

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# Barriers to Electrification of the Energy System

Meeting Rising Electricity Demand from Industry and Transport

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Department of Environmental and Energy Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

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Acknowledgements, dedication, and similar personal statements in this thesis reflect the author's own views.

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## Abstract

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In the face of accelerating climate change, electrification is central to the low-carbon transition. However, meeting rising electricity demand from industry and transport requires coordination across technologies, institutions, and actors. This thesis examines barriers to meeting this demand in Swedish and European electricity systems, focusing on stakeholder perspectives, operational and regulatory conditions, and long-term electricity supply under alternative demand and technology pathways.

The research combines three analytical approaches. First, Q methodology identifies stakeholder perspectives on barriers to electrification in Sweden. Second, a bridging analysis between socio-technical and techno-economic perspectives examines bottlenecks across three electricity futures with predetermined investments in offshore wind and nuclear power in Sweden. Third, an energy systems optimization model investigates how barriers to wind and solar deployment, alternative demand trajectories, and uncertainty in nuclear construction affect long-term European electricity investment.

The results highlight governance and institutional capacity as important determinants of electrification. In Sweden, stakeholders cite procedural deadlocks, political disagreements, and coordination challenges as obstacles to electricity infrastructure expansion. Across the three scenarios, bottlenecks emerge in all pathways but differ by technology. Wind and solar deployment is constrained by regulatory and operational arrangements developed around dispatchable generation, while new nuclear power faces financing challenges and uncertainty in construction times.

At the European level, barriers to wind and solar deployment can be represented as capacity expansion constraints in techno-economic models. When national constraints such as land-use acceptance and lengthy permitting reduce wind and solar deployment, reliance on more costly thermal generation increases. The analysis also shows that the timing and magnitude of electricity demand growth influence investment in solar PV, offshore wind, and nuclear power, while onshore wind remains comparatively stable. However, high upfront capital requirements limit the value of early investment to hedge against demand uncertainty.

Overall, the thesis finds that large-scale wind and solar deployment can provide a least-cost basis for electrification, but realizing this potential depends on overcoming institutional, regulatory, and infrastructure barriers. The challenge lies not only in identifying cost-effective pathways, but also in creating the conditions to implement them at the scale and pace decarbonization requires.

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**Keywords:** *Energy transition; Electrification; Energy system modeling; Q methodology; Transition bottlenecks; Meta-challenges; Technology deployment; Multi-level perspective*



# List of publications

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The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

- I. Phan, N. A., Hellsmark, H., Göransson, L., & Johnsson, F. (2025). Electrifying tensions: Stakeholder narratives to electrification of industry and transport in Sweden. *Energy Research & Social Science*, 126, 104142. <https://doi.org/10.1016/j.erss.2025.104142>
- II. Phan, N. A., Göransson, L., & Johnsson, F. (2026). Mind the gap: Mixed-methods approach to investigate transition bottlenecks to low-carbon energy futures. *Energy Reports*, 15, 108973. <https://doi.org/10.1016/j.egyr.2025.108973>.
- III. Öberg, S., Phan, N. A., Göransson, L., Vetier, M., Jewell, J., & Kazlou, T. (2026). Learning from history: applying empirical growth patterns of wind and solar power to model Europe's electricity transition. Submitted for publication.
- IV. Phan, N. A., Göransson, L., Johnsson, F., & Öberg, S. (2026). If not now, when? The impact of demand development on the evolution of the European electricity system. Manuscript.

## Author contributions

Nhu Anh Phan is the principal author of **Paper I**, **Paper II**, and **Paper IV**, and a co-author of **Paper III**, having the main responsibility for conceptualization and writing. Professor Lisa Göransson contributed to editing and discussions in **Papers I** and **II**, as well as the method development in **Papers III** and **IV**. Professor Filip Johnsson contributed to the discussions and editing of **Paper I**, **Paper II**, and **Paper IV**. Professor Hans Hellsmark contributed to the methodology, as well as editing and discussions in **Paper I**. Dr. Simon Öberg contributed to the methodology, investigation, and writing of **Paper III** as the principal author, as well as discussions and data visualization in **Paper IV**. Dr. Marta Vetier contributed to the methodology, writing, and discussion of **Paper III**. Professor Jessica Jewell contributed to the discussion and editing of **Paper III**. Dr. Tsimafei Kazlou contributed to the methodology and discussion of **Paper III**.



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Throughout the process of preparing the dissertation, I am cognizant of the fact that although the thesis bears my name, no research is ever undertaken alone. The work presented here has been shaped and supported by many people. The following words are an attempt to express my gratitude to all those who have contributed to the development of this work.

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To those who are just beginning their PhDs, I hope you find your footing, your people, and your place. I hope you hold onto a spirit of curiosity and adventure that lets you explore beyond the boundaries of what we know.

Finally, I am deeply grateful to my family and friends, who have been understanding and patient with my seemingly endless preoccupation with research. Your care and presence are woven into every page of this thesis.

Nhu Anh Phan,  
Göteborg, 30<sup>th</sup> September 2026

# Notes

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## Use of generative AI tools

In preparing this thesis, I have used AI models primarily for text editing and proofreading. In addition, during the development of the modeling process, AI assistance through GitHub Copilot has been used to interpret, clarify, and restructure code, as well as to identify and debug issues. All text, figures, and tables have been reviewed and verified, and I take full responsibility for the content of this thesis.



*“Action is hope. There is no hope without action.”*

- *Ray Bradbury*



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# 1. Introduction

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To address the numerous interconnected social, economic, and ecological challenges that climate change entails, systemic transformations are necessary across a broad range of socio-technical systems (Schot & Kanger, 2018). As energy use encompasses many economic sectors, a low-carbon energy transition lies at the heart of climate change mitigation and adaptation (IEA, 2021b).

The transition to a low-carbon energy system is characterized by substantial uncertainties regarding technological developments (Foxon, 2011; Usher & Strachan, 2012), policy directions (Vakulchuk et al., 2020), stakeholder responses, and future energy demands. While low-carbon technologies are available, their deployment depends on a broader socio-technical context. As electricity systems evolve, changes in technology portfolios, industrial activities, and energy supply chains (Bauer et al., 2022; Verbong & Geels, 2007) create both opportunities and tensions among stakeholders, influencing the pace and direction of the transition. As a consequence, the challenges associated with decarbonization extend beyond techno-economic considerations and relate to the capacities of socio-technical systems to adapt and coordinate change.

Furthermore, low-carbon energy transitions unfold along multiple timescales. Although long-term targets provide strategic direction, transition pathways are shaped by near-term constraints and uncertainties. Stakeholder preferences, expectations in relation to different technologies, regulatory and permitting processes, infrastructure deployment limitations, and uncertainty surrounding future demands can all influence how rapidly the energy transition progresses and which pathways ultimately emerge (Devine-Wright & Sherry-Brennan, 2019; Ellis et al., 2007;

## *1. Introduction*

Wretling et al., 2022). Understanding these factors is, therefore, essential for assessing the feasibility of low-carbon energy systems and the conditions required to achieve them.

Energy system optimization models (ESOMs) have long been used to inform energy policy and planning by identifying cost-efficient pathways for future energy systems (e.g., DeCarolis et al., 2017; Lombardi et al., 2020; Pfenninger et al., 2014; Strachan et al., 2016; Süsser et al., 2021). While these models provide valuable insights into technical and economic feasibility, they are often limited in capturing the socio-technical conditions that influence how transitions unfold in practice (e.g., Foxon et al., 2010; Hughes et al., 2013; Turnheim et al., 2015).

To tackle these limitations, there is a growing interest in integrating socio-technical perspectives into energy system analysis. Such integration can take several forms (DeCarolis et al., 2017; Li et al., 2015; Trutnevyte et al., 2019) including the representation of societal constraints within modeling frameworks (Cotterman et al., 2021; Hirt et al., 2020; Trutnevyte, 2014), the incorporation of uncertainty related to technology deployment (Heggarty et al., 2024) and demand development (Huang et al., 2016; Yue et al., 2018), and the combination of optimization models with complementary qualitative approaches (Li & Pye, 2018; Pye et al., 2018).

Despite recent advances, interdisciplinary approaches that bridge socio-technical transition research and energy system modeling remain underdeveloped. Given the scale and urgency of decarbonization, further methodological development is needed to better understand not only which future electricity systems are technically feasible, but also the conditions for their realization. This thesis contributes to that effort by examining how stakeholder perspectives, socio-technical bottlenecks, technological deployment, and long-term electricity demand evolution shape the capacity of electricity systems to undergo rapid transformation.

### **1.1. Electrification in focus**

Electricity plays a critical role in powering modern economies. Electricity makes up about 21% of global final energy consumption (IEA, 2025a) and 24% in the EU (European Commission, 2026a) in 2025, with about 60% and 30% of the generation share derived from fossil sources, respectively (IEA, 2023, 2025b). Electricity use is growing rapidly, becoming increasingly central to economic activities and serving as the primary energy source for many households.

Among the measures enabling the low-carbon energy transition, electrification, defined as the replacement of fossil-based energy carriers in industry and transport with the direct or indirect

use of electricity, is the cornerstone of the decarbonization of the energy system. The defining feature of the transition is the shift from energy systems dependent on mined or drilled fuels to systems dependent on the manufacture and deployment of technologies such as solar panels, batteries, electrolyzers, and power electronics. Both systems require extracted materials, but the low-carbon technologies primarily require metals, including rare earth elements, embodied in infrastructure, which underscore the importance of securing these minerals (IEA, 2021a) as well as developing different circular economy strategies to reuse these materials (Carrara et al., 2023; Savvidou et al., 2026). Meanwhile, fossil fuel systems depend on the ongoing extraction and consumption of fuels, resulting in overall high mining needs (Nijmens et al., 2023; Ritchie, 2024).

The World Energy Outlook 2025 heralded the new era, claiming that “The Age of Electricity is here” (IEA, 2025a), while the European Commission envisions Europe as the “first electro-powered continent” (European Commission, 2026a). These sentiments reflect an expected strong increase in electricity demand from both new sectors, such as data centers, and existing sectors that are undergoing electrification, such as heavy industries. The scenarios proposed by the International Energy Agency (IEA) assume a large increase in electricity demand, rising by up to 50% in 2035. Investments in electricity generation and end-use electrification already represent half of global energy-related spending (IEA, 2025a). However, the speed at which the associated infrastructure, including electricity generation capacity, transmission and distribution grids, seasonal storage, and other flexibility resources, can be deployed remains a challenge. Delays in their deployment risk stalling electrification projects under development and increasing electricity costs.

Across Europe, the declining emissions intensity of electricity generation has increased the attractiveness of electrification as a key strategy for achieving net-zero climate targets, supported by a growing suite of policy instruments and regulatory initiatives (European Commission, 2026c). However, the expansion of electrification also unfolds within a complex geopolitical context that is characterized by evolving energy trade dynamics and energy security concerns (IEA, 2025a).

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Sweden is a compelling case in that its electricity system is already largely decarbonized, and the country has adopted ambitious climate objectives while actively pursuing demand-side electrification and flexibility measures (Government Offices of Sweden, 2024b; Swedish Energy Agency, 2023b; Swedish Government Office, 2021). Nevertheless, there are still substantial challenges with respect to the broader decarbonization of the energy system, particularly given ongoing political debates and competing visions regarding the future directions of energy and climate policies. Thus, studying barriers to energy system electrification in Sweden provides relevant insights for countries and regions that have similar conditions.

### **1.2. Aims and scope**

This thesis explores the barriers to large-scale electrification and the factors shaping its pace and direction. To address this aim, the thesis adopts multiple analytical perspectives, examining stakeholder perspectives, transition bottlenecks, and future electricity system development under electricity supply growth constraints and uncertain demand trajectories. The analytical focus is illustrated in Figure 1.

The overarching research question is: How do different transition barriers influence the ability of the energy system to handle large-scale electrification? This question is linked to three supporting research questions, which are associated with the four appended papers:

- How are challenges to electrification perceived and framed by key stakeholders? (**Paper I**)
- What bottlenecks emerge across different electrification pathways? (**Paper II**)
- How do electricity supply growth limitations and varying demand trajectories shape future electricity system development? (**Papers III and IV**)

In this thesis, **Papers I** and **II** focus on Swedish case studies and provide snapshots of the present electrification challenges, while **Papers III** and **IV** adopt a European perspective and examine the long-term development of electricity systems. The research progresses from understanding stakeholder perspectives on barriers to electrification (**Paper I**) and identifying the transition bottlenecks for alternative future electricity systems (**Paper II**) to investigating how limitations on wind and solar power growth (**Paper III**) and demand-related constraints and uncertainties (**Paper IV**) will shape future electricity system development.

**Paper I** presents an assessment of the perceived importance of a variety of socio-technical challenges to the electrification of industry and transport, taking stock of both the scientific literature and the viewpoints of stakeholders in a narrative analysis. The so-called Q methodology is applied, which combines both quantitative and qualitative elements in analyzing stakeholder viewpoints. This exercise addresses a gap in the absence of narrative analysis methods that involve stakeholders with high stakes in the key decisions on energy transition, focusing on a group of pathways instead of individual technologies, and with an emphasis on barriers or challenges to follow selected pathways. The study enhances our understanding of how challenges are conceptualized in the context of low-carbon transitions, providing a crucial basis for transition policy design. Beyond empirical insights, the theoretical aim is to contribute to transition studies by demonstrating how contested stakeholder interpretations of individual challenges aggregate into structured meta-challenges.

**Paper II** applies a method that bridges a socio-technical analysis through the Multi-Level Perspective (MLP) and a techno-economic analysis using energy system modeling, in order to identify and delineate transition bottlenecks. **Paper II** assumes that different modeled pathways yield bottlenecks of different strengths, so the strengths and characteristics within and across the pathways are analyzed. This paper builds upon an emerging body of literature that connects quantitative scenario analysis with qualitative storylines. The socio-technical analysis enables us to specify the logic that drives the Swedish electricity regime, including the context, the challenges, and enabling factors for expansion or further implementation of the key technologies. This analysis is coupled with the results from a techno-economic analysis, which concerns not only a cost-optimal technological mix, but also explores options that could, for instance, be politically driven. The transition bottlenecks are then mapped out based on the gap between the current regime and the requirements for different future pathways.

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**Papers III and IV** are built on future scenario developments using a multi-year model, with the aim of understanding the evolution of the electricity system in Europe under conditions of supply and demand uncertainties. **Paper III** is developed on the premise that while multiple socio-technical and socio-political barriers impact the deployment of energy technologies such as wind and solar power, representing them in modeling practices is challenging, since they exhibit different characteristics depending on the barriers they represent. To quantify the compound impact of these barriers, an optimization modeling framework is developed accounting for different growth limits on the continental, national, and system levels based on historical deployments, and the outputs are compared across Europe.

**Paper IV** focuses on how electricity demand trajectories impact the generation mix and investment decisions. This study reflects the growing interest in understanding how the uncertainties linked to supply and demand development influence future low-carbon technology mixes. In the model, different assumptions are applied regarding the magnitude and uncertainty of electricity demand, as well as the uncertainty of the construction time for nuclear power. Because growth constraints on electricity generation technologies can amplify the effects of demand uncertainty, this work extends previous techno-economic analyses of demand uncertainty by accounting for technology growth limits in such a model.

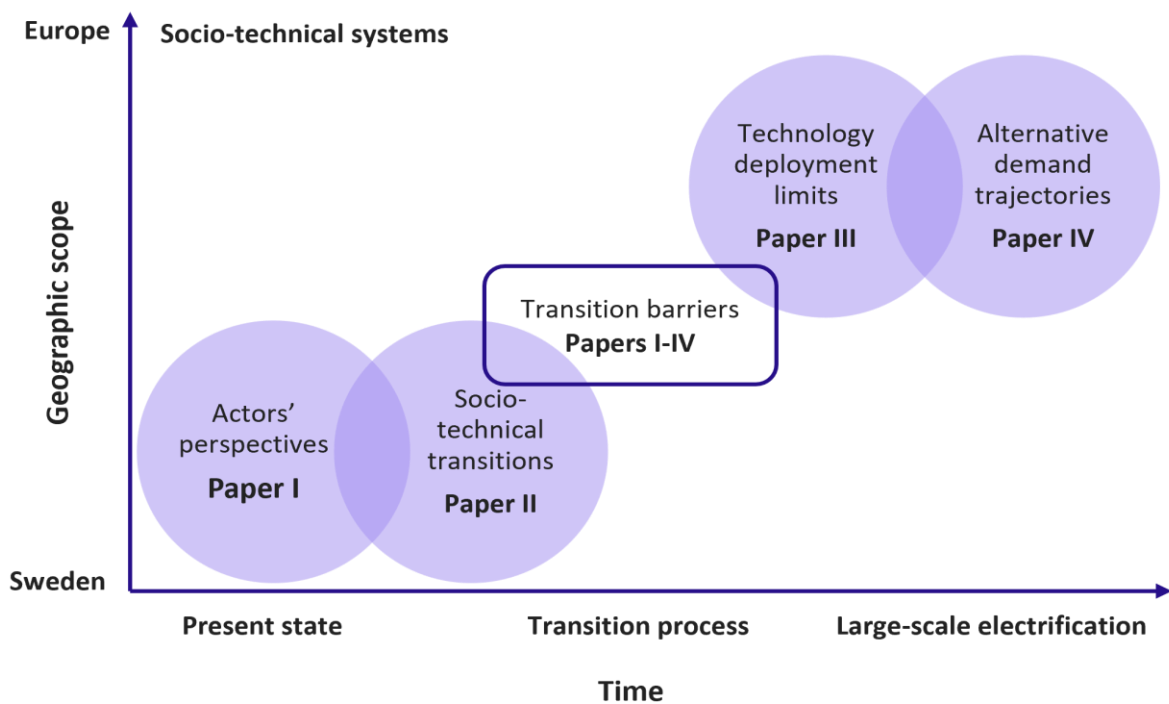


Figure 1: Analytical focus of the appended papers.

Methodologically, all of the appended papers utilize a mixed-methods approach that combines qualitative and quantitative analyses to identify socio-technical challenges in the Swedish electrification case. The work employs three analytical angles to address the factors that hinder the electrification of industry and transport, including narrative, socio-technical, and techno-economic analyses. The narrative analysis, which focuses on the challenges faced by key stakeholders and institutions regarding the transition, is conducted in **Paper I**. **Paper II** incorporates socio-technical and techno-economic analyses to identify the transition bottlenecks to electrification. **Papers III** and **IV** extend the energy system optimization modeling by incorporating socio-technical dimensions through deployment constraints on wind power, solar power, and nuclear power, and under shifting demand trajectories.

Terminology-wise, the thesis refers to factors that hinder the transition, using the terms barriers, challenges, and bottlenecks. While these terms generally refer to factors that block or halt the transition, there are slight differences in the connotations of these words, and these align with how our research has been developed. Barriers are specific activities or elements that must be overcome for the transition to succeed. Challenges, which can be driven by barriers or a group of barriers, are regarded as not only factors that limit the transition but also offer opportunities to transform the system. Meta-challenges are the aggregated narratives on challenges as interpreted and assessed by key stakeholders associated with **Paper I**. The transition bottlenecks and their levels of criticality instead differ depending on the specific transition pathway, i.e., they are linked to the transition to different electricity futures linked to **Paper II**.

The findings of this work increase the understanding of the factors that influence the electrification of industry and transport in Europe and in regions with similar conditions, as a major strategy for the low-carbon energy transition. Thus, the outcomes contribute to more informed decision-making by improving understanding of the challenges associated with alternative energy transition pathways. Theoretically, the aim is to broaden our understanding of the energy transition by incorporating discursive aspects through the concept of meta-challenges, as well as the interplay between institutional, infrastructural, and regulatory elements, through the concept of transition bottlenecks. From the modeling perspective, this thesis integrates socio-technical considerations into techno-economic optimization frameworks. This is achieved through the representation of wind and solar deployment constraints and the treatment of demand and nuclear construction uncertainties using stochastic programming with probabilistic scenario pathways.

### 1.3. Outline of the thesis

The thesis consists of this summary essay and the four appended papers. The essay highlights the key outcomes from the studies described in the papers and places the work in context. Following this *Introduction*, Chapter 2 provides the background to the work, followed by Chapter 3 on the research context. Chapter 4 synthesizes the key methodologies used. Chapter 5 highlights and discusses the results relevant to the above-mentioned aims and research questions. A reflection on the methodology and findings is included in Chapter 6. Chapter 7 lists the conclusions drawn from the work.

## 2. Background

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This chapter introduces the conceptual foundations of the thesis. It reviews the theoretical frameworks and analytical approaches used to investigate the challenges to the transition, with particular focus on low-carbon energy transitions, and outlines how these frameworks inform the methodological approach adopted in the thesis. Section 2.1 examines the socio-technical transition theory, which is relevant to all the appended papers, with an emphasis on the Multi-Level Perspective (MLP) framework used in **Paper II**. The contestation and consensus of low-carbon energy transitions through narrative analysis, with the Q methodology implemented in **Paper I**, is described in Section 2.2. Section 2.3 describes approaches to analyze the transition pathways from the Energy Systems Optimization Modeling (ESOM) used in **Papers II-IV**, focusing on three analytical dimensions: MLP-ESOM bridging; growth limits; and uncertainty treatment with stochastic programming.

### 2.1. Socio-technical transitions and the Multi-Level Perspective

Socio-technical system theory posits that societal systems depend on the interactions between social (actors, institutions, and cultures) and technical sub-systems (technologies and materials) (Geels, 2002; Rip & Kemp, 1998). When these systems that span domains such as energy, food, and mobility undergo change to fulfill new societal functions (Geels, 2004), new socio-technical configurations emerge. This process is termed a socio-technical transition. Consequently, socio-technical transitions are inherently multi-actor and multi-dimensional, typically unfolding along different spatial and temporal scales.

## *2. Background*

Research on sustainability transitions focuses on the meso-level of socio-technical systems (Geels, 2010). Rather than concentrating on macro-level transformations, such as changes in capitalism or society-nature relations, or on micro-level changes in individual behaviors, transition research examines how the interactions between technologies, institutions, infrastructures, markets, and actors shape the processes of system transformation (Köhler et al., 2019). While these transitions are often motivated by sustainability objectives, the analytical focus remains on the dynamics through which socio-technical systems evolve and change.

One of the most widely applied frameworks for analyzing socio-technical transitions is the MLP framework. Drawing on structuration theory (Geels, 2014), the MLP conceptualizes transitions as the outcomes of interactions between social structures, actor practices, and technological developments (Geels, 2004; Turnheim et al., 2015). It focuses on the rules, norms, institutions, and material artifacts that shape and constrain the actions of actors within a socio-technical system. The framework has been applied to study large-scale and long-term shifts, such as the transition of horse-drawn carriages to automobiles (Geels, 2005) and the decarbonization pathways of the German electricity system (Rogge et al., 2020).

