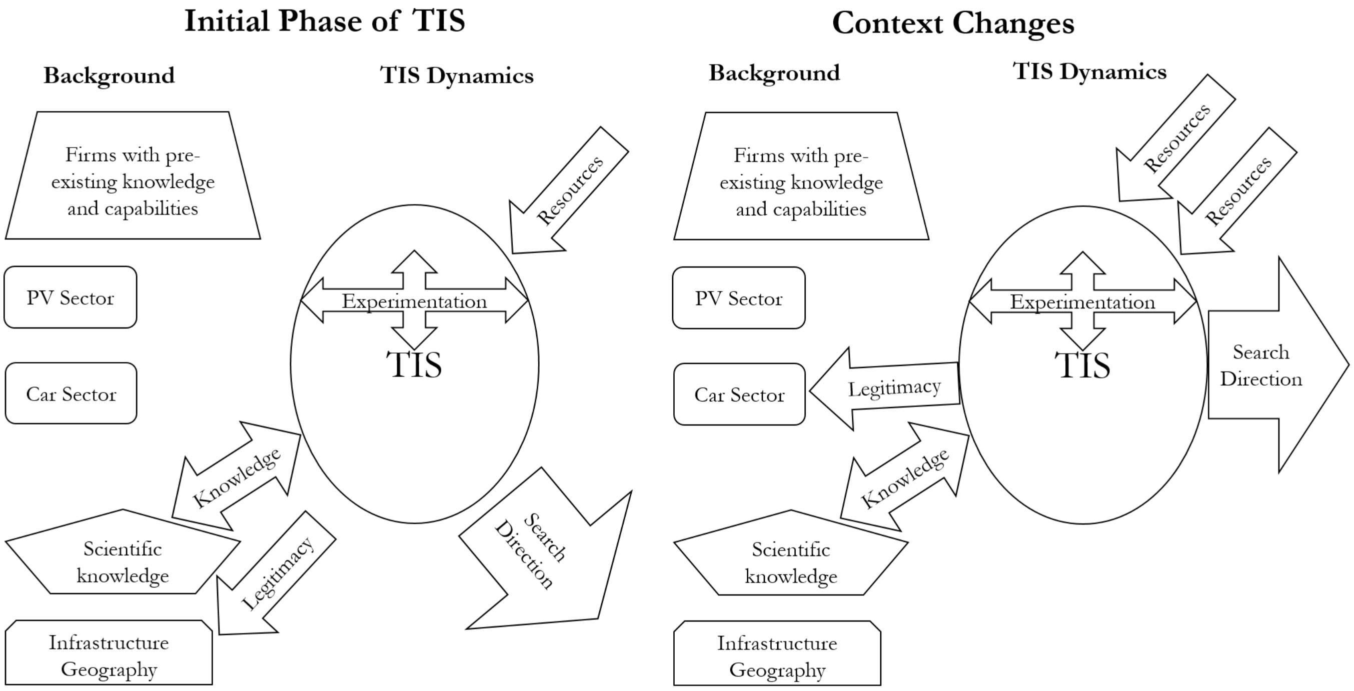


Figure 8.1: Stylized illustration of the background, the initial development phase of the battery energy technology innovation systems, and the phase shift due to context changes.

dition, this phase saw the creation of practical **knowledge** in firms and public research institutes. The case studies provide evidence that there was **knowledge diffusion** through joined projects and the hiring of graduates.

However, this study could not find evidence for substantial, continuous, and self-sustaining demand for stationary battery storage systems in the **domestic markets**. Thus, home storage systems were usually not economically viable for households and remained niche products for enthusiasts. Moreover, industrial batteries and battery power plants were primarily installed in demonstration projects, and interviews suggested that there were mostly learning and showcasing motives behind it. Mentioned reasons for the lack of market-driven demand were the low electricity prices, readily available other flexibility options, and non-existent flexibility **markets**.

8.1.2.3 Changes in Context of the BES-TIS

The importance of **contextual factors** for the TIS development became particularly visible in the German BES-TIS case study. Here, the results suggest that the 2016 "diesel-scandal" in which prominent car markers such as *Volkswagen* were involved changed the neighboring car sector. As carmakers shifted towards electric vehicles, they also focused more on battery systems.

The interviews suggested that these changes in the context structures allowed formerly predominantly stationary BES-focused firms to **legitimize** their activities by shifting from the intermittency problem to EV as central vehicles for "meaning-making" (Van Leeuwen, 2007) and as the main "hook" for **legitimation**. Also, within the TIS, it appears that this led to a change in **search direction** resulting in a shift in **knowledge creation** and **experimentation** that moved towards batteries for electric vehicles. At the same time, public **financial resources** did the same.

8.1.3 Policy Mix - Technological Innovation System Dynamics

One topic that ran through all chapters of this thesis is the impact of different policies on the diffusion speed and development direction of BES, on which this subsection focuses. This includes different types of policies that were decided on multiple governance levels. For example, these can be different levels, such as the European, national or regional level, and technical decisions by regulatory authorities, laws by governments, or semi-state actors' initiatives. The impact of these policies can vary greatly from region to region and from sector to sector. While classical innovation research primarily focused on the rule-setting aspect and the provision of basic research (Schot and Kanger, 2018), recent studies recognize the steering effect of government action through, for example, targeted applied funding and research (Foray, 2019; Mazzucato, 2018) or the state acting as a buyer of technologies (Edquist and Zabala-Iturriagagoitia, 2012).

For these reasons, the policy-mix approach, which is gaining popularity in sustainable transition studies (Kern et al., 2019), appears to have been a suitable conceptual framework for the two case studies of Austria and Germany (Chapters 5 and 6). It enabled focusing on the variety of different policies and brought clarity into their complexity. Although some studies using a quantitative policy-mix approach have been conducted (e.g., Schmidt and Sewerin, 2019), it is predominantly used in qualitative research.

Consequently, this thesis established that comprehensive policy mixes affected BES in both Austria and Germany. Moreover, there were legacy policies designed for entirely different purposes that also shaped the development of the BES-TIS. From the policy mix perspective, several TIS blocking mechanisms were caused by regulatory factors, indicating inconsistencies between elements of the policy mix. However, while potentially unconducive for BES diffusion, the incumbent regulatory design might have been advantageous for other policy objectes, e.g., by relying primarily on grid expansion and other more centralized solutions.

8.1.3.1 Pre-Phase Background

It seems that in the pre-phase, which formed the later background for the TIS development, several policies were crucial for shaping the **context**. These were economic pull elements that created a demand for renewable energies, technology push elements that addressed **financial resources** for RD&D, and systemic regulation that formed the basis for own consumption of renewable energies and later storage markets.

All these policy elements and the appearing strategies emphasized that the governments committed to strengthening renewables in the future. In Austria, even more decidedly with the thematization of future storage needs. Both influenced later **search direction** and **legitimation** attempts.

8.1.3.2 Initial Development Phase

In the initial phase of the TIS, a whole set of policy measures, and thus an entire policy mix, emerged, some of which were coordinated and interrelated.

On the one hand, there were many technology push measures through RD&D policies for storage projects and economic pull policies to create **market** demand, which probably provided **resource** and **knowledge development** and **diffusion**.

On the other hand, systemic regulations increased storage demand, many of which came from the EU level. Overall, however, energy policies had the objective of making the entire power system work. Thereby, they often favored more centralized solutions. In the sense of the whole system, these policies set regulatory limits to an unrestrained storage**market**. The guiding policy strategies also reflected all of this, likely influencing the **search direction**.

The shift in the German BES-TIS is reflected in the policy mix. National RD&D measures were now increasingly focused on the topic of automotive batteries, thereby reinforcing the shift in **search direction**. This shift has also been implemented at the EU level through information policy elements and strategy papers on battery promotion.

8.1.4 Comparison

Comparing the synthesized results from the two case studies on BES-TIS development in Austria and Germany with the scientific literature on the life cycle of TIS, it is striking that many of the results of this thesis coincide with the findings there. However, it must be clear that the results of this thesis do not include information on each of these dimensions and that undiscovered dynamics may nevertheless exist.

This subsection attempts now to compare the BES-TIS development with other literature. First, in Subsection 8.1.4.1, by positioning the current state of development of the BES-TIS within a stylized developmental progressions of a theoretical TIS. Second, in Subsection 8.1.4.2, by comparing the BES-TIS with other renewable energy TIS.

8.1.4.1 The Life Cycle of BES-TIS in Comparison to Others

In an excellent review of the different life cycle phases in a TIS—which also includes findings from the industry and technology life cycle literature—Markard (2020) emphasizes not only the differences in TIS development in itself but also the changing interactions between the focal TIS and context structures that differ among the phases. This life cycle concept, which is briefly summarized below, sees two phases of (1) formative and (2) growth and two phases of (3) maturation and (4) decline. The former two appear relevant for this thesis' case studies and are used to position the latest stage of BES-TIS development.

Stylized Formative Phase

In this stylized version, the formative stage has a few actors, almost no scales, who mainly receive public R&D funding. Moreover, informal and cognitive institutions such as collective expectations and frames are vital for TIS development. The actors still have competing ideas, and a variety of technological designs exists.

Most importantly, in Markard's (2020) conceptualization of the formative phase, the TIS depends on **context structures** unidirectional. These **context factors** provide **resources** and **guidance** but also constrain development (see also Bergek et al., 2015). But TIS actors manage these relationships with the **context** actively and adapt to it by **creating legitimacy**, for example, by framing their technology as a solution to neighboring sectors' problems. Moreover, they build linkages to other TIS actors, research institutions, and financiers. From all this comes some form of guidance of the **search direction**. However, this guidance is not necessarily straightforward. It is more likely that actors will **experiment** with functions and possible applications of their technology.

Stylized Growth Phase

In the stylized growth phase, the TIS shows high growth, high entry rates of actors, and increasing sales volumes that remain below the market potential (Markard, 2020). Moreover, a critical mass of actors performing different roles in the innovation system shows increasing levels of specialization. Also, technology associations and standardization committees, and other intermediaries appear, and a conflict over which (technical) standards to use occurs. Consequently, the technology diversity declines. Overall, this phase can be described by higher institutional structuration.

As the TIS grows, linkages with **context structures** multiply. These ties can be in the form of emerging producer supplier relations that connect the TIS with neighboring sectors and complementary TIS. However, this can also lead to new conflicts with said **context structures**. Overall, the context relations become bi-directional, and their TIS starts to influence its surrounding.

The BES-TIS Between the Stylized Phases

The comparison of the case study results of the latest BES-TIS development with the theoretical phases of Markard (2020) shows that a transition perspective, i.e., with a focus on systemic change, can usually only be carried out with some certainty after the events have occurred. Since these phases also do not have clear-cut boundaries but are instead characterized by fluid transitions, a classification into these stylized development phases is all the more difficult to perform. Hence, the following conjectures should rather be seen as a speculative attempt of classification than a definitive one with a high degree of certainty.

As the overview in table 8.1 shows, it can be assumed based on the rough synthesis of the two case studies that the BES-TIS can be majorly classified as being in the formative phase but also showing signs of the growth phase in some dimensions.

Concerning the size & actor base dimension, there is evidence that the BES-TISs in

Table 8.1: Comparison of Theoretical TIS Phases on Markard (2020) with BES-TIS Case Study Results. As it was outside the scope of this thesis, the dimension "technology performance & variation" was left out of the comparison.

Analytical Dimensions	**Formative Phase**	**Growth Phase**	**Latest Development Phase of BES-TIS**
Size & actor base	Sales close to zero; little growth; small number of actors; high degree of vertical integration; low entry/exit rates	Sales are moderate at first but grow rapidly; medium to large number of actors in different roles; specific associations & intermediaries emerge; high entry rates; strong competition and struggles over standards	Sales seem small to moderate for all BES-types; a medium number of actors in different roles; intermediaries such as interest groups, standardization committees, and trade fairs exist; high entry and exit rates; strong competition; no data on struggles over standards
Institutional structure & networks	Low structuration; high degree of uncertainty; cognitive institutions central; loose networks, incomplete value chains	Increasing structure; markets take shape; technology-specific institutions emerge; increasing formalization; collaboration in networks	Low structuration in BES-TIS; high degree of uncertainty; cognitive institutions such as shared frames and legitimization attempts important, increasing formalization; collaboration in networks
Context & TIS-context relationship	TIS depends on context and adapts to it; first ties emerge	Ties to context multiply and formalize; TIS has increasing impact on context; potential conflicts arise; co-dependence	BES-TIS appear to depend heavily on context and adapt to its changes; multiple ties to context exist and multiplied

their latest stage of development were between the formative and the growth phase. While the sales tended to be small to medium, there was a medium amount of actors. In addition, as is more typical for the growth phase, there were already a few central intermediaries. In addition, there were high entry and exit rates and strong competition.

Regarding the institutional structure & networks, the BES-TIS so far show signs of both phases. Characteristically formative phase, there was low structuration and evidence of high uncertainty in the BES-TIS. In addition, cognitive institutions and legitimation approaches seem to have been central and had a high degree of variety. Typical for the growth phase, there was an increasing collaboration in formalized networks.

Concerning context & TIS-context relationship, the results showed the BES-TIS as having been very dependent on context structures, which suggests a categorization in the formative phase. However, there were signs of early conflicts with context structures over the role of storage in the energy system. These emerging frictions are the first indications of emerging bidirectional relationships, suggesting the growth phase.

In summary, the BES-TISs in their latest stages of development in the Austria and Germany case studies showed signs that can be categorized as mainly belonging to the formative while also showing signs of the growth phase. However, a more precise classification and final assessment can only be made as an ex-post evaluation in a few years.

8.1.4.2 BES-TIS in Comparison with Other Renewable Energy TIS

A starting point of this thesis was Markard's (2018b) conjecture about the next phase of the energy transition, which highlighted that researchers should review technologies like battery storage differently from renewable energy such as wind and photovoltaic. As explained again in Chapter 4, energy storage in general and stationary battery storage in particular are, in the context of a sustainable energy transition, auxiliary technologies that are supposed to enable the diffusion of other renewables, thereby being a solution to the "intermittency problem" by providing flexibility. Thus, this subsection briefly discusses how BES-TIS results compare to past renewable energy TIS developments for the three topics (a) policy, (b) context structures, (c) and legitimation.

Policy

As it turns out, the differences between the BES-TIS development in Austria and Germany and earlier PV or wind-technology TIS developments in similar European countries, as briefly reviewed in section 2.5.1, are relatively marginal.

In those countries, the studies showed that demand-supporting regulation and public finance were essential for the initial development of the TIS. However, if this then declines, it can sometimes stop the development of TIS again (see, e.g., in the case of the German PV sector (Quitzow, 2015)). For BES-TIS, we see both public RD&D funding and demand support, which were necessary, as battery storage use has only been financially viable in a few use cases in domestic markets. So far, therefore, we can rather consternate a typical TIS development in BES-TIS.

Moreover, the results from the case studies suggest that there was a connection via the legitimation issue to how state support can be mobilized for research and technology development. Findings in both countries give first indication to the assumption that government support was vital for kick-starting TIS formation. First, because governments were among the key financers of early technology research, and second, they were able to reform regulatory frameworks to the (dis)advantage of emerging technologies. These conclusions align with the recent shift in innovation studies that emphasize governments' central role for innovation (Mazzucato, 2015; Foray, 2019).

In both countries, stationary power storage was seen as a "perfect" solution where one does something good for the energy transition and at the same time creates a new industry that enables jobs and profits. This approach, which is also reflected in the overall policy mix of both countries, ecological modernization, seeks to reconcile economic growth with ecological constraints (Hovardas, 2016).

Context Structures

The analysis suggests that pre-existing context structures, such as production infrastructure in firms, knowledge capacity in both firms and research institutes, and networks among different firms, customers, and regulators, facilitated BES-TIS formation. These findings supports the theory that pre-existing sector configurations and overall set-up of the innovation system are critical determinants of TIS development (Suurs et al., 2010; Stephan et al., 2017). Moreover, engaging with battery storage technologies was a logical next step in their business development strategy for many firms. Even though their previous ventures in the PV sector were declining, they were well connected and had tacit domain knowledge in the renewable energies sector, indicating a clear development trajectory (see, e.g., Dosi and Nelson, 2018).

There are first indications that the TIS shifts due to context shifts. In the case of Germany, it thus seems likely that stationary BES will move with battery storage for e-vehicles in one "development block" (Dahmén, 1989; Haley, 2018). This influence of the—for the national economy—important automotive sector gives another indication for the interlinkages between different national, sectoral, and technological innovation systems (Bergek et al., 2015). Moreover, it re-affirms the ontological understanding of TISs as layered systems as argued in Section 3.2. The importance of contextual structures that partly, in some cases, predated the emerging BES-TIS, such as other sectors and research institutions, can also be shown for different renewable energies TIS developments.

Moreover, country-specific contextual factors such as geography, prevalent energy system design, and demand conditions appear relevant to further TIS development in both countries. However, the evidence suggest that this is not because these factors signified a direct demand in the national markets for BES in the case studies. As such, the connection seems to be rather indirect. In both countries, market demand for BES was fostered by firms, who have invested in legitimacy creation to advance BES as a critical technology for the energy system transition.

Legitimation

As argued above, part of the significance of context structures is that actors can use them to generate legitimacy for new technologies, products, and companies. However, opposing actors, e.g., incumbents, who try to delegitimize certain activities, use context structures and derived discourses to "anchor" their meaning-making attempts. So, it is not without a certain irony that the legitimacy of energy storage as a solution to the "intermittency problem" seems to be derived from de-legitimization attempts of PV and wind energy opponents, as the results of this thesis suggest. Consequently, according to this view, energy storage is a solution to the legitimacy problem of other renewables. Of course, it also derives part of its legitimacy from its supposed contribution to the energy transition.

Regarding the role of legitimacy-creation for TIS development, this study contributes to a growing body of literature stressing the relative importance of legitimacy creation (Bergek et al., 2008b; Markard et al., 2016). Both young and long-existing firms involved in the BES-TIS seem to have "created meaning" for their activities and products by justifying their existence (Van Leeuwen, 2007) and thereby legitimacy. There is an indication that central to this was the influence of energy transition discourses. In particular, while the supposed shortage of energy storage was long considered an argument against renewables (see intermittency problem in, e.g., Zöphel et al., 2018), the political will to transition to renewables now provided a basis for legitimacy creation of BES by BES firms.

Next to the energy transition discourse that permeates many societal discourses (see, e.g., Buschmann and Oels, 2019), the studies found that some firms and other proponents created legitimation in various distinct ways. They did this by stressing “green security and autonomy,” which references the issue of energy autonomy (McKenna, 2018), by stressing the importance of “electric vehicles” and referencing German discourses about the future of the automotive sector (Held et al., 2018; Mögele and Rau, 2020). Other legitimation is related to discourses of regionalization (Suitner and Ecker, 2020; Späth and Rohracher, 2010), security (Scrase and Smith, 2009), and the “coolness” of (Silicon Valley) technology (Kohlenberger, 2015). However, these results do not represent the entire spectrum but are distinct examples as other forms to legitimize energy storage likely exist.

Some other TIS studies for renewable technologies such as wind and PV have tried to capture legitimacy in a very different and detailed way, e.g., via quantitative indicators like the number of brochures or the outcome of surveys on technologies (see, Section 2.2.3) However, this thesis’ qualitative approach allowed to consider a variety of legitimacy approaches simultaneously.

The concluded results show that besides the legitimacy of storage industries from an industry growth perspective, which this thesis did not consider in-depth, a wavering of legitimacy anchors prevails. For example, as with other value-driven technologies, the link to the *Energiewende* does not appear to be quite as direct as the focus shift in Germany, due to the rise of electric vehicles, indicates. And so, the BES development shares rather several characteristics with the TIS development of other (consumer) technologies, which have less of a societal value-focus. These indicate that the BES-TIS development might be different from other renewables TIS cases. However, other TIS studies on renewable energies chose different research approaches and did often not look as in-depth as this thesis did. Therefore, this conclusion has to be treated as being highly speculative.

8.2 Diffusion of Technological Innovation

Chapter 7 moved away from stable contextual factors such as geography and economic systems and considered changing energy systems, societies, and policies as possible influences on diffusion. By using quantitative methods, instead of just two country cases, it included several high-income countries—according to the definition of the World Bank (2020a)—together. In contrast to the Chapters 5 and 6, which focused upon the entire technological innovation system with development and diffusion, this chapter only concentrated on diffusion. Also, instead of including several types of stationary battery storage technology, it addressed only the topic of large-scale battery storage (LSBS) facilities due to data limitations. It investigated a time period from 1992 to 2018. The next section thus attempts to combine the results from all three empirical chapters, first in subsection 8.2.1 by discussing the necessary methodological challenges that occurred while mixing qualitative and quantitative results, second, in subsection 8.2.2, by comparing the empirical results.

8.2.1 Methodological Considerations

This brief subsection reiterates the underlying methodological considerations related to comparing the qualitative country case study results on LSBS diffusion with the quantitative cross-country results. One of the reasons for this was the declared goal to apply both qualitative and quantitative methods in this dissertation.

As already stated in section 3.2, critical realism is a valuable philosophy of science foundation for both qualitative case studies and quantitative regression research. For instance, regressions are not to be understood as a model (as a whole or only partially) approximating a general law (Ron, 2002). Instead, they aim at interpreting mechanisms that cannot be detected by the data alone. Likewise, qualitative research can primarily see the first signs of potential mechanisms and must also rely on hermeneutic explanations, especially in the study of social systems (Durdovic, 2018).

Integrating the very different study results was neither entirely possible nor planned. Thus, the mixing process of the methods happened first on the design level. Therefore, this thesis does not contain a complete triangulation but a bridging of the parts via the contents. Both components of the study were developed in parallel, but with selected interaction.

The overlap in content worked best where the same research object was concerned: the diffusion of LSBS. However, LSBS appears only on the margins in the case studies of Austria and Germany. Nevertheless, some evidence for the current state could be obtained from interviewee statements and secondary data. Such interviewee claims also served as a starting point for focusing the quantitative research on the selected influencing variables. Furthermore, the results also allow for general comparison because a TIS' other innovation functions influence the diffusion of technologies functions, as the TIS research shows (see, Section 2.2.3). Unfortunately, the LSBS diffusion results could not be compared with a similar study on home storage, as there were insufficient data for this.

8.2.2 Comparison of Qualitative and Quantitative Results

The fixed-effects model eliminated country-specific static factors (e.g., geography or stable set-ups of the economic system) and elements that changed simultaneously in all countries (e.g., technological developments or the global financial crisis) in the sample. This subsection discusses the focused topics innovation policy, energy mix, public issues salience and legitimacy, and the rationality of firms.

Innovation Policy and Resources

As a first finding, the econometric analysis suggests a positive correlation between the national level of LSBS diffusion and the level of RD&D expenditures for electricity storage systems. This confirms earlier research results emphasizing the role of supply-push policies in the policy mix for TIS development (Carley et al., 2017; Albrecht et al., 2015).

The findings of qualitative case studies in Germany and Austria support this observation. For example, many research and demonstration projects in both countries were primarily funded publicly, many of which also focused on LSBS projects. Although some interviews suggested that these investments would have occurred anyway, the results indicate that public funding for RD&D expenditures was supportive of the diffusion of LSBS.

Surprisingly, the quantitative analysis did not yield findings in support of the positive effect of demand-pull policies (e.g., guaranteed feed-in tariffs). While no comparable research was, to the author's knowledge, carried out on LSBS diffusion, the insignificance of demand-pull policies uncovered in this study, could not confirm findings from other renewable energy technology studies. These show a significant positive effect of feed-in tariff guarantees for PV and wind-based energy technologies, as, most likely, the guarantee reduces investment (adoption) risk (Alizada, 2018; OECD, 2020).

There is also something to be said about the results of the qualitative studies on demand-pull policies. In both countries, there were direct subsidies for LSBS of commercial operators, which interviewees saw as drivers of diffusion. Regarding the influence of guaranteed feed-in tariffs on LSBS, there were only unclear results from the case studies so far. For example, some (e.g., a PV and storage lobby association) said feed-in tariffs increased PV deployment and storage use. In contrast, others (e.g., a storage lobby association) said that high feed-in tariffs reduced the incentive for self-consumption and storage. Future studies will have to show if any of these effects prevail.

Energy Mix

The following result from Chapter 7 might explain why no significant pull-policy effect was recorded: no positive correlation was found between LSBS diffusion and changes in national electricity mixes (higher share of renewables, or other flexibility solutions, such as gas-fired power plants or pumped storage power plant). In fact, the study found a weak negative relationship between PV electricity share and LSBS diffusion. One possible interpretation of this result is that there has been no unmet demand for flexibility services from the grid and energy systems. While a small share of LSBS continued to be used for frequency holding, other applications such as holding control energy or offering other services were not yet in high enough demand to explain LSBS diffusion (Sterner et al., 2019a; Zöphel et al., 2018). The low prices for flexibility services show that demand today has been relatively negligible in particular in Europe (Gaudard and Madani, 2019) and to a lesser extent in the US (Sakti et al., 2018). Conversely, the magnitude of future demand is uncertain (Sterner et al., 2019a; Child et al., 2019). Thus, investing in BES today is likely strongly linked to positive future demand expectations rather than current demand.

For Germany, but especially for Austria, the qualitative country case studies showed no increased demand for LSBS resulting from the current conditions of the energy mix. One reason for this was sufficient flexibility capacities available through grids, gas plants, pumped storage power plants, and system inertia. Low market prices for balancing energy also reflected these ample capacities. While some LSBS projects claimed to operate commercially, it seems reasonable to assume that they did fail to do so yet. However, this study uncovered a range of expectations for the future energy system, some of which suggested that such LSBS storage projects will become more worthwhile in the future.

Public Issue Salience and Legitimacy

It seems that, for their current operations, there is no direct economic advantage in large companies and utilities acquiring storage facilities yet. However, the reasons given in the case studies provide a possible explanation. For Austria, there was the example of a large utility using LSBS in projects because everyone else was supposedly doing the same. For Germany, some interviewees shared the observation that many companies were interested in keeping their balancing groups as small as possible to supply themselves with green electricity.

The results from the quantitative study provide the first confirmation for these observations. A key finding is that the prevalence of publicly salient environmental issues likely influenced the diffusion speed of LSBS. The proxy votes for green parties tested for alternative explanations, measured for this green issue's public salience.

Here again, as mentioned above, the role of legitimacy and salient societal issues come into play. As discussed, actors used visions of the future that relate to those issues. They attached themselves to relevant discourses to create meaning by justifying their existence and activities, create trust, and generate legitimacy for their product and company (Markard et al., 2016; Bergek et al., 2008b).

Firms and Rationality

According to some mainstream economic theory, commercial decision-makers are usually behaving differently from households: They are assumed to make more calculated decisions based on cost-benefit rationale (Day and Herbig, 1990).

However, another explanation for this is that firms show a mimicry behavior towards societal zeitgeists and institutions (see, e.g., Rodrigues and Child, 2008). This suggests that firms' economic rationale goes beyond simple cost-benefit decisions. More and more evidence has emerged suggesting that herd behavior, narratives, and public discourse also matter for entrepreneurial decision making, especially in financial markets (Shiller, 2017) (reminiscent of Keynes' (1936) animal spirits).

The qualitative results from the country case studies show that firms acquired LSBS was for reasons such as the need to learn and showcasing. Thus, their rationale was not exclusively a matter of deriving economic benefits directly in the present, but instead of investing in one's knowledge stock and future. Another major reason seems to be the marketing of a "green" and "innovative" image. In this case, it makes sense for the firms to correspond to a zeitgeist, which keeps them attractive for employees, investors, and customers.

Overall, the findings presented in this chapter have to be interpreted with caution, as the focus on LSBS facilities essentially limits the analysis to commercial applications of BES, for either industry, grid providers, energy providers, or services for a multitude of users at once (see Chapter 4). Simply put, households do not constitute a potential adopter group for LSBS. While there is reason to assume that influences that act on commercial BES adopters affect households too, this cannot be inferred from this quantitative analysis.

8.3 Some Implications for Policy Design and Directionality

We can assume that there is no single correct path for the energy transition. Which path is selected, how relevant policy measures and regulations are designed, is the result of ongoing social and political debate and power struggle (Jessop, 2008). The remaining contradictions between policy elements illustrate this. Both case studies in Chapters 5 and 6 presented results emphasizing the importance of other economic interests and industrial policy's influence on the BES policy mix. In the process, the actors attempted, at least rhetorically, to link these economic interests with higher socially relevant interests, such as climate protection. Thereby ‘doing good business while saving the world.’

However, a central critique towards the innovation policy as currently commonly practiced is that “innovation is whatever happens to emerge from incumbent structures of interest, privilege and power in prevailing innovation systems” (Genus and Stirling, 2018, p. 62). However, the extent to which a supposedly innovative solution is a new approach to solving societal challenges or merely a disguise for conventional approaches is not always immediately apparent.

On the one hand, industrial policy wants to provide a testbed to showcase the BES technology, aiming to scale up exports. On the other hand, the use of BES for the domestic energy system is limited. In Austria and Germany, other flexibility solutions (grid expansion, curtailment, demand-response, etc.) might be equally or more useful as they can, for example, be economically more viable. A policy conflict ensues.

Another aspect is the temporal nature of policies and their effects that sometimes materialize only years after their implementation. In addition to legacy policies, whose unintended consequences cast their long shadows years after circumstances have completely changed, this is also exemplified by infrastructures and slowly evolved social structures. Thus, regional (Cooke et al., 1997; Doloreux and Parto, 2005) and also national innovation systems (Lundvall, 1992; Godin, 2009; Cirillo et al., 2019) have a long history and can only be changed at great expense. However, they also benefit from previous decisions that have led to the emergence of assemblages of, for example, firms and research institutions that share trust and implicit knowledge amongst each other (Mattes et al., 2015; Cooke et al., 1998). These cannot merely be replicated and are unique in their form and place (Polanyi, 1958). Thus, BES technology innovation shows path dependency and historical contingency (David, 1985; Faber and Proops, 1989), suggesting a long time horizon similar to other energy technologies (Gross et al., 2018).

This aspect of struggle shows that technologies such as battery storage are the scene of social power struggles, whereby values are inscribed in these technologies (Gailing, 2016). Conversely, the long time horizon of such political decisions highlights policymakers' limited information due to the complexity involved. Both these challenges of energy technology policy illustrate the relevance of scientific fields such as technology assessment. A field that emphasizes reflexivity in decision making (Grunwald, 2018, chap. 4) by anticipating the unintended consequences and subsequent social and environmental costs of technology in the face of uncertain futures. One way of doing this is introducing other values and rationalities beyond techno-economic considerations, which tend to dominate political discourse (Schot and Kanger, 2018). Therefore, proponents of technology assessment call for the inclusion of different stakeholders and laypeople in the assessment process to include more diverse perspectives and types of knowledge (Grunwald, 2018; Gudowsky and Peissl, 2016; Nentwich, 2017). It points out alternatives for innovation policy to keep options open (Collingridge, 1980). Moreover, these practices extend beyond policymaking, for example, fostering public dialogue and democratizing technology making (Grunwald, 2018, chap. 4).

8.4 Concluding Remarks

This thesis went through an entire cycle of analyzing innovation and diffusion of battery energy storage technologies. Many firm-level factors, such as firm infrastructure and existing knowledge, seem to influence the development of battery storage. Infrastructural factors, such as the domestic electricity system's current composition, likely affect the development and diffusion mostly indirectly by legitimizing firms' activities concerning expected futures. Thus, from this thesis' result, we can conclude that public salience of environmental issues was likely a key influencing factor for large-scale battery storage diffusion, as the international results from high-income countries indicate. It appears to be also a critical influencing factor for developing battery storage solutions, as the in-depth country studies show.

Many of these contextual structures blocking battery energy storage diffusion are slow to change by means of policy measures (e.g., power plant mix, grid infrastructure, or technical demand-side capabilities). Others can be changed more quickly through interventions such as (guided) research funding and market regulations. For example, one solution is to incentivize flexibility provision by creating markets for more kinds of operating reserves while penalizing carbon-intensive flexibility options such as gas through a carbon tax. However, as stated, several hindering regulations are there for a reason, i.e., to aid a different (conflicting) policy target such as financial burden-sharing in maintaining grid infrastructure, where storage operators quickly become free-riders. Therefore, a holistic view and an opening of the technology assessment and the policymaking process are needed. Moreover, most crucially, the policy design process for energy transition needs to align industrial and innovation policy with further societal issues, requiring broad societal discussion.

Chapter 9

Summarizing Conclusion and Outlook

This concluding chapter starts with a review of the results and the fulfillment of the thesis' objective. Then, it reflects on this thesis' contribution(s) to the literature. Next, it briefly summarizes its limitations and closes by suggesting a future research agenda.

9.1 Fulfillment of the Thesis' Objective

This thesis set out to find *influencing factors on the dynamics of stationary battery storage systems' diffusion and development direction*. It entails an intensive literature review, a brief technical review on stationary battery storage, a qualitative country case study of the development and diffusion of all kinds of battery energy storage technologies in Austria, and a similar country case study in Germany. This thesis used a theoretical framework based on the technological innovation system (TIS), and policy mix (PM) approaches to identify development phases. In addition, it included a quantitative large-N chapter on the diffusion of large-scale battery storage (LSBS) in high-income countries. Therefore, it had a narrower object focus but covered more countries. In this thesis, three sub-research questions were examined more intensively around the topics of (1) context structures, (2) legitimation, and (3) policy. This section briefly summarizes the central aspects of these results.

9.1.1 Context Structures

The first sub-research question asked *how context structures such as geography, infrastructure, and national economy influenced the development and diffusion of stationary battery storage systems.* It thereby highlighted influences that came from outside the focal TIS around stationary battery storage (BES-TIS).

Technological Innovation System The results of the case studies suggest that various context structures influenced the BES-TIS differently in its development phases. First, even before the focal TIS emerged, specific context structures laid the groundwork. They provided the necessary background for the BES-TIS' emergence, such as production infrastructure in firms, knowledge capacity in both firms and research institutes, and networks between firms, customers, and regulators. In the case studies, the neighboring sectors PV and automotive were critical, from which later spin-offs and startups formed and employees were recruited.

At the beginning of the formative phase of the BES-TIS, these relations to said context structures remained particularly close and the influence unidirectional from the context to the BES-TIS. They remained a source of human and financial resources as well as knowledge diffusion and creation.

Other physical contextual structures—e.g., physical infrastructure—were already influencing the creation of domestic markets for stationary energy storage at this early development stage. This indirect influence on the market creation function (diffusion) of the BES-TIS was even more indirect for spatial elements such as geography and nature, which influenced the state of the energy infrastructure. However, a central function of these physical context structures was that they serve as an "anchor point" of legitimation for the BES-TIS. Thus, they were critical influences on the search direction.

The relevance of context structures for the development of the BES-TIS to date became apparent when they changed. As the—for the national economy important—automotive sector suddenly began a transformation process towards electric cars, it also affected the development of the BES-TIS on several levels. We can interpret this as a shift in the search direction, which influenced the orientation of publicly funded research programs and thus knowledge development. This change could be seen in first firm exits towards "batteries for cars" and the promotion of new business models that promote stationary storage in connection with EVs. Thus, the BES-TIS started to influence other sectors gradually, especially the automotive sector. Some researchers suggested that such bi-directional relationships are signs of growth phases of TIS development.

LSBS Diffusion For the specific case of LSBS diffusion, the results from the two **qualitative country case studies** suggest that in both countries, infrastructure, physical conditions, and the current electricity mix have not yet created a particular demand for LSBS. Thus, according to the assessment of stakeholders, there seems to be sufficient flexibility capacity in the form of grids, thermal power plants, and pumped hydropower plants, which explains why market prices for balancing measures remained low. However, deploying LSBS seems to make sense for some actors. These LSBS using projects seem to be primarily for learning and showcasing purposes. In addition, this study suggests that many of those actors expect the physical context structures and the energy mix to change so radically due to the energy transition that LSBS facilities will become economically viable in the future. Thus, physical context structures already have an impact through their expected future state.

The results of the **quantitative large-N study** are consistent with the qualitative results, despite the much higher number of countries included. For these high-income countries, no positive correlation could be found between LSBS diffusion and changes in the national electricity mix (e.g., a higher share of renewables, but also alternative flexibility options such as gas power and pumped hydro storage). In fact, the case study found a weakly correlated negative relationship between PV electricity share and LSBs diffusion, i.e., the higher the PV share, the lower was the LSBS diffusion. Other research suggesting that PV, contrary to commonly assumed, has a stabilizing impact on the electricity system may explain this finding. Overall, however, this thesis could not find evidence for LSBS storage demand from the energy system at this point, which suggests that there was no substantial unmet market demand for flexibility that existing flexibility solutions did not cover.

9.1.2 Legitimation and Public Issue Salience

The second sub-research question asked *how the legitimacy for the development and use of stationary battery storage was created, and how it influenced the innovation system's development*. It thereby focused on the social context and how actors referred to salient public issues for legitimation.

Technological Innovation System The **qualitative country case studies** indicated that a central "anchor point" for creating legitimacy lay in the aforementioned context structures. One central mechanism through which contextual factors influenced the development of new products and the establishment of new companies is that they provided an anchor for legitimation. Evidence suggests that opponents of the energy transition used the alleged "intermittency problem" to de-legitimize the energy transition. According to this view, the unstable generation of PV and wind electricity would make base-load capable caloric power plants further necessary. This resulting supposed need for energy storage established a basis on which the first actors of the newly forming TIS legitimized the demand for their products. In the same way were also financial resources and knowledge creation activities legitimized.