The MLP framework distinguishes between three analytical levels: niches, regimes, and landscapes. Niches are protected spaces in which novel technologies, practices, and business models can emerge and develop. Regimes constitute the dominant socio-technical configuration, including established technologies, infrastructures, regulations, institutions, and actor networks. The regime is considered “dynamically stable” and “incumbent” (Geels, 2002; Geels et al., 2017). The landscape level encompasses exogenous developments, such as demographic trends, macroeconomic conditions, cultural values, and climate change, which influence but are largely beyond the direct control of actors who are operating within regimes. Transitions of socio-technical systems occur through struggles between actors, technologies, and institutions across different levels, as interactions between these levels enable niche innovations to gain momentum under landscape pressures and potentially challenge existing regimes, leading to regime shifts or even regime replacement (Geels, 2004).

The socio-technical transition process is often characterized as both complex and non-linear, akin to evolutionary processes. This poses analytical challenges in linking the present systems, shaped by historical developments and institutional legacies, and future systems for which multiple trajectories remain possible, both of which contain nested and dependent elements and processes (Turnheim et al., 2015).

Defining characteristics of socio-technical regimes are their tendency toward stability and resistance to change (e.g., Bergek & Onufrey, 2014). Existing technologies, infrastructures, regulations, and institutional arrangements reinforce one another through path-dependent processes that favor established practices and investments. While such path dependencies contribute to the continuity of socio-technical systems, they can also create lock-in effects that hinder innovation and slow transitions toward more sustainable configurations (Aklın & Urpelainen, 2013; Barazza & Strachan, 2021). The persistence of fossil fuel-based energy systems across many industrialized economies illustrates how path dependency can constrain transformative change (Unruh, 2000).

Earlier transition studies focused predominantly on the emergence of novel technologies, particularly green innovations at the niche level (Geels, 2014; Späth & Rohracher, 2012), even though technological innovation constitutes only one aspect of broader societal transitions (Geels, 2004). Furthermore, the MLP framework deliberately remains flexible regarding how analytical levels are defined and what elements they encompass (Geels, 2010). This flexibility has enabled the performance of rich, qualitative analyses that capture the heterogeneous, contingent, and multi-level natures of transitions (Andersson et al., 2014). At the same time, it offers limited guidance for assessing long-term transition pathways in relation to technical feasibility and system-wide constraints.

The four papers included in this thesis share a common focus on the transformation of the electricity system, which is regarded as a socio-technical system. Drawing on the socio-technical regime concept developed by Geels (2004), the electricity system is regarded not merely as a collection of physical assets and technologies but as an interconnected configuration of technologies, actors, institutions, policies, and narratives that both shape and are shaped by broader technical and societal developments (Geels, 2010; Geels et al., 2016; Hofman et al., 2004). The papers engage with this perspective to different extents and from different angles. **Paper I** focuses on the narrative dimension of socio-technical change, while **Paper II** examines the dynamics across multiple dimensions of the socio-technical regime. **Papers III** and **IV** focus on how the deployment limits to wind and solar power, as well as nuclear power, which reflect the regime resistance to change, impact the investment needs of energy technologies and infrastructure within a changing socio-technical context.

## 2. Background

### 2.2. Contestation and consensus within transition narratives

The energy transition, and more broadly, sustainability transitions, are usually defined as complex problems that involve multiple actors from different segments of society. How the system evolves is contingent upon how these actors perceive and unravel the challenges and take steps to address them, which in turn depends on the values and interests of these actors and actor groups. Such values and interests form cognitive frameworks for how they interpret problems and evaluate solutions (Bogner et al., 2024; van den Broek et al., 2024).

As transitions unfold, contestations emerge from differing actor interpretations of the transition and the pathways that they seek to advance (Andersson et al., 2026; Sovacool, 2017). These divergent perspectives highlight the need for analytical approaches that can systematically examine how actors make sense of the transition process. This prompts research that aims to understand transition narratives (e.g., Bauer, 2018; Luederitz et al., 2017; Moezzi et al., 2017), which shed light on how transitions might unfold to address grand societal challenges.

There exist different methods to conduct narrative analyses. Given that (1) narratives make sense of a transition, and (2) a narrative is formed based on the viewpoints of a stakeholder, which are then shaped by their values and norms to decide which problems and solutions should be collectively prioritized, it is important to investigate the subjectivity in how stakeholders express the challenges that are hindering the energy transition. In this process of analyzing narratives, the viewpoints of these actors emerge beyond the organizations to which they are affiliated, although their opinions are ultimately shaped by their sectoral domains.

To identify and analyze the key narratives in relation to the challenges, here referred to as meta-challenges, to electrification as a means to achieve net-zero carbon emissions, this thesis applies the so-called *Q methodology*. Originally developed by Stephenson (1953), the Q methodology is designed to study human subjectivity and perception in structured and replicable ways (Brown, 1996; Stephenson, 1953; Watts & Stenner, 2012). To operationalize a Q study, participants are presented with a set of statements about a topic and asked to rank them on a forced distribution grid, with the responses typically ranging from "mostly disagree" to "mostly agree", or from "least important" to "most important". The resulting rankings, or Q sorts, are then analyzed statistically to identify groups of participants who share similar response patterns. These patterns are extracted as factors and interpreted qualitatively as coherent storylines (narratives) that represent distinct ways of understanding the issue at hand.

Unlike traditional survey techniques that generalize opinions by correlating variables from large, representative samples, or transition research, which tends to have a strong qualitative component, the Q methodology applies surveys and interviews to a relatively small group of stakeholders in order to explore and analyze different viewpoints. Its purpose is not to determine how common a view is in a larger population or present a comprehensive set of narratives in a discourse (Bauer, 2018), but to demonstrate the diversity of perspectives within a topic (Cuppen, 2012), including the identification of underrepresented or new perspectives (Rodhouse et al., 2021). As a result, the Q methodology combines elements of both qualitative and quantitative research. The ranking process and factor analysis provide a systematic and transparent way of identifying perspectives, while the interpretation of the results preserves the contextual richness of qualitative research. Importantly, the Q methodology is specifically designed to study subjectivity. Rather than examining factual knowledge, the method explores how people understand, value, prioritize, and frame complex issues. These elements make the Q methodology suitable for investigating and mapping narratives for complex topics, such as environmental issues and the energy transition (Brown, 1996; Watts & Stenner, 2012).

The Q methodology has been applied in many studies related to sustainability transitions, covering technological topics such as bioenergy (Bauer, 2018; Lobensteiner & Losacker, 2026; Sleenhoff et al., 2015), carbon capture and storage (Setiawan & Cuppen, 2013), geoengineering framing (Cairns & Stirling, 2014), hydrogen technology (Baxter & Hacking, 2015), renewable power (Ellis et al., 2007; Späth, 2018), and industrial decarbonization (Andersson et al., 2026; Steen et al., 2024). Some of these studies have focused on policy-related topics, such as resistance to carbon tax (Mehleb et al., 2021) and energy transition policy preferences (Kilpeläinen et al., 2019). In terms of stakeholder viewpoints, while some studies have emphasized areas of consensus and conflict (J. Andersson et al., 2026; Bauer, 2018; Ligtvoet et al., 2016), others have concentrated on trade-offs and challenges (Ellis et al., 2007; Olazabal & Pascual, 2015; Späth, 2018; Steen et al., 2024). Fewer studies have examined the cognitive and emotional perceptions of a given policy direction or technological development (Olazabal & Pascual, 2015; Sleenhoff et al., 2015). Most Q studies apply only the Q methodology, while some also combine it with other participatory approaches (Cuppen et al., 2020). Nonetheless, compared to its impact on adjacent fields, the Q methodology remains underutilized in transition research (Hansmeier et al., 2021).

## 2. Background

**Paper I** addresses the gap in stakeholder narratives concerning the challenges associated with electrification in Sweden. Given the influential roles of key stakeholders in the decision-making processes underpinning the Swedish energy transition, their perspectives constitute the primary focus of this research. The approach highlights the subjective nature of these challenges and reveals areas of contestation and consensus among the stakeholders. By aggregating the diverse viewpoints into overarching meta-challenges, the study provides a nuanced understanding of the challenges associated with electrification. Theoretically, **Paper I** proposes the concept of meta-challenges as a discursive lens to assess the challenges to sustainability transitions as they are collectively perceived by stakeholders at a given point in time.

### 2.3. Modeling the low-carbon energy transition pathways

There is growing interest in combining social science studies on energy transition with modeling approaches. Phan (2025) provides an overview of the different approaches to link qualitative research and quantitative modeling. Such integrative exercises can improve models by providing a more comprehensive representation of reality (Trutnevyte et al., 2019). This can support more effective climate and energy solutions, particularly in contexts where decision-making must account for uncertainty (Bock & Pfenninger-Lee, 2025; Süsser et al., 2021).

In the appended papers, the incorporation of various socio-technical elements of the energy transition is reflected in three ways. **Paper II** bridges the insights of the socio-technical analysis and techno-economic analysis in a case study of Sweden. This exercise has a forward-looking perspective that enables us to move from identifying problems to discussing solutions that are grounded in the context of the investigated systems and plausible futures.

**Paper III** applies several implementations of the growth limits on wind and solar power to assess the long-term development of the European electricity system. This method increases the realism of the model results by accounting for the interplay between empirical factors that impact the growth of wind and solar electricity generation.

**Paper IV** examines how uncertainties in relation to the future electricity demand and technology-specific deployment constraints on wind, solar, offshore wind, and nuclear power affect the optimal technology mix of the European electricity system. The approach helps to identify both shared and divergent investment patterns across different demand trajectories, thereby providing insights into investment robustness under demand uncertainty.

### 2.3.1. Bridging between socio-technical analysis and energy systems optimization models

**Paper II** combines the MLP as a socio-technical transition framework and ESOM as a techno-economic framework. By systematically characterizing the processes and factors operating at each level, the analysis provides a bridge between qualitative transition theory and quantitative energy-system modelling, enabling socio-technical insights to be interpreted alongside assessments of technically feasible futures.

Accordingly, this thesis applies the concept of transition bottlenecks to operationalize the combination between MLP as a socio-technical transition framework and ESOM as a techno-economic framework. In the transition literature, Geels et al. (2020) propose to use the concept of transition bottlenecks as a “methodological aid” to mediate the “tension” between energy system optimization modeling (ESOM) and multi-level perspective analysis due to their different focuses, e.g., on technical and operational feasibility for ESOM versus social and political feasibility for MLP, and timeframes, e.g., on future low-carbon technological mixes for ESOM versus historical development and contemporary trajectories for MLP (Geels et al., 2020).

A transition bottleneck can be seen as a factor or a group of factors that hinder the progress or development of the transition. These factors could be derived from events such as an economic crisis (Geels, 2024), institutional structures such as decision-making traditions (Fuenfschilling & Truffer, 2014), organizational routines (Smith, 2007), cultural norms (Geels & Verhees, 2011), or conflicts of interest that could resist changes due to different ideas of what, how, why, by, and to whom changes should entail. Transition bottlenecks are strongly tied to the path dependency of the electricity system. Thus, an understanding of these transition bottlenecks, which represents the gap between the current and end-state of the regime, could contribute to, for instance, a more concrete and differentiated identification of the typology of transition pathways, as described in Geels & Schot (2007), or transition policy, as laid out in Rogge et al. (2020).

## 2. Background

While **Paper II** adopts the MLP-ESOM bridging approach proposed by Geels et al. (2020), two key modifications are introduced. First, rather than using MLP and ESOMs as parallel analytical frameworks, the MLP is used to examine the socio-technical feasibility of the modeled energy system cases and to interpret the model results. Building on the identification of transition bottlenecks, the focus is on specifying the enabling conditions required to realize each case, rather than constructing transition narratives. This approach is particularly suited to the objective of systematically comparing alternative pathways for achieving the electrification of Swedish industry and transport, with and without nuclear power expansion. While this emphasis on enabling conditions supports a structured comparison of modeled futures, it provides less insight into the dynamics and sequencing of socio-technical change than narrative-based pathway approaches.

Second, whereas the original study by Geels et al. (2020) generates transition pathways through the integration of MLP and ESOM analyses, our case design is structured around three model outcomes: a cost-optimal reference case and two higher-cost alternatives that could be motivated by other factors such as political preference. This design allows us to examine the requirements and challenges associated with energy futures rooted in distinct political preferences, rather than to develop new transition pathways from the methodological integration itself.

### 2.3.2. *Implementation of technological growth in energy systems optimization models*

To explore cost-optimal mitigation pathways for low-carbon electricity systems, ESOMs are widely used (Eurelectric, 2023; Lo Piano et al., 2023). It is crucial to represent barriers and drivers to capacity expansion beyond techno-economic feasibility in scenario analyses, for example by incorporating technology deployment dynamics into ESOMs (Pfenninger et al., 2014). The combined impact of the barriers to growth can, for example, be parameterized as maximum investment rates (Heggarty et al., 2024; Heuberger et al., 2017), as well as spatial limitations, such as the maximum deployment rate of wind power (Hedenus et al., 2022). There have also been implementations of heuristic strategies that limit technological deployment at a location, so as to enable a more spatially balanced electricity generation infrastructure (Lombardi et al., 2020, 2023; Tröndle et al., 2020). Furthermore, a technological learning or experience curve has been incorporated into ESOMs to correlate cost estimates with deployment levels (Heuberger et al., 2017; Ouassou et al., 2021).

**Paper III** focuses on deployment limits for wind and solar power because of their central role in climate mitigation pathways (IEA, 2024a; IRENA, 2024) and their modular design, which enables rapid scaling (Jakhmola et al., 2026). Nevertheless, there is considerable debate regarding how quickly these technologies can continue to expand and whether the deployment rates required to meet climate targets are consistent with (van Sluisveld et al., 2015; Wilson et al., 2013), or exceed, historical patterns of technological change (Napp et al., 2017; Smil, 2016). To better understand these prospects, the diffusion of energy technologies has been widely studied (Grubler, 2012; Wilson et al., 2013).

Technology diffusion is typically characterized by distinct growth phases and stylized growth rates that are shaped by a combination of barriers and drivers to deployment (Cherp et al., 2021). As technologies progress from a formative phase of erratic growth and initial acceleration, they eventually reach an inflection point, followed by a period of steady growth (Jewell et al., 2026). The S-curve has therefore become one of the most widely used frameworks for describing the long-term diffusion of low-carbon technologies, including wind and solar power. However, empirical evidence suggests that deployment rarely follows a smooth S-shaped trajectory. Instead, growth is often characterized by periods of acceleration and deceleration (Kulmer et al., 2022; Vetier et al., 2026), introducing uncertainty regarding when deployment rates may slow and how long rapid growth can be sustained. In contrast, deployment limits for nuclear power are assessed using historical deployment experience, reflecting its large unit sizes, long construction times (Brutschin et al., 2021), and stepwise expansion patterns (Jakhmola et al., 2026), which differ fundamentally from the scalability of wind and solar technologies.

There are different ways to implement capacity expansion constraints in ESOMs. Exogenous constraints are commonly applied to annual capacity expansion rates across different technologies and regions (Leibowicz et al., 2016). These constraints, expressed either as absolute values or percentages, represent the investment limits for a given technology within a specific region.

For instance, Heuberger et al. (2017) have used historical maxima of annual build rates for countries with similar conditions as the upper limit for thermal and renewable power generation technologies, while Heggarty et al. (2024) have allocated rates of deployment of nuclear and renewable power based on the deployment in countries that have been forerunners in different technologies, e.g., France in nuclear power and Germany in solar power, and have scaled the limit according to the growth in annual electricity demand.

## 2. Background

Linsel et al. (2025) have assumed the maximum capacity growth from historical data, extrapolating that technologies expand according to a logistic function. Although these contributions recognize that realistic deployment limits must be integrated into capacity-expansion modeling, they are not ideal in terms of representing how limits on supply expansion interact with different demand trajectories to shape system outcomes.

In **Paper III**, growth rates for wind and solar power are given exogenously to evaluate the system-level impacts of limiting wind and solar power growth rates in a capacity expansion model. These deployment constraints are represented using technology-specific approaches, including historical growth patterns for wind and solar power, simulation-derived estimates for offshore wind, and historical construction rates for nuclear power. While many of the economic, infrastructural, social, and political barriers that affect deployment are not represented explicitly as individual model parameters, their effects are captured through the empirically derived growth trajectories associated with different implementation pathways. In this way, the techno-economic model links barriers to growth with the characteristics of continental, national, and system-scaled implementations: differences in observed deployment trajectories reflect how these barriers, together with their associated drivers, have constrained or enabled the diffusion of each implementation. The resulting growth trajectories therefore provide an empirical means of representing the compounded effects of multiple underlying constraints without requiring each barrier to be modelled individually. This connection between barriers to growth and implementation-specific deployment trajectories is a key feature of the approach.

**Paper III** further investigates the interplay between the assumed growth rates, the technical potential for wind and solar deployment, and the cost-competitiveness of wind and solar resources. By comparing the influences of these factors, the analysis seeks to identify which ones exert the strongest effects on the long-term development of a country's electricity system. The outcome helps to improve the realism and feasibility of long-term capacity expansion modeling by incorporating growth dynamics that better reflect the observed patterns of technology diffusion.

### 2.3.3. *Dealing with uncertainties in energy system optimization models*

The energy transition raises a range of political, social and technological uncertainties for which hard data are sparse and non-linear, while there is an urgent need for solutions and decisions. Therefore, capturing uncertainties associated with the energy transition is essential for accurate assessments of the feasibility levels of different decarbonization pathways and for designing robust policy frameworks (Lo Piano et al., 2023; Lombardi et al., 2020). As interest grows in understanding how uncertainty shapes future energy systems, modeling approaches have moved beyond simple sensitivity analyses toward more systematic and comprehensive techniques for treating uncertainty.

In energy systems research, uncertainty regarding future systems may be understood in terms of parametric and structural uncertainties. Parametric uncertainty arises from uncertainties related to the values of a given factor that stem from inadequacies in the modeling inputs used to represent real-life or future conditions (DeCarolis, 2011). This can be studied using uncertainty analysis tools, such as sensitivity analyses, the Monte-Carlo technique, robust optimization, and stochastic programming, each of which is used to address different questions (Yue et al., 2018). Both Monte Carlo analysis (MCA) and stochastic programming require probabilistic information about uncertain factors, which can be obtained from the literature, from expert elicitation, or deduced based on the modeler's judgment. Monte Carlo analysis systematically explores the relationship between uncertain inputs and model outputs by evaluating a high number of realizations, and it can be combined with global sensitivity analysis to identify those factors that contribute most to output uncertainty (Saltelli & Annoni, 2010). It has been applied in many studies (Mavromatidis et al., 2018; Pilpola & Lund, 2020).

Stochastic programming, in contrast, incorporates uncertainty directly into the optimization problem by representing a limited number of possible states of the world and assigning probabilities to each scenario (Huang et al., 2016; Möst & Keles, 2010; Yin & Hou, 2024). When information about the underlying uncertainties or their probability distributions is unreliable or unavailable, robust optimization provides an alternative approach by defining plausible uncertainty sets, rather than relying on probabilistic assumptions (Babonneau et al., 2012; Labriet et al., 2015). This allows for a broader set of uncertain parameters to be considered and identifies decisions that take into account adverse realizations of uncertainty.

## 2. Background

Structural uncertainties are uncertainties linked to the modeling constraints and equations (or non-equations). A common approach to structurally modifying models is to use modeling to generate alternatives (MGA), which is used to explore near-optimal solutions in the feasible space (Brill, 1979; Brown et al., 2018; DeCarolís, 2011; Lombardi et al., 2020, 2023; Neumann & Brown, 2021, 2023). It uses cost-optimal results as the starting point, from which cost relaxation levels are determined to represent values not captured in the model formulations.

However, efforts to incorporate uncertainties into ESOMs render the model intractable without simplifications in relation to the temporal and spatial scopes. Furthermore, grand societal challenges, such as climate change, involve instances of uncertainty for which the probability distributions are unknown or not fixed, and it is difficult to represent tail events that have low probabilities but high impacts, such as heatwaves, *Dunkelflaute* (i.e., a period of time during which little or no energy can be generated with wind and solar power), and geopolitical shocks.

Much of the uncertainty in energy transitions arises from future policy choices, including transition objectives, policy targets, and political priorities. Such uncertainties are difficult to represent within standard energy system modeling frameworks because they depend on decisions that have not yet been made and may evolve over time (Yin & Hou, 2024). As a result, modeling studies often examine a limited set of policy pathways or target scenarios, which can either support existing policy directions (Ellenbeck & Lilliestam, 2019; Süsser et al., 2021) or justify delaying action (Sgouridis et al., 2022) until greater certainty emerges. Given these challenges, selecting which uncertainties to investigate requires balancing three considerations: their importance for future system developments, their influence on model outcomes, and the degree of uncertainty surrounding their input values (Pye et al., 2018).

While several variants of stochastic optimization exist (Bistline & Weyant, 2013; Yue et al., 2018), they generally incorporate multiple possible futures with associated probabilities and identify decisions that perform well across these futures. In doing so, they quantify the trade-off between early action and postponing decisions until additional information becomes available. The resulting hedging strategies favor moderate investments when they are more cost-effective than either premature commitment or inaction, enhancing both model realism (Hirt et al., 2020) and policy relevance (Bistline & Weyant, 2013).

Stochastic programming requires discernment as to which uncertainty is key for the scenarios. The approach has been applied to integrate uncertainties regarding: the demand side, such as the uncertainties linked to the price elasticity of demand and load variations; the supply side, such as technology availability and deployment (Korkmaz et al., 2021); the variability of renewable energy (Spiecker & Weber, 2014); and regulatory and market factors that impact electrical grid planning, climate policy, and commodity and fuel prices (e.g., Möst & Keles, 2010; Riepin et al., 2021). In the literature, studies that explore the evolution of generation investments under the dual, mid-term uncertainties of demand and technological developments are lacking. In this context, Riepin et al. (2021) and Spiecker & Weber (2014) have articulated the need to incorporate electricity demand uncertainty with increasing renewable energy capacity in a pan-European model, while Pilpola & Lund (2020) have emphasized the importance of considering projected energy consumption levels for future scenarios in a Finnish case study.

For ESOMs, stochastic programming has been applied to a variety of topics, including electricity price, emissions caps, technological availability, renewable resource availability, and policy instruments. In general, these variables, or a combination thereof, act as stressors when they materialize, making hedging a strategy that can prepare for real-life uncertainty and be represented in the model.

Building on the existing literature, **Paper IV** explores how Europe's electricity demand trajectories, in terms of level, pace, and associated uncertainties, shape supply-side technology outcomes in the presence of investment constraints and decision hedging. The study focuses on nuclear power construction rates and future demand developments. Historical evidence reveals that nuclear power build times vary substantially (Csereklyei et al., 2016), and although there are renewed discussions regarding a nuclear power revival in Europe (Andersson, 2024; World Nuclear Association, 2026), the pace at which new capacity could realistically be deployed (and whether such momentum could be replicated across countries) remains uncertain. While many European scenarios project increasing demands for electricity (IEA, 2024b; Weiss et al., 2024), the mechanisms to be used for scaling demand rely heavily on how quickly both the supply and demand infrastructures expand, making the trajectory far from clear. By combining deployment constraints on wind power, solar power, and nuclear power with demand uncertainty representation, this study captures demand uncertainty under constrained supply growth.



## 3. Research context

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This chapter focuses on the context in which the thesis is situated, which revolves around electrification as the key strategy to achieve the low-carbon energy transition. An overview of the transition is provided. Section 3.1 delves into the policy efforts and commitments regarding electrification, and the drivers and barriers to renewable and nuclear electricity in the European context in Section 3.1, in connection to **Papers III** and **IV**. Within the broader policy and institutional framework of Europe's energy transition, the development of Sweden's electricity regime and progress toward electrification are described in Section 3.2, which is relevant to **Papers I** and **II**.

### 3.1. Electrification in Europe - Ambition and implementation gap

#### *3.1.1. EU policy commitments to electrification*

Given the focus of the thesis on the electrification of the energy system, this section presents the targets and priorities associated with electrification in the European Union in the supply, distribution, and demand sides. This provides relevant background to all appended papers, especially **Papers III** and **IV**.

The EU's Electrification Action Plan lays out target on how much electricity should reach in the final energy consumption, with a target of 46% by 2040 from 25% of final energy consumption in 2025 (European Commission, 2026a). Electrifying the energy systems involves the dual process of removing fossil fuels from the energy system and adding low-carbon electricity to industry and transport processes.

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To achieve this, a variety of instruments are introduced in the Action Plan. These include: closing the price ratio gap between electricity and gas; streamlining permitting and boosting investments in grid connections; and enabling cost-effective technologies, such as heat pumps and electric vehicles, for end-use sectors (European Commission, 2026b). The uptake of electrification innovations is incentivized through instruments such as the Innovation Fund (European Commission, 2025c). These policy proposals work together with the European Union Emissions Trading System (EU-ETS) as a decarbonization driver within the region, which is now being revised to enable investment at scale and to provide flexibility for hard-to-abate sectors (European Commission, 2026c). According to the European Commission, electrification is not only a strategy to reduce emissions, but also a way to enhance energy security and competitiveness (European Commission, 2026c).

Efforts to decarbonize the electricity system in the region include different regulatory initiatives concerned with electricity generation expansion, grid buildouts, and demand-side electrification. On the supply side, the Renewable Energy Directive aims to raise the share of renewables in the energy mix to 42.5%, with the aspiration of achieving a 45% share of energy use by 2030 (European Commission, 2025b). Actions to speed up permit-granting procedures for renewable energy projects have also been initiated (European Commission, 2022). To accommodate a system with a high share of renewable electricity, an electricity market reform has been adopted by the European Council (European Council, 2024). This is designed to enhance price stability, for example, through supporting power purchase agreements and two-way contracts for difference (European Council, 2024). Structural elements that account for capacity adequacy are to be incorporated into the market regulation process, as well as measures to protect vulnerable groups against price volatility (European Commission, 2023b).

Regarding grid expansion and modernization, an EU action plan for grids has also been presented. This plan includes guidance for network planning on both the transmission and distribution levels, easing access to finance, and streamlining administrative processes, among other regulatory incentives (European Commission, 2023b).

For electricity-intensive industries, the *Fit for 55* package, which represents a reform of the EU-ETS, has been introduced to accelerate the reduction and phase-out of free emissions allowances for the energy-intensive industries (European Commission, 2025a; European Council, 2026). The system is also now extended to the maritime, transport, and building sectors (European Commission, 2025a; European Council, 2026). To ensure viable conditions for net-zero technologies and projects, the European Commission has also proposed a Net-Zero Industry Act within the European Green Deal (European Commission, 2023a). The 2026 proposal integrates carbon removals for hard-to-abate sectors, introduces Market Stability Reserve reforms, and reinforces coverage of the aviation and maritime sectors (European Commission, 2026c).

In addition, the proposed target for the transport sector, which requires new cars to be run on emissions-free fuels from 2035, is aimed at motivating transport actors to deploy their decarbonization roadmaps, especially for battery-electric vehicles (European Parliament, 2023). However, the proposal faces some backlash from lobbyists for internal combustion engine (ICE) automotive manufacturers (Dahl, 2024). These incentives are intended to encourage the further development of several innovations: from the electrification of manufacturing processes, as in the case of hydrogen-based steel production, to experimentation with flexibility measures, to scale-up solutions for vehicles run on lithium-ion batteries to accommodate heavy-duty transport. These incentives and targets reflect the role of electrification of the demand side in stimulating investments in electricity generation (Gladushenko et al., 2026; IEA, 2024e).

#### 3.1.2. *Uncertainties associated with the demand and supply of electricity*

Given the growing importance of electricity for economies, a key concern is how much and how quickly the electricity demand will increase, and whether a reliable, affordable electricity supply and supporting infrastructure can keep pace with this growth. The former provides the context for the method implementation in **Paper III**, while the latter is characterized in **Paper IV**.

In the recent projections for the European Union (EU) published by ENTSO-E in the *Ten-Year Network Development Plan* (TYNDP), the scenarios assume that the direct electricity demand in the EU-27 will increase by 35% to 55% by 2050 (ENTSO-E & ENTSOG, 2025). The net-zero scenarios studied by Eurelectric suggest that electricity in Europe will supply 50%–70% of the final energy use by 2050, as compared with 23% in 2024 (Eurelectric, 2024). The net-

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zero scenarios of the EU (European Union, 2020; Tsiropoulos et al., 2020) include scenarios with a doubling of the electricity share of final energy use, potentially reaching levels of 4,000–6,000 TWh/year, as compared with about 2,800 TWh/year currently. Despite short-term stagnation of the electricity demand due to industrial shutdowns and relocation (Eurelectric, 2025; Eurostat, 2025a), longer-term projections suggest that the acceleration of the electricity demand will intensify due to drivers such as technology adoption, sector-specific characteristics, the rise of new demand sources, such as data centers (Enerdata, 2025), and broader changes in population levels and economic structures (IEA, 2023; Weiss et al., 2024).

The scope, pace, and shape of electrification raise questions about the roles of different electricity generation technologies, notably renewable- and nuclear-powered electricity generation. For renewable electricity, despite the modest growth in the total electricity demand in Europe, the share has steadily risen over the past decades, accounting for almost half of the net electricity generated in the EU in 2024 (Eurostat, 2025b). This progress is made possible by various factors. These include stringent climate targets at the EU level, which assign renewable energy deployment as a key pillar of climate neutrality (European Commission, 2025b). In addition, support policies in individual countries have enabled successful deployment of wind and solar power, ranging from feed-in tariffs in Germany in the early growth phase (Lauber & Jacobsson, 2016) to auction schemes as the technologies become more cost-competitive (Danish Energy Agency, 2024b, 2024a; UK Department for Energy Security and Net Zero, 2016). With accelerating growth in the last decade, the global decline in costs has become the main driver for the deployment of onshore wind and solar power (Batz Liñeiro & Müsgens, 2025; Catsaros, 2025; IEA, 2024c).

However, in Europe, increasing the pace of wind and solar power deployment has been hindered by: lengthy permitting processes (European Commission et al., 2023; Ferris, 2022; Pettersson et al., 2010; Piotrowski & Gislén, 2024); a lack of social legitimacy (Flachsbarth et al., 2021; Harper et al., 2019; Koecklin et al., 2021; Lindvall et al., 2025); insufficient long-term system planning, which is associated with the slow pace of infrastructure scale-up (Battaglini et al., 2012; Dedecca et al., 2019; Tenggren et al., 2016; Verzijlbergh et al., 2017); and insufficiently rapid upscaling of system flexibility to accommodate a higher level of variability in the system (Belhomme et al., 2021; Bergaentzlé et al., 2017; Nagel et al., 2022).

While financing instruments for wind and solar power have become diversified over the years, it is complicated to determine the effectiveness of these instruments (Iskandarova et al., 2021; Shivakumar et al., 2019), particularly when the technologies have reached cost-competitiveness. For offshore wind power, the financing and securing of grid connections remain serious challenges. A failure to attract developers has occurred even in places where offshore wind power is more established, such as in Denmark (WindEurope, 2024) and the UK (Watson & Boston, 2024; WindEurope, 2023), due to auction designs.

To date, the exploitation of renewable energy resources has been uneven across the EU, ranging from 88% of the total electricity produced in Denmark to 5% of that produced in Luxembourg (Eurostat, 2025b). Regional disparities in technological diffusion exist due to differences in socio-economic development, administrative hurdles, and system integration challenges (Gajdzik et al., 2023; Menegaki, 2011), as well as different resource conditions. The differences observed across EU Member States suggest that some countries need to exceed their historic deployment levels significantly in order to meet climate targets.

Meanwhile, nuclear power accounted for about 23% of the total electricity generation in the EU in 2024 (Eurostat, 2025b), and it is receiving renewed interest in several European countries (World Nuclear Association, 2026b). Within the EU, the ambitions with regard to new nuclear capacity vary substantially. This includes Member States that are strongly supportive of nuclear power, such as Hungary (IAEA, 2025; World Nuclear Association, 2026c), Poland (Polskie Elektrownie Jądrowe, 2023; World Nuclear Association, 2026d) and Czechia (European Commission, 2024; Government of the Czech Republic, 2024), Member States that are taking steps to expand their nuclear power programs, such as Sweden (Government Offices of Sweden, 2026a), those expressing ambivalence, such as Belgium (World Nuclear Association, 2026a) and the Netherlands (World Nuclear Association, 2026e), and those showing opposition to nuclear power, such as Germany (Serrao, 2026; Thureau, 2026) and Denmark (World Nuclear Association, 2025). Nuclear power-supporting governments that are interested in expanding or developing their nuclear power fleet for electricity generation are required to take steps to secure investments (Barkatullah & Ahmad, 2017; European Commission, 2024), and to make progress in paving the way for its future development, e.g., reversing phaseout regulations, as in Belgium and Sweden (DW, 2025; Faber, 2023).

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As a lumpy technology, capital costs and construction times represent major uncertainties in relation to the development of nuclear power (Pye et al., 2015). Although nuclear power has been historically deployed during periods of strong electricity demand growth (Jewell, 2011), its deployment is constrained by long lead times, political opposition, and economic risk (Barkatullah & Ahmad, 2017; Sovacool et al., 2014). Differences across national systems, such as security priorities, governing party stances, recent or ongoing reactor construction, the presence (or absence) of a nuclear industry, and recent demand trends, influence both the likelihood of pursuing nuclear power and expectations in relation to future demand. Moreover, as most of the nuclear fleet in Europe and in other Western countries was constructed during the 1970s and 1980s, the elapsed time without significant nuclear power project development may have led to a decline in expertise and institutional capacity for delivering large-scale, technically complex engineering projects (Leibowicz et al., 2016). Yeh & Rubin (2012) have argued that this deployment gap leads to an institutional ‘forgetting phenomenon’, which adds significant uncertainty to the deployment; such discontinuity in levels of experience, coupled with the changes in the electricity regime, could drive up the cost and extend the construction time.

#### 3.2. The Swedish case of electrification

This section charts the historical developments of the electricity regime in Sweden before mapping out the landscape, regime, and niche factors that impact the Swedish electricity system. It provides a context relevant to the research design of **Paper II**.

The historical development of the electricity regime in Sweden is characterized by several phases, each of which entails key events and turning points. Stabilizing and destabilizing forces that contribute to changes within the regime are described in Table 1. These forces include political, policy, and other events that contribute to the socio-technical regime over time. Stabilizing forces reinforce the stability of the regime, while destabilizing forces challenge the regime and may lead to turning points within the regime, or even regime shifts. Three phases are presented, spanning from 2000 to 2025.

The development is set in the background period, covering the 1970s up to 2000, and is characterized by post-war modernization efforts. Almost the entire electricity sector was state-owned. Hydropower capacity was maxed out (Högselius & Kaijser, 2010), and the state invested heavily in nuclear power as a key component of the modern electricity system and as

a response to the oil crises (Faber, 2023), in addition to the expansion of combined heat and power and district heating. With the expansion of cities and the population, extensive electrical grids were built in Sweden (Myhr, 2025). In 1980, a referendum on nuclear power was held, which established an ambiguous, yet likely declining, fate for the further development of the technology. The 1990's financial crisis destabilized the established system. Vattenfall became a power corporation owned by the Swedish state in 1992, and the electricity market was deregulated in 1996 (Högselius & Kaijser, 2010). More details of the key events and developments before the deregulation of the energy market can be found in Phan (2025).

The first phase in Table 1 was characterized by an early wind power rush. The contribution of onshore wind power to the system increased with the introduction of the green electricity certificate system in 2003 (Boasson et al., 2020). The political coalition that made up the government elected in 2006 declined to phase out nuclear power, although it did not allow plant construction at new sites (Edberg & Tarasova, 2016). Before 2006, the Barsebäck 1 reactor closed in 1999, followed by the closure of the Barsebäck 2 reactor in 2005.

The second phase in Table 1 was marked by onshore wind maturity and continued decommissioning of nuclear power between the years 2006 and 2022. During this period, onshore wind power increased to 20% of the share in the system (IEA, 2024d; Swedish Energy Agency, 2025) and it became competitive even without subsidies (and the value of the electricity certificate eventually became zero) (Ganhammar, 2021).

Meanwhile, 6 out of 12 commercial nuclear reactors were decommissioned. The nuclear meltdown in Fukushima in 2011 intensified concerns about the need for investments in safety for the Swedish nuclear industry, which was already experiencing low profit levels. Afterwards, Oskarshamn 1 and Oskarshamn 2 reactors shut down in 2017 and 2016, respectively. Ringhals 2 reactor closed in 2019, and the Ringhals 1 reactor followed in 2020 due to a combination of economic pressure and changing company strategies. In the Energy Agreement in 2016 (Faber, 2023; Lindvall et al., 2025), the capacity tax for nuclear producers was removed (Faber, 2023; Sonnsjö, 2024). Bidding zones were introduced to inform Svenska Kraftnät on transmission bottlenecks and to enable more wind power to be established in high-price areas (Sonnsjö, 2024).

### 3. Research context

Table 1: Key phases in Swedish electricity regime (Edberg & Tarasova, 2016; Faber, 2023; Högselius & Kaijser, 2010; Sonnsjö, 2024).

| Phase                                                                              | Stabilizing forces for the regime                                                                                                                                                                                                                                        | Destabilizing forces for the regime                                                                                                                                                                                                                                                                                                                                                                                    | Policy agenda                                                                                                                                                                       |
|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>1970–2000</b><br>Background of post-war modernization and market liberalization | Heavy investment in nuclear power, with an initial interest in weapon proliferation <sup>1</sup><br>Hydropower capacity maxed out (further expansion strongly limited by environmental regulations)<br>Grid expansion<br>Formation and consolidation of energy companies | Cities expanded<br>Economic growth<br>1970: Oil crisis<br>1979 and 1986: Nuclear accidents at the Three-Mile Island and Chernobyl plants, respectively<br>1980s: Nuclear referendum and public resistance to nuclear power <sup>1</sup><br>1987: The Brundtland report on sustainable development <sup>1</sup><br>1990: Global financial crisis <sup>1</sup><br>1996: Deregulation of electricity markets <sup>1</sup> | Meeting demand with supply at low cost<br>Modernization of the electricity system<br>Energy security (security of supply in the face of the oil crisis)<br>Industry competitiveness |
| <b>2000–2006</b><br>Early wind power rush (Phase 1)                                | 2003: Electricity certificate system introduced, incentivizing renewables development <sup>2</sup><br>2006: Decision not to phase out nuclear power, but new sites not allowed <sup>1</sup>                                                                              | Barsebäck 1 reactor closed in 1999, followed by closure of the Barsebäck 2 reactor in 2005 <sup>1</sup>                                                                                                                                                                                                                                                                                                                | Meeting demand with supply at low cost<br>Decarbonization<br>Early interest in wind power                                                                                           |

<sup>1</sup> Political aspects (ideologies, policy proposal, public opinions)

<sup>2</sup> Policy aspects (ratified regulations)

|           |                                                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                                                                           |
|-----------|------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2006–2022 | Wind power expansion and nuclear power decommissioning (Phase 2) | 2011: Implementation of bidding zones <sup>2</sup><br>2016: Energy Agreement that removes capacity tax for nuclear producers <sup>1</sup><br>2017: A legally binding climate policy framework to reach net-zero emissions by 2045 set in force <sup>2</sup><br>2019: Nordic balancing model established to balance electricity supply and demand within the Nordic countries <sup>2</sup><br>Onshore wind becomes competitive without reliance on subsidies | 2007: Global financial crisis <sup>1</sup><br>2010: Nuclear power policy reversal, although building reactors <sup>1</sup> at existing sites is allowed (compared to the referendum result in the 1980s) <sup>1</sup><br>2011: Fukushima Daiichi nuclear reactor meltdown<br>Oskarshamn 1 and Oskarshamn 2 reactors shut down in 2017 and 2016, respectively. Ringhals 2 reactor closed in 2019, and Ringhals 1 reactor followed in 2020 <sup>1</sup><br>Increasing social resistance to wind power <sup>1</sup> | Meeting demand with supply at low cost<br>Decarbonization<br>Increasing wind penetration                                                                                                                                                                                                                                                                  |
|           | 2022–2025                                                        | Extensive electrification plans, ambiguous pathways (Phase 3)                                                                                                                                                                                                                                                                                                                                                                                               | Implementation of the REPowerEU Plan to phase out Russian fossil fuel imports <sup>1</sup><br>EU-level hydrogen incentives and declining cost of renewable hydrogen<br>Tidö agreement that changes the energy goal to fossil-free and State aid proposal for new nuclear capacity <sup>1</sup><br>Establishment of local flexibility markets<br>Proposal for economic compensation for municipalities hosting wind power <sup>1</sup>                                                                            | Right-wing government with pro-nuclear agenda comes into power in late 2022 <sup>1</sup><br>Sweden slows down emissions reductions. Many wind power projects get delayed or rejected in the permit granting process <sup>1</sup><br>Many wind power applications were rejected<br>Expected increase in demand for electricity from industry and transport |

### *3. Research context*

From 2022, in the third phase in Table 1, Sweden reduced the pace of emissions reductions under the current government. The Tidö political agreement resurrected governmental interest in nuclear power, together with a guarantee of state aid. At the same time, many wind power projects have been delayed or rejected in the permit-granting process. Offshore wind is practically non-existent, with no incentive scheme in place, while solar PV contributes modestly to the system. With the Russian invasion of Ukraine and new conflicts in the Middle East, energy security has heightened significance in the policy agenda globally (IEA, 2025a). Compared to the security concerns that arose from the oil crisis, this interest in security manifests itself as a regime with increasing variable weather-based generation, with increases in both critical material imports and fuel imports. Thus, developments aimed at diversification of supply strategies and improving preparedness for supply chain disruptions due to geopolitical conflicts constitute a key element of the energy transition (De Rosa et al., 2022; Proedrou, 2023; Vakulchuk et al., 2020).

Figure 2 illustrates the characteristics of the Swedish electricity regime, applying the MLP framework described in Section 2.2. The historical Swedish regime for operating the electricity system is dominated by large-scale, dispatchable, and synchronous generators. However, the conditions for new investments in electricity generation on a landscape level have changed. Notably, since deregulation of the electricity market, investments in electricity generation with high upfront investment costs and long lifetimes, such as hydropower and nuclear power, have not occurred. Meanwhile, the use of renewable resources, especially wind power, has been on the rise. Onshore wind power has rapidly and substantially expanded since the turn of the century, meeting 20% of electricity generation in Sweden (IEA, 2024d), with 1.8 GW of capacity being installed in 2025 (WindEurope, 2025). Offshore wind power accounts for less than 1% of the supply mix, reaching less than 0.2 GW of installed capacity by 2025 (WindEurope, 2025). Overall, 11 out of 13 offshore wind projects were rejected by the Government of Sweden in 2026 (Government Offices of Sweden, 2026b). At the same time, solar photovoltaic (PV) generation has seen strong growth in both the residential and commercial arenas, increasing to more than 2.5% of the contribution of the fossil-free electricity generation mix (Swedish Energy Agency, 2025).

On the other hand, there is growing interest in developing new nuclear power capacity, so much so that the financing possibilities have been investigated by the 2022-2026 government (Government Offices of Sweden, 2024a), and the conditions to invest in nuclear power have

been eased. This situation has intensified the tension that has suffused the energy discourse between wind power and nuclear power supporters (Faber, 2023; Lindvall et al., 2025; Sonnsjö, 2024). This tension is an extension of the debate that has raged on the role and optimal level of dispatchable versus weather-dependent electricity generation in the energy mix, which has strongly influenced Swedish energy politics (Bjärstig et al., 2022).

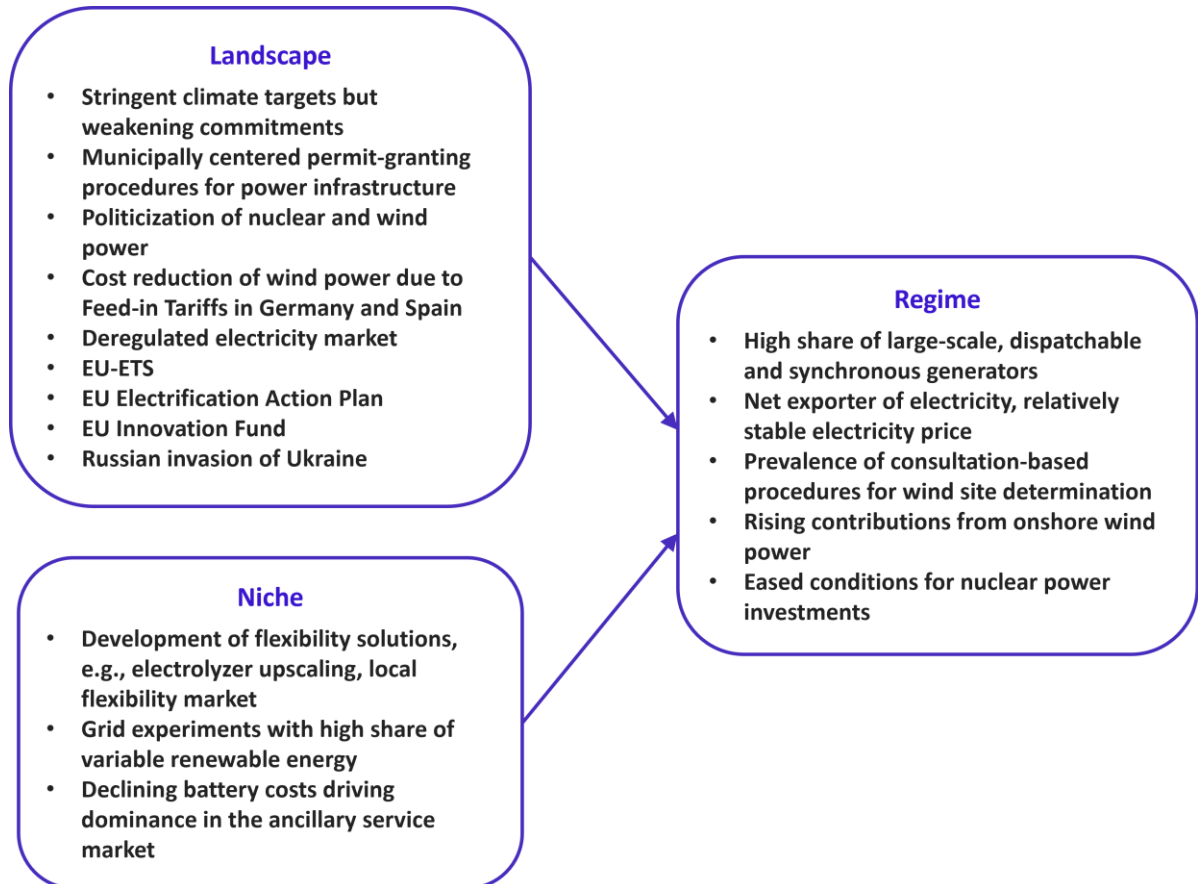


Figure 2: Characteristics of the Swedish electricity regime.