Thus, one interpretation is that the context structures were not directly responsible for the legitimation attempts but the associated discourses and associated salient public issues. Next to the intermittency issue, actors used additional energy transition-related discourses and connecting points to create legitimacy for energy storage, a phenomenon which other research claimed to be typical for still forming TISs. Observed examples were "regionalization", "green energy security", and the "coolness" of technological innovations. Many of these issues related to the energy system's future design and showed first signs of frictions and conflicts with the prevailing context structures; other research sees this as a sign for the beginning of the growth phase of a TIS.

The evidence from the case studies suggests that relevant new emerging public issues and discourses can also have substantial influence on TIS legitimation. In the observed cases, the moment a central context structure such as the automotive sector began transforming, the rising importance of electric vehicles became a central "legitimacy anchor" for TIS actors. It influenced how policy actors justified RD&D spending for battery research and how TIS actors legitimized their demand for stationary battery storage.

LSBS Diffusion The results of the **qualitative country case studies** suggest that at least in the two countries studied, no broader market demand for LSBS emerged to date, as the demand for flexibility remained sufficiently met. However, one of the case studies suggested that some users, such as utilities, started LSBS projects because other companies are doing the same. As such, energy storage technologies fit into a zeitgeist that emphasizes green and innovative products.

The rationality behind such firm decisions can be explained by how they learn how to deal with potential future issues. Another explanation is that the companies can better legitimize their existence by conforming to a dominant zeitgeist. Thus, firms that bought and used LSBS legitimized their activity derived from salient public green issues. In turn, they could market the resulting image to investors, politicians, employees, and customers.

The **quantitative results** of the large-N study support the hypothesis of public salience of green issues as a driver for LSBS diffusion. This thesis used the share of green party votes as a proxy and could establish a significant positive relationship between salient green issues and LSBS diffusion.

9.1.3 Policy

The last sub-research question asked *how energy and innovation policies influenced the development and diffusion of stationary battery storage*. It thereby asks which regulations and other policy initiatives influenced development directionality as well as diffusion and touches implicitly upon the topic of the government's room to maneuver.

Technological Innovation System In the two **qualitative country case studies**, we see evidence that both innovation policy and energy policy have in part enabled and subsequently guided BES-TIS development to date.

The above-mentioned contextual conditions in the energy system, which were essential for the lack of domestic energy storage markets, were already driven by regulatory energy policy. While regulation made the expansion of renewables slightly easier, regulators have set tighter limits for unrestricted energy storage expansion. These restricting conditions were set, for example, for reasons of supply security.

A substantial stimulus for the development and diffusion of battery energy storage in the countries came from public funding provided through technology push and demand-pull measures. These initiatives can be attributed to innovation policy and encouraged initial knowledge generation, and supported entrepreneurial experimentation. Providing resources for applied research allowed a TIS to form around these topics slowly. So, we can say, due to the negligible demand for battery storage in these countries, innovation policy measures such as RD&D funding and subsidies remained an important driver. This dynamic was, in turn, strongly dependent on the legitimization attempts for storage. However, the evidence suggests that innovation policy also impacted the search direction and thus the directionality of the TIS through its focus on solving assumed societal problems via innovation (i.e., a mission-driven approach). This dependence on legitimation was especially noticeable when its "anchor point" shifted to the topic of electric vehicles as an anchor point. Consequently, this thesis argues that the search direction in the R&D policy also changed.

Using a policy mix approach in this thesis enabled the author first to judge their overall impact on the BES-TIS beyond these single policy elements. This holistic perspective highlighted that the many policies affecting the BES-TIS, particularly energy policy regulation, often considered energy storage only peripherally and focused on context issues. For example, there was an inconsistency in policy objectives between increasing liberalization attempts of the energy market, often originating at the EU governance level, and energy security regulation at the national level that focused mainly on centralized solutions. Nevertheless, these frictions always seemed to be mediated at the policy level so far, and thus, this thesis could find no inconsistencies in the policymaking process.

LSBS Diffusion The results of the **qualitative country case study** suggest that systemic energy policy regulations were decisive for the current state of the market for LSBS in those countries, as they said the boundary conditions for diffusion. While regulative energy policy might have posed some challenges for further LSBS diffusion, innovation policies were likely a driver. In Austria and Germany, LSBS adoption occurred through predominantly public-funded RD&D projects.

The results from the **quantitative large-N study** also suggest that diffusion of LSBS is contingent on funds from innovation policy. Thus, this thesis provided evidence that spending on research and development of electrical storage positively influenced the diffusion of LSBS. This result confirms the hypothesis that LSBS remained predominantly experimental and only partially driven by market demand.

A surprising result of the quantitative analysis was that it did not produce any evidence that demand-side measures (e.g., guaranteed feed-in tariffs) had a positive effect on LSBS diffusion. Although, to the author's knowledge, no comparable studies have been conducted, the lack of impact of demand-side measures found in this study did not corroborate the results of other studies of renewable energy technology diffusion.

9.2 Contribution to the Literature

The thesis contains several contributions to the academic literature, which are listed briefly in the following section.

Legitimation One contribution of this thesis was to the understanding of the role of legitimation in the development direction of TISs, which has already been discussed very extensively in the literature. In particular, it showed how context structures could be indirectly relevant for legitimation by using salience issues and discourses as anchor points for legitimation attempts. Thus, it brought another empirical case into the debate.

Energy and Innovation Economics This thesis also added to the areas of energy and innovation economics, particularly in the field of diffusion of technological innovation. It is unique in its approach by investigating the actual diffusion of large stationary battery storage projects. Applying a previously unused data set with data on new large-scale battery storage projects in high-income countries and using a Bass-model-based fixed-effect panel regression approach, the findings on the relationship between salient green issues and the diffusion rate of large-scale storage are unique.

Technological Innovation Systems and Critical Realism Another contribution of this thesis to the academic literature is in its methods section. To the author's knowledge, this is the first time the compatibility of ontological and epistemological foundations from critical realism in connection with the TIS approach has been directly discussed. Thus, the comparisons drawn here may serve as a point of reference for further methodological work.

Suggested Amendments to the TIS Framework Moreover, one input to the literature was the theoretical conceptualization of potential extensions for the TIS approach. This was done by proposing to add spatial factors such as physical nature as a fifth element. In addition, it argues for considering the impact of the broader capitalist relations in future TIS analyses. Moreover, it suggested connecting the social acceptance literature with the market function of the TIS literature. An article based on an early draft of the theory chapter was published under Bettin 2020.

Empirical Evidence for TIS in the Next Phase of the Energy Transition Also, the thesis contributed to the academic debate by empirically investigating one of these auxiliary technologies, which are expected to be important in the next phase of the energy transition (see Markard, 2018b)—using a TIS and diffusion of technology innovation approach. While similar studies along these lines have emerged recently, the case studies in this thesis stand out due to their specific focus on stationary energy storage systems and the related topics investigated, such as context structures, legitimation, and policy.

It thereby provides an in-depth case study on TIS development, which was called for by Bergek (2019).

TIS and Policy Mix Interactions Finally, this thesis provided another empirical example in the rapidly growing literature on the interaction and co-evolution of TIS and policy mix. It could demonstrate the usefulness of the research approach for identifying characteristics and properties of multiple policies. The combined use of both theoretical approaches showcased a further example of how the interaction of single policy elements—and the entire policy mix—can be linked to particular innovation functions of a TIS.

9.3 Limitations

A few limitations of this thesis result from the research questions and the time of investigation of the study. Others result from resource constraints that made these research design decisions necessary.

A significant limitation of the study is that the observed dynamics around the research object undergo substantive change. Hence, the development dynamics of stationary battery storage systems are still in their infancy. Unlike other transition studies, it is impossible to draw on a long history with many data points. Thus, the findings remain clouded by a certain degree of uncertainty. Furthermore, the diffusion of electricity storage is not isolated but is part of a much larger societal transformation in which energy and sustainability transitions interact with many other dynamics. The topicality of electricity storage development and still to be seen future development make this thesis' topic exciting from research and societal perspectives. However, this dynamic environment implies that obtained results require more careful interpretation and analysis, and its external validity should not be overstretched. This uncertainty has probably been exacerbated by the Covid-

19 pandemic, which we can assume has permanently altered some potentially influential parts of society.

Another limitation has methodological reasons. For example, the study revealed the difficulties of grasping technological innovation systems empirically in their entirety. Although the combination of interviews, policy analysis, secondary literature, and descriptive data made it possible to obtain a rough overview of the system and its development over time, the identification of mechanisms and thus causal relationships were only possible partially on a speculative basis. While this thesis is not alone with this methodological challenge and threat to the internal validity, the implications for the drawn conclusions are that we can only conditionally assume them correct.

Extrapolating the results from the qualitative case studies to other countries remains limited. Austria and Germany are both rich Western European countries, which most likely cannot cover the entire spectrum of development and distribution dynamics. For this thesis, the reduction to these countries made sense, on the one hand, to allow comparability, on the other hand, due to the author's linguistic and country knowledge as well as access to professional networks. A similar limitation also existed for the international quantitative large-N study, which included only high-income countries due to the insufficient data situation in others.

Another key constraint came from insufficient data available for the global diffusion of small-scale electricity storage. Thus, the quantitative study of diffusion was limited to large-scale storage, while the qualitative country case studies could consider both. Therefore, there is a slight mismatch between the qualitative and quantitative parts of the dissertation.

The quantitative large-N study also had limitations resulting from the study design. Here, the use of endogenous innovation dynamics as control and of country and entity fixed-effect made sense with regard to data quality and the research question. Still, it prevented other potentially relevant aspects from being examined in greater detail. For example, the study could not identify how geographic factors affect the diffusion of large-scale battery storage. The influence of incumbent forces that prevent change could also only be examined superficially.

9.4 Future Research Agenda

The importance of the physical and social context suggests that the socio-technical dynamics would unfold differently with other contextual structures. Thus, there is a need for further country case studies in the future, especially from different parts of the world, to compare with the results. As this thesis shows, there is a potential contribution to be made by studies that bring together results from in-depth country case studies with quantitative large-N studies to better illuminate global dynamics and linkages.

It is also essential to replicate research with improved data by extending the time series, including more countries, and adding more types of storage. Initiatives such as that of the German Federal Network Agency (BNetzA, 2021), which is since 2019 in the process of introducing a mandatory register for all energy generation plants—including those in the residential sector—provide hope in this regard.

Another research approach that could replicate the quantitative studies lies in quantifying the entire policy mix and not just individual policies. Such a study could contribute further insights into the effectiveness of policy mixes on technology diffusion.

Furthermore, the study of incumbents and other opposing forces that hinder large-scale storage diffusion still needs to be investigated quantitatively. It could only be considered on the surface in this thesis. Here, improved data availability and a different empirical study design could provide further insights.

The importance of legitimacy and public salience of environmental issues, which this thesis highlights, also suggests further investigation of discourses and their influence on technical development. Discourse comparisons, especially internationally, are thus a potentially fruitful avenue.

Furthermore, this thesis focused exclusively on electricity storage. Since these usually occur in combination with other technologies, it would also be interesting to discuss this in further studies. In particular, as more and more different areas such as heat, housing, and mobility are linked together through sector coupling, this may change the view of storage.

Thus, another open research avenue lies in looking even more closely at the motives of companies that purchase large storage facilities. While there are first attempts (see, e.g., Schriever and Halstrup, 2018), the phenomenon does not seem to be sufficiently illuminated yet.

Something that was beyond the scope of this thesis but remains to be explored is the modeling of TIS dynamics in conjunction with qualitative research. While this thesis provided a supporting description for such an endeavor through the case studies, modeling innovation and diffusion dynamics, especially under the assumption that the next phase of the energy transition might be different, could be further explored.

Appendix A

Appendix

A.1 Interview Guide

Topic: The strategic positioning of companies and scientific institutions in the field of electro-chemical storage influences its diffusion in Europe.

The interviews are intended to provide an overview of the business location as well as to shed particular light on **outstanding business concepts**. In addition, current challenges for further dissemination (such as through regulation) will be examined.

Interview with you as a **user of electro-chemical storage in context**.

Intro

Do you agree to the recording of the interview?	Results will be anonymized

1 Development and history

How did the venture come about?	Previous company knowledge Where did the idea come from?
What were the most important goals?	Have they changed?
What challenges do they face	

2 Participants - Actors

Who is involved?	Cooperation partner Organizations Important persons What roles do they take on?
Who shaped the technical design	
Who are the customers/users	Customers
How are users involved?	

3 Product - Service

What solutions were implemented?	Coherent Product Is it possible to isolate solutions from each other?
What is necessary for the solutions to work?	All elements Technical, maintenance, rules, contracts, users

4 Market

Typical customers	Important
Market acceptance	What have you done to gain market acceptance? How is awareness achieved?
Who are the big players?	Germany Europe
How do you see the growth potential?	

5 Experiences

What experiences have you had with the project over time?	positive negative
What did you learn in the project?	Were there any unexpected effects?
What role do contextual conditions play in the success of the project?	Legal conditions Market conditions Etc. What would have to change?
Are there similar projects?	Did your project serve as a role model? Distribution

6 Other actors

What are other players	major players Research Germany Abroad China
Who influences the technology (development)?	Suppliers?
Suppliers Where are they located? What do they do?	Austrian companies European companies Asian companies/Chinese companies
How do you cooperate with other actors?	Cooperation with universities/research institutions Cooperation with companies

7 Regulation

Taxes, prices, the energy sector	
Pressure from the state (certificates)	
Do politics hear you? What do you do to be heard by politics (EU, Austria, Burgenland)?	

8 Obstacles and drivers

Can you find suitable employees?	Do you team up with other companies?
To what extent does standardization of processes and products take place?	
Banks/ Financing	How do they react?
If you could tell the government or the EU Commission one wish, what would it be?	

9 Who else should I talk to?

A.2 Large-N Regression Study

A.2.1 Data Info

The following table A.1 provides an overview of the high-income countries, according to the 2020 World Bank classification, that is in this study. Moreover, it also provides the total kW capacity in electricity large-scale story systems that are publicly known and thus included in the database. Although some countries have only zero entries, this thesis assumes that some projects exist but are not included in the database. This study uses country-fixed effects for the models above to control these data problems to account for short-coming. Thus, the models used above can focus on change, with other measurement effects (e.g., increased measurement of storage projects by a research project in a given time) controlled for by time fixed effects.

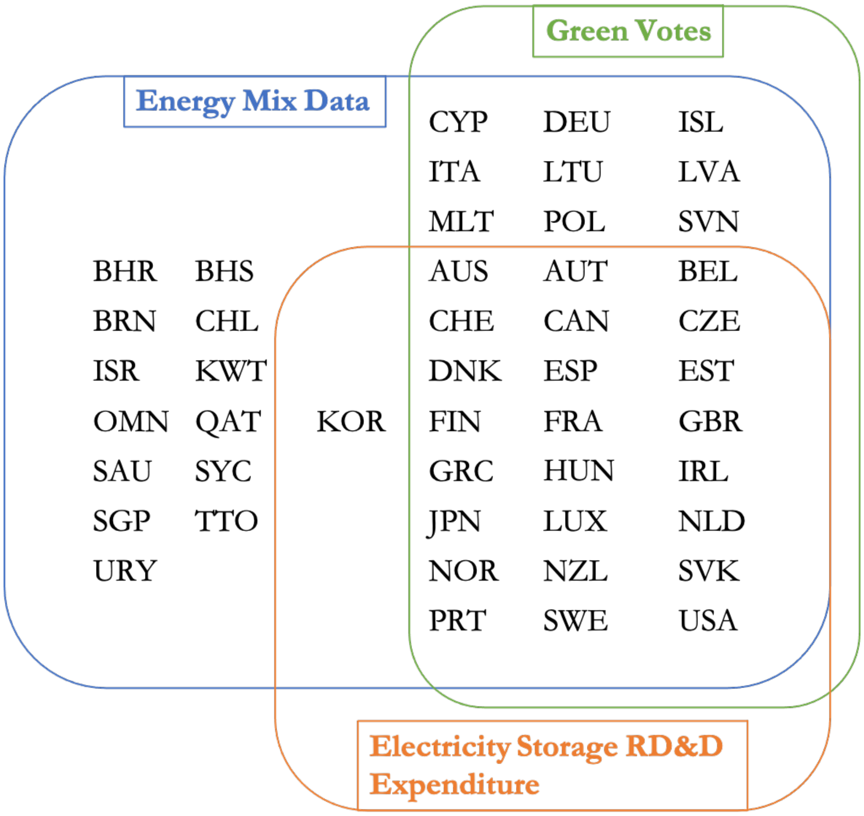


Figure A.1: Overview of included countries

Table A.1: List of Included Countries

Total LSBS (per capita)	Country
0.0	AND
123.1	AUS
2.9	AUT
26.6	BEL
0.0	BHR
0.0	BHS
0.0	BRN
16.4	CAN

Table A.1: Countries *(continued)*

Total LSBS (per capita)	Country
3.7	CHE
30.0	CHL
0.0	CYP
0.0	CZE
0.0	DEU
2.9	DNK
2.4	ESP
0.0	EST
11.6	FIN
2.7	FRA
83.4	GBR
0.7	GRC
1.1	HUN
3.2	IRL
0.0	ISL
0.1	ISR
13.8	ITA
20.5	JPN
0.0	KNA
39.9	KOR
0.0	KWT
0.0	LIE
0.0	LTU
0.0	LUX

Table A.1: Countries *(continued)*

Total LSBS (per capita)	Country
0.0	LVA
0.0	MCO
0.0	MLT
15.3	NLD
0.0	NOR
0.5	NZL
0.0	OMN
0.0	PLW
0.3	POL
5.8	PRT
8.7	QAT
0.0	SAU
0.0	SGP
0.0	SMR
0.0	SVK
0.0	SVN
0.1	SWE
0.0	SYC
0.0	TTO
0.0	TWN
0.0	URY
40.8	USA

A.2.2 Robustness Analysis

To test the robustness of the results, different specifications of the dependent variable LSBS diffusion were chosen. While for the main analysis we examined all storage facilities with $kW >= 50$–under the assumption that these facilities are usually grid-useful–now only all facilities with $kW >= 500$ were aggregated. The previous results were tested again (Table A.2).