Since 2017, a legally binding climate policy framework to reach net-zero emissions by 2045 (Swedish Government Office, 2021) has been in force in Sweden. Sweden aims to curb 59% of its greenhouse gas emissions in 2030, as compared to the level in 2005, and to achieve net-zero carbon emissions by 2045. To meet these goals, several demand-side projects aimed at electrifying industrial processes (Heidelberg Materials, 2018; Vattenfall, 2021), producing fossil-free hydrogen (Vattenfall, 2026b) and electrofuels (Vattenfall, 2026a), and directly electrifying road transport (Preem, 2024; Volvo Cars, 2024; Volvo Trucks, 2025) have been set in motion by large industrial actors.

### *3. Research context*

For example, Sweden is home to one of the world's first major projects on hydrogen-based steel production (Vattenfall, 2021). Such changes in energy use and energy carriers are estimated to double the Swedish electricity demand over the next two decades (Swedish Energy Agency, 2023b).

Although Sweden has reduced its domestic levels of greenhouse gas emissions at a faster pace than the EU average (European Parliament, 2021), the Swedish Climate Policy Council concluded in its latest assessment report that the efforts to reduce emissions must increase substantially if the 2045 target is to be met, partly due to the increase in emissions during the last years (Swedish Climate Policy Council, 2026). Electrification is expected to transform the Swedish electricity system and may affect the competitiveness of Swedish industries and utilities. Following a prolonged period of relatively stable electricity demand, an important question is how the electricity demand projected under expanded electrification can be met. In the Nordic countries, hydropower capacities in Finland, Norway and Sweden, and some nuclear power capacities in Finland and Sweden are likely to be retained in the system (Kilpeläinen et al., 2019). However, there remain significant uncertainties as to the conditions for investing in electricity generation, grids, and demand-side electrification projects. These lead to different transition pathways, which come with different challenges and possibilities.

## 4. Methodology

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This chapter presents an overview of the research design of this thesis, as illustrated in Figure 3. The application of the Q methodology in **Paper I** is introduced in Section 4.1. The transition bottleneck identification applied in **Paper II** is described in Section 4.2, including the application of the socio-technical analysis in Section 4.2.1 and the techno-economic analysis in Section 4.2.2. Finally, the model development applied in **Papers III and IV** is elaborated in Section 4.3.

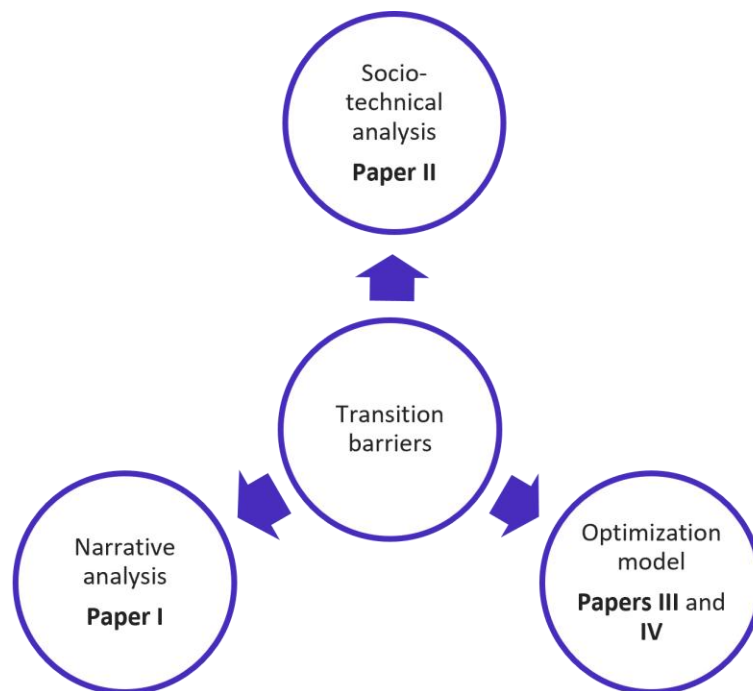


Figure 3: Overview of the methods implemented in the thesis.

## 4. Methodology

### 4.1. Applications of the Q methodology to explore Meta-challenges

**Paper I** uses the Q methodology to explore the ways in which key stakeholders perceive and prioritize the socio-technical challenges to electrification in Sweden. The Q methodology in general comprises five steps: 1) identifying the concourse and selecting statements; 2) selecting participants; 3) conducting the Q survey and interviews; 4) performing a Q analysis; and 5) interpreting the results from the factor analysis (Cuppen et al., 2010). How each step is applied in the research process is summarized in Figure 4 and described in detail in **Paper I**.

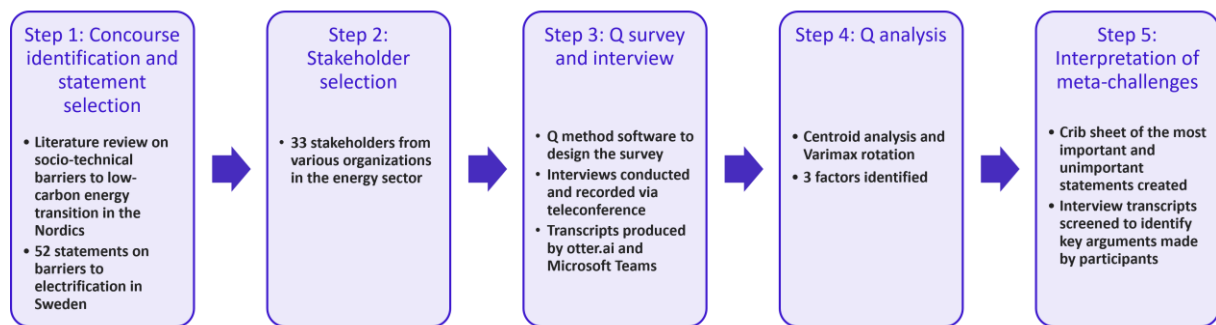


Figure 4: Application of the Q methodology. Source: **Paper I**.

The work was initiated with a literature review<sup>3</sup> on barriers to the Nordic energy transition. The formulation of the statements is generated iteratively based on this scientific literature review, newspaper searches, and discussions with the research team. The initial versions of the survey are tested on several colleagues before being formally launched. This results in a list of 52 statements, which are codified as s1 to s52 and provided in the Appendix.

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<sup>3</sup>A semi-systematic literature review was conducted using Web of Science and Google Scholar to investigate the topic. The review was carried out between 2021 and 2022 and initially included 125 articles. Based on this review, a set of key non-technical barriers to electrification was identified and categorized into social, economic, regulatory, and other barriers. Additional articles were incorporated on an ad hoc basis to support and refine the characterization of these barriers. The following search queries were used:

Keywords:

"electrification" OR "clean electricity production" OR "clean electricity generation" OR "clean electricity transition" OR "sustainable electricity production" OR "sustainable electricity generation" OR "sustainable electricity transition" OR "sustainable energy transition"

barrier\* OR constraint\* OR obstacle\* OR challenge\*

Geographic scope: Nordic\* OR Scandinavia\* OR Swed\* OR Denmark OR Finland OR Finnish OR Norway OR Norwegian OR Iceland\*

The categorization is shown in Figure 5. The grouping of statements is performed to ensure that important topical issues are represented, even though the root causes and developments of these barriers may overlap between groups. The resulting distribution across the groups is quite even, with higher concentrations of statements for contested norms (27%) than for economic (25%) and governance (17%) statements.

In the research for **Paper I**, stakeholders from various organizations associated with the energy sector were invited, as well as those affected by the strategy of using electrification as a way to decarbonize the energy sector, to rank statements about potential challenges in order of their perceived importance. The survey and interview process were conducted with 33 key stakeholders from different parts of the energy sector. Their perspectives on the levels of importance of barriers were measured based on their evaluations of the provided statements on a scale of -5 (*most unimportant*) to +5 (*most important*). These individual stakeholder rankings are aggregated and statistically analyzed to extract overarching themes, which are termed *Meta-challenges*.

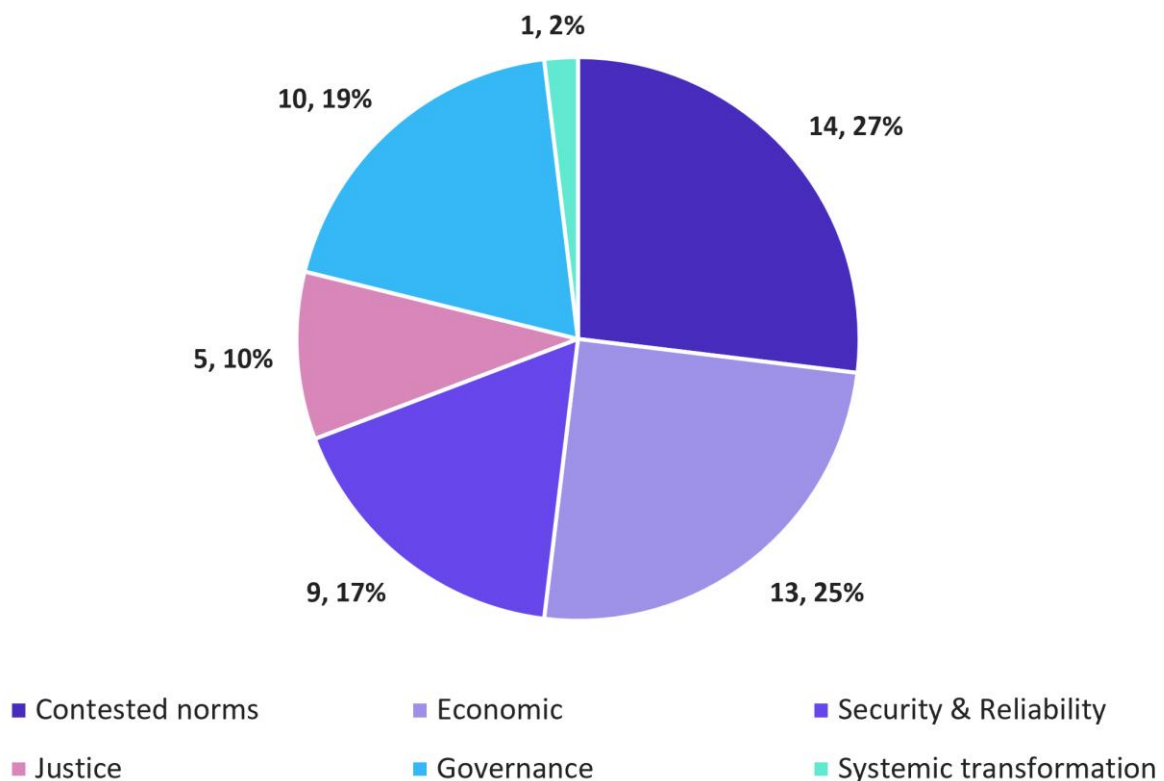


Figure 5: Statement representation in each barrier category, including the number of statements and the percentage for each group. Based on the data used for **Paper I**.

### 4.2. Identification of transition bottlenecks

To identify and analyze transition bottlenecks, as performed in **Paper II**, a combination of a socio-technical analysis and techno-economic analysis is conducted, as proposed by Geels et al. (2020) and illustrated in Figure 6. Focusing the analysis on a single country enables an in-depth examination of country-specific conditions. For Sweden, these conditions are particularly relevant given the political ambiguity surrounding transition pathways despite ambitious climate targets.

The MLP is a conceptual framework that characterizes how a socio-technical system undergoes large-scale and long-term transformations on three levels: niche, landscape, and regime. The socio-technical analysis draws on the existing literature to trace the key historical events and processes that have shaped the current electricity systems in Sweden and its neighboring countries. On the other hand, ESOM minimizes the total system cost while satisfying the electricity demand for three alternative, low-carbon electricity futures. The preconditions for the cases differ mainly with respect to the pre-determined levels of investment in offshore wind and nuclear power. Accordingly, while the MLP framework provides important insights into how technologies interact with the institutional, regulatory and operational environments within society, ESOM generates cost-optimal technological mixes under different sets of assumptions linked to future conditions.

To map the transition bottlenecks connected to each modeled case, both analyses are done initially in parallel with a focus on key technologies that have strong impacts on the electricity system in Sweden, including wind power, nuclear power, flexibility solutions, and ancillary services of the power grid. With the techno-economic analysis, **Paper II** showcases the investment patterns of the generation and storage technologies, annual generation levels, and marginal cost of electricity. Through the socio-technical analysis, the context, challenges for further expansion or implementation, and the enabling conditions for further expansion or implementation are delineated.

The two analyses are combined to identify transition bottlenecks by linking the historical development of the current electricity system to modeled low-carbon futures with expected increases in electricity demand. The ESOM analysis reveals the operational and economic requirements of future system configurations, whereas the MLP analysis elucidates the socio-technical conditions that shaped the existing system. Transition bottlenecks emerge from the gap between requirements for future modeled systems and the present regime. Their criticality levels are evaluated based on the extent of technology deployment across the modeled scenarios. The details of each step are described in the following chapters.

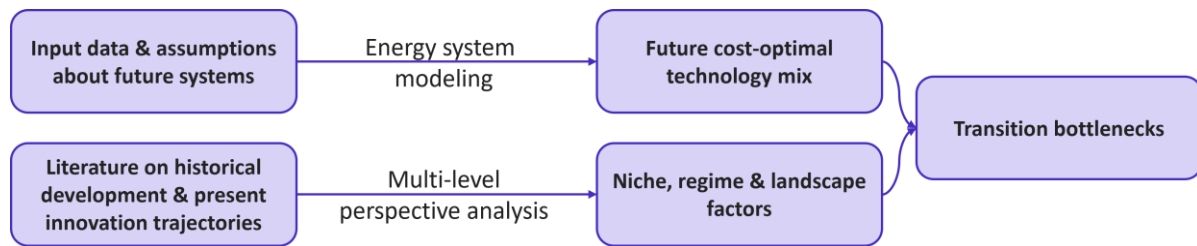


Figure 6: Overview scheme of the energy system optimization model and multi-level perspective analysis combined method to investigate energy transition bottlenecks on the deployment of each technology. Source: **Paper II**.

#### 4.2.1. Multi-level perspective framework as socio-technical analysis

The socio-technical analysis is carried out using the MLP framework in **Paper II**. The electricity supply and distribution is conceptualized as a socio-technical regime, using Sweden as the case. Its developments relate primarily to electricity production and distribution activities, each of which is associated with a network of technologies, actors and rules, thus interrelating social, technological, political and cultural factors. While the developments of the demand-side regime are not explored in depth, the development of flexibility solutions is explored from the perspectives of the supply and grid actors.

The analysis characterizes the historical and institutional contexts that shape the development of selected electricity generation technologies and infrastructure. Document analysis serves as the primary method, drawing on the scientific literature, policy documents, regulations, regulatory guidelines, and governmental and industry reports. The characteristics of each MLP level are illustrated in Figure 7.

#### 4. Methodology

At the regime level, the institutional, regulatory, and infrastructural characteristics that shape the current electricity system, including historical development trajectories, planning and permitting processes, consultation procedures, and the main rationales underpinning the deployment of specific technologies are examined. At the landscape level, the broader governance traditions and policy-making practices that influence the development of regulations and procedures for the electricity sector are analyzed. At the niche level, the focus is on emerging technologies and innovations that have not yet become established within the regime, including technologies that are at different stages of development and novel organizational arrangements that depend on protected environments and that may facilitate the entry of new actors.

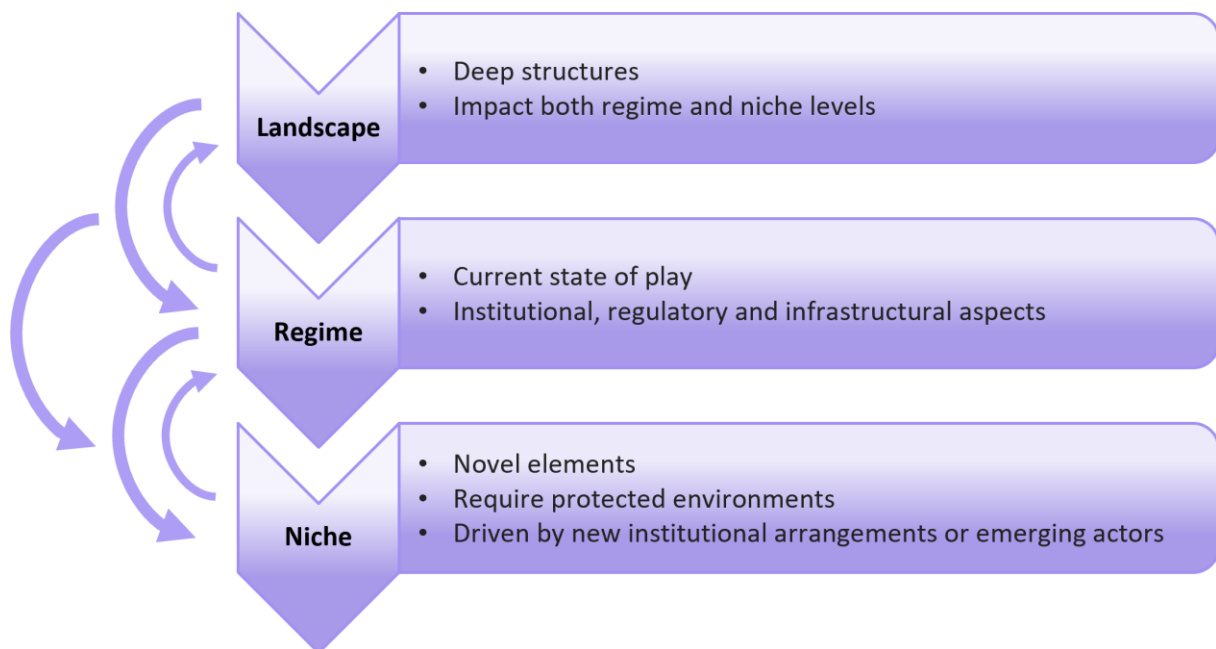


Figure 7: Characteristics of and interactions between levels of the Multi-level Perspective framework based on **Paper II**.

##### 4.2.2. Energy system modeling as techno-economic analysis

For the ESOM development, **Paper II** applies the ENODE model, which is a greenfield, bottom-up investment model of the electricity system, to conduct a techno-economic analysis. The model formulation was first presented by Göransson et al. (2014) and thereafter developed further to evaluate the impacts of thermal plant cycling (Göransson et al., 2017), variation management (Johansson & Göransson, 2020), and thermal energy storage (Holmér et al., 2020) on cost-optimal electricity and heating systems. The technical details and cost properties of selected technologies are detailed elsewhere (Göransson, 2023).

The model minimizes the annualized investment and operational costs while meeting the demands for electricity, heat, and electricity-based hydrogen for the year 2050. The model is applied with a 3-hourly resolution and a time horizon of 2 years, corresponding to high and low water inflows to hydropower reservoirs. The geographic scope covers the northern European regions to account for the effects of imports and exports between Sweden and the neighboring countries. The demands associated with the electrification of industry and transport are exogenously specified. Three different cases are developed with respect to Sweden, applying the assumptions listed in Table 2.

The three cases differ with regard to the minimum required nuclear power capacity and offshore wind power capacity in Sweden in 2050, as follows:

- A “cost-optimal” case, without constraints on the minimum level of capacity of any generation technology;
- A nuclear case for which 9 GW of nuclear power in Sweden is assigned in the model. This case is aligned with one of the long-term scenarios of the Swedish transmission grid operator (Svenska Kraftnät, 2024); and
- An offshore wind case prescribing 22 GW of offshore wind in Sweden, corresponding to 120 TWh of offshore wind production applying the 2050 offshore wind power plans, as proposed in an offshore planning exercise conducted by governmental agencies (Swedish Energy Agency, 2023a).

Table 2: Assumptions made for the three modeled electricity futures. Source: **Paper II**.

| Case             | Cost optimal                                                                 | 9-GW Nuclear | 22-GW Offshore wind |
|------------------|------------------------------------------------------------------------------|--------------|---------------------|
| % available land | Onshore: 4%<br>Offshore: 33%                                                 |              |                     |
| Flexible demand  | 30% of cars charged flexibly, possibility to store heat and hydrogen         |              |                     |
| Transmission     | According to projection scenarios for 2040 by TYNDP (ENTSO-E & ENTSOG, 2023) |              |                     |
| Storage options  | Hydrogen storage, stationary batteries, thermal energy storage               |              |                     |

### 4.3. Electricity long-term investment model development

For **Papers III** and **IV**, the Electricity Long-term Investment (ELLI) model, which is a capacity expansion model of the electricity system, is used to conduct a techno-economic analysis. ELLI is a multi-year variant of the ENODE model, which is a linear optimization model, the original formulation of which is presented elsewhere (Göransson et al., 2014). The full mathematical formulation can be found in Öberg et al. (2026). Figure 8 presents the schematics of the model development, including the key inputs, model structure, and key outputs, while Table 3 presents the key model setups used in each of the papers. The main developments pertaining to the thesis include the implementation of deployment constraints for solar power, wind power, and nuclear power, which represent the compound impact of growth barriers. The key contribution of the thesis involves the characterization of the barriers to wind and solar power that bridges technology diffusion research with the ESOM research. This relationship and its impact are investigated in **Paper III** and applied in **Paper IV**. In **Paper IV**, the stochastic programming framework for nuclear deployments and demand levels is developed and applied to ELLI.

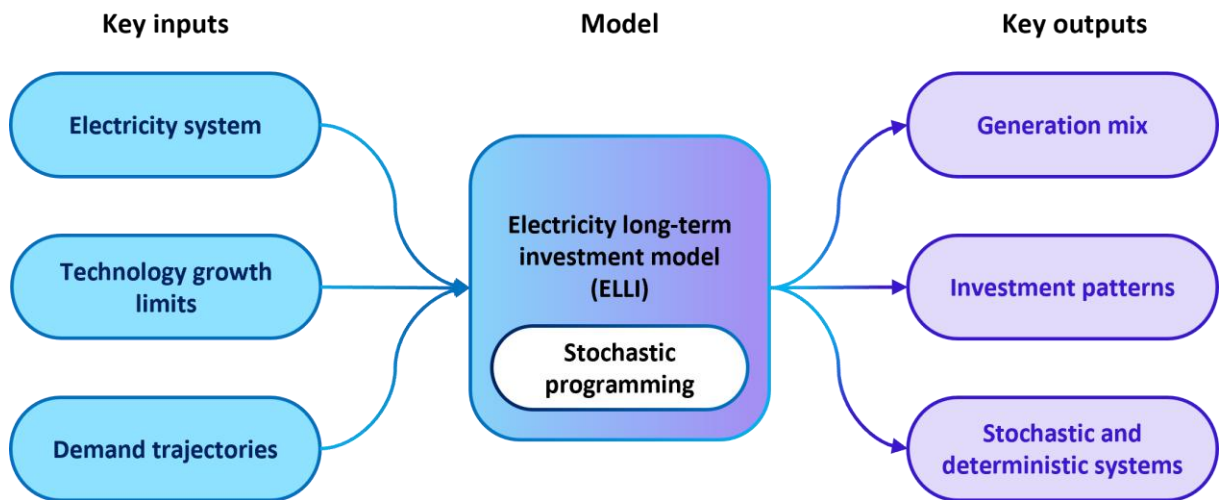


Figure 8: Schematics of the model setups for **Papers III** and **IV**.

The model determines the cost-optimal investments and dispatch levels needed to meet the electricity, hydrogen, and heating demands by minimizing the discounted system cost. The initial system state includes the existing power-generation fleet, which is decommissioned according to installation year and technical lifetime. After 2050, the demand and cost assumptions are stabilized. A steadily increasing carbon price is incorporated into the model that drives the technology mix toward low-carbon options over time, with assumptions taken from (BloombergNEF, 2024).

Table 3: Comparison of the ELLI model implementations in **Paper III** and **Paper IV**.

| <b>ELLI implementation</b>       | <b>Paper III</b> (Technology growth impact on the electricity system)                                                                                                                                    | <b>Paper IV</b> (Demand development Impact on the electricity system)                                                                                                                                                     |
|----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Modeled period                   | 2025–2075                                                                                                                                                                                                | 2025–2065                                                                                                                                                                                                                 |
| Geographic scope                 | 37 modeled regions                                                                                                                                                                                       |                                                                                                                                                                                                                           |
| Weather year                     | 1991 (low level of water inflows for hydropower production), 1992 (high level of water inflows for hydropower production)                                                                                | 2019 (balanced water inflows)                                                                                                                                                                                             |
| Temporal scope                   | 2,920 timesteps                                                                                                                                                                                          | 730 timesteps                                                                                                                                                                                                             |
| Growth limits                    | No limit, Aggregate capacity, Regional capacity, Relative demand                                                                                                                                         | Regional capacity                                                                                                                                                                                                         |
| Onshore wind                     | <i>G</i> for countries with steady growth<br>Q2 and Q3 for countries with accelerating growth                                                                                                            | <i>G</i> for countries with steady growth<br>Q3 for countries with accelerating growth                                                                                                                                    |
| Solar PV                         | Q2 and Q3 for all countries                                                                                                                                                                              | Q3 for all countries                                                                                                                                                                                                      |
| Offshore wind                    | Simulations of future markets at the country level                                                                                                                                                       |                                                                                                                                                                                                                           |
| Nuclear power                    | Overnight investment cost: 6,181 €/kW                                                                                                                                                                    | Overnight investment cost: Fast nuclear, 6,960 €/kW with a 5-year construction period; Slow nuclear, 9,060 €/kW with a 15-year construction period                                                                        |
|                                  | Upper limit as historical deployment at continental level                                                                                                                                                | Upper limit as historical deployment at continental level                                                                                                                                                                 |
|                                  | No investment limit after 2055                                                                                                                                                                           | No investment prior to 2030                                                                                                                                                                                               |
|                                  | Exogenous recent capacity additions: UK (Hinkley Point C – 3.2 GW by 2030), France (Flamanville – 1.63 GW by 2025), Poland (Lubiatowo-Kopalino – 1.1 GW by 2035), and Hungary (Paks II – 2.4 GW by 2035) | Investment limit set at 1,000 GW/investment period in the years of 2060 and 2065<br><br>Exogenous capacity additions: Same as <b>Paper III</b> + Czechia (Dukovany 5 and 6 – 1.05 GW by 2035) (European Commission, 2024) |
| Stochastic considerations        | No                                                                                                                                                                                                       | Yes                                                                                                                                                                                                                       |
| Investigated demand trajectories | Fixed levels, S-shaped                                                                                                                                                                                   | High vs. Low demand, S-shaped vs. Linear                                                                                                                                                                                  |

#### *4. Methodology*

The geographic scope is 27 European countries divided into 37 regions. The model advances in 5-year steps from the year 2025 to 2065, with each of the 5 years representing an investment period. Within a specific year, the temporal resolution is 730 timesteps for **Paper IV** and 2,960 steps for **Paper III**, applying the time period clustering method described previously (Pineda & Morales, 2018).

Trade between regions is limited by the transmission capacity, with the existing grid capacity and investments in additional grid capacity being based on the TYNDP 2022 projections of transmission line investments up to 2040 (ENTSO-E, 2023). The model does not allow for endogenous investments in additional transmission capacity. In addition to the existing electricity and heating demands, new loads are exogenously introduced to represent the electrification of the transport and industrial sectors. Existing demands for electricity are based on Eurostat consumption data (Eurostat, 2025a) and ENTSO-E hourly profiles (ENTSO-E, 2026), which are assumed to remain unchanged in a future low-emissions system.

The transport-related demand for electricity is based on the full electrification of passenger cars and heavy-duty vehicles, with assumptions made as to driving patterns and electricity consumption levels being derived from earlier work (Taljegård et al., 2019). The electrification rate of road transport corresponds to the electrification rate of industry. Between 2010 and 2025, the vehicle stock data is obtained from Eurostat (Eurostat, 2026), while the projection of the future number of cars till 2050 is based on estimates from the Swedish Transport Administration (Swedish Transport Administration, 2026).

For the industrial sector, current production volumes are assumed to remain constant while production processes are electrified, as described by Toktarova et al. (2025). The resulting electricity demand is estimated using a bottom-up approach for each sector and region. This includes direct and hydrogen-based electrification of steel production and, in high-demand scenarios, also the production of cement, ammonia, and plastics, as well as e-fuel production for the shipping and aviation sectors. In the heating sector, individual natural gas heating is assumed to be replaced by heat pumps, while the electrification of district heating systems through large-scale heat pumps and electric boilers is determined endogenously within the model. The economic and technical input data for selected technologies follow the Danish Energy Agency's technology catalogue (Danish Energy Agency, 2025).

All costs are represented by EUR-2020 values. The cost of nuclear power in **Paper III** corresponds to large-scale Generation III units, with parameters based on expert estimates of future nuclear costs (Government Offices of Sweden, 2024a). This leads to an overnight investment cost of 6,181 €<sub>2020</sub>/kW. While the reference accounts for a 7-year construction time, **Paper IV** applies 5-year and 15-year construction times, and the accrued interest rate during the construction phase, included in the investment cost, has been adjusted accordingly. This amounts to 6,960 €<sub>2020</sub>/kW for the 5-year construction time, and 9,060 €<sub>2020</sub>/kW for the 15-year construction time. The lifetime of the nuclear capacity is set at 80 years. Small Modular Reactors are excluded due to their uncertain future costs and state of development, although SMR projects have been actively supported across several EU Member States (Director-General for Energy, 2026), such as Sweden (GE Gernova Hitachi, 2026; Vattenfall, 2026c).

Both **Paper III** and **Paper IV** apply a continental nuclear power investment cap that mirrors nuclear power development in Europe during the period of 1965–1985 (IAEA, 2025). The cap rises in each investment period up to 2050, which is consistent with historical investments in continental nuclear power capacity. Moreover, the capacity under construction in the UK (Hinkley Point C –3.2 GW by 2030) and the newly completed project in France (Flamanville –1.63 GW by 2025) are added exogenously. Similarly, the planned capacities of nuclear power in Czechia (Dukovany 5 and 6 –1.05 GW by 2035) (only implemented in **Paper IV**), Poland (Lubiatowo-Kopalino –1.1 GW by 2035), and Hungary (Paks II –2.4 GW by 2035) are added to the model exogenously because financing and secured vendors are available for these projects.

For **Paper IV**, endogenous investments in new nuclear power are not allowed in the model prior to 2030. From 2030 to 2065, investments in large nuclear reactors are allowed across all the modeled countries and regions. Wind and solar power production potentials are derived by combining the reanalysis of the ERA5 climate model (European Centre for Medium-Range Weather Forecasts, 2018) and the Global Wind Atlas (Global Wind Atlas, 2025), using the method applied by Mattsson et al. (2021). From the data used by Hedenus et al. (2022), 5% of the physical potentials, i.e., after land sites deemed unsuitable for the considered generation technology (mainly high-population areas and natural conservation areas for wind power), have been removed, is assumed to be utilized. An exception is made for Germany, Belgium, and the Netherlands, for which the share of onshore wind power is set at 10% to reflect their present deployment levels.

## 4. Methodology

### 4.3.1. Technology growth limit implementation

The growth of wind and solar power generation is, in **Papers III** and **IV**, defined as the difference between the installed capacity and retired capacity over a certain period of time. Based on historical data for the installed onshore wind and solar capacity and the total electricity supply, country-specific growth limits for all the modeled countries for each investment period are implemented. While the maximum growth limits constrain capacity expansion of a technology within a specific period, different growth metrics are implemented as maximum limits for wind and solar power, to account for their different levels of maturity in different countries. For technologies that have reached a steady growth phase, mainly onshore wind, the mature growth rate  $G$  is estimated using the logistic curve-fitting method proposed by Cherp et al. (2021), which identifies the maximum growth rate at the inflection point on the historical growth curve. For technologies that are still in the growth acceleration phase, most commonly solar power, the recent 3-year average of empirical deployed capacity, called  $R3$ , is used according to Vinichenko et al. (2023). Since  $R3$  can underestimate stable growth levels, a cross-country distribution of the  $G$  and  $R3$  values is constructed, and the median quartile (Q2) and upper quartile (Q3) are extracted.

For **Paper IV**, the values of Q3 are used to replace  $R3$  in the few countries that are still showing accelerating growth for onshore wind, unless  $R3$  already exceeds Q3. For solar power, Q3 is applied uniformly due to its widespread early-stage deployment. Offshore wind power, which is still in an early formative stage with limited historical data, relies on the deployment simulations described by Kazlou et al. (2024), who incorporate seabed constraints, auction governance, and project implementation factors. The electricity prices in these simulations were adjusted to remove endogenous cost effects, and near-term growth was bounded by the existing project pipeline. **Paper III** implements a similar approach with additional implementation of the Q2 values.

### 4.3.2. Electricity demand-increase levels

For **Paper IV**, the main scenarios apply a high-demand increase and a low-demand increase, both with an S-shaped increase, as shown in Figure 9. Electricity demand evolves over the modeling horizon according to a stylized technology diffusion pathway, reflecting a plausible transition in which the demand increases gradually in the early years, accelerates during the middle of the period, and slows in the final period as climate targets are achieved.

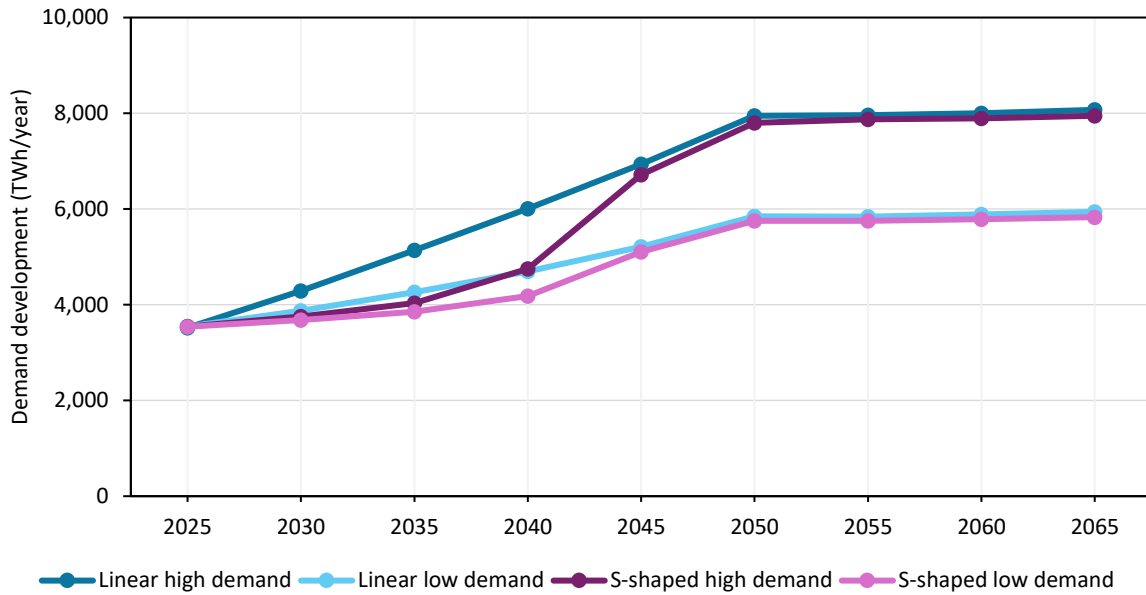


Figure 9: High and low demand developments with S-shaped and linear trajectories. Source: **Paper IV**.

In scenarios that have low demand, electrification of industry and transport is limited to the steelmaking industry, for which multiple plans and projects are underway (Kanthal, 2024; Toktarova, 2026), and the transport sector, which experiences increasing levels of adoption of passenger cars and heavy-duty vehicles (Salmon et al., 2026). In contrast, the development of high electricity demands reflects widespread electrification across all sectors in which it is technically feasible, including cement manufacturing, chemical refineries, and e-fuel production for maritime and aviation, in addition to the sectors that are included in the low-demand scenario. Net demand is comparable across the high- and low-demand scenarios in the initial modeled years, with substantial divergence emerging only after 2040, which is in line with the progression of industrial electrification.

For comparison with the S-shaped trajectory, a linear demand development is also applied, i.e., one in which the demand grows at a constant rate over the entire modeled period (Figure 9). Relative to the S-shaped growth trajectory, the linear demand pathway yields higher cumulative electricity demand, amounting to roughly 3,500 TWh and 1,600 TWh additional demand in the high- and low-demand scenarios, respectively, over the modeled period.

## 4. Methodology

### 4.3.3. Stochastic programming

To investigate the effects of hedging under uncertainty, **Paper IV** implements a two-stage stochastic model within the standard ELLI model structure. The stochastic setup is compared with a deterministic (perfect-foresight) formulation, both applying an S-shaped demand rate of change. The stochastic runs consider uncertainty in both the nuclear build rate (slow vs. fast) and demand development (high vs. low) scenarios.

Figure 10 illustrates how nuclear power capacity and electricity demand evolve, connect, and branch within the modeled European scope in the stochastic model runs, for different future model worlds.

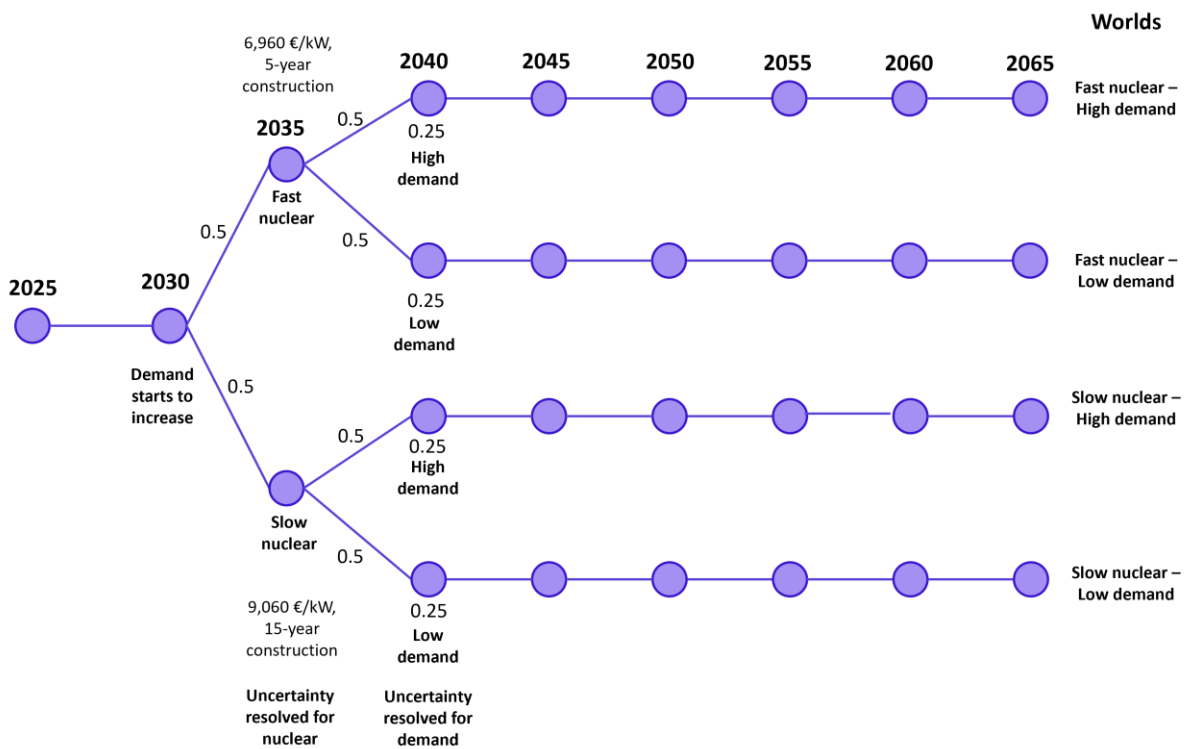


Figure 10: Probabilistic future branching into nuclear construction speed and demand change in Europe for different future modeled worlds. Source: **Paper IV**.

Prior to resolving the uncertainty, the stochastic model requires all branches to follow a common investment pathway for the 2025 and 2030 investment periods. Decisions on nuclear power are assumed to precede decisions associated with demand development, considering that some countries in the region, such as Poland and Czechia, are already advancing their nuclear development programs.

Consequently, the uncertainty surrounding nuclear power construction (fast versus slow nuclear) is resolved in 2035, before the uncertainty in demand development (high versus low demand) is resolved in 2040. This implies that by 2035, constraints on the nuclear power build rate are relaxed, and by 2040, constraints related to demand development are relaxed. Once both sources of uncertainty are resolved, the system diverges into four distinct scenarios depending on the realized state of the scenario. Given the uncertainties associated with both nuclear power and demand development, the probability is set to be equal for all of the scenarios.



## 5. Key findings

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This chapter describes selected findings from the appended papers. Linked to the first two research questions, Section 5.1 details the main findings from **Papers I** and **II** on the challenges to electrification in Sweden. Section 5.2 highlights the key insights from **Papers III** and **IV** regarding the long-term electricity system development under different supply constraints and demand trajectories in Europe, which is linked to the third research question. The findings are synthesized and presented in Section 5.3.

### 5.1. Challenges to the Swedish electrification

The first two research questions of the thesis ask what hinders electrification in Sweden, as framed by stakeholders and emerging across alternative electrification pathways. The results from the narrative analysis in **Paper I**, which identifies three main Meta-challenges as the aggregated perceptions of barriers from stakeholders, intersect strongly with the findings of the transition bottlenecks per technology and across scenarios in **Paper II**, where different patterns of the regime shifts required are articulated. The constituents of the three main Meta-challenges are summarized in Figure 11. The identified transition bottlenecks and their criticality levels across three modelled cases and per technology are summarized in Table 4. This chapter presents a synthesis of the findings shared in the two papers, so as to provide insights into the key challenges to Swedish electrification.

## 5. Key findings

From the narrative analysis using the Q methodology, the Meta-challenges are defined as follows:

1. **Procedural Deadlock.** This refers to the procedural deadlock associated with expanding variable electricity generation and is concerned with scaling up the demand for new electricity generation on time.
2. **Competing Political Preferences.** This highlights carbon prices, flexibility instruments, and political disputes as the main issues hampering the transition.
3. **Poor Governance.** This challenge focuses on multi-stakeholder coordination, particularly with respect to putting new grid capacity in place. Poor governance hinders an effective electrification process.

To compare the above-mentioned Meta-challenges, Figure 11 displays in a Venn diagram the concerns that are shared by and differ for each Meta-challenge. The overlapping areas highlight issues that are viewed similarly, while the formulation process of the 52 statements, numbered from s1 to s52, is described in Section 4.1 of the methodology. All three Meta-challenges share the highest (most-important) ranking item: the need for **broad system transformation** (s44). **Permitting** (s40 and s14) and **coordination** issues (s45) are considered important by Meta-challenges 1 and 3, while **market instruments for flexibility** (s51) are regarded as critical for Meta-challenges 1 and 2. In contrast, **fuel dependence** on other countries (s41) is regarded as unimportant for Meta-challenges 1 and 3, which is similar to **support for Small Modular Reactors** (s9) for Meta-challenges 2 and 3.

Since Meta-challenge 1 on Procedural Deadlock has the highest eigenvalue, this Meta-challenge has the highest explanatory power. This implies that the issues rated as *most important* and *most unimportant* for this challenge share the ranking with a high number of stakeholders in the sample. In contrast, Meta-challenge 2 on Competing Political Preferences has the lowest correlation and has less in common with the other two Meta-challenges. This indicates that the viewpoints that constitute the content of this challenge differ from the viewpoints of the other two Meta-challenges and are mainly shared by those stakeholders who associate with this challenge rather than the other Meta-challenges.

Based on the identification of transition bottlenecks in **Paper II**, different patterns of the regime shifts required can be articulated. The challenges perceived by stakeholders and reported in **Paper I** relate largely to these regime shifts. The transition bottlenecks identified per technology and their criticality levels across the three modelled cases described in **Paper II**, including the cost-optimal case, the 9-GW nuclear case, and the 22-GW offshore wind case, are summarized in Table 4.