Table A.2: Comparison of influencing factors on LSBS with >= 500 kW diffusion

	LSBS >= 500 kW diffusion			
	Public Acceptance	Energy System		Innovation Expenditure
Y_{t-1}	0.324	0.084	0.087	1.249***
	(−0.103, 0.750)	(−0.220, 0.388)	(−0.213, 0.387)	(0.541, 1.958)
${Y_{t-1}}^2$	0.006	0.008***	0.008***	−0.010**
	(−0.001, 0.013)	(0.002, 0.014)	(0.002, 0.014)	(−0.020, −0.0003)
$VoteGreen_{t-2}$	0.023***			
	(0.006, 0.040)			
$SolarProd_t$		−0.00003		
		(−0.0001, 0.00003)		
$WindProd_t$			−0.00002	
			(−0.0002, 0.0001)	
$RDDElsto_{t-2}$				1.043**
				(0.180, 1.906)
T	24-25	18	4-11	2-25
Countries	33	47	28	28
N	822	891	893	222
R^2	0.314	0.229	0.230	0.330
Adjusted R^2	0.261	0.166	0.167	0.129
F Statistic	116.141*** (df = 3; 762)	81.388*** (df = 3; 823)	82.079*** (df = 3; 825)	27.943*** (df = 3; 170)

*p < .1; **p < .05; ***p < .01

These results show that the findings are also robust to the main changes in our original definition of what constitutes LSBS. Thus, the percentage of green voters and RD&D expenditures for electricity storage technologies still seems to influence the diffusion of LSBS.

In contrast, the changes in wind and solar electricity production do not influence LSBS diffusion. This difference in results, as mentioned above, indicates a possible weakness in the results concerning the apparent negative relationship between LSBS diffusion and solar production.

Table A.3: Influence of wind and solar electricity at adoption point growth on LSBS diffusion

	LSBS diffusion	
	Growth Wind	Growth Solar
Y_{t-1}	0.072	0.072
	(−0.231, 0.375)	(−0.236, 0.380)
${Y_{t-1}}^2$	0.009***	0.009***
	(0.003, 0.015)	(0.002, 0.015)
$GrowthWind_t$	0.00000	
	(−0.00000, 0.00000)	
$GrowthSolar_t$		−0.00000
		(−0.00000, 0.00000)
T	18	17-18
Countries	47	47
N	846	844
R^2	0.244	0.243
Adjusted R^2	0.180	0.179
F Statistic	83.886*** (df = 3; 779)	83.078*** (df = 3; 777)

*p < .1; **p < .05; ***p < .01

Table A.3 also shows an alternative power system specification using the growth rates for wind and solar power. However, these variants do not show a significant relationship between the increase in their growth rate and the diffusion of LSBS.

Considering the impact of electricity prices on the adoption decisions of LSBS, the presented results (Table A.4) appear to show a connection between the two. For both points-time of decision with $p < 0.01$ and time of adoption with $p < 0.05$-there is a positive effect of the electricity price on the diffusion of LSBS and explanatory power of the models with an adjusted $R^2 = .5$. However, the presented are based on a relatively small number of observations N due to the limited number of countries and years available.

Table A.4: Influence of electricity price at decision and adoption point on the diffusion of LSBS

	Delta LSBS	
	Electricity price decision	Electricity price adoption
$StockLSBS_{t-1}$	-0.680^{***}	-0.800^{***}
	$(-1.158, -0.201)$	$(-1.305, -0.296)$
${StockLSBS_{t-1}}^2$	0.074^{***}	0.076^{***}
	$(0.055, 0.093)$	$(0.057, 0.096)$
$ElectricityPrice_t$	35.332^{***}	
	$(12.516, 58.148)$	
$ElectricityPrice_{t-2}$		39.442^{**}
		$(8.160, 70.725)$
T	4-11	3-9
Countries	28	28
N	297	242
R^2	0.575	0.576
Adjusted R^2	0.509	0.497
F Statistic	115.619^{***} (df = 3; 256)	91.911^{***} (df = 3; 203)

$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$

While these direct effects of changes in the energy system could not be confirmed as influencing LSBS diffusion, there is the first indication that end consumers' electricity prices are influencing factors. In previous qualitative studies (chapters 5 and 6), various actors were optimistic that increased volatility in electricity markets due to VRE would lead to electricity storage incentives. Rising electricity prices can be partially attributed to these changes as other flexibility measures such as grid extension and more re-dispatch capabilities all show up in electricity prices. However, it is also quite likely that rising electricity prices do not directly show an economic incentive for adopters yet but indicate their rising importance and potential economic possibilities in the future, thus changing expectations on future demand for LSBS. However, these results have to be taken with particular care due to the limited number of statistical observations. Thus, these results are excluded from the primary analysis.

A.2.3 Additional Results

While the direct influence of green parties was not shown, the composition of government cabinets according to the right-left scheme, based on the Schmidt-index (Armingeon et al., 2019), showed an influence on the spread of LSBS (Table A.5) with $-.2$ units given on the Schmidt-index and with a significance of $p > 0.05$. That is, the more left a government is, the more new LSBS diffused.

This influence is mainly present in political systems with proportional representation, as shown by the modeling with an interaction term between the government composition and the electoral system. Government composition is treated here as a continuous variable a with $a \in 1, 2, 3, 4, 5$ and political representation is a discrete variable with value $1 =$ Majoritarian, $2 =$ Proportional, and $3 =$ Mixed (Bormann and Golder, 2013). The results, also in Figure A.2, the significant results of of $p < 0.05$ for the majoritarian interaction term and $p < 0.01$ for all the other interaction terms. The results show that in a majoritarian system, the cabinet composition has with -2.94 units on the Schmidt-index a significant effect on LSBS diffusion. This means that the more left-leaning a government is, the more LSBS is built, the more right-leaning a government is, the fewer LSBS is built. While these results are interesting, they move slightly outside this thesis's scope and are therefore excluded from the main analysis.

Table A.5: Cabinet composition (Schmidt Index) and type of electoral system on LSBS diffusion

	New Storage	
	Cabinet Composition	Interaction
Y_{t-1}	0.321	0.313
	(−0.108, 0.750)	(−0.105, 0.730)
${Y_{t-1}}^{2}$	0.007^{*}	0.006^{*}
	(−0.001, 0.014)	(−0.001, 0.014)
$CabinetComposition_{t-2}$	-0.200^{**}	-0.893^{***}
	(−0.389, −0.012)	(−1.327, −0.459)
$ElectoralSystem$		-2.921^{**}
		(−5.396, −0.446)
$InteractionMajoritarian$		-2.047^{**}
		(−3.991, −0.103)
$InteractionProportional$		0.833^{***}
		(0.332, 1.334)
$InteractionMixed$		0.986^{***}
		(0.410, 1.563)
T		
Countries		
N	819	818
R^2	0.333	0.351
Adjusted R^2	0.281	0.296
F Statistic	126.127^{***} (df = 3; 759)	58.142^{***} (df = 7; 754)

*p < .1; **p < .05; ***p < .01

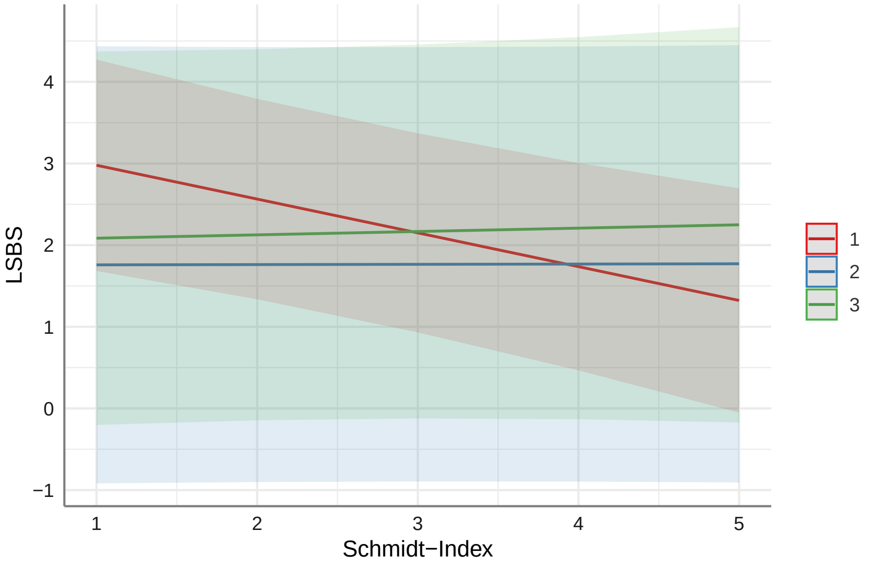


Figure A.2: Cabinet composition and type of electoral system on LSBS diffusion

Bibliography

Definition of dynamic noun. *Oxford Advanced Learner's Dictionary.*

E. Abrahamson. Managerial Fads and Fashions: The Diffusion and Rejection of Innovations. *The Academy of Management Review*, 16(3):586–612, 1991. ISSN 03637425. doi: 10.2307/258919.

E. Abrahamson and L. Rosenkopf. Institutional and Competitive Bandwagons: Using Mathematical Modeling as a Tool to Explore Innovation Diffusion. *The Academy of Management Review*, 18(3):487–517, 1993. ISSN 03637425. doi: 10.2307/258906.

D. Acemoglu, U. Akcigit, D. Hanley, and W. Kerr. Transition to Clean Technology. *Journal of Political Economy*, 124(1):52–104, Jan. 2016. ISSN 0022-3808. doi: 10.1086/684511.

P. Aghion, A. Dechezleprêtre, D. Hémous, R. Martin, and J. Van Reenen. Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. *Journal of Political Economy*, 124(1):1–51, Jan. 2016. ISSN 0022-3808. doi: 10.1086/684581.

S. Agnew and P. Dargusch. Consumer preferences for household-level battery energy storage. *Renewable and Sustainable Energy Reviews*, 75:609–617, 2017. ISSN 13640321. doi: 10.1016/j.rser.2016.11.030.

Agora Energiewende. Die Energiewende im Corona-Jahr: Stand der Dinge 2020. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2021. Technical report, Agora Energiewende, Berlin, Jan. 2021.

J. Albrecht, R. Laleman, and E. Vulsteke. Balancing demand-pull and supply-push measures to support renewable electricity in Europe. *Renewable and Sustainable Energy Reviews*, 49:267–277, Sept. 2015. ISSN 1364-0321. doi: 10.1016/j.rser.2015.04.078.

H. E. Aldrich and C. M. Fiol. Fools Rush in? The Institutional Context of Industry Creation. *Academy of Management Review*, 19(4):645–670, Oct. 1994. ISSN 0363-7425. doi: 10.5465/amr.1994.9412190214.

K. Alizada. Rethinking the diffusion of renewable energy policies: A global assessment of feed-in tariffs and renewable portfolio standards. *Energy Research & Social Science*, 44: 346–361, Oct. 2018. ISSN 22146296. doi: 10.1016/j.erss.2018.05.033.

B. B. Allan. Paradigm and nexus: Neoclassical economics and the growth imperative in the World Bank, 1948–2000. *Review of International Political Economy*, 26(1):183–206, Jan. 2019. ISSN 0969-2290. doi: 10.1080/09692290.2018.1543719.

O. H. Anuta, P. Taylor, D. Jones, T. McEntee, and N. Wade. An international review of the implications of regulatory and electricity market structures on the emergence of grid scale electricity storage. *Renewable and Sustainable Energy Reviews*, 38:489–508, 2014. ISSN 13640321. doi: 10.1016/j.rser.2014.06.006.

M. S. Archer. *Realist Social Theory: The Morphogenetic Approach.* Cambridge University Press, Cambridge, 1995. ISBN 978-0-521-48176-2. doi: 10.1017/CBO9780511557675.

K. Armingeon, V. Wenger, F. Wiedemeier, C. Isler, L. Knöpfel, D. Weisstanner, and S. Engler. Comparative political data set 1960-2017. *Bern: Institute of Political Science, University of Berne*, 2019.

W. B. Arthur. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal*, 99(394):116–131, Mar. 1989. ISSN 0013-0133. doi: 10.2307/2234208.

Z. Bakaki, T. Böhmelt, and H. Ward. The triangular relationship between public concern for environmental issues, policy output, and media attention. *Environmental Politics*, pages 1–21, Aug. 2019. ISSN 0964-4016. doi: 10.1080/09644016.2019.1655188.

G. Bakke. *The Grid - The Fraying Wires Between Americans and Our Energy Future*. Bloomsbury USA, New York, 1st edition, July 2016. ISBN 978-1-60819-610-4.

Banner. The Power Company | Banner. https://www.bannerbatterien.com/en/Company/The-Power-Company, 2020.

F. M. Bass. A New Product Growth for Model Consumer Durables. *Management Science*, 15(5):215–227, Jan. 1969. ISSN 0025-1909. doi: 10.1287/mnsc.15.5.215.

T. Baumann and F. Baumgartner. Home Batteriespeicher. Studie, ZHAW/IEFE, Winterthur, 2017.

N. Beck and J. N. Katz. What to do (and not to do) with Time-Series Cross-Section Data. *The American Political Science Review*, 89(3):634–647, 1995. ISSN 00030554, 15375943. doi: 10.2307/2082979.

N. Bento and M. Fontes. The capacity for adopting energy innovations in Portugal: Historical evidence and perspectives for the future. *Technological Forecasting and Social Change*, Sept. 2015. ISSN 00401625. doi: 10.1016/j.techfore.2015.09.003.

A. Bergek. Technological innovation systems: A review of recent findings and suggestions for future research. In *Handbook of Sustainable Innovation*, page c 384. Edward Elgar Publishing, Cheltenham, UK, 2019. ISBN 978-1-78811-256-7.

A. Bergek, S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, 37(3):407–429, Apr. 2008a. ISSN 00487333. doi: 10.1016/j.respol.2007.12.003.

A. Bergek, S. Jacobsson, and B. A. Sandén. 'Legitimation' and 'development of positive externalities': Two key processes in the formation phase of technological innovation systems. *Technology Analysis & Strategic Management*, 20(5):575–592, Sept. 2008b. ISSN 0953-7325. doi: 10.1080/09537320802292768.

A. Bergek, M. Hekkert, S. Jacobsson, J. Markard, B. Sandén, and B. Truffer. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions*, 16:51–64, Sept. 2015. ISSN 22104224. doi: 10.1016/j.eist.2015.07.003.

S. S. Bettin. Electricity infrastructure and innovation in the next phase of energy transition—amendments to the technology innovation system framework. *Review of Evolutionary Political Economy*, 1(3):371–395, Nov. 2020. ISSN 2662-6144. doi: 10.1007/s43253-020-00021-4.

R. Bhaskar. *A Realist Theory of Science*. Routledge, Milton Park, Abingdon, Oxon, 1975. ISBN 0-415-45494-8.

R. Bhaskar. *Enlightened Common Sense: The Philosophy of Critical Realism*. Routledge, London, 1st edition, 2016. ISBN 978-1-315-54294-2.

M. Bianchi, A. D. Benedetto, S. Franzò, and F. Frattini. Selecting early adopters to foster the diffusion of innovations in industrial markets. *European Journal of Innovation Management*, Oct. 2017. ISSN 1460-1060. doi: 10.1108/EJIM-07-2016-0068.

P. Biermayr, C. Dißauer, M. Eberl, M. Enigl, H. Fechner, B. Fürnsinn, M. Jaksch-Fliegenschnee, K. Leonhartsberger, S. Moidl, E. Prem, C. Schmidl, C. Strasser,

W. Weiss, M. Wittmann, P. Wonisch, and E. Wopienka. Innovative Energietechnologien in Österreich Marktentwicklung 2019. Technical Report 14/2020, Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, Vienna, Austria, 2020.

C. Binz and B. Truffer. Global Innovation Systems—A conceptual framework for innovation dynamics in transnational contexts. *Research Policy*, 46(7):1284–1298, Sept. 2017. ISSN 0048-7333. doi: 10.1016/j.respol.2017.05.012.

C. Binz, T. Tang, and J. Huenteler. Spatial lifecycles of cleantech industries – The global development history of solar photovoltaics. *Energy Policy*, 101(October):1–14, 2016. ISSN 03014215. doi: 10.1016/j.enpol.2016.10.034.

BMBF. Batterieforschung und Transfer stärken –Innovationen beschleunigen Dachkonzept „Forschungsfabrik Batterie“. Technical report, Federal Ministry of Education and Research, Jan. 2019a.

BMBF. Forschungsfertigung Batteriezelle. Technical report, Federal Ministry of Education and Research, July 2019b.

BMLFUW. Die österreichische Strategie zur Anpassung an den Klimawandel. Technical report, Ministerium für ein lebenswertes Österreich, Vienna, Austria, 2012.

BMNT and BMVIT. #mission2030. Die österreichische Klima- und Energiestrategie. Technical report, Bundesministerium für Nachhaltigkeit und Toursimus, Bmundesministerium für Verkehr, Innovation und Technologie, Wien, June 2018.

BMVIT and Klimafonds. Energie. Forschungs- und Innovationsstrategie e2050. Technical report, Bundesministerium für Verkehr, Innovation und Technologie/Klima- und Energiefonds, Wien, 2017.

BMWFJ and BMLFUW. Energiestrategie Österreich. Technical report, Ministry of Economy, Family and Youth and Ministry of Agriculture, Forestry, Environment and Water Management, Vienna, 2010.

BMWi. Ein Strommarkt für die Energiewende - Ergebnispapier des Bundesministeriums für Wirtschaft und Energie (Weißbuch). Technical report, Federal Ministry for Economic Affairs and Energy, Bonn, 2015.

BMWi. SINTEG – Smart energy showcases A programme for funding showcase regions for the energy supply of the future. Technical report, Federal Ministry for Economic Affairs and Energy, Bonn, Feb. 2018.

BMWi. Mittelstand Global Exportinitiative Energie. https://www.german-energy-solutions.de/GES/Navigation/DE/Home/home.html, 2019.

BMWi and BMU. Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Technical report, Bundesministerium fürWirtschaft und Technologie (BMWi), Berlin, Sept. 2010.

BNEF. Electric Vehicles Outlook 2020. Technical report, Bloomberg New Energy Finance, 2020.

BNetzA. Marktstammdatenregister. https://www.marktstammdatenregister.de/MaStR, 2021.

A. Bogner, B. Littig, and W. Menz. *Interviews Mit Experten: Eine Praxisorientierte Einführung*. Springer, Heidelberg, 2014.

A. Bogner, B. Littig, and W. Menz. Generating Qualitative Data with Experts and Elites. In U. Flick, editor, *SAGE Handbook of Qualitative Data Collection*, chapter 2017/01/01/, pages 652–667. SAGE, London, Dec. 2017.

N.-C. Bormann and M. Golder. Democratic Electoral Systems around the world, 1946–2011. *Electoral Studies*, 32(2):360–369, June 2013. ISSN 0261-3794. doi: 10.1016/j.electstud.2013.01.005.

G. Bridge, S. Bouzarovski, M. Bradshaw, and N. Eyre. Geographies of energy transition: Space, place and the low-carbon economy. *Energy Policy*, 53:331–340, 2013. ISSN 03014215. doi: 10.1016/j.enpol.2012.10.066.

R. Bromley-Trujillo and J. Poe. The importance of salience: Public opinion and state policy action on climate change. *Journal of Public Policy*, 40(2):280–304, 2020. ISSN 0143-814X. doi: 10.1017/S0143814X18000375.

D. Brounen, N. Kok, and J. M. Quigley. Energy literacy, awareness, and conservation behavior of residential households. *Energy Economics*, 38:42–50, July 2013. ISSN 0140-9883. doi: 10.1016/j.eneco.2013.02.008.

A. Bryman. Integrating quantitative and qualitative research: How is it done? *Qualitative Research*, 6(1):97–113, 2006. ISSN 1468-7941. doi: 10.1177/1468794106058877.

Bundesnetzagentur. MaStR | Webhilfe. https://www.marktstammdatenregister.de/MaStRHilfe/subpages/ 2019.

M. Bunge. Systemism: The alternative to individualism and holism. *The Journal of Socio-Economics*, 29(2):147–157, 2000. ISSN 10535357. doi: 10.1016/S1053-5357(00)00058-5.

A. Burlinson and M. Giulietti. Non-traditional business models for city-scale energy storage: Evidence from UK case studies. *Economia e Politica Industriale*, 45(2):215–242, 2017. ISSN 0391-2078 1972-4977. doi: 10.1007/s40812-017-0083-8.

P. Burstein. The Impact of Public Opinion on Public Policy: A Review and an Agenda.

Political Research Quarterly, 56(1):29–40, Mar. 2003. ISSN 1065-9129. doi: 10.1177/106591290305600103.

P. Buschmann and A. Oels. The overlooked role of discourse in breaking carbon lock-in: The case of the German energy transition. *WIREs Climate Change*, 10(3):e574, May 2019. ISSN 1757-7780. doi: 10.1002/wcc.574.

K. Buß, P. Wrobel, and C. Doetsch. Global distribution of grid-connected electrical energy storage systems. *International Journal of Sustainable Energy Planning and Management*, 9:2, 2016. ISSN 22462929. doi: 10.5278/ijsepm.2016.9.4.

BVES. BVES Branchenanalyse 2020 - Entwicklung und Perspektiven der Energiespeicherbranche in Deutschland, Mar. 2020.

M. Callon and F. Muniesa. Peripheral Vision: Economic Markets as Calculative Collective Devices. *Organization Studies*, 26(8):1229–1250, Aug. 2005. ISSN 0170-8406. doi: 10.1177/0170840605056393.

S. Carley and C. J. Miller. Regulatory Stringency and Policy Drivers: A Reassessment of Renewable Portfolio Standards. *Policy Studies Journal*, 40(4):730–756, Nov. 2012. ISSN 0190-292X. doi: 10.1111/j.1541-0072.2012.00471.x.

S. Carley, E. Baldwin, L. M. MacLean, and J. N. Brass. Global Expansion of Renewable Energy Generation: An Analysis of Policy Instruments. *Environmental and Resource Economics*, 68(2):397–440, Oct. 2017. ISSN 1573-1502. doi: 10.1007/s10640-016-0025-3.

B. Carlsson and R. Stankiewicz. On the nature, function and composition of technological systems. *Journal of Evolutionary Economics*, 1(2):93–118, 1991. ISSN 09369937. doi: 10.1007/BF01224915.

G. Castagneto Gissey, D. Subkhankulova, P. E. Dodds, and M. Barrett. Value of energy storage aggregation to the electricity system. *Energy Policy*, 128:685–696, May 2019. ISSN 0301-4215. doi: 10.1016/j.enpol.2019.01.037.

M. Cheng, S. S. Sami, and J. Wu. Benefits of using virtual energy storage system for power system frequency response. *Applied Energy*, 194:376–385, May 2017. ISSN 0306-2619. doi: 10.1016/j.apenergy.2016.06.113.

A. Cherp and J. Jewell. The concept of energy security: Beyond the four As. *Energy Policy*, 75:415–421, Dec. 2014. ISSN 0301-4215. doi: 10.1016/j.enpol.2014.09.005.

A. Cherp, V. Vinichenko, J. Jewell, and M. Suzuki. Comparing energy transitions : A historical analysis of nuclear , wind and solar power in Germany and Japan 1 Introduction. *Energy Policy*, 101(February):612–628, 2017. ISSN 03014215. doi: 10.1016/j.enpol.2016.10.044.

M. Child, C. Kemfert, D. Bogdanov, and C. Breyer. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy*, 139:80–101, Aug. 2019. ISSN 0960-1481. doi: 10.1016/j.renene.2019.02.077.

T. H. Christensen, F. Friis, S. Bettin, W. Throndsen, M. Ornetzeder, T. M. Skjølsvold, and M. Ryghaug. The role of competences, engagement, and devices in configuring the impact of prices in energy demand response: Findings from three smart energy pilots with households. *Energy Policy*, 137:111142, Feb. 2020. ISSN 0301-4215. doi: 10.1016/j.enpol.2019.111142.

V. Cirillo, A. Martinelli, A. Nuvolari, and M. Tranchero. Only one way to skin a cat? Heterogeneity and equifinality in European national innovation systems. *Research Policy*, 48(4):905–922, May 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2018.10.012.

L. Coenen, P. Benneworth, and B. Truffer. Toward a spatial perspective on sustainability transitions. *Research Policy*, 41(6):968–979, 2012. ISSN 00487333. doi: 10.1016/j.respol.2012.02.014.

D. Collingridge. *The Social Control of Technology.* Frances Pinter, 1980. ISBN 978-0-903804-72-1.

D. Comin and M. Mestieri. Technology Diffusion: Measurement, Causes, and Consequences. In P. Aghion and S. N. Durlauf, editors, *Handbook ofEconomic Growth*, volume 2B of *Handbook of Economic Growth*, pages 565–622. Elsevier, 2014. ISBN 978-0-444-53546-7. doi: 10.1016/b978-0-444-53540-5.00002-1.

P. Cooke, M. Gomez Uranga, and G. Etxebarria. Regional innovation systems: Institutional and organisational dimensions. *Research Policy*, 26(4):475–491, Dec. 1997. ISSN 0048-7333. doi: 10.1016/S0048-7333(97)00025-5.

P. Cooke, M. G. Uranga, and G. Etxebarria. Regional Systems of Innovation: An Evolutionary Perspective. *Environment and Planning A: Economy and Space*, 30(9):1563–1584, Sept. 1998. ISSN 0308-518X. doi: 10.1068/a301563.

R. Costello, D. Toshkov, B. Bos, and A. Krouwel. Congruence between voters and parties: The role of party-level issue salience. *European Journal of Political Research*, 60(1): 92–113, Feb. 2021. ISSN 0304-4130. doi: 10.1111/1475-6765.12388.

T. Couture and Y. Gagnon. An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy*, 38(2):955–965, Feb. 2010. ISSN 0301-4215. doi: 10.1016/j.enpol.2009.10.047.

G. Crabtree. Perspective: The energy-storage revolution. *Nature*, 526(7575):S92–S92, Oct. 2015. ISSN 1476-4687. doi: 10.1038/526S92a.

R. Crescenzi, L. Gagliardi, and S. Iammarino. Foreign multinationals and domestic innovation: Intra-industry effects and firm heterogeneity. *Research Policy*, 44(3):596–609, Apr. 2015. ISSN 00487333. doi: 10.1016/j.respol.2014.12.009.

J. W. Cresswell and V. L. Plano Clark. *Designing and Conducting Mixed Methods Research.* Sage Publications, Thousand Oaks, London, New Delhi, 2nd editio edition, 2011. ISBN 978-1-4129-7517-9.

Y. Croissant and G. Millo. Panel Data Econometrics in R: The plm Package. *Journal of Statistical Software; Vol 1, Issue 2 (2008)*, July 2008.

Y. Croissant and G. Millo. *Panel Data Econometrics with R: The Plm Package.* Wiley, 2018.

Y. Croissant, G. Millo, K. Tappe, O. Toomet, C. Kleiber, A. Zeileis, A. Henningsen, L. Andronic, N. Schoenfelder, and M. Y. Croissant. Package ‘plm’. *Choice*, 139(1): 227–240, 2020.

R. M. Cyert and J. G. March. *A Behavioral Theory of the Firm.* Prentice-Hall, Englewood Cliffs, NJ, 1963.

E. Dahmén. ‘Development Blocks’ in Industrial Economics. In B. Carlsson, editor, *Industrial Dynamics: Technological, Organizational, and Structural Changes in Industries and Firms*, pages 109–121. Springer Netherlands, Dordrecht, 1989. ISBN 978-94-009-1075-1. doi: 10.1007/978-94-009-1075-1_5.

G. D’Alisa, F. Demaria, and G. Kallis. *Degrowth: A Vocabulary for a New Era.* Routledge, London, 2015.

B. Dallinger, D. Schwabeneder, G. Lettner, and H. Auer. Socio-economic benefit and profitability analyses of Austrian hydro storage power plants supporting increasing renewable electricity generation in Central Europe. *Renewable and Sustainable Energy Reviews*, 107:482–496, June 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2019.03.027.

B. Danermark, M. Ekström, L. Jakobsen, and J. Karlsson. *Explaining Society: Critical Realism in Social Sciences*. Routledge, London and New York, 1st edition, Jan. 2002. ISBN 0-415-22182-X.

S. Dasgupta and E. De Cian. The influence of institutions, governance, and public opinion on the environment: Synthesized findings from applied econometrics studies. *Sustainable energy transformations in an age of populism, post-truth politics, and local resistance*, 43:77–95, Sept. 2018. ISSN 2214-6296. doi: 10.1016/j.erss.2018.05.023.

P. A. David. Clio and the Economics of QWERTY. *The American Economic Review*, 75 (2):332–337, 1985. ISSN 00028282.

D. M. Davies, M. G. Verde, O. Mnyshenko, Y. R. Chen, R. Rajeev, Y. S. Meng, and G. Elliott. Combined economic and technological evaluation of battery energy storage for grid applications. *Nature Energy*, 4(1):42–50, Jan. 2019. ISSN 2058-7546. doi: 10.1038/s41560-018-0290-1.

R. L. Day and P. A. Herbig. How the diffusion of industrial innovations is different from new retail products. *Industrial Marketing Management*, 19(3):261–266, Aug. 1990. ISSN 0019-8501. doi: 10.1016/0019-8501(90)90018-Q.

L. G. S. De Oliveira, J. Subtil Lacerda, and S. O. Negro. A mechanism-based explanation for blocking mechanisms in technological innovation systems. *Environmental Innovation and Societal Transitions*, 37:18–38, Dec. 2020. ISSN 2210-4224. doi: 10.1016/j.eist.2020.07.006.

Deutsche ÜNB. Anforderungen an die Speicherkapazität bei Batterien für die Primärregelleistung. Technical report, 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, Sept. 2015.

Deutsche ÜNB. Netzentwicklungsplan Strom 2030, Version 2019, 2. Entwurf. Technical report, 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, Apr. 2019.

P. Devine-Wright, S. Batel, O. Aas, B. Sovacool, M. C. LaBelle, and A. Ruud. A conceptual framework for understanding the social acceptance of energy infrastructure: Insights from energy storage. *Energy Policy*, 107(January):27–31, 2017. ISSN 03014215. doi: 10.1016/j.enpol.2017.04.020.

U. Dewald and B. Truffer. Market Formation in Technological Innovation Systems—Diffusion of Photovoltaic Applications in Germany. *Industry and Innovation*, 18(3):285–300, Apr. 2011. ISSN 1366-2716. doi: 10.1080/13662716.2011.561028.

Die Presse. Arnold Schwarzenegger schwärmt von Kreisel und dem elektrischen Hummer. *Die Presse*, Sept. 2017.

Die Presse. Batterien: Bausteine der Energiewende. *Die Presse*, Dec. 2019a.

Die Presse. Tojners Varta holt sich Geschäft mit Haushaltsbatterien zurück. *Die Presse*, May 2019b.

L. Dobusch and J. Kapeller. Heterodox United vs. Mainstream City? Sketching a Framework for Interested Pluralism in Economics. *Journal of economic issues*, XLVI:1035–1058, 2012. ISSN 0021-3624. doi: 10.2753/jei0021-3624460410.

DoE. US Department of Energy Global Energy Storage Database. https://www.energystorageexchange.org/, 2017.

D. Doloreux and S. Parto. Regional innovation systems: Current discourse and unresolved issues. *Technology in Society*, 27(2):133–153, Apr. 2005. ISSN 0160-791X. doi: 10.1016/j.techsoc.2005.01.002.

K. Dopfer and R. R. Nelson. The Evolution of Evolutionary Economics. In A. Pyka, C. E. Helfat, F. Malerba, G. Dosi, K. Lee, K. Dopfer, P. P. Saviotti, R. R. Nelson, and S. G. Winter, editors, *Modern Evolutionary Economics: An Overview*, pages 208–230. Cambridge University Press, Cambridge, 2018. ISBN 978-1-108-42743-2. doi: 10.1017/9781108661928.007.

G. Dosi. Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change. *Research Policy*, 11(3):147–162, 1982. ISSN 00487333. doi: 10.1016/0048-7333(82)90016-6.

G. Dosi and R. R. Nelson. Technological Advance as an Evolutionary Process. In A. Pyka, C. E. Helfat, F. Malerba, G. Dosi, K. Lee, K. Dopfer, P. P. Saviotti, R. R. Nelson, and S. G. Winter, editors, *Modern Evolutionary Economics: An Overview*, pages 35–84. Cambridge University Press, Cambridge, 2018. ISBN 978-1-108-42743-2. doi: 10.1017/9781108661928.002.

D. H. Doughty, P. C. Butler, A. A. Akhil, N. H. Clark, and J. D. Boyes. Batteries for large-scale stationary electrical energy storage. *The Electrochemical Society Interface*, 19(3):49–53, 2010. doi: 10.1149/2.f05103if.

P. Downward and A. Mearman. Critical Realism and Econometrics: Constructive Dialogue with Post Keynesian Economics. *Metroeconomica*, 53(4):391–415, Nov. 2002. ISSN 0026-1386. doi: 10.1111/1467-999X.00149.

M. Durdovic. Generative hermeneutics: Proposal for an alliance with critical realism.

Journal of Critical Realism, 17(3):244–261, May 2018. ISSN 1476-7430. doi: 10.1080/14767430.2018.1511189.

E-Control. Assets. https://www.e-control.at/en/statistik/strom/bestandsstatistik, 2020.

E3/DC. About us. https://www.e3dc.com/en/about-us/, 2019.

D. L. Edmondson, F. Kern, and K. S. Rogge. The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions. *Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies*, 48(10):103555, Dec. 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2018.03.010.

C. Edquist. Systems of Innovation: Perspectives and Challenges. In J. Fagerberg and D. C. Mowery, editors, *The Oxford Handbook of Innovation*. Oxford University Press, Oxford, 2006.

C. Edquist and J. M. Zabala-Iturriagagoitia. Public Procurement for Innovation as mission-oriented innovation policy. *The need for a new generation of policy instruments to respond to the Grand Challenges*, 41(10):1757–1769, Dec. 2012. ISSN 0048-7333. doi: 10.1016/j.respol.2012.04.022.

D. Elder-Vass. *The Causal Power of Social Structures: Emergence, Structure and Agency*. Cambridge University Press, Cambridge, 2010. ISBN 978-0-521-19445-7.

ENTSO-E. ENTSO-E 2025, 2030, 2040 Network Development Plan 2018 Connecting Europe:Electricity 2025 - 2030 - 2040 Final version after consultation and ACER opinion. Technical report, European Network of Transmission System Operators for Electricity, TYNDP, Oct. 2019.

B. Epstein. Social ontology. In E. N. Zalta, editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, summer 2018 edition, 2018.

European Commission. Second Report on the Energy Union. Progress reports on the Energy Union Framework Strategy adopted in 2015 to bring about the transition to a low-carbon, secure and competitive economy, 2017.

European Commission. EUROPE ON THE MOVE Sustainable Mobility for Europe: Safe, connected and clean. Annex to the Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, European Commission, Brussels, May 2018.

European Commission. Database of the European energy storage technologies and facilities - European Union Open Data Portal. https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities, 2020a.

European Commission. Taxonomy: Final report of the Technical Expert Group on Sustainable Finance. Technical report, European Commission, Brussels, 2020b.

M. Faber and J. Proops. Time Irreversibility in Economic Theory. *Seoul Journal of Economics*, 2(2):109–130, July 1989. ISSN 1225-0279.

K. R. Fabrizio, S. Poczter, and B. A. Zelner. Does innovation policy attract international competition? Evidence from energy storage. *Research Policy*, 46(6):1106–1117, July 2017. ISSN 0048-7333. doi: 10.1016/j.respol.2017.04.003.

J. Fagerberg and M. Srholec. National innovation systems, capabilities and economic development. *Research Policy*, 37(9):1417–1435, Oct. 2008. ISSN 0048-7333. doi: 10.1016/j.respol.2008.06.003.

G. Feola. Capitalism in sustainability transitions research: Time for a critical turn? *Environmental Innovation and Societal Transitions*, Feb. 2019. ISSN 2210-4224. doi: 10.1016/j.eist.2019.02.005.

J. Figgener, P. Stenzel, K.-P. Kairies, J. Linßen, D. Haberschusz, O. Wessels, G. Angenendt, M. Robinius, D. Stolten, and D. U. Sauer. The development of stationary battery storage systems in Germany–A market review. *Journal of energy storage*, 29:101153, 2020. ISSN 2352-152X.

L. Fischer. Marktentwicklung von PV-Heimspeicher in Österreich 2017, Feb. 2019.

K. Flanagan, E. Uyarra, and M. Laranja. Reconceptualising the 'policy mix' for innovation. *Research Policy*, 40(5):702–713, June 2011. ISSN 0048-7333. doi: 10.1016/j.respol.2011.02.005.

S. Fleetwood. The critical realist conception of open and closed systems. *Journal of Economic Methodology*, 24(1):41–68, Jan. 2017. ISSN 1350-178X. doi: 10.1080/1350178X.2016.1218532.

U. Flick. *An Introduction to Qualitative Research.* Sage Publishing, London, fourth edi edition, 2009.

D. Foray. On sector-non-neutral innovation policy: Towards new design principles. *Journal of Evolutionary Economics*, 29(5):1379–1397, Nov. 2019. ISSN 1432-1386. doi: 10.1007/s00191-018-0599-8.

T. J. Foxon. *Energy and Economic Growth: Why We Need a New Pathway to Prosperity.* Routledge, 2017. ISBN 1-317-21018-2.

Fraunhofer. Fraunhofer-Allianz Batterien. https://www.batterien.fraunhofer.de/en.html, 2020.