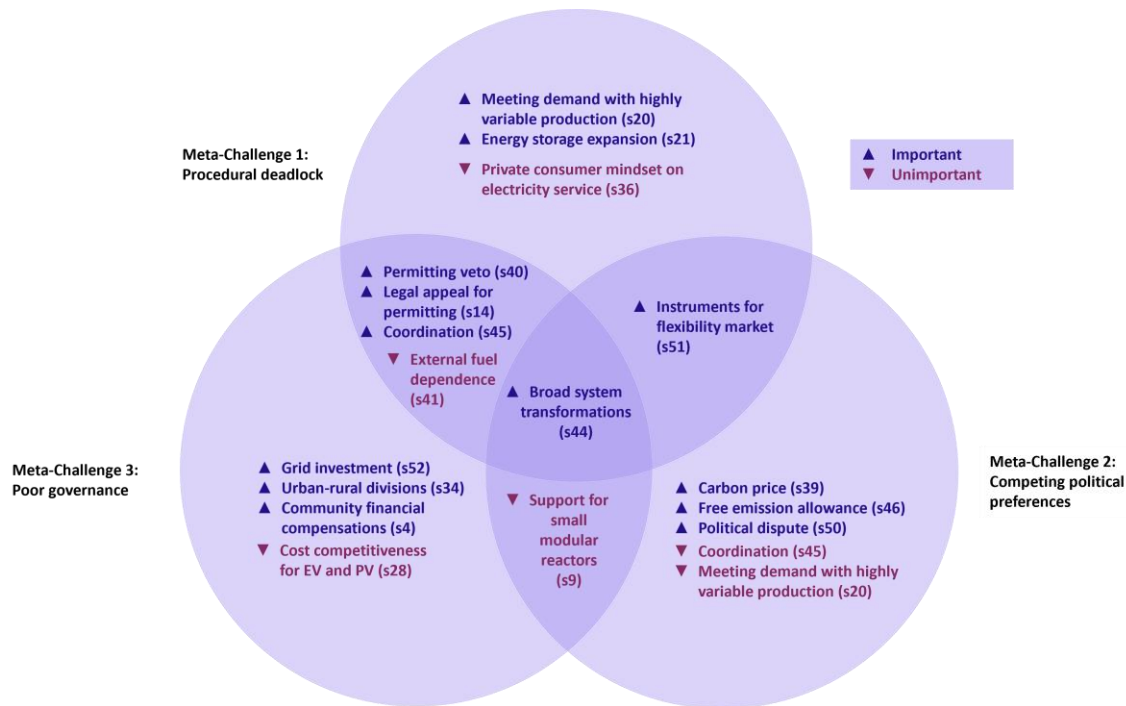


Figure 11: Barriers that are shared and unique in the rank-order of the three identified meta-challenges, each linked to its original statement in brackets. Texts are colored according to their ranks, from the *most important* to the *most unimportant*. Black text with upward arrows: issues ranked as important; white text with downward arrows: issues ranked as unimportant. The full list of statements is provided in the Appendix. Source: **Paper I**.

## 5. Key findings

Table 4: Transition bottlenecks identified per key technologies in the Swedish electricity regime. The criticality of addressing transition bottlenecks for each modeled case is shaded based on new capacity needed compared to the other two cases (Light purple: low criticality; Purple: medium criticality; Dark purple: high criticality). Source: **Paper II**.

| Key technologies      | Transition bottlenecks                                                                                                              | Criticality of overcoming bottlenecks                                                                        |                                                                             |                                                                                   |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
|                       |                                                                                                                                     | Cost-optimal case                                                                                            | 9 GW of nuclear power case                                                  | 22 GW of offshore wind power case                                                 |
| Onshore wind power    | Unpredictability in permitting procedures                                                                                           | Doubling of the current permit-granted capacity                                                              | In line with the permit-granted capacity                                    | In line with the permit-granted capacity                                          |
|                       | Absence of economic compensation to stimulate social acceptance                                                                     |                                                                                                              |                                                                             |                                                                                   |
|                       | Absence of planning support                                                                                                         |                                                                                                              |                                                                             |                                                                                   |
| Offshore wind power   | Unpredictability in permitting procedures                                                                                           | In line with the permit-granted capacity                                                                     | No investment                                                               | Large increase in capacity                                                        |
|                       | Absence of conflict resolution measures among governmental actors                                                                   |                                                                                                              |                                                                             |                                                                                   |
|                       | Absence of financial support                                                                                                        |                                                                                                              |                                                                             |                                                                                   |
| Nuclear power         | Absence of financial support                                                                                                        | 0 GW                                                                                                         | 9 GW of new nuclear capacity                                                | 0 GW                                                                              |
|                       | Absence of sustaining political support                                                                                             |                                                                                                              |                                                                             |                                                                                   |
|                       | Uncertainty in licensing procedures                                                                                                 |                                                                                                              |                                                                             |                                                                                   |
| Flexibility solutions | Lack of coordination among system operators on flexibility                                                                          | 230 GWh expansion of hydrogen; 300 GWh expansion of heat storage and 5 GWh expansion of stationary batteries | 170 GWh expansion of hydrogen storage and 120 GWh expansion of heat storage | 170 GWh expansion of hydrogen storage and 210 GWh expansion of heat storage       |
|                       | Absence of measures to protect against high price volatility                                                                        |                                                                                                              |                                                                             |                                                                                   |
|                       | Absence of niche applications for electrolyzers                                                                                     |                                                                                                              |                                                                             |                                                                                   |
|                       | Absence of investment support for flexibility                                                                                       |                                                                                                              |                                                                             |                                                                                   |
| Power grid            | Operational disparity between a power grid mainly tailored to synchronous generation and one adapted for converter-based generation | Increase in capacity of converter-based generators, e.g., up to 90% in some hours                            | Maintained level of synchronous generators                                  | Increase in capacity of converter-based generators, e.g., up to 90% in some hours |

### 5.1.1. Wind power

Despite the increase in Swedish onshore wind power production, further expansion faces key barriers, such as procedural uncertainty in the permit-granting process and the absence of local incentives to stimulate acceptance, as showcased in **Papers I** and **II**. For offshore wind, conflicts between governmental actors and the lack of financial support represent a bottleneck for the transition in both papers.

All three modeled cases in **Paper II** show a need for the expansion of wind power, albeit to varying extents, highlighting the criticality of transition bottlenecks to wind power in Sweden. Removing bottlenecks to onshore wind power is critical for the cost-optimal case in which the level of onshore wind power is highest, although this is also highly relevant to the other two cases, including that with investment in 9 GW of new nuclear power.

The 22-GW offshore wind case necessitates extensive development of the offshore wind infrastructure. The major challenges to this development relate to how governmental actors can resolve conflicts that relate to the process of approving offshore siting locations, and the lack of systems for attracting offshore wind investors and for allocating financial risks. Furthermore, at the time of writing the thesis, offshore grid connections supplied by the TSO are not in place for the subsequent development of offshore wind power in Sweden (TT, 2023), as compared to the infrastructure for nuclear power and onshore wind power. These challenges are reinforced by the low electricity price and the currently low levels of commitment exhibited by industries to electrify (which would stimulate investments in more-expensive electricity generation).

The unpredictability of permitting procedures, the absence of planning support for onshore wind power, and the absence of conflict resolution measures among governmental actors are in line with the perceived importance attached to the permitting and coordination of new electricity infrastructure associated with the Meta-challenges 1 and 3 (see Figure 11) of the Q methodology in **Paper I**. Furthermore, concerns regarding the plausibility of a system with **increasing share of variable electricity production** (s20) are considered important for Meta-challenge 1 and unimportant for Meta-challenge 2. Issues related to a just transition, including the **urban-rural division in the transition and community compensation** (s34 and s4), are also flagged as important for Meta-challenge 3 on Poor Governance. Overall, the results highlight the landscape push to resolve conflicts of interest, increase clarity in the permitting process, and systematize economic support for offshore wind power.

## 5. Key findings

### 5.1.2. Nuclear power

Nuclear power development in Sweden, while receiving strong support from the government during the period of 2022–2026, comes with heavy political weight and economic uncertainty. The key bottlenecks identified in **Paper II** lie in the high investment cost, which requires financial scheme development, the challenges of sustaining political support, and procedural uncertainties. The bottlenecks for nuclear power are only present in the 9-GW nuclear case.

The highlighted bottlenecks, as found in **Paper II**, reflect the barriers associated with **political disputes** regarding wind and nuclear power (s50), which are rated as highly important for Meta-challenge 2 on Competing Political Preferences of **Paper I**. Overall, the 9-GW nuclear case would not lead to a transformative shift but would require incumbent actors to secure the directionality of the transition. Moreover, **support for Small Modular Reactors** (s9) is considered unimportant for Meta-challenges 2 and 3, which would suggest that large-scale nuclear power plants will remain the focus should future investments in nuclear power materialize in **Paper I**<sup>4</sup>.

Extensive expansion of nuclear power capacity will require the development of financial support schemes, such as those in Finland, the UK, and Czechia, alongside political stability and regulatory learning. This primarily necessitates landscape pressures that could sustain support for nuclear power beyond economic motivations.

### 5.1.3. Flexibility measures

From **Paper II**, the main transition bottlenecks to harnessing flexibility resources include: the lack of coordination between system operators at different voltage levels; the lack of measures to ensure long-term acceptance of the energy-only market; the absence of niche applications for electrolyzers; and poor investment support for flexibility. These transition bottlenecks are the most critical ones for the cost-optimal case, followed by the 22-GW offshore wind power case and the 9-GW nuclear power case.

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<sup>4</sup> At the time of writing the thesis, the SMR technology has been chosen for the first new Swedish nuclear power initiative at the Ringhals site (Vattenfall, 2026c). This choice is partly for logistic and project cost reasons (Borglund, 2025).

The modeled results reveal the need to complement flexible hydropower with demand-side flexibility from heat pumps in district heating systems, together with the provision of electrolyzers and heat storage units for hydrogen production and storage. These investments are present in all three cases, albeit with lower investment levels for heat storage in the 9-GW nuclear case. The results show the importance of having a broad range of demand-side flexibility measures to complement the supply-side measures.

On the landscape level, an energy-only market with an extended power reserve may deliver cost-efficient flexibility, provided that investment signals remain strong, flexibility deployment keeps pace with renewable energy expansion, and long-term contracting arrangements help reduce investment risks for industrial and transport-sector electrification.

For hydrogen production as a large-scale flexibility measure, despite EU-level incentives, early market and investment plans from domestic industrial actors are only now emerging and have not yet made inroads into the electricity regime. Given the wide range of end-uses of hydrogen and the long lifetimes of industrial assets (IRENA, 2025), the rate of change may represent a bottleneck with respect to upscaling and utilizing the hydrogen infrastructure (Odenweller & Ueckerdt, 2025). The lack of niche-level applications for hydrogen presents a tension between niche and regime interactions.

On the niche level, small-scale flexibility is still hindered by access to harmonized load control equipment and the ease with which one can trade on this level in Sweden (Johansson et al., 2020). Pricing mechanisms to achieve more-efficient load responses that incentivize small-scale flexibility provisions could be applied, such as adjustments to grid tariff structures at the distribution level (Askeland et al., 2021).

Barriers related to **market instruments for flexibility** (s51) are regarded as critical for Meta-challenges 1 and 2, as learned from stakeholders in **Paper I**. To enable the implementation of flexibility, securing investments to ensure large-scale flexibility, stronger engagement between the grid operators, aggregators, and flexibility service providers, and consumer protection against extreme price peaks are needed.

## 5. Key findings

### 5.1.4. Ancillary services of the power grid

The main bottleneck to the development of ancillary services is the operational disparity between a power grid that is mainly tailored to synchronous generation and one that is adapted for converter-based generation. The model results in **Paper II** indicate that the level of synchronous generation is significantly reduced in the cost-optimal and 22-GW offshore wind cases, and that there are hours during which converter-based generation supplies up to 90% of the electricity demand.

Several niche factors support the adjustments to frequency control and voltage control of the power grid that are needed to meet a high level of converter-based electricity generation. However, the lack of large-scale, converter-based experimentation becomes a concerning bottleneck if left unaddressed. As other countries and technology developers take the lead, grid codes and ancillary service markets have begun to adapt to accommodate systems with a higher share of converter-based generation, although further changes will still be necessary.

Within Meta-challenge 3 on Poor Governance in **Paper I**, the concerns related to **insufficient grid investment** (s52) are considered the most important. The enabling factors include grid code updates, continued development of ancillary service markets, and implementing long-term development plans for the electric grid infrastructure, similar to what is conducted in Germany.

In addition to these landscape factors, technological experimentation to support variable electricity production and to trade small-scale flexibility resources in an effective manner are needed to leverage the changes in generation capacity. This is relevant to all three cases, albeit less so to the 9-GW nuclear case in **Paper II**.

## 5.2. Long-term electricity system development in Europe

### 5.2.1. Evolution of supply mix under different demand magnitudes

Figure 12 shows how the generation mix evolves in the high-demand and low-demand scenarios for both slow and fast nuclear power expansion in Europe, with the S-shaped demand development pattern associated with **Paper IV**. Across all scenarios, wind and solar power increase dramatically, from a 45% share of the annual generation in 2025 to a 75% share in 2065 in the fast-nuclear power scenario and to 79% in the slow-nuclear scenario, with up to 42% of this share attributed to solar PV.

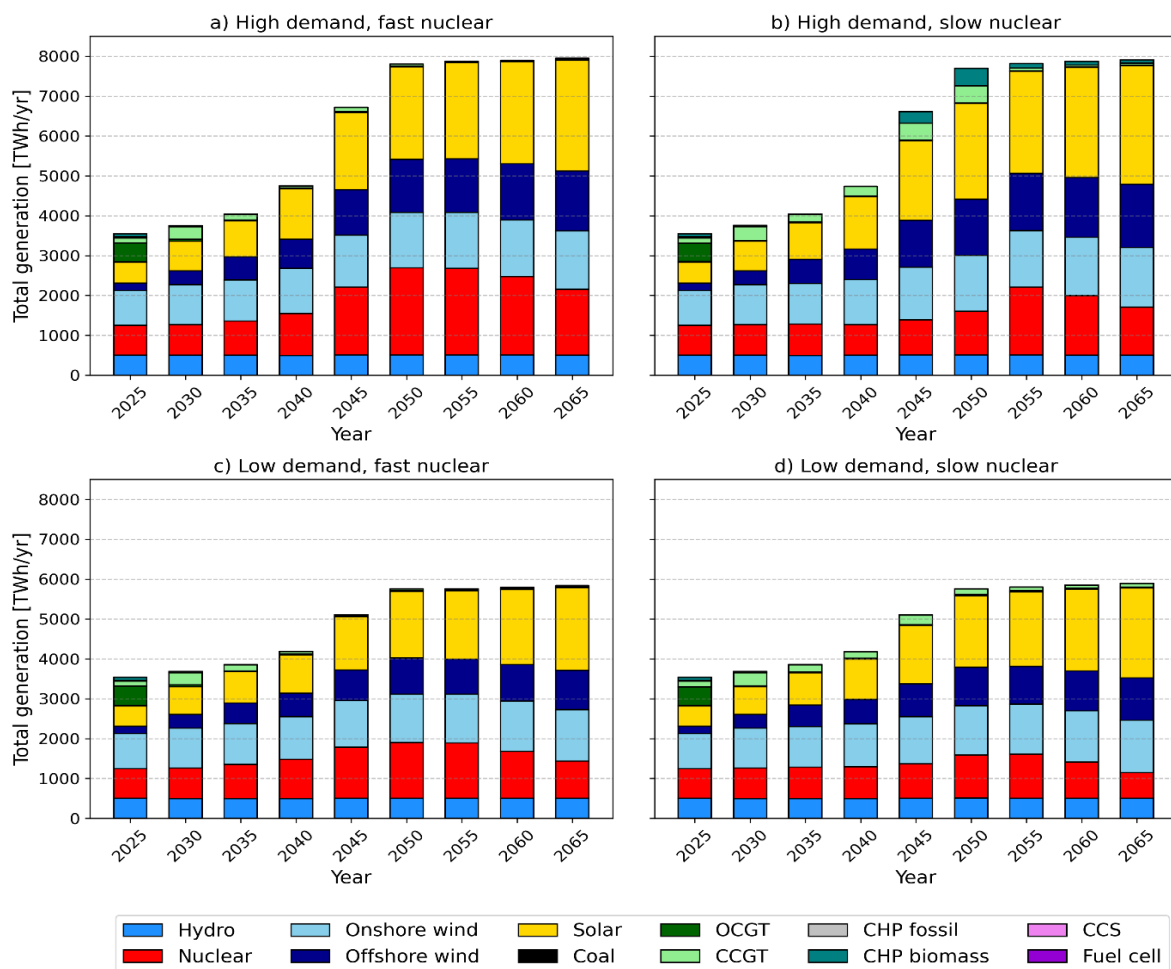


Figure 12: Annual electricity production mixes at low and high demands with S-shaped trajectory in Europe. Source: **Paper IV**.

## 5. Key findings

The results highlight a structural shift toward wind- and solar-dominated generation in the electricity system, with solar PV taking over once economically viable onshore wind potential is largely exhausted around 2035. The size of the demand impacts cost-efficient investments in nuclear power, solar PV, and offshore wind power. Onshore wind power remains essentially flat across all scenarios with a slight decrease in the share of the generation mix, whereas solar PV and offshore wind power account for most of the late-period growth, reflecting their larger remaining resource potentials and increased cost-competitiveness.

Nuclear power's share of the annual generation ranges from 10% to 28%, peaking during the mid-century period due to the rapid increase in the demand for power during these years. The lower share of generation happens at the end of the model horizon under slow nuclear power construction and low demand increase. Faster builds shift the peak earlier, although they do not dramatically change the overall range. With a 5-year construction period, nuclear peaks at 28% in 2050 (2,200 TWh/year) under high-demand conditions, and 24% in 2045 (1,400 TWh/year) under low-demand conditions. With a 15-year construction period, the peak only shifts modestly: 21% in 2055 (approximately 1,700 TWh/year) for high demand, and 24% in 2050 (1,100 TWh/year) for low demand. The low total impact of demand level and nuclear construction on nuclear power generation results from the concentration of nuclear power deployment in a few countries with poor renewable resources, even in low demand cases.

Fossil-fueled thermal generation steadily declines as carbon prices rise, and shows only small differences between the scenarios: Open Cycle Gas Turbine (OCGT) generation peaks at a 14% share (450–490 TWh/year) in 2025, while Combined Cycle Gas Turbine (CCGT) generation peaks at 9% (300–350 TWh/year) in 2030. In the slow-nuclear power construction, high-demand scenario, biomass Combined Heat and Power (CHP) appears briefly in the period of 2040–2045 (250–450 TWh/year), and there is a small contribution from 2055 to 2065 of under 100 TWh/year, distributed across various Central European and Balkan States. Biomass CHP, accounting for up to 6% of the generation mix, acts as a last-resort option when nuclear power buildout is slow and expensive and when there is a rapid demand surge.

The implementation of different growth limits further shows the dominance of wind and solar power in the future production mix in **Paper III**. As shown in Figure 13, when a growth limit is absent, solar PV plays a dominant role in the electricity mix, accounting for up to 45% at the end of the modeled period, alongside rapid early expansion of onshore wind.

The shares and production patterns of onshore wind power and solar power decrease with the implementation of growth rates. Thermal generation units, such as nuclear power and CCS power plants, as well as offshore wind power, partially contribute to the lower shares of onshore wind power and solar power. The growth limit becomes more binding in the regional capacity implementation, as opposed to the aggregate European level, which displays a broadly similar production mix compared to the case without a growth limit. Q3 implementation is also less restrictive than Q2 growth levels, resulting in more solar PV deployment and reducing reliance on thermal capacity.

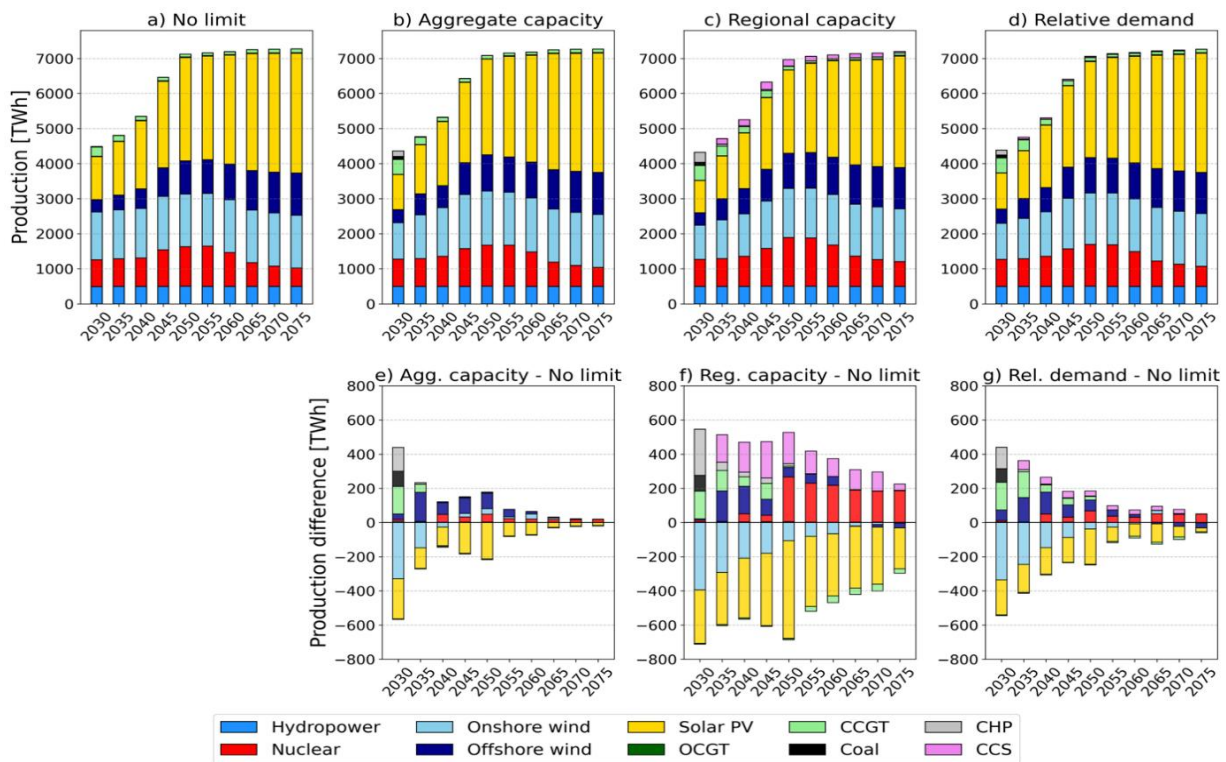


Figure 13: Annual generation mix in Europe, assuming Q2 growth rate limits for the four implementations in a)-d), while e)-g) display the difference between No limit and Aggregate capacity, Regional capacity, and Relative demand, respectively. Source: **Paper III**.

### 5.2.2. Evolution of supply mix under different demand development patterns

Figures 14-16 describe the net capacity additions, e.g., investment beyond repowering, of wind and solar power for the S-shaped and linear demand development across the modeled European countries for each 5-year investment period in **Paper IV**. Overall, timing and investment patterns differ between the technologies depending on the rate of change and the level of demand development.

## 5. Key findings

The linear development experiences earlier peaks in net capacity additions of wind and solar power, which is then followed by a decrease in additions in the later modeled periods. Wind and solar power deployment peaks in the S-shaped development in 2045, with one smaller peak in the early modeling horizon.

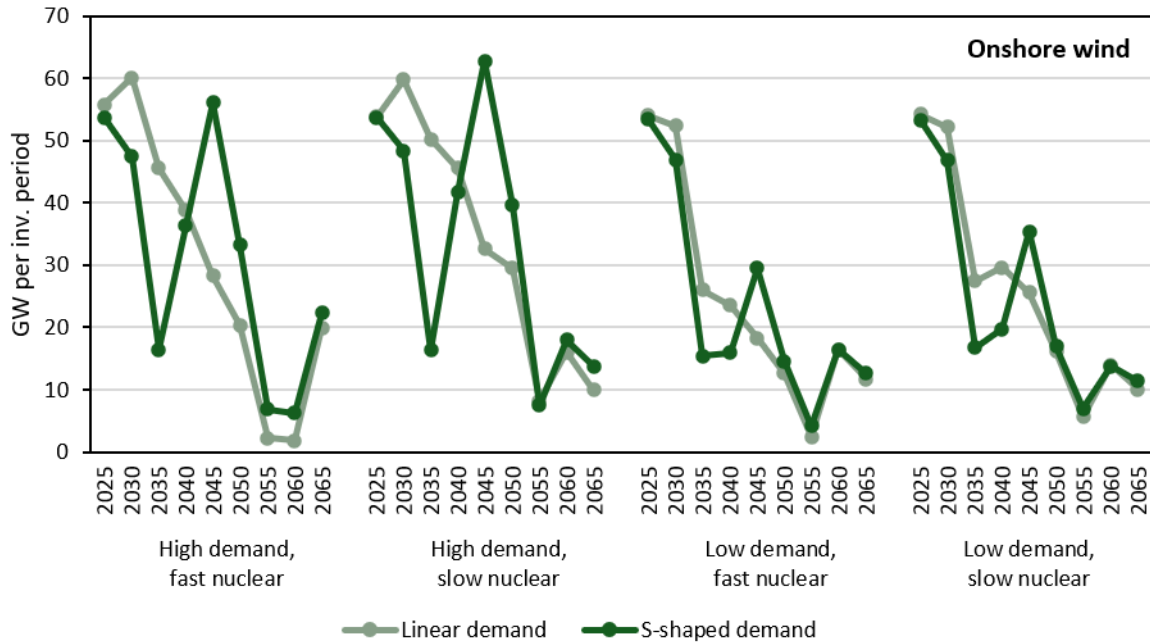


Figure 14: Net capacity additions of onshore wind power with linear and S-shaped demand development in Europe. Unit: GW per 5-year investment period.

Onshore wind power investments are characterized by high initial deployment in all scenarios, as shown in Figure 14. In the linear development pathway, capacity additions increase more gradually and peak around 2030, whereas in the S-shaped pathway they peak later, around 2045. Peak net capacity additions reach approximately 60 GW per investment period in both cases. Thereafter, net investment slows as the most cost-effective onshore wind power sites are exhausted and the resource potential limit is approached. Additional deployment only occurs when rising electricity demand makes less favorable sites economically viable. This effect is most evident in the high-demand scenarios, which exhibit higher peak capacity additions than the low-demand scenarios. Overall, net capacity additions range from 7 to 60 GW per 5-year investment period in the high-demand cases and from 4 to 53 GW in the low-demand cases. The relatively small differences across development rates and demand levels indicate that cost-effective expansion of onshore wind is ultimately constrained by resource availability.

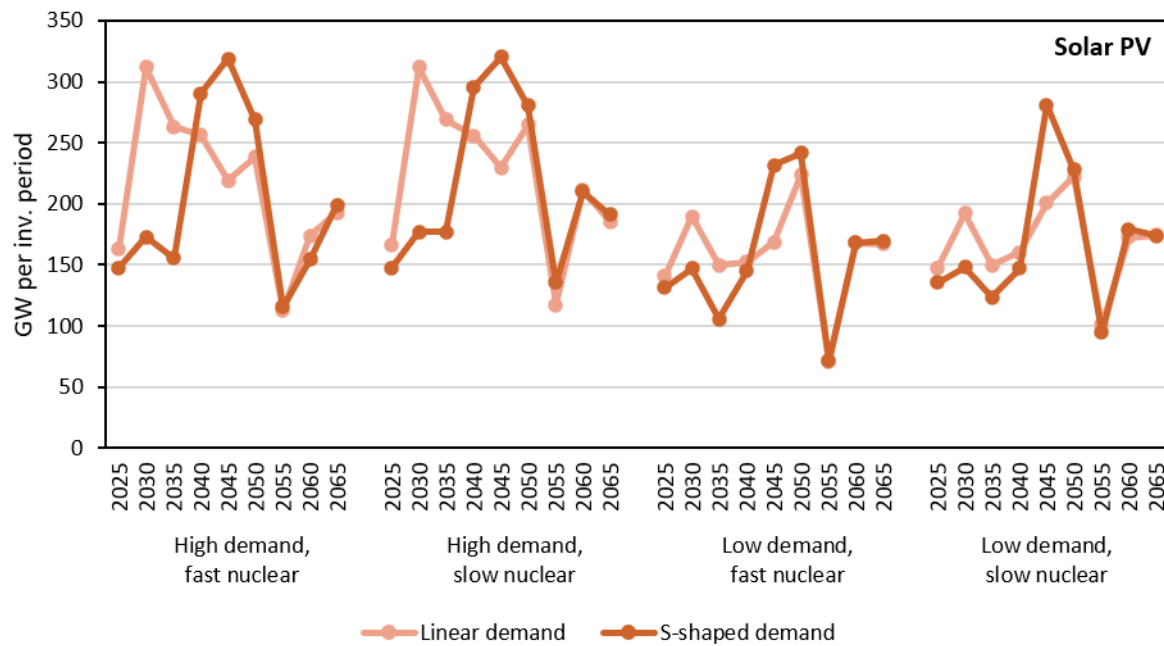


Figure 15: Net capacity additions of solar PV power with linear and S-shaped demand development in Europe. Unit: GW per 5-year investment period.

Solar power experiences two investment peaks: in 2030 and 2055 for the linear rate and in the years 2030 and 2045 for the S-shaped rate, as shown in Figure 15. The second peak has a much larger volume of investment for the S-shaped rate due to the rapid demand increase that occurs in the mid-model horizon. For the linear rate, the uptick in investment in 2030 is higher than that in 2055 for the high-demand cases and lower for the low-demand cases. The net capacity additions vary between 150 GW and 320 GW per investment period for the high-demand cases and between 70 GW and 280 GW per investment period for the low-demand cases. Solar PV responds closely to the high and low demands and plays a critical role under the pressure of high demand.

## 5. Key findings

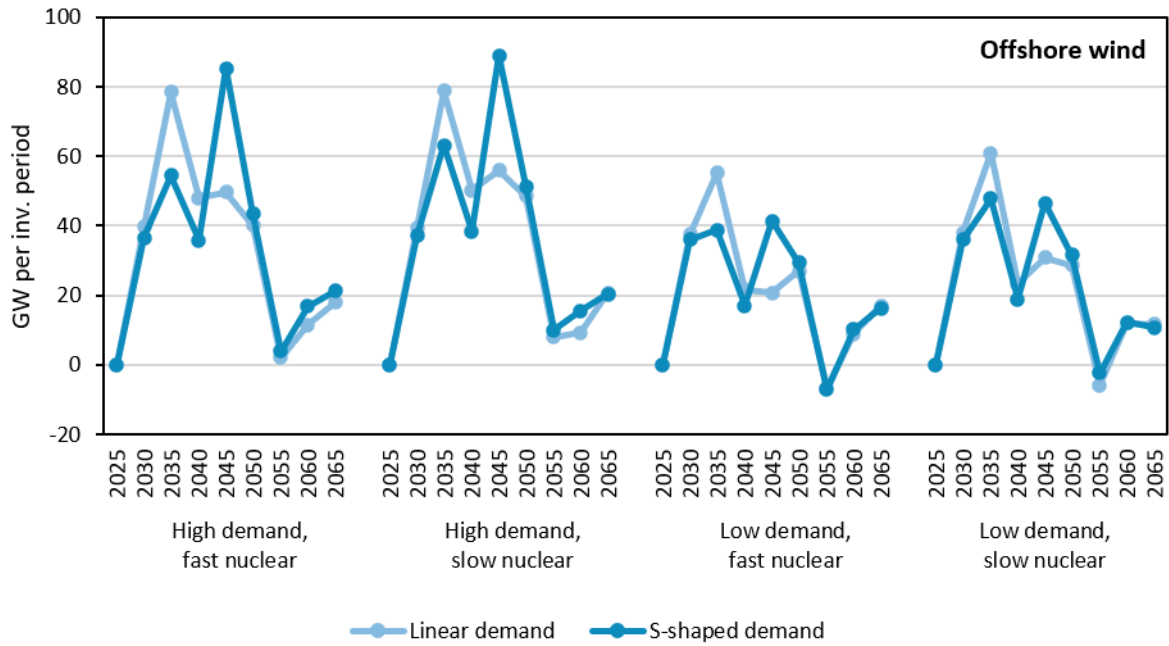


Figure 16: Net capacity additions of offshore wind power with linear and S-shaped demand development in Europe. Unit: GW per 5-year investment period.

For offshore wind power in Figure 16, there are two investment peaks across levels and rates of change in the 2035 and 2045 investment periods, forming an M-shaped pattern. The first peak appears later than the peaks for solar power and onshore wind under the linear development due to the increasing cost-competitiveness of offshore wind. The second peak corresponds to the period with the highest increase in demand in the S-shaped development, while for the linear development the peak is more prominent in 2035. Past the peaks, investments decline before rising again from 2060, which is when retirements of major existing nuclear power plants happen. The range of net capacity additions goes from 0 GW to 88 GW per investment period under the high-demand scenario. For the low-demand scenario, the net investment reaches almost 50 GW per investment period, and in 2055 more offshore wind capacity is retired than is added. This offshore wind power buildout pattern underlines the increasing importance of offshore wind in the investment mix.

### 5.2.3. Geography of future investments

To investigate the factors that shape the evolution of national electricity systems, the findings of **Papers III** and **IV** together illustrate how countries invest in wind and solar power under the interplay of growth-rate implementations and demand trajectories described in **Paper IV**. Across both high-demand and low-demand scenarios, solar PV and wind power frequently reach their maximum growth limits, though the timing and underlying causes vary substantially between countries. In several cases, countries also exhaust their assumed site availability limits, particularly in the case of onshore wind. Investments in nuclear power occur in regions where there is limited wind and solar potential relative to the demand development.

The findings, which group the modeled countries into four categories based on their constraints, including limitations imposed on value factors, growth limits, physical potential, and cost-competitiveness, are synthesized in Table 5.

The first group consists of countries in which the selected growth-rate implementation has only a marginal influence on the resulting system mix. In these cases, scenarios with unconstrained growth produce outcomes that closely resemble those seen under more-restrictive assumptions. This suggests that further wind and solar deployment is primarily limited by a cannibalization effect rather than by growth rates, resource availability, or resource quality. A high demand for electricity scales up solar PV significantly but also triggers new waves of onshore wind power investments in Spain, Sweden, and Ireland as additional sites become cost-effective.

The second group includes countries for which growth rate assumptions significantly alter long-term system development. In the absence of offshore wind power, historical growth patterns, scaled by projected demand, become the main limitation for system expansion in Hungary, Czechia, and Slovakia. Historical growth levels of onshore wind power also constrain Poland's deployment, which increases dependence upon rapid offshore wind expansion unless the short-term growth in solar PV or onshore wind can be accelerated. Across demand levels, onshore wind and solar power reach the maximum growth limits in Poland over the modeled horizon. There is significant nuclear power investment in Poland in both the low-and high-demand scenarios, while Czechia and Slovakia only invest in nuclear power under high-demand conditions.

## 5. Key findings

The third group comprises countries that are constrained both by assumed growth rates and by the assumed socially acceptable wind and solar potentials. Denmark, with some of Europe's highest-quality onshore wind resources, rapidly exhausts its entire onshore potential despite a modest level of demand, becoming one of the largest net exporters relative to system size (as shown in Figure 8). Belgium, the Netherlands, and Germany experience high industrial demands relative to their available wind and solar resources, with the consequence that system development eventually becomes limited by these assumed potentials. This situation also leads to significant nuclear investments in the region, with the exception of Denmark. At both high and low demands, the onshore wind power capacity is physically used up early on, while solar PV approaches its physical potential in 2045.

Finally, the fourth group includes countries in which system development is shaped jointly by growth constraints and the cost-competitiveness of available wind and solar resources. Greece and Italy only invest in onshore wind power early on, before cost-efficient sites are capped, leading to solar PV reaching its growth limit throughout the modeled horizon. In Austria and Switzerland, the cost for a large share of the onshore wind potential is  $>100$  €/MWh, limiting deployment. Therefore, Austria expands solar PV and relies on net imports, while Switzerland becomes a net exporter of electricity by deploying its solar resources. More than half of the onshore wind potential in Italy lies above the same cost threshold, restricting deployment under conditions of unconstrained growth. Greece also has nearly 60% of its onshore wind potential costing  $>100$  €/MWh. Despite strong solar resources, limited growth rates and trade constraints lead to transitional investments in wind power before the system stabilizes.

Table 5: Impacts on investments for four country groups based on dominant wind and solar growth rates at different demand levels in Europe. The groups reflect differences in growth-rate saturation, socially acceptable wind and solar potentials, and resource cost-competitiveness across different European regions. The investment patterns are derived from the findings of **Paper III** and **Paper IV**.

| <b>National system constraints</b>           | <b>Representative regions</b>                                                              | <b>Main wind and solar power expansion limitations</b>                                                                     | <b>Impacts on investment patterns at different demand levels</b>                                                                                                                                                                                                                        |
|----------------------------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Value factor-constrained systems             | Northern Europe (Ireland, Norway, Sweden) and Spain                                        | Cannibalization and declining value factors limit further wind and solar expansion; growth-rate choices have little impact | High demand unlocks new onshore wind sites and saturates solar growth limits for more periods to meet demand surges                                                                                                                                                                     |
| Growth rate-constrained systems              | Central Europe (Hungary, Czechia, Slovakia, Poland)                                        | Historical growth rates restrict scaling; onshore wind saturates early                                                     | Onshore wind saturates growth limits consistently<br>Solar PV maxes out the growth limit across the modeled horizon.<br>Nuclear investment in Poland across demand levels and in Czechia and Slovakia at high demand levels                                                             |
| Wind and solar potential-constrained systems | Northwestern Europe (Denmark, Germany, BENELUX countries)                                  | Physical limits restrict system development                                                                                | Onshore wind sites exhausted early<br>Solar PV approaches physical potential by mid-century in BENELUX countries<br>Offshore wind saturates growth limits until physically constrained<br>Significant nuclear investment due to limited wind and solar resources relative to the demand |
| Cost-competitiveness-constrained systems     | Southern Europe (Italy, Greece), Alpine landlocked region (Austria, Switzerland, Slovenia) | Large shares of wind potential exceed cost thresholds (>100 €/MWh); cost-efficient sites saturate early                    | Early investments in onshore wind before cost efficiency is capped<br>Solar PV maxes out the growth limit across the modeled horizon<br>Nuclear investment in Italy across demand levels and in Greece at high demand levels                                                            |

## 5. Key findings

### 5.2.4. *Impact of demand uncertainty on capacity investments*

The modeling work carried out in **Paper IV** indicates that stochastic variation exerts only a modest influence on investment outcomes. Since the system is dominated by technologies with high upfront capital costs and the costs of wind and solar power and storage investments decrease over time, it is economically unattractive to build capacity before it is required. Investing early as a hedging measure against high demand increases risks creating assets that become underutilized or stranded.

Figure 17a-d describes the deterministic capacity mixes of thermal and renewable generation following the S-shaped demand development. The investments follow closely how demand accelerates, with increased contributions from investments in wind and solar power observed in the later modeled years.

Figure 17e-h highlights how new investments differ between the stochastic and deterministic model runs, showing how the system adapts once uncertainty is resolved versus how much it prepares in advance in terms of both investment volumes and the timing of investments. Since investments are shared across all futures until Year 2035 in the stochastic case, the model builds some capacity to accommodate all four possible states of the world before diverging to prepare for a potential scaling up of generation under low-demand conditions, whereas in the deterministic cases the system is optimized over the entire modeled period. Compared with the deterministic low-demand scenario, the stochastic scenario brings forward approximately 60 GW of investments to 2035. By 2040, this difference is reversed as the deterministic scenario catches up, indicating a temporal shift in investment timing rather than a substantial difference in total capacity additions. In the high-demand scenarios, the two approaches look broadly similar, showing less than a 20 GW per 5-year period difference, as both systems experience similar pressures by mid-century despite uneven information prior to this period.

In terms of renewable investments, as illustrated in Figure 17e-h, there is 42 GW more solar PV capacity from 2025 to 2035 per 5-year period in the stochastic low-demand scenarios compared to the deterministic scenario. This showcases a hedging strategy in the stochastic case, whereby early investments help prepare for the possibility of a high future electricity demand.

Offshore wind power investments also differ between the stochastic and deterministic model runs in some regions. In the high-demand scenarios, the deterministic run adds a higher net capacity than the stochastic model run in regions such as France, southern Sweden, and northern Spain. In contrast, in the low-demand scenarios, the stochastic low-demand run invests in more offshore wind power in the period of 2040–2050 relative to the deterministic runs in the UK, France, southern Sweden, and northern Spain. These patterns reflect different hedging strategies: earlier offshore and solar build-out in the stochastic low-demand scenarios, and heavier offshore expansion in the deterministic high-demand scenarios.

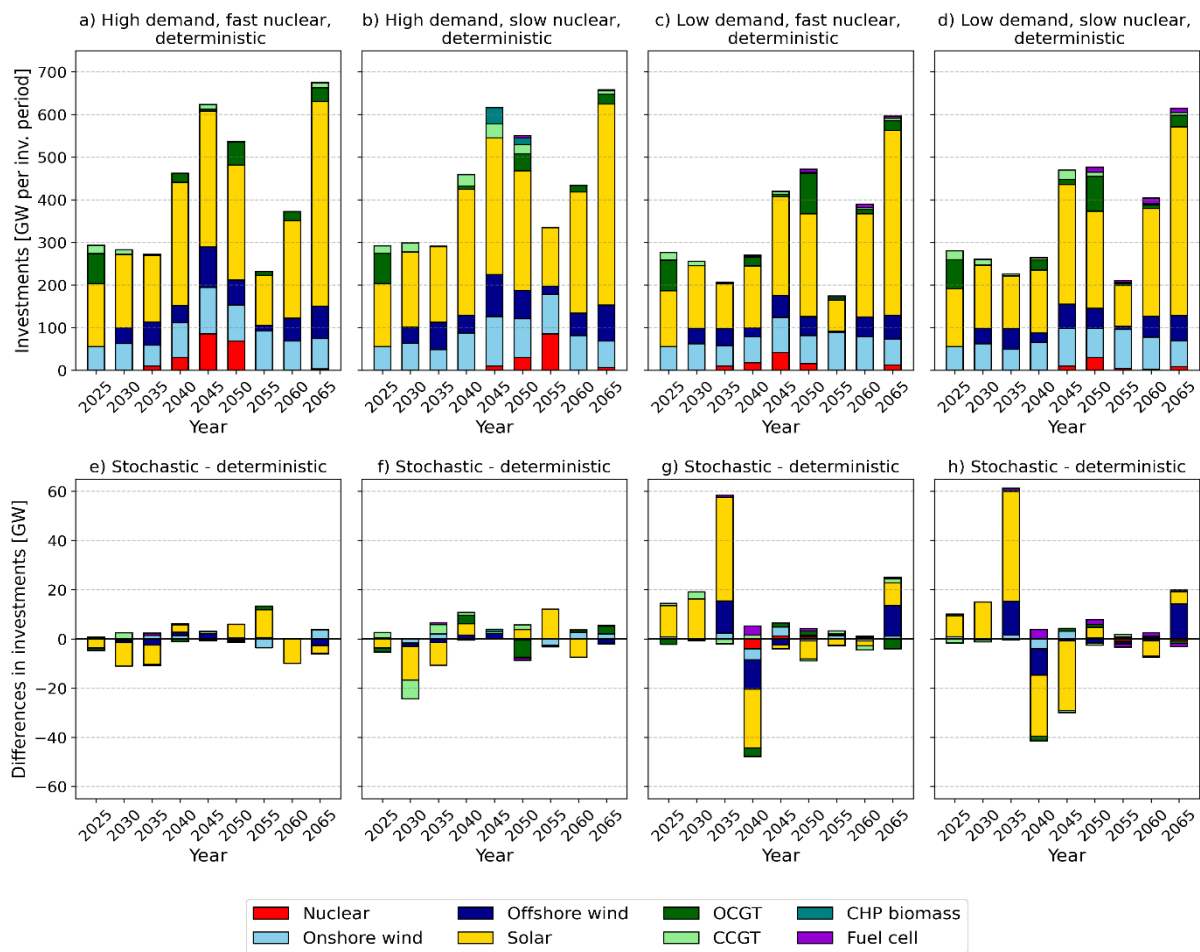


Figure 17: Capacity mixes of deterministic runs (a-d), and differences in new capacity investment between the stochastic and deterministic runs (e-h) in Europe. Positive values: greater investment in the stochastic scenario; Negative value: greater investment in the deterministic scenario. CHP, Combined heat and power; CCGT, Combined Cycle Gas Turbines; OCGT, Open Cycle Gas Turbines. Unit: GW per 5-year investment period.

## 5. Key findings

### 5.3. Synthesis of findings

**Papers I and II** focus on the challenges to electrification in Sweden, which are illuminated through stakeholder viewpoints in **Paper I** and the bottlenecks between the present and end states in **Paper II**. Drawing on stakeholder surveys and interviews, **Paper I** applies the Q methodology as a narrative analysis to explore and aggregate stakeholder viewpoints on the challenges to electrification in Sweden. Three *Meta-challenges* to electrification are identified: 1) *Procedural deadlocks, hindering the expansion of variable electricity production*; 2) *Competing political preferences, slowing the progress of electrification*; and 3) *Poor governance, hindering an effective electrification process*. By revealing patterns across diverse perspectives, the Q methodology offers valuable insights for both policy design and socio-technical investigations.