P. G. Fredriksson and D. L. Millimet. Electoral rules and environmental policy. *Economics Letters*, 84(2):237–244, Aug. 2004. ISSN 0165-1765. doi: 10.1016/j.econlet.2004.02.008.

C. Freeman. *Technology Policy and Economic Performance*. Pinter Publishers Great Britain, 1989. ISBN 0-86187-928-7.

C. Friedl and J. Reichl. Realizing energy infrastructure projects - A qualitative empirical analysis of local practices to address social acceptance. *Energy Policy*, 89:184–193, 2016. ISSN 03014215. doi: 10.1016/j.enpol.2015.11.027.

W. Friedl and J. Kathan. Innovative Energiespeichersysteme in und aus Österreich – Empfehlungen für Innovation// Umsetzungsschritte // Wertschöpfungskette. Technical report, Bundesministerium für Verkehr, Innovation und Technologie/Klima- und Energiefonds, Wien, 2018.

W. Friedl, V. Wild, H. Popp, K. Kubeczko, J. Kathan, G. Zahradnik, B. Windholz, K.-H. Leitner, S. Kaser, and F. Hengstberger. Technologie-Roadmap "Energiespeichersysteme in und aus Österreich". Technical report, KLIEN, Vienna, Aug. 2018.

Futurezone. Wien Energie nimmt Stromspeicher in Betrieb, Dec. 2019.

L. Gailing. Transforming energy systems by transforming power relations. Insights from dispositive thinking and governmentality studies. *Innovation: The European Journal of Social Science Research*, 29(3):243–261, July 2016. ISSN 1351-1610. doi: 10.1080/13511610.2016.1201650.

A. B. Gallo, J. R. Simões-Moreira, H. K. M. Costa, M. M. Santos, and E. Moutinho dos Santos. Energy storage in the energy transition context: A technology review. *Renewable and Sustainable Energy Reviews*, 65:800–822, 2016. ISSN 13640321. doi: 10.1016/j.rser.2016.07.028.

S. Ganowski and I. Rowlands. Read all about it! Comparing media discourse on energy storage in Canada and the United Kingdom in a transition era. *Energy Research & Social Science*, 70:101709, Dec. 2020. ISSN 2214-6296. doi: 10.1016/j.erss.2020.101709.

R. Garud, H. Berends, and P. Tuertscher. Qualitative Approaches for Studying Innovation as Process. In *The Routledge Companion to Qualitative Research in Organization Studies*, pages 226–247. Routledge, London, 1st edition, Aug. 2017. ISBN 978-1-315-68610-3. doi: 10.4324/9781315686103-15.

L. Gaudard and K. Madani. Energy storage race: Has the monopoly of pumped-storage in Europe come to an end? *Energy Policy*, 126:22–29, Mar. 2019. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.11.003.

F. Gault. Defining and measuring innovation in all sectors of the economy. *Research Policy*, 47(3):617–622, Apr. 2018. ISSN 0048-7333. doi: 10.1016/j.respol.2018.01.007.

GEA. *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012. ISBN 9781 10700 5198 hardback 9780 52118 2935 paperback.

A. Genus and A. Stirling. Collingridge and the dilemma of control: Towards responsible and accountable innovation. *Research Policy*, 47(1):61–69, Feb. 2018. ISSN 0048-7333. doi: 10.1016/j.respol.2017.09.012.

N. Georgescu-Roegen. *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge, Massachusetts, 1971. ISBN 1-58348-600-3. doi: 10.2307/2231206.

P. A. Geroski. Models of technology diffusion. *Research Policy*, 29(4-5):603–625, 2000. ISSN 00487333. doi: 10.1016/S0048-7333(99)00092-X.

A. Giddens. *The Constitution of Society.* University of California Press, Berkeley, CA., 1984.

J. Globisch, P. Plötz, E. Dütschke, and M. Wietschel. Consumer preferences for public charging infrastructure for electric vehicles. *Transport Policy*, 81:54–63, Sept. 2019. ISSN 0967-070X. doi: 10.1016/j.tranpol.2019.05.017.

B. Godin. National Innovation System: The System Approach in Historical Perspective. *Science, Technology \& Human Values*, 34(4):476–501, Feb. 2009. ISSN 0162-2439. doi: 10.1177/0162243908329187.

J. Goldstein. *Die Technik*, volume 40 of *Die Gesellschaft.* Literarische Anstalt Rütten & Loening, Frankfurt am Main, 1st edition, 1912.

C. Gräbner and J. Kapeller. New Perspectives on Institutionalist Pattern Modeling: Systemism, Complexity, and Agent-Based Modeling. *Journal of Economic Issues*, 49(2): 433–440, 2015. ISSN 0021-3624, 1946-326X. doi: 10.1080/00213624.2015.1042765.

M. S. Granovetter. Granovetter - 1973 - The Strength of Weak Ties. *American Journal of Sociology*, 78:1360–1380, 1973. ISSN 19391854. doi: 10.1037/a0018761.

R. Greenwood, R. Suddaby, and C. R. Hinings. Theorizing Change: The Role of Professional Associations in the Transformation of Institutionalized Fields. *The Academy of Management Journal*, 45(1):58–80, 2002. ISSN 00014273. doi: 10.2307/3069285.

R. Gross, R. Hanna, A. Gambhir, P. Heptonstall, and J. Speirs. How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. *Energy Policy*, 123:682–699, Dec. 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.08.061.

A. Grunwald. *Technology Assessment in Practice and Theory*. Routledge, London, 1st edition edition, 2018. ISBN 978-0-429-44264-3.

L. Grunwald. PV-Batteriespeicher: Betriebsweisen - Akteure - Anwendungsbeispiele. Forschungsbericht, IKT Fraunhofer Umsicht, Oberhausen, June 2017.

N. Gudowsky and W. Peissl. Human centred science and technology—transdisciplinary foresight and co-creation as tools for active needs-based innovation governance. *European Journal of Futures Research*, 4(1):8, Oct. 2016. ISSN 2195-2248. doi: 10.1007/s40309-016-0090-4.

M. Guerzoni and E. Raiteri. Demand-side vs. supply-side technology policies: Hidden treatment and new empirical evidence on the policy mix. *Research Policy*, 44(3):726–747, Apr. 2015. ISSN 0048-7333. doi: 10.1016/j.respol.2014.10.009.

B. Haley. Integrating structural tensions into technological innovation systems analysis: Application to the case of transmission interconnections and renewable electricity in Nova Scotia, Canada. *Research Policy*, 47(6):1147–1160, July 2018. ISSN 0048-7333. doi: 10.1016/j.respol.2018.04.004.

T. Hansen and L. Coenen. The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environmental Innovation and Societal Transitions*, 17:92–109, Dec. 2015. ISSN 2210-4224. doi: 10.1016/j.eist.2014.11.001.

G. Harper, R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, K. Ryder, L. Gaines, and P. Anderson. Recycling lithium-ion batteries from electric vehicles. *Nature*, 575(7781):75–86, Nov. 2019. ISSN 1476-4687. doi: 10.1038/s41586-019-1682-5.

B. Hartmann, D. Divényi, and I. Vokony. Evaluation of business possibilities of energy storage at commercial and industrial consumers – A case study. *Applied Energy*, 222: 59–66, July 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2018.04.005.

M. Hartner and A. Permoser. Through the valley: The impact of PV penetration levels on price volatility and resulting revenues for storage plants. *Renewable Energy*, 115: 1184–1195, Jan. 2018. ISSN 0960-1481. doi: 10.1016/j.renene.2017.09.036.

N. Healy, J. C. Stephens, and S. A. Malin. Embodied energy injustices: Unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains. *Energy Research & Social Science*, 48:219–234, Feb. 2019. ISSN 2214-6296. doi: 10.1016/j.erss.2018.09.016.

M. Hekkert, R. Suurs, S. Negro, S. Kuhlmann, and R. Smits. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74(4):413–432, May 2007. ISSN 00401625. doi: 10.1016/j.techfore.2006.03.002.

M. Held, D. Weidmann, D. Kammerl, C. Hollauer, M. Mörtl, M. Omer, and U. Lindemann. Current challenges for sustainable product development in the German automotive sector: A survey based status assessment. *Journal of Cleaner Production*, 195:869–889, Sept. 2018. ISSN 0959-6526. doi: 10.1016/j.jclepro.2018.05.118.

P. A. Herbig. A cusp catastrophe model of the adoption of an industrial innovation. *Journal of Product Innovation Management*, 8(2):127–137, June 1991. ISSN 0737-6782. doi: 10.1016/0737-6782(91)90006-K.

J. Hernández, I. Gyuk, and C. Christensen. DOE global energy storage database — A platform for large scale data analytics and system performance metrics. In *2016 IEEE International Conference on Power System Technology (POWERCON)*, pages 1–6, 2016. doi: 10.1109/POWERCON.2016.7754009.

A. Hipp and C. Binz. Firm survival in complex value chains and global innovation systems: Evidence from solar photovoltaics. *Research Policy*, 49(1):103876, Feb. 2020. ISSN 0048-7333. doi: 10.1016/j.respol.2019.103876.

R. F. Hirsh and C. F. Jones. History's contributions to energy research and policy. *Energy Research and Social Science*, 1:106–111, 2014. ISSN 22146296. doi: 10.1016/j.erss.2014.02.010.

M. Hlavac. *Stargazer: Well-Formatted Regression and Summary Statistics Tables*. Bratislava, Slovakia, 2018.

T. Hovardas. Two paradoxes with one stone: A critical reading of ecological modernization. *Ecological Economics*, 130:1–7, Oct. 2016. ISSN 0921-8009. doi: 10.1016/j.ecolecon.2016.06.023.

T. P. Hughes. *Networks of Power - Electrification in Western Society, 1880-1930.* The Johns Hopkins University Press, Baltimore, Maryland, 1983. ISBN 0-8018-2873-2.

IEA. Commentary: Who wants to be in charge? Technical report, International Energy Agency, Paris, 2017a.

IEA. Insights Series 2017 - Real-world policy packages for sustainable energy transitions. Technical report, International Energy Agency, Paris, Dec. 2017b.

IEA. RD&D Budget. *IEA Energy Technology RD&D Statistics*, 2019a.

IEA. Status of Power System Transformation. Technical report, IEA, Paris, 2019b.

IEA. World Energy Outlook 2019. Technical report, IEA, Paris, 2019c.

IEA. *World Energy Statistics 2019.* IEA, Paris, 2019d.

IEA. Austria 2020. Technical report, IEA, Paris, 2020a.

IEA. Innovation in Batteries and Electricity Storage. Technical report, IEA, Paris, 2020b.

IEA. World Energy Investment 2020. Technical report, IEA, Paris, 2020c.

IEA. World Energy Outlook 2020. Doi:https://doi.org/10.1787/557a761b-en, IEA, Paris, 2020d.

IPCC. Summary for Policymakers. In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Intergovernmental Panel on Climate Change, Aug. 2019.

M. Jaccard, L. Agbenmabiese, C. Azar, A. de Oliveira, C. Fischer, B. Fisher, A. Hughes, M. Ohadi, Y. Kenji, and X. Zhang. Chapter 22 - Policies for Energy System Transformations: Objectives and Instruments. In *Global Energy Assessment - Toward a Sustainable Future*, pages 1549–1602. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012. ISBN 9781 10700 5198 hardback 9780 52118 2935 paperback.

S. Jacobsson and A. Bergek. Transforming the energy sector: The evolution of technological systems in renewable energy technology. *Industrial and Corporate Change*, 13(5):815–849, Oct. 2004. ISSN 0960-6491. doi: 10.1093/icc/dth032.

S. Jacobsson and V. Lauber. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy Policy*, 34(3):256–276, Feb. 2006. ISSN 0301-4215. doi: 10.1016/j.enpol.2004.08.029.

A. B. Jaffe and M. Trajtenberg. *Patents, Citations, and Innovations - A Window on the Knowledge Economy*. The MIT Press, Cambridge, Massachusetts, 2002. ISBN 0-262-10095-9.

M. Jegen and X. D. Philion. Power and smart meters : A political perspective on the social acceptance of energy projects. *Canadian Public Administration*, 60(1):68–88, 2017.

B. Jessop. *State Power - A Strategic-Relational Approach.* Polity, Cambridge, 2008.

Z. Jiang, F. M. Bass, and P. I. Bass. Virtual Bass Model and the left-hand data-truncation bias in diffusion of innovation studies. *International Journal of Research in Marketing*, 23(1):93–106, Mar. 2006. ISSN 01678116. doi: 10.1016/j.ijresmar.2006.01.008.

R. B. Johnson and A. J. Onwuegbuzie. Mixed Methods Research: A Research Paradigm whose Time has Come. *Educational Researcher*, 33(7):14–26, 2004.

L. Kainiemi, K. Karhunmaa, and S. Eloneva. Renovation realities: Actors, institutional work and the struggle to transform Finnish energy policy. *Energy Research & Social Science*, 70:101778, Dec. 2020. ISSN 2214-6296. doi: 10.1016/j.erss.2020.101778.

K.-P. Kairies, J. Figgener, D. Haberschusz, O. Wessels, B. Tepe, and D. U. Sauer. Market and technology development of PV home storage systems in Germany. *Journal of Energy Storage*, 23:416–424, June 2019. ISSN 2352-152X. doi: 10.1016/j.est.2019.02.023.

B. J. Kalkbrenner. Residential vs. community battery storage systems – Consumer preferences in Germany. *Energy Policy*, 129:1355–1363, June 2019. ISSN 0301-4215. doi: 10.1016/j.enpol.2019.03.041.

G. Kallis. In defence of degrowth. *Ecological Economics*, 70:873–880, 2011. ISSN 09218009.

R. Kattel and M. Mazzucato. Mission-oriented innovation policy and dynamic capabilities in the public sector. *Industrial and Corporate Change*, 27(5):787–801, Oct. 2018. ISSN 0960-6491, 1464-3650. doi: 10.1093/icc/dty032.

KBA. Neuzulassungen von Personenkraftwagen in den Jahren 2009 bis 2018 nach ausgewählten Kraftstoffarten. Database, Kraftfahrt-Bundesamt, Flensburg, 2019.

W. Keller. International Technology Diffusion. *Journal of Economic Literature*, 42(3): 752–782, 2004. doi: 10.1257/0022051042177685.

F. Kern and M. Howlett. Implementing transition management as policy reforms: A case study of the Dutch energy sector. *Policy Sciences*, 42(4):391, Aug. 2009. ISSN 1573-0891. doi: 10.1007/s11077-009-9099-x.

F. Kern, K. S. Rogge, and M. Howlett. Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies. *Research Policy*, 48(10):103832, Dec. 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2019.103832.

J. M. Keynes. *The General Theory of Employment, Interest, and Money.* Macmillan, London, 1936.

I. Khorsand, C. Kormos, E. G. MacDonald, and C. Crawford. Wind energy in the city: An interurban comparison of social acceptance of wind energy projects. *Energy Research & Social Science*, 8:66–77, July 2015. ISSN 2214-6296. doi: 10.1016/j.erss.2015.04.008.

T. Kim and J. Hong. Bass model with integration constant and its applications on initial demand and left-truncated data. *Technological Forecasting and Social Change*, 95:120–134, June 2015. ISSN 00401625. doi: 10.1016/j.techfore.2015.02.009.

N. Kittner, F. Lill, and D. M. Kammen. Energy storage deployment and innovation for the clean energy transition. *Nature Energy*, 2(July):17125, 2017. ISSN 2058-7546. doi: 10.1038/nenergy.2017.125.

P. Kivimaa and F. Kern. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Research Policy*, 45(1):205–217, Feb. 2016. ISSN 00487333. doi: 10.1016/j.respol.2015.09.008.

Klimafonds. Abschlussbericht der Speicherinitiative Startphase - Zusammengestellt auf Basis der Ergebnisse aus den sechs Arbeitsgruppen. Technical report, Klimafonds, Wien, June 2016.

S. Kloppenburg, R. Smale, and N. Verkade. Technologies of Engagement: How Battery Storage Technologies Shape Householder Participation in Energy Transitions. *Energies*, 12(22):4384, 2019.

J. Kohlenberger. *The New Formula For Cool-Science, Technology, and the Popular in the American Imagination*. Number 12 in American Culture Studies. transcript, Bielefeld, first edition, 2015. ISBN 978-3-8376-3092-3.

A. R. Köhler, Y. Baron, W. Bulach, C. Heinemann, M. Vogel, S. Behrendt, M. Degel, N. Krauß, and M. Buchert. ökologische und ökonomische Bewertung des Ressourcenaufwands - Stationäre Energiespeichersysteme in der industriellen Produktion. Studie, VDI Zentrum Ressourceneffizienz (ZRE), Berlin, Apr. 2018.

J. Köhler, F. W. Geels, F. Kern, J. Markard, E. Onsongo, A. Wieczorek, F. Alkemade, F. Avelino, A. Bergek, F. Boons, L. Fünfschilling, D. Hess, G. Holtz, S. Hyysalo, K. Jenkins, P. Kivimaa, M. Martiskainen, A. McMeekin, M. S. Mühlemeier, B. Nykvist, B. Pel, R. Raven, H. Rohracher, B. Sandén, J. Schot, B. Sovacool, B. Turnheim, D. Welch, and P. Wells. An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, 31:1–32, June 2019. ISSN 2210-4224. doi: 10.1016/j.eist.2019.01.004.

B. P. Koirala, E. van Oost, and H. van der Windt. Community energy storage: A responsible innovation towards a sustainable energy system? *Applied Energy*, 231:570–585, Dec. 2018. ISSN 03062619. doi: 10.1016/j.apenergy.2018.09.163.

N. Komendantova and A. Battaglini. Beyond Decide-Announce-Defend (DAD) and Not-in-My-Backyard (NIMBY) models? Addressing the social and public acceptance of electric transmission lines in Germany. *Energy Research & Social Science*, 22:224–231, Dec. 2016. ISSN 2214-6296. doi: 10.1016/j.erss.2016.10.001.

P. Kukk, E. H. Moors, and M. P. Hekkert. Institutional power play in innovation systems: The case of Herceptin®. *Research Policy*, 45(8):1558–1569, Oct. 2016. ISSN 0048-7333. doi: 10.1016/j.respol.2016.01.016.

E. Kyritsis, J. Andersson, and A. Serletis. Electricity prices, large-scale renewable integration, and policy implications. *Energy Policy*, 101:550–560, Feb. 2017. ISSN 0301-4215. doi: 10.1016/j.enpol.2016.11.014.

M. C. Labelle. A state of fracking: Building Poland's national innovation capacity for shale gas. *Energy Research & Social Science*, 23:1–10, 2017. doi: 10.1016/j.erss.2016.11.003.

V. Lagendijk. *Electrifying Europe: The Power of Europe in the Construction of Electricity Networks*. Amsterdam University Press, Amsterdam, Jan. 2008. ISBN 978-90-5260-309-4. doi: 10.2307/j.ctt6wp62s.

J. O. Lanjouw, A. Pakes, and J. Putnam. How to Count Patents and Value Intellectual Property: The Uses of Patent Renewal and Application Data. *The Journal of Industrial Economics*, 46(4):405–432, Dec. 1998. ISSN 0022-1821. doi: 10.1111/1467-6451.00081.

M. Lawhon and J. T. Murphy. Socio-technical regimes and sustainability transitions: Insights from political ecology. *Progress in Human Geography*, 36(3):354–378, 2012. ISSN 0309-1325. doi: 10.1177/0309132511427960.

I. Lazkano, L. Nøstbakken, and M. Pelli. From fossil fuels to renewables: The role of electricity storage. *Combating Climate Change. Lessons from Macroeconomics, Political*

Economy and Public Finance, 99:113–129, Oct. 2017. ISSN 0014-2921. doi: 10.1016/j.euroecorev.2017.03.013.

U. Liebe, A. Bartczak, and J. Meyerhoff. A turbine is not only a turbine: The role of social context and fairness characteristics for the local acceptance of wind power. *Energy Policy*, 107:300–308, Aug. 2017. ISSN 0301-4215. doi: 10.1016/j.enpol.2017.04.043.

R. Lindner, S. Daimer, B. Beckert, N. Heyen, J. Koehler, B. Teufel, P. Warnke, and S. Wydra. Addressing directionality: Orientation failure and the systems of innovation heuristic. Towards reflexive governance. Discussion Papers "Innovation Systems and Policy Analysis" 52, Fraunhofer Institute for Systems and Innovation Research (ISI), 2016.

F. List. *Das nationale System der politischen Ökonomie*. JG Cotta, Stuttgart, 1841.

N. Luhmann. *Vertrauen*. UVK Verlagsgesellschaft, Konstanz & München, 5. auflage edition, 1968.

B.-Å. Lundvall. *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*. Pinter Publishers, London, 1992.

B.-Å. Lundvall. *The Learning Economy and the Economics of Hope*. Anthem Press, 2016. ISBN 978-1-78308-596-5.

D. Mackenzie. Is Economics Performative? Option Theory and the Construction of Derivatives Markets. *Journal of the History of Economic Thought*, 28(1):29–55, 2006. ISSN 1053-8372. doi: 10.1080/10427710500509722.

E. Magro and J. R. Wilson. Policy-mix evaluation: Governance challenges from new place-based innovation policies. *Research Policy*, 48(10):103612, Dec. 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2018.06.010.

V. Mahajan, E. Muller, and F. M. Bass. Diffusion of New Products: Empirical Generalizations and Managerial Uses. *Marketing Science*, 14(3_supplement):G79–G88, Aug. 1995. ISSN 0732-2399, 1526-548X. doi: 10.1287/mksc.14.3.G79.

J. Málek, L. Rečka, and K. Janda. Impact of German Energiewende on transmission lines in the central European region. *Energy Efficiency*, 11(3):683–700, Mar. 2018. ISSN 1570-6478. doi: 10.1007/s12053-017-9594-4.

F. Malerba. Sectoral systems of innovation and production. *Research Policy*, 31(2):247–264, Feb. 2002. ISSN 0048-7333. doi: 10.1016/S0048-7333(01)00139-1.

A. Malm. *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*. Verso Books, London and New York, 2016. ISBN 1-78478-130-4.

K. Maréchal and N. Lazaric. Overcoming inertia: Insights from evolutionary economics into improved energy and climate policies. *Climate Policy*, 10(1):103–119, Jan. 2010. ISSN 1469-3062. doi: 10.3763/cpol.2008.0601.

J. Markard. The life cycle of technological innovation systems. *Technological Forecasting and Social Change*, page 119407, July 2018a. ISSN 0040-1625. doi: 10.1016/j.techfore.2018.07.045.

J. Markard. The next phase of the energy transition and its implications for research and policy. *Nature Energy*, 3(8):628–633, Aug. 2018b. ISSN 2058-7546. doi: 10.1038/s41560-018-0171-7.

J. Markard. The life cycle of technological innovation systems. *Technological Forecasting and Social Change*, 153:119407, Apr. 2020. ISSN 0040-1625. doi: 10.1016/j.techfore.2018.07.045.

J. Markard, M. Hekkert, and S. Jacobsson. The technological innovation systems framework: Response to six criticisms. *Environmental Innovation and Societal Transitions*, 16:76–86, Sept. 2015. ISSN 22104224. doi: 10.1016/j.eist.2015.07.006.

J. Markard, S. Wirth, and B. Truffer. Institutional dynamics and technology legitimacy - A framework and a case study on biogas technology. *Research Policy*, 45(1):330–344, 2016. ISSN 00487333. doi: 10.1016/j.respol.2015.10.009.

A. Masini and E. Menichetti. Investment decisions in the renewable energy sector: An analysis of non-financial drivers. *Future-Oriented Technology Analysis*, 80(3):510–524, Mar. 2013. ISSN 0040-1625. doi: 10.1016/j.techfore.2012.08.003.

J. Mattes, A. Huber, and J. Koehrsen. Energy transitions in small-scale regions – What we can learn from a regional innovation systems perspective. *Energy Policy*, 78:255–264, Mar. 2015. ISSN 03014215. doi: 10.1016/j.enpol.2014.12.011.

M. Mazzucato. *The Entrepreneurial State - Revised Edition*. Anthem Press, London, 2015.

M. Mazzucato. Mission-oriented innovation policies: Challenges and opportunities. *Industrial and Corporate Change*, 27(5):803–815, Oct. 2018. ISSN 0960-6491, 1464-3650. doi: 10.1093/icc/dty034.

M. Mazzucato and C. C. Penna. Beyond market failures: The market creating and shaping roles of state investment banks. *Journal of Economic Policy Reform*, 19(4):305–326, 2016. doi: 10.1080/17487870.2016.1216416.

M. Mazzucato and G. Semieniuk. Public financing of innovation: New questions. *Oxford Review of Economic Policy*, 33(1):24–48, Feb. 2017. ISSN 0266-903X. doi: 10.1093/oxrep/grw036.

M. Mazzucato, R. Kattel, and J. Ryan-Collins. Challenge-Driven Innovation Policy: Towards a New Policy Toolkit. *Journal of Industry, Competition and Trade*, 20, June 2020. doi: 10.1007/s10842-019-00329-w.

R. McKenna. The double-edged sword of decentralized energy autonomy. *Energy Policy*, 113:747–750, Feb. 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2017.11.033.

D. Meissner and S. Kergroach. Innovation policy mix: Mapping and measurement. *The Journal of Technology Transfer*, Nov. 2019. ISSN 1573-7047. doi: 10.1007/s10961-019-09767-4.

C. A. Miller, J. Richter, and J. O'Leary. Socio-energy systems design: A policy framework for energy transitions. *Energy Research and Social Science*, 6:29–40, 2015. ISSN 22146296. doi: 10.1016/j.erss.2014.11.004.

R. Milne. Battery maker Northvolt scales up ambitions with factory push. *Financial Times*, Nov. 2019.

J. Mingers. The Contribution of Systemic Thought to Critical Realism. *Journal of Critical Realism*, 10(3):303–330, July 2011. ISSN 1476-7430. doi: 10.1558/jcr.v10i3.303.

S. A. R. Mir Mohammadi Kooshknow and C. B. Davis. Business models design space for electricity storage systems: Case study of the Netherlands. *Journal of Energy Storage*, 20:590–604, 2018. ISSN 2352152X. doi: 10.1016/j.est.2018.10.001.

M. Mögele and H. Rau. Cultivating the "car state": A culturally sensitive analysis of car-centric discourses and mobility cultures in Southern Germany. *Sustainability: Science, Practice and Policy*, 16(1):15–28, Dec. 2020. ISSN null. doi: 10.1080/15487733.2020.1756188.

D. C. Mowery, R. R. Nelson, and B. R. Martin. Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won't work). *Research Policy*, 39(8):1011–1023, Oct. 2010. ISSN 0048-7333. doi: 10.1016/j.respol.2010.05.008.

J. Musiolik and J. Markard. Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany. *Energy Policy*, 39(4): 1909–1922, Apr. 2011. ISSN 03014215. doi: 10.1016/j.enpol.2010.12.052.

J. Musiolik, J. Markard, and M. Hekkert. Networks and network resources in technological innovation systems: Towards a conceptual framework for system building. *Contains Special Section: Actors, Strategies and Resources in Sustainability Transitions*, 79(6): 1032–1048, July 2012. ISSN 0040-1625. doi: 10.1016/j.techfore.2012.01.003.

G. Myrdal. *Economic Theory and Under-Developed Regions*. G. Duckworth, London, 1957.

C. P. Naidoo. Relating financial systems to sustainability transitions: Challenges, demands and design features. *Environmental Innovation and Societal Transitions*, Nov. 2019. ISSN 2210-4224. doi: 10.1016/j.eist.2019.10.004.

S. O. Negro, F. Alkemade, and M. P. Hekkert. Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews*, 16(6):3836–3846, Aug. 2012. ISSN 13640321. doi: 10.1016/j.rser.2012.03.043.

R. R. Nelson. *National Innovation Systems: A Comparative Analysis*. Oxford University Press on Demand, 1993. ISBN 0-19-507617-6.

R. R. Nelson. Economics from an Evolutionary Perspective. In A. Pyka, C. E. Helfat, F. Malerba, G. Dosi, K. Lee, K. Dopfer, P. P. Saviotti, R. R. Nelson, and S. G. Winter, editors, *Modern Evolutionary Economics: An Overview*, pages 1–34. Cambridge University Press, Cambridge, 2018. ISBN 978-1-108-42743-2. doi: 10.1017/9781108661928.001.

R. R. Nelson and S. Winter. *An Evolutionary Theory of Economic Change.* The Belknapp Press of Harvard University Press, Cambridge, Massachusetts, 1982.

M. Nentwich. A short response to van Lente, Swierstra and Joly's essay 'Responsible innovation as a critique of technology assessment'. *Journal of Responsible Innovation*, 4 (2):262–267, May 2017. ISSN 2329-9460. doi: 10.1080/23299460.2017.1325698.

H. E. Normann and J. Hanson. The role of domestic markets in international technological innovation systems. *Industry and Innovation*, 25(5):482–504, May 2018. ISSN 1366-2716. doi: 10.1080/13662716.2017.1310651.

S. Nykamp, T. Rott, K. Keller, and T. Knop. Forecast the grid oriented battery operation to enable a multi-use approach and discussion of the regulatory framework. *CIRED - Open Access Proceedings Journal*, 2017(1):2760–2763, Oct. 2017. ISSN 2515-0855. doi: 10.1049/oap-cired.2017.0115.

C. Obi. Oil and conflict in Nigeria's Niger Delta region: Between the barrel and the trigger. *Extractive Industries and Society*, 1(2):147–153, 2014. ISSN 2214790X. doi: 10.1016/j.exis.2014.03.001.

OECD. *Policy Mix for Business R&D and Innovation.* Organisation for Economic Co-operation and Development, 2016. doi: 10.1787/sti_in_outlook-2016-22-en.

OECD. OECD Economic Surveys: Austria. Technical report, OECD, Paris, Nov. 2019.

OECD. Renewable energy feed-in tariffs. https://www.oecd-ilibrary.org/content/data/f68de84b-en, 2020.

V. Oikonomou and C. J. Jepma. A framework on interactions of climate and energy policy instruments. *Mitigation and Adaptation Strategies for Global Change*, 13(2):131–156, Feb. 2008. ISSN 1573-1596. doi: 10.1007/s11027-007-9082-9.

A. J. Onwuegbuzie and N. L. Leech. Sampling Designs in Qualitative Research : Making the Sampling Process More Public. *The Qualitative Report*, 12(2):19–20, 2007. ISSN ISSN-1052-0147. doi: 10.1007/s11135-006-9000-3.

ORF. Beinahe-Blackout: Pumpspeicher-Kraftwerke halfen. https://vorarlberg.orf.at/stories/3084428/, Jan. 2021.

M. Ornetzeder, S. Bettin, and D. Wasserbacher. *Zwischenspeicher Der Zukunft Für Elektrische Energie Endbericht Juni 2019*. Number 9 in ITA-AIT. Institut für Technikfolgen-Abschätzung/Austrian Institute of Technology, Wien, 2019. doi: 10.1553/ITA-pb-AIT-9.

A. Papke and M. Kahles. Neue EU-Regelungen zur Eigenversorgung – Auswirkungen des Art. 21 der neuen Erneuerbare-Energien-Richtlinie auf das deutsche Recht. Technical Report 36, Stiftung Umweltenergierecht, Würzburg, Dec. 2018.

S. M. Pfotenhauer, J. Juhl, and E. Aarden. Challenging the "deficit model" of innovation: Framing policy issues under the innovation imperative. *New Frontiers in Science, Technology and Innovation Research from SPRU's 50th Anniversary Conference*, 48(4): 895–904, May 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2018.10.015.

J. Planko, J. Cramer, M. P. Hekkert, and M. M. Chappin. Combining the technological innovation systems framework with the entrepreneurs' perspective on innovation. *Technology Analysis & Strategic Management*, 29(6):614–625, July 2017. ISSN 0953-7325. doi: 10.1080/09537325.2016.1220515.

V. L. Plano Clark and N. V. Ivankova. Mixed Methods Research: A Guide to the Field. pages 105–134. SAGE Publications, Inc., Thousand Oaks, California, Oct. 2020. doi: 10.4135/9781483398341.

K. Polanyi. *The Great Transformation: Economic and Political Origins of Our Time*. Beacon Press, New York, beacon pap edition, 1944.

M. Polanyi. *Personal Knowledge - Towards a Post-Critical Philsophy*. Routledge, London, 1958.

D. Popp. Environmental Policy and Innovation: A Decade of Research. *International Review of Environmental and Resource Economics*, 13(3-4):265–337, 2019. ISSN 1932-1465. doi: 10.1561/101.00000111.

D. Popp, I. Hascic, and N. Medhi. Technology and the diffusion of renewable energy. *Special Issue on The Economics of Technologies to Combat Global Warming*, 33(4):648–662, July 2011. ISSN 0140-9883. doi: 10.1016/j.eneco.2010.08.007.

L. Price and L. Martin. Introduction to the special issue: Applied critical realism in the social sciences. *Journal of Critical Realism*, 17(2):89–96, Mar. 2018. ISSN 1476-7430. doi: 10.1080/14767430.2018.1468148.

PRNewswire. CATL starts construction of its first overseas factory in Germany. https://www.prnewswire.com/news-releases/catl-starts-construction-of-its-first-overseas-factory-in-germany-300941142.html, Oct. 2019.

PV-Austria. Photovoltaik und Speicherförderung in Österreich. https://www.pvaustria.at/forderungen/, 2019.

PV-Austria. PV-Austria Website. https://www.pvaustria.at/, 2021.

R. Quitzow. Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany. *Environmental Innovation and Societal Transitions*, 17:126–148, Dec. 2015. ISSN 22104224. doi: 10.1016/j.eist.2014.12.002.

R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna, Austria, 2020.

M. Rakas and D. S. Hain. The state of innovation system research: What happens beneath the surface? *Research Policy*, 48(9):103787, Nov. 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2019.04.011.

K. Reichardt, S. O. Negro, K. S. Rogge, and M. P. Hekkert. Analyzing interdependencies between policy mixes and technological innovation systems: The case of offshore wind in Germany. *Technological Forecasting and Social Change*, 106:11–21, May 2016. ISSN 0040-1625. doi: 10.1016/j.techfore.2016.01.029.

O. Renn and J. P. Marshall. Chapter 2 - History of the energy transition in Germany: From the 1950s to 2019. In O. Renn, F. Ulmer, and A. Deckert, editors, *The Role of Public Participation in Energy Transitions*, pages 9–38. Academic Press, Jan. 2020. ISBN 978-0-12-819515-4. doi: 10.1016/B978-0-12-819515-4.00002-7.

A. Rip and R. Kemp. Technological change. In S. Rayner and E. L. Malone, editors, *Human Choice and Climate Change*, volume Vol. II, Resources and Technology, pages 327–399. Battelle Press, Columbus, Ohio, 1998. ISBN 1-57477-046-2.

S. B. Rodrigues and J. Child. *Corporate Co-Evolution: A Political Perspective*. John Wiley & Sons, New York, 2008. ISBN 978-1-4051-2164-4.

E. M. Rogers. *Diffusion of Innovations*. Free Press, New York London Toronto Sydney, 5. edition edition, 2003. ISBN 978-0-7432-2209-9.

K. S. Rogge and K. Reichardt. Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Research Policy*, 45(8):1620–1635, 2016. ISSN 00487333. doi: 10.1016/j.respol.2016.04.004.

A. Ron. Regression analysis and the philosophy of social science: A critical realist view. *Journal of Critical Realism*, 1(1):119–142, 2002. doi: 10.1558/jocr.v1i1.119.

RStudio Team. *RStudio: Integrated Development Environment for r*. Boston, MA, 2015.

A. Sakti, A. Botterud, and F. O'Sullivan. Review of wholesale markets and regulations for advanced energy storage services in the United States: Current status and path forward. *Energy Policy*, 120:569–579, Sept. 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.06.001.

C. Samaras, W. J. Nuttall, and M. Bazilian. Energy and the military: Convergence of security, economic, and environmental decision-making. *Energy Strategy Reviews*, 26: 100409, Nov. 2019. ISSN 2211-467X. doi: 10.1016/j.esr.2019.100409.

B. A. Sandén and K. M. Hillman. A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research Policy*, 40(3):403–414, Apr. 2011. ISSN 0048-7333. doi: 10.1016/j.respol.2010.12.005.

A. Sayer. *Method in Social Science - A Realist Approach*. Routledge, Milton Park, Abingdon, Oxon, revised 2nd edition edition, 2010. ISBN 978-0-415-58159-2.

F. Schiavone and M. Simoni. Strategic marketing approaches for the diffusion of innovation in highly regulated industrial markets: The value of market access. *Journal of Business & Industrial Marketing*, Aug. 2019. ISSN 0885-8624. doi: 10.1108/JBIM-08-2018-0232.

M. Schmelzer. *The Hegemony of Growth - The OECD and the Making of the Economic Growth Paradigm*. Cambridge University Press, Cambridge, 2016.

O. Schmidt, S. Melchior, A. Hawkes, and I. Staffell. Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule*, 3(1):81–100, Jan. 2019. ISSN 2542-4351. doi: 10.1016/j.joule.2018.12.008.

T. S. Schmidt and J. Huenteler. Anticipating industry localization effects of clean technology deployment policies in developing countries. *Global Environmental Change*, 38: 8–20, May 2016. ISSN 0959-3780. doi: 10.1016/j.gloenvcha.2016.02.005.

T. S. Schmidt and S. Sewerin. Technology as a driver of climate and energy politics. *Nature Energy*, 2(6):17084, May 2017. ISSN 2058-7546. doi: 10.1038/nenergy.2017.84.

T. S. Schmidt and S. Sewerin. Measuring the temporal dynamics of policy mixes – An empirical analysis of renewable energy policy mixes' balance and design features in nine countries. *Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies*, 48(10):103557, Dec. 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2018.03.012.

J. Schot and L. Kanger. Deep transitions: Emergence, acceleration, stabilization and directionality. *Research Policy*, 47(6):1045–1059, July 2018. ISSN 0048-7333. doi: 10.1016/j.respol.2018.03.009.

J. Schot and W. E. Steinmueller. Three frames for innovation policy: R&D, systems of innovation and transformative change. *Research Policy*, 47(9):1554–1567, Nov. 2018. ISSN 0048-7333. doi: 10.1016/j.respol.2018.08.011.

M. Schriever and D. Halstrup. Exploring the adoption in transitioning markets: Empirical findings and implications on energy storage solutions-acceptance in the German manufacturing industry. *Energy Policy*, 120:460–468, Sept. 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.03.029.

J. A. Schumpeter. *Business Cycles - A Theoretical, Historical and Staticial Analysis of* *the Capitalist Process*, volume 1. McGraw Hill Book Company, New York and London, reprint edition, 1939.

I. Scrase and A. Smith. The (non-)politics of managing low carbon socio-technical transitions. *Environmental Politics*, 18(5):707–726, 2009. ISSN 0964-4016. doi: 10.1080/09644010903157008.

K. C. Seto, S. J. Davis, R. B. Mitchell, E. C. Stokes, G. Unruh, and D. Ürge-Vorsatz. Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, 41(1):425–452, Oct. 2016. ISSN 1543-5938. doi: 10.1146/annurev-environ-110615-085934.

R. J. Shiller. Narrative Economics. *American Economic Review*, 107(4):967–1004, 2017. doi: 10.1257/aer.107.4.967.

E. Shove. Changing human behaviour and lifestyle: A challenge for sustainable consumption? In I. Ropke and L. Reisch, editors, *Consumption - Perspectives from Ecological Economics*, pages 111–132. Elgar, 2005.

M. H. Shubbak. The technological system of production and innovation: The case of photovoltaic technology in China. *Research Policy*, 48(4):993–1015, May 2019. ISSN 0048-7333. doi: 10.1016/j.respol.2018.10.003.

A. Silvast. Energy, economics, and performativity: Reviewing theoretical advances in social studies of markets and energy. *Energy Research & Social Science*, 34:4–12, Dec. 2017. ISSN 2214-6296. doi: 10.1016/j.erss.2017.05.005.

H. A. Simon. A Behavioral Model of Rational Choice. *The Quarterly Journal of Economics*, 69(1):99–118, Feb. 1955. ISSN 0033-5533. doi: 10.2307/1884852.

H. A. Simon. Bounded Rationality and Organizational Learning. *Organization Science*, 2 (1):125–134, Feb. 1991. ISSN 1047-7039. doi: 10.1287/orsc.2.1.125.

V. Smil. *Energy and Civilization: A History.* The MIT Press, Cambridge, Massachusetts, 2017.

S. Sorrell and J. Sijm. Carbon Trading in the Policy Mix. *Oxford Review of Economic Policy*, 19(3):420–437, Sept. 2003. ISSN 0266-903X. doi: 10.1093/oxrep/19.3.420.

B. K. Sovacool and D. J. Hess. Ordering theories: Typologies and conceptual frameworks for sociotechnical change. *Social Studies of Science*, 47(5):703–750, 2017. ISSN 14603659. doi: 10.1177/0306312717709363.

C. L. Spash. This Changes Nothing: The Paris Agreement to Ignore Reality. *Globalizations*, 13(6):928–933, Nov. 2016. ISSN 1474-7731. doi: 10.1080/14747731.2016.1161119.

P. Späth and H. Rohracher. 'Energy regions': The transformative power of regional discourses on socio-technical futures. *Research Policy*, 39(4):449–458, 2010. ISSN 00487333. doi: 10.1016/j.respol.2010.01.017.

R. Squillace. Technology and market dynamics in the wind energy sector: Do first mover advantages exist? An exploratory analysis on the level of (national) innovation systems. 2012.

I. Stadelmann-Steffen and C. Dermont. The unpopularity of incentive-based instruments: What improves the cost–benefit ratio? *Public Choice*, 175(1):37–62, Apr. 2018. ISSN 1573-7101. doi: 10.1007/s11127-018-0513-9.

I. Stadelmann-Steffen and C. Eder. Public opinion in policy contexts. A comparative analysis of domestic energy policies and individual policy preferences in Europe. *Inter-*

national Political Science Review, page 0192512120913047, May 2020. ISSN 0192-5121. doi: 10.1177/0192512120913047.

I. Stadler, B. Riegel, D. Ohms, E. Cattaneo, G. Langer, and M. Herrmann. Electrochemical Energy Storage Systems. In M. Sterner and I. Stadler, editors, *Handbook of Energy Storage: Demand, Technologies, Integration*, pages 227–324. Springer Berlin Heidelberg, Berlin, Heidelberg, 2019. ISBN 978-3-662-55504-0. doi: 10.1007/978-3-662-55504-0_7.

A. Stephan, T. S. Schmidt, C. R. Bening, and V. H. Hoffmann. The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy*, 46(4):709–723, May 2017. ISSN 00487333. doi: 10.1016/j.respol.2017.01.009.

M. Sterner and F. Bauer. Definition and Classification of Energy Storage Systems. In M. Sterner and I. Stadler, editors, *Handbook of Energy Storage: Demand, Technologies, Integration*, pages 23–47. Springer Berlin Heidelberg, Berlin, Heidelberg, 2019. ISBN 978-3-662-55504-0. doi: 10.1007/978-3-662-55504-0_2.

M. Sterner and M. Thema. Comparison of Storage Systems. In M. Sterner and I. Stadler, editors, *Handbook of Energy Storage: Demand, Technologies, Integration*, pages 637–672. Springer, Berlin, Heidelberg, 2019. ISBN 978-3-662-55504-0. doi: 10.1007/978-3-662-55504-0_12.

M. Sterner, C. Breuer, T. Drees, F. Eckert, A. Maaz, C. Pape, N. Rotering, and M. Thema. Speicherbedarf in der Stromversorgung. In M. Sterner and I. Stadler, editors, *Energiespeicher - Bedarf, Technologien, Integration*, pages 53–140. Springer Vieweg, Berlin, 2. edition, 2017.

M. Sterner, C. Breuer, T. Drees, F. Eckert, A. Maaz, C. Pape, N. Rotering, and M. Thema. Storage Demand in Power Supply. In M. Sterner and I. Stadler, editors, *Handbook of Energy Storage: Demand, Technologies, Integration*, pages 51–136. Springer Berlin Heidelberg, Berlin, Heidelberg, 2019a. ISBN 978-3-662-55504-0. doi: 10.1007/978-3-662-55504-0_3.

M. Sterner, I. Stadler, F. Eckert, N. Gerhardt, C. von Olshausen, M. Thema, and T. Trost. Storage Integration for Coupling Different Energy Sectors. In M. Sterner and I. Stadler, editors, *Handbook of Energy Storage: Demand, Technologies, Integration*, pages 757–803. Springer Berlin Heidelberg, Berlin, Heidelberg, 2019b. ISBN 978-3-662-55504-0. doi: 10.1007/978-3-662-55504-0_14.

M. Sterner, I. Stadler, F. Eckert, and M. Thema. Storage Integration in Individual Energy Sectors. In M. Sterner and I. Stadler, editors, *Handbook of Energy Storage: Demand, Technologies, Integration*, pages 675–755. Springer, Berlin, Heidelberg, 2019c. ISBN 978-3-662-55504-0. doi: 10.1007/978-3-662-55504-0_13.

M. Steup and R. Neta. Epistemology. In E. N. Zalta, editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, fall 2020 edition, 2020.

Stiftung Umweltenergierecht. Batteriespeicher in Netzen. https://stiftung-umweltenergierecht.de/projekte/batteriespeicher-in-netzen/, 2018.

J. H. Stock and M. M. Watson. *Introduction to Econometrics*. Pearson, London, updated third edition edition, 2015. ISBN 978-1-292-07131-2.

N. P. Stromquist. *Education in a Globalized World: The Connectivity of Economic Power, Technology, and Knowledge*. Rowman & Littlefield, 2002.

J. Suitner and M. Ecker. “Making energy transition work”: Bricolage in Austrian regions’ path-creation. *Environmental Innovation and Societal Transitions*, 36:209–220, Sept. 2020. ISSN 2210-4224. doi: 10.1016/j.eist.2020.07.005.

N.-L. Sum and B. Jessop. *Towards a Cultural Political Economy - Putting Culture in Its Place in Political Economy.* Edward Elgar, Cheltenham, UK, 2014. ISBN 978 0 85793 071 2.

L. Summer. How Giant Batteries Are Protecting The Most Vulnerable In Blackouts, March 8, 2021 6:38 PM ET.

R. A. Suurs, M. P. Hekkert, S. Kieboom, and R. E. Smits. Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel. *Energy Policy*, 38(1):419–431, Jan. 2010. ISSN 0301-4215. doi: 10.1016/j.enpol.2009.09.032.

The World Bank. Doing Business 2020. Technical report, The World Bank Group, Washington D.C., Oct. 2019.

G. Thomas, C. Demski, and N. Pidgeon. Deliberating the social acceptability of energy storage in the UK. *Energy Policy*, 133:110908, Oct. 2019. ISSN 0301-4215. doi: 10.1016/j.enpol.2019.110908.

F. Tödtling, C. Höglinger, T. Sinozic, and A. Auer. Factors for the Emergence and Growth of Environmental Technology Industries in Upper Austria. *Mitteilungen der Österreischischen Geographischen Gesellschaft*, 156:1–25, 2014.

Transport and Environment. Can electric cars beat the COVID crunch? The EU electric car market and the impact of the COVID-19 crisis. Technical report, European Federation for Transport and Environment AISBL, Brussels, May 2020.

B. Turnheim and F. W. Geels. Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913–1997). *Special Section: Past and Prospective Energy Transitions - Insights from History*, 50:35–49, Nov. 2012. ISSN 0301-4215. doi: 10.1016/j.enpol.2012.04.060.

B. Turnheim and F. W. Geels. The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). *Research Policy*, 42(10):1749–1767, Dec. 2013. ISSN 0048-7333. doi: 10.1016/j.respol.2013.04.009.

B. Turnheim and B. K. Sovacool. Forever stuck in old ways? Pluralising incumbencies in sustainability transitions. *Environmental Innovation and Societal Transitions*, Nov. 2019. ISSN 2210-4224. doi: 10.1016/j.eist.2019.10.012.

F. Ueckerdt, R. Brecha, and G. Luderer. Analyzing major challenges of wind and solar variability in power systems. *Renewable Energy*, 81:1–10, Sept. 2015. ISSN 0960-1481. doi: 10.1016/j.renene.2015.03.002.

G. C. Unruh. Understanding carbon lock-in. *Energy Policy*, 28(12):817–830, 2000.

G. C. Unruh. Escaping carbon lock-in. *Energy Policy*, 30(4):317–325, 2002. ISSN 03014215. doi: 10.1016/S0301-4215(01)00098-2.

G. C. Unruh and J. Carrillo-Hermosilla. Globalizing carbon lock-in. *Energy Policy*, 34(10): 1185–1197, 2006. ISSN 03014215. doi: 10.1016/j.enpol.2004.10.013.

A. H. Van de Ven and R. Garud. Innovation and industry development: The case of cochlear implants. *Research on Technological innovation, Management and Policy*, 5: 1–46, 1993.

J. C. J. M. Van Den Bergh, B. Truffer, and G. Kallis. Environmental innovation and societal transitions: Introduction and overview. *Environmental Innovation and Societal Transitions*, 1(1):1–23, 2011. ISSN 22104224. doi: 10.1016/j.eist.2011.04.010.

J. C. J. M. van den Bergh, A. Angelsen, A. Baranzini, W. J. W. Botzen, S. Carattini, S. Drews, T. Dunlop, E. Galbraith, E. Gsottbauer, R. B. Howarth, E. Padilla, J. Roca, and R. C. Schmidt. A dual-track transition to global carbon pricing. *Climate Policy*, pages 1–13, July 2020. ISSN 1469-3062. doi: 10.1080/14693062.2020.1797618.

H. A. van der Loos, S. O. Negro, and M. P. Hekkert. International markets and technological innovation systems: The case of offshore wind. *Environmental Innovation and Societal Transitions*, 34:121–138, Mar. 2020. ISSN 2210-4224. doi: 10.1016/j.eist.2019.12.006.

T. Van Leeuwen. Legitimation in discourse and communication. *Discourse & Communication*, 1(1):91–112, Feb. 2007. ISSN 1750-4813. doi: 10.1177/1750481307071986.

T. Van Leeuwen. Legitimation and multimodality. In R. Wodak and B. Forchtner, editors, *The Routledge Handbook of Language and Politics*, page 15. Routledge, London, 1st edition, 2017. ISBN 978-1-315-18371-8.

M. Vasseur. Convergence and Divergence in Renewable Energy Policy among US States from 1998 to 2011. *Social Forces*, 92(4):1637–1657, June 2014. ISSN 0037-7732. doi: 10.1093/sf/sou011.

T. Veblen. Why is economics not an evolutionary science? *The Quarterly Journal of Economics*, 12(4):373–397, 1898. ISSN 0309-1325, 1477-0288. doi: 10.1177/0309132512463300.

A. Vega and M. Chiasson. A comprehensive framework to research digital innovation: The joint use of the systems of innovation and critical realism. *The Journal of Strategic Information Systems*, 28(3):242–256, Sept. 2019. ISSN 0963-8687. doi: 10.1016/j.jsis.2019.06.001.

E. Verdolini, F. Vona, and D. Popp. Bridging the gap: Do fast-reacting fossil technologies facilitate renewable energy diffusion? *Energy Policy*, 116:242–256, May 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.01.058.

M. A. R. Villaraigosa, V. Sivaram, and R. Nichols. Powering Los Angeles with renewable energy. *Nature Climate Change*, 3(9):771–775, Sept. 2013. ISSN 1758-6798. doi: 10.1038/nclimate1985.

V. Vinichenko. *Mechanisms of Energy Transitions : National Cases and the Worldwide Uptake of Wind and Solar Power*. PhD Thesis, Central European University, Budapest, 2018.

M. Waterson. The characteristics of electricity storage, renewables and markets. *Energy Policy*, 104:466–473, May 2017. ISSN 0301-4215. doi: 10.1016/j.enpol.2017.01.025.

M. Watts. Empire of oil: Capitalist dispossession and the scramble for Africa. *Monthly Review*, 58(4):1, 2006. ISSN 0027-0520.

K. M. Weber and H. Rohracher. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Research Policy*, 41(6):1037–1047, 2012. ISSN 00487333. doi: 10.1016/j.respol.2011.10.015.

J. Wesche, S. Negro, E. Dütschke, R. Raven, and M. Hekkert. Configurational innovation systems – Explaining the slow German heat transition. *Energy Research & Social Science*, 52:99–113, June 2019. ISSN 2214-6296. doi: 10.1016/j.erss.2018.12.015.

H. Wickham. *Ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2016. ISBN 978-3-319-24277-4.

S. Wicki and E. G. Hansen. Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage. *Journal of Cleaner Production*, 162:1118–1134, Sept. 2017. ISSN 0959-6526. doi: 10.1016/j.jclepro.2017.05.132.

M. Winfield, S. Shokrzadeh, and A. Jones. Energy policy regime change and advanced energy storage: A comparative analysis. *Energy Policy*, 115:572–583, Apr. 2018. ISSN 03014215. doi: 10.1016/j.enpol.2018.01.029.

J. Wiseman. The great energy transition of the 21st century: The 2050 Zero-Carbon World Oration. *Energy and the Future*, 35:227–232, Jan. 2018. ISSN 2214-6296. doi: 10.1016/j.erss.2017.10.011.

M. Wolsink. Wind power and the NIMBY-myth: Institutional capacity and the limited significance of public support. *Renewable Energy*, 21(1):49–64, Sept. 2000. ISSN 0960-1481. doi: 10.1016/S0960-1481(99)00130-5.

M. Wolsink. Social acceptance revisited: Gaps, questionable trends, and an auspicious perspective. *Energy Research & Social Science*, 46:287–295, Dec. 2018. ISSN 2214-6296. doi: 10.1016/j.erss.2018.07.034.

World Bank. World Bank Country and Lending Groups. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups, 2020a.

World Bank. World Development Indicators: Electricity production, sources, and access. http://wdi.worldbank.org/table/3.7, 2020b.

R. Wüstenhagen, M. Wolsink, and M. J. Bürer. Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, 35(5):2683–2691, 2007. ISSN 03014215. doi: 10.1016/j.enpol.2006.12.001.

D. Yergin. *The Quest: Energy, Security, and the Remaking of the Modern World*. Penguin Books, London, updated, revised, reprint edition, 2012.

R. K. Yin. *Case Study Research : Design and Methods*. Sage, Los Angeles, 2009. ISBN 978-1-4129-6099-1 1-4129-6099-1.

A. Zeileis. Econometric computing with HC and HAC covariance matrix estimators. *Journal of Statistical Software, Articles*, 11(10):1–17, 2004. ISSN 1548-7660. doi: 10.18637/jss.v011.i10.

A. Zeileis. Object-oriented Computation of Sandwich Estimators. *Journal of Statistical Software; Vol 1, Issue 9 (2006)*, Aug. 2006.

A. Zerrahn, W.-P. Schill, and C. Kemfert. On the economics of electrical storage for variable renewable energy sources. *European Economic Review*, 108:259–279, 2018.

C. Zhang, Y.-L. Wei, P.-F. Cao, and M.-C. Lin. Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews*, 82:3091–3106, 2018a. ISSN 13640321. doi: 10.1016/j.rser.2017.10.030.

X.-Q. Zhang, C.-Z. Zhao, J.-Q. Huang, and Q. Zhang. Recent Advances in Energy Chemical Engineering of Next-Generation Lithium Batteries. *Engineering*, 4(6):831–847, Dec. 2018b. ISSN 2095-8099. doi: 10.1016/j.eng.2018.10.008.

C. Zöphel, S. Schreiber, T. Müller, and D. Möst. Which Flexibility Options Facilitate the Integration of Intermittent Renewable Energy Sources in Electricity Systems? *Current Sustainable/Renewable Energy Reports*, 5(1):37–44, Mar. 2018. ISSN 2196-3010. doi: 10.1007/s40518-018-0092-x.