**Paper II** explores how technological development and policy conditions could shape alternative electricity futures in Sweden. By combining energy system modeling with socio-technical analysis based on the MLP, the study identifies transition bottlenecks across three electrification scenarios. The results show that all pathways face significant barriers, in that wind- and solar-based systems are constrained by operational and regulatory regimes shaped by the existing synchronous generation system, while new nuclear power struggles to achieve cost-competitiveness in a deregulated market. Consequently, bottlenecks emerge across all future electricity system configurations, albeit in different forms.

The transition bottleneck study in **Paper II** identifies structural and regulatory aspects that are not addressed in the Q study described in **Paper I**. The ESOM results can be used to identify technological requirements within the energy system, while the MLP framework can be applied to examine whether existing socio-technical regimes provide sufficient incentives for the development and adoption of the corresponding flexibility technologies. For example, the discussion of flexibility instruments could be strengthened by linking ESOM-identified flexibility needs to the MLP analysis of incentives and barriers within the current regime in **Paper II**.

While flexibility services currently represent a niche-level innovation, the uptake of such services would require interactions between the niche and regime levels. Similarly, operational disparity between power grids, which are mainly tailored to synchronous generation and not adapted for converter-based generation, necessitates more niche-regime interactions, and this is addressed in detail in **Paper II**. The difference in the analytical angles between the two papers results from the hierarchical structure embedded in the MLP framework, which enables the barriers to flexibility solutions and grid operations to be more analytically delineated.

On the other hand, the discursive elements in the energy transition in focus in **Paper I** contextualize the challenges and cluster them based on a ranking of priority. Highlighting the diverse perspectives on the challenges provided a robust foundation, while the stakeholder surveys and interviews enabled the co-construction of the processes through which certain challenges are prioritized. This type of analysis with the Q methodology is essential for examining contested issues, such as the tensions that occur between nuclear and wind power in Sweden, for which relying solely on numerical data and scientific literature is insufficient.

To address the third research question, how supply-side constraints and electricity demand trajectories are examined interact to shape the future European electricity system. On the supply side, different growth constraints are implemented for wind and solar power, as well as the continental investment limits imposed on nuclear power. On the demand side, alternative levels, rates, and uncertainties related to electricity demand growth are considered, including stochastic representations of different future states of the world.

**Paper III** examines how different representations of constraints on wind and solar power growth affect the transition to a low-carbon European electricity system. Using an energy system optimization model, three types of limits are applied: 1) continental constraints, representing supply-chain limitations; 2) national limits that reflect the barriers manifested within national borders, such as local permitting delays and weak social acceptance; and 3) system-scaled constraints that correlate with the collective capacity to expand renewable infrastructure alongside the growing electricity demand. **Paper IV** investigates how the size, trajectory, and uncertainty of the electricity demand influence the evolution of the European power system.

The results from **Paper III** show that if the growth rates of wind and solar power are limited on a continental level, deployment is concentrated geographically such that countries with good wind and solar resources experience capacity expansions that far exceed their historical levels.

## 5. Key findings

Meanwhile, **Paper IV** shows that the size of the demand influences the levels of cost-efficient investments, mainly those in solar PV, offshore wind power, and nuclear power that are restricted to a few regions, while cost-competitive onshore wind power resources are already fully utilized early on regardless of the demand development. This perspective complements **Paper I**, where some stakeholders stressed the importance of the availability of financing frameworks for capital-intensive technologies, such as offshore wind, nuclear power, and electrolyzers.

On the other hand, other stakeholders participating in **Paper I** expressed the importance of more general support measures, such as carbon policy, grid investment, and instruments to incentivize flexibility. Together with the findings of **Papers III** and **IV**, this suggests that overcoming national barriers is critical for enabling rapid renewable deployment and reducing dependence on thermal generation, but whether to do this through directed financial support for specific technologies or general support measures is contested.

When implemented as a capacity expansion constraint at the national level, the growth limit represents challenges associated with local acceptance, protracted permitting processes, and domestic political disputes. **Paper III** shows that these constraints lead to a more conservative and less efficient deployment pattern, as investment decisions become less flexible geographically. These findings align closely with those of **Papers I** and **II**, which identify permitting uncertainty, veto and appeal processes, coordination challenges, and political disagreements as key barriers to the energy transition. While the stakeholders in **Paper I** generally perceive social acceptance of specific technologies as being of low importance, broader political and governance issues emerge as significant challenges. Similarly, **Paper II** highlights the unpredictability of permitting processes, particularly for wind power, as critical in the cost-optimal and 22-GW offshore wind cases owing to their reliance on large-scale renewable deployment. The 9-GW nuclear case may face similar challenges if new reactor types are to be developed. From a European perspective, **Paper IV** shows that an S-shaped demand trajectory leads to a more geographically dispersed and temporally concentrated deployment of wind and solar power, as compared with a linear demand growth trajectory. Realizing such a deployment would require multiple countries to overcome domestic barriers within a relatively narrow timeframe, especially if the electricity demand increases rapidly.

Finally, system-sized growth limits reflect the ability of the broader socio-technical system to absorb and support accelerating deployment. In **Paper III**, renewable expansion increases alongside system growth, particularly in countries that have had historically low deployment rates. The importance of removing barriers so that renewables can scale up with the electricity demand is also in line with the findings of **Paper II**, which emphasizes the importance of regulatory frameworks, flexibility markets, and grid adaptation. At the same time, as shown in **Paper IV**, demand uncertainty provides only limited incentives for early hedging investments, as most low-carbon technologies are characterized by similar capital-intensive cost structures. Together, these findings suggest that the scaling up of electrification requires not only technological deployment, but also institutional and operational changes that enable the energy system to accommodate increasingly large shares of renewable electricity generation.



## 6. Discussion

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This chapter comprises a discussion on the findings and methodologies underlying the thesis. It provides an account of the implications of the findings in Section 6.1. Section 6.2 reflects on how the research design of each appended paper shapes the thesis, and what this implies for the robustness and limits of the insights gained. Some considerations for future work are listed in Section 6.3.

### 6.1. From ‘what if’ to ‘what next’ - Implications of the findings

This thesis focuses on several aspects of the barriers to the energy transition, with a focus on electrification in a Swedish context. The work involves stakeholder perspectives and their aggregated narratives, transition bottlenecks identified from a combination of socio-technical analysis and energy systems optimization modeling, technological growth implementations, and demand uncertainty in future technology configurations. From this analysis, the common and specific requirements for each transition pathway, in terms of capabilities and modes of operation, emerge.

In terms of socio-technical dimensions, the findings from **Papers I** and **II** highlight holistically the factors that hinder the energy transition in Sweden. It emphasizes how the electrification progress could be undermined by infrastructural lock-in, insufficient incentives to address financing challenges and the development of flexibility solutions, and fragmented governance practices, notably in relation to permit-granting processes. These challenges are mutually reinforcing and further complicated by political tugs-of-war between technological pathways. In systems with higher levels of variable renewable generation, the criticality of bottlenecks is characterized by both operational and infrastructural changes from the current regime, while the financing needs are greater in a system that is predominated by nuclear power or offshore

wind power. The high financing requirements for new nuclear power are also echoed in studies of other European countries, such as the Netherlands (Lucchi, 2026) and Switzerland (Bardow et al., 2026), and are actively being secured in Czechia (European Commission, 2024) and Poland (World Nuclear Association, 2026a), where deployment plans are being established. Use of the transition bottlenecks allows **Paper II** to articulate different ways in which the system could diversify and reorient both technologically and societally.

Thereafter, **Papers III** and **IV** expand the scope to the long-term electricity system evolution in Europe under demand and supply constraints. In terms of cost-effective investments, early investments in wind and solar power provide possibilities to reduce reliance on thermal capacity in later modeled years, while nuclear power seems to be critical in regions that have a high demand relative to the available hydropower, wind, and solar resources. The findings also indicate that the timing and placement of such wind and solar power investments offer a degree of freedom to enable wind and solar power expansion and therefore avoid higher-cost investments. At the same time, a temporary decline in net capacity additions does not necessarily signal a loss of momentum. Instead, it may indicate that the installed fleet already provides adequate generation capacity relative to the current demand, thereby reducing the need for new investments.

From the historical growth of wind and solar power, European countries do not present a uniform landscape in terms of renewable energy deployment. In the absence of nationally defined growth constraints, the model will minimize the total system costs by allocating capacity to sites where it is most cost-competitive, typically in countries with historically low levels of deployment despite having good renewable resources. In practice, these countries exhibit distinct technological trajectories shaped by historical deployment, available policy, and socio-political conditions (Creutzig et al., 2014). This begs the question, in similar veins with existing research (Lilliestam & Hanger, 2016; Tröndle et al., 2020): Should wind and solar power deployment be more evenly distributed in their shares in the electricity systems across countries, or concentrated where resources are most favorable, or should historically leading nations be expected to expand further deployment? This thesis shows that the volume and speed of wind and solar power investments are modulated by four key factors: the relative cost-effectiveness of socially acceptable renewable energy sites; the availability of renewable resources compared with demand growth; the capacity to invest in complementary infrastructure; and the historical patterns of technology deployment. For instance, several

Central European countries invest in nuclear power once the most economically attractive wind and solar power opportunities have been developed and increasing industrial demand requires additional low-carbon generation. Conversely, the Iberian Peninsula possesses considerable remaining solar potential, enabling continued solar power expansion to satisfy increasing electricity demand.

Because regions have different conditions and needs, support for low-carbon energy infrastructure should be tailored nationally while still ensuring that the overall transition remains coordinated and focused on common goals. This is particularly evident in **Paper I**, in that the findings suggest that it is important to accommodate diverse political preferences to overcome short-term policy deadlocks. **Paper II** discusses the importance of political stability and long-termism in planning for future grid infrastructure that accommodates a high share of variable electricity generation. In **Paper III**, the results indicate that limiting the growth of wind and solar power on different scales leads to different system compositions and suggests that transition pathways remain sensitive to both the stage of technological development and the context-specific barriers faced by individual technologies to sustain successive phases of growth and diffusion.

Finally, **Paper IV** highlights the importance of accounting for future demand trajectories. Rather than relying on the overexpansion of generating capacity, the findings suggest that the cost of not knowing is modest, given that there are many technologies with similar cost levels and possible placements in the model horizon. This contrasts with the commonly held belief that stronger commitments to singularly defined transition pathways are necessary to guide investment decisions and to support long-term system transformation. This does not imply that long-term commitment is unnecessary. Rather, it suggests that commitment may be more valuable when directed toward transition objectives and enabling conditions than toward prescribing specific technological pathways. To enable society's capacity to undergo such a transition of the energy system, barriers to the deployment of large-scale infrastructure need to be addressed, including access to capital for projects with high upfront investment requirements, regulatory incentives for flexibility solutions, long-term power grid planning, and effective governance of the transition.

## 6. Discussion

Despite the possible trajectories, there are commonalities in the findings, including the growing importance of renewables in an electrified energy system, new nuclear capacity investments in certain regions such as Germany, Poland, and Italy, and the need for ancillary infrastructure to adapt to a higher level of variable electricity generation. Across demand levels, onshore wind expansion is critical in the near term, while solar power and offshore wind power will play increasingly important roles when demand levels increase. Nuclear power is crucial for regions with low wind and solar resources relative to the demand. In addition to generation technologies, securing investments in large-scale flexibility and storage technologies and preparing for prolonged scarcity of green fuels when there is geopolitical volatility, as described in Odenweller & Ueckerdt (2025), are important. On the landscape level, this will bring about a change in global energy politics, including trade pattern shifts, supply chain vulnerabilities, and the need to broaden energy security from gas and oil disruption to electricity system resilience and cybersecurity risks.

Collectively, the appended papers suggest that electrification is constrained not by a single bottleneck but by a broader capacity to enact and coordinate change. Based on the stakeholder perceptions, institutional adaptations, renewable deployment, and investment responses to uncertainty, the findings point to transition capability as an integrative lens to understand the pace and direction of the energy system transformation. Rather than viewing challenges as individual entities, they can be understood as different manifestations of a system's ability, or inability, to coordinate and sustain rapid socio-technical change. The ways in which transition capacities are handled in each paper are summarized in Table 6. These include the abilities of stakeholders to align around transition objectives and to navigate uncertainty, institutions to adapt to new technologies, and infrastructures to scale deployment.

The various barriers identified throughout the thesis can, therefore, be interpreted as limitations for the transition capacity rather than isolated technological or economic barriers. Accordingly, with the Meta-challenges of **Paper I**, the transition capacity is limited by perceived contestations that materialize in situations involving procedural deadlock, different political preferences, and governance challenges. With the transition bottlenecks described in **Paper II**, the transition capacity is set by the confluence of institutions, markets, and system operations to adapt to an electricity system with a large share of variable, converter-based generation. A higher share of nuclear power requires changes in the market and fiscal regime, while the operational regime must be changed to accommodate a higher level of converter-based variable

electricity generation. Flexibility solutions have to be deployed to different extents, but the changes in ancillary services and grid code would be more substantial with wind power.

With the implementation of growth limits in **Paper III**, the transition capacity depends on how the barriers to the diffusion of wind and solar power can be overcome, while cost-efficient site availability and supporting infrastructure also play important roles in the transition capacity of certain regions. Finally, with the different growth in demand trajectories and supply scaling constraints implemented in **Paper IV**, the transition capacity can be understood as the abilities of different technologies to respond to demand pressure depending on their relative cost structures, which are limited due to the prevalence of technologies with high upfront cost. Furthermore, differences in resource availability and electricity demand growth between regions, together with technology-specific characteristics such as construction times and cost structures, imply that generation technologies may play different roles in meeting growing electricity demand across regions. Onshore wind and solar power can be deployed quickly and may therefore serve as the primary options for addressing near-term demand increases where suitable resources and permitting conditions are available. As these opportunities become increasingly constrained, offshore wind power may provide an additional source of generation, particularly as investment costs decline. In regions with limited potential to expand wind and solar power, new nuclear power capacity may represent a more suitable long-term option despite its high upfront costs and long construction times. This suggests that the sequencing and composition of low-carbon technologies should reflect regional conditions rather than follow a uniform transition pathway.

Table 6: Implications on transition capacity across appended papers

| Paper | What is studied                                                                     | How it explains transition capacity                                                                                                                                          |
|-------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| I     | Stakeholder perspectives and meta-challenges                                        | Capacity is limited by conflicting narratives, procedural deadlock, and governance challenges.                                                                               |
| II    | Bottlenecks across electrification scenarios                                        | Capacity depends on whether institutions, markets, and system operation can adapt to new technologies.                                                                       |
| III   | Implementation of wind and solar power growth constraints into energy systems model | Capacity depends on how quickly renewable deployment can scale given the compound effects of growth barriers.                                                                |
| IV    | Demand uncertainty and system evolution                                             | Capacity depends on the ability to respond to uncertain future conditions based on the cost structures of the technology mix and the ability to scale technology deployment. |

### 6.2. Reflections on the methodology

Given the breadth of methods applied and the geographic and temporal scopes of the studies, the thesis presents a bird's-eye view of transition barriers to electrification of the energy system. The focus of this section is to reflect upon how each method contributes to this understanding.

The methodological approaches of **Papers I** and **II** capture a snapshot of reality during the transition. The Q methodology is grounded in capturing subjectivities. It uncovers the underlying norms, perspectives, and narratives that stakeholders associate with transition processes. This approach is particularly effective in revealing contested discourses and the plurality of meanings attached to change. However, it relies heavily on the construction and interpretation of statements, which can introduce subjectivity to both the data collection and analysis. Another challenge relates to the selection of participants. Q studies rely on sampling a limited number of participants, typically between 15 and 40 people, and it is important to consider a diversity of perspectives. However, it might be difficult to ensure the inclusion of participants with critical or marginalized opinions.

**Paper I** focuses on the key stakeholders, who are primarily sampled based on affiliated organizations, including utilities, state agencies, research institutes, civil societies, and political representatives. A mix of workplaces and professional backgrounds can help to ensure a range of perspectives, although it does not fully address these challenges. Participants must also share a common understanding of the issue and its context when sorting statements. This requires a clearly defined empirical setting and may warrant the use of complementary methods, such as interviews, workshops, surveys, or textual analysis, to explore key perspectives in greater depth.

In contrast, the MLP approach conceptualizes transitions within a systems framework, focusing on institutional, regulatory, and infrastructural dimensions. It offers analytical power for addressing concrete aspects, such as market flexibility instruments, financing mechanisms, procedural dynamics (such as in the permit-granting procedure of wind power), and social acceptance. When paired with the output from energy system modeling to identify transition bottlenecks, it lends itself to a more top-down analysis, which means that the perspectives and actions of different social groups, including potential agents of change involved in the transition, are less well-developed. This means that while the bridging strength lies in systemic comprehensiveness, it may inadequately capture the interpretive and discursive elements of the transition, particularly the evolving values and viewpoints of stakeholders.

The bridging exercise brings into focus the tensions that exist between the existing regime and future system configurations, helping to clarify and articulate these challenges.

The scenario development in **Papers II–IV** is exploratory in nature, i.e., focusing on what could happen, rather than what will or should happen. The three cases investigated in **Paper II** are anchored in a reading of today’s political discussions in Sweden, while **Papers III** and **IV** explore how different growth implementations and demand levels impact the evolution of a future system. Although **Paper I** focuses on the stakeholder-motivated importance of various barriers other than scenarios, the research design also aims to explore stakeholders’ perspectives on the challenges. This means that the studies do not assume how the energy transition will unfold, but rather that there are different possible directions, each of which comes with its own storylines, barriers, and enabling conditions. Rather than identifying single optimal pathways or silver-bullet technologies that fit certain normative goals, exploratory scenarios enable a systematic comparison of plausible technology mixes and their techno-economic and socio-technical implications. Consequently, the findings should be interpreted as conditional on the selected assumptions and scenarios rather than as predictions of policy outcomes.

**Papers II–IV** implement an optimization model framework that follows a central planner logic that seeks to minimize the cost and assumes perfect market competition. Uncertainties have been incorporated parametrically by varying the levels of predetermined investments in wind and nuclear power in Sweden (**Paper II**), and structurally by applying the growth limit implementations (**Paper III**) and stochastic programming (**Paper IV**). The findings should be interpreted in light of these assumptions. Technology diffusion is represented in the model development in **Paper III** and **Paper IV** by imposing growth limits on wind and solar power and investment constraints on nuclear power, capturing past deployments of nuclear power in different European countries.

The growth constraints limit the model space that is available to populate the investment portfolio with variable generation technologies that exceed their historical levels of deployment. However, similar limits are not implemented for other generation technologies. For thermal technologies, such as gas turbines or CHP plants, as these technologies are both lumpy and mature in terms of deployment, further expansion would be based less on historical patterns from a regulated electricity regime and more on governmental decisions.

## 6. Discussion

Furthermore, investments in these technologies are limited to gas turbines and a low number of biomass-CHPs under conditions of high demand and slow nuclear deployment. Thus, imposing further constraints on these technologies would add little insight into the research question.

In **Paper IV**, nuclear power construction times and levels of electricity demand growth were selected as uncertain factors because they represent important real-world uncertainties that may influence long-term energy system development and investment decisions. As reliable estimates of the likelihood of the different future states were not available, all scenarios were assigned equal probabilities in the stochastic programming model in **Paper IV**. Setting similar probabilities across states of the world is similar to that adopted by Korkmaz et al. (2021), who investigated transport decarbonization pathways under uncertainty related to battery learning rates and biomass availability in Europe, and differs from the approach used by Bistline & Weyant (2013), who set different probabilities for emission caps when considering electricity sector investments in the US.

Given the multiple factors that can influence the transition, selecting modeled uncertainties is critical and should reflect knowledge of their nature and system-wide effects. To this end, both expert elicitation exercises and modelers' judgement are often dependent upon the research context and cannot fully compensate for a lack of empirical data for determining the range and likelihood of uncertain factors (Bock & Pfenninger-Lee, 2025; Böse et al., 2026). For example, the future costs of nuclear power remain highly uncertain, given that many Western nuclear projects were deployed under a different political regime and safety regulations, typically under regulated market conditions.

Böse et al. (2026) have further illustrated the discrepancy between the assumptions about the cost of capital of nuclear power across different models, such as the MESSAGE and GCAM model families, and the overnight costs of recent projects, such as those involving the Olkiluoto-3, Flamanville-3 and Vogtle power plants. On the one hand, this suggests that technological imaginaries can create overly optimistic or pessimistic cost assumptions (Böse et al., 2026), making modeling results highly sensitive to data, model structure, and underlying assumptions (Bock & Pfenninger-Lee, 2025). On the other hand, for emerging technologies such as green hydrogen, expert elicitation and literature reviews can help bridge the gap between announced and realized projects (Odenweller & Ueckerdt, 2025) by capturing political, institutional, and societal conditions shaping future developments.

It is possible to draw parallels between the framing of technological growth phases, as employed in the ESOMs in **Paper III**, and the niche, regime, and landscape levels in the MLP applied in **Paper II**. The niche level aligns with the early growth phase, in which developments are uneven, dependent upon support from incumbent actors, and generally associated with lower political risk. As technologies gain momentum and enter the acceleration phase, they begin to interact more directly with regime structures. Once they reach the steady growth phase, regime and landscape dynamics can slow their progress, and competing interests may disrupt or redirect their trajectories.

One key assumption made throughout this thesis is that the electricity demand will increase substantially under decarbonization, although the magnitude of that increase remains uncertain. The pace of the increase in demand will most likely differ between sectors, due to the progression from niche experimentation to commercial applications and the deployment characteristics. For example, given the gap between the announced 2030 targets and the realized projects on low-emissions hydrogen globally (IEA, 2026; Odenweller & Ueckerdt, 2025), industrial hydrogen applications will likely follow a steady pace in the near term, while data centers are inclined to enter the system in a steep trajectory (Director-General for Energy, 2025; IEA, 2024b). Meeting this demand requires the rapid deployment of a low-carbon infrastructure, while also acknowledging potential constraints, including material availability and supply-chain dependencies (Carrara et al., 2023; Riva Sanseverino & Luu, 2022).

Several limitations to the work described in the thesis should be noted. The thesis assumes a relatively stable residential electricity demand, based on the expectation that changes in population, energy efficiency, housing stocks, and associated policies will largely offset one another. Furthermore, the thesis adopts a broad definition of electrification and does not systematically assess the technical and economic electrification potentials of individual sectors. Even in situations in which electrification is technically feasible and cost-effective, significant challenges remain regarding grid capacities, availability of labor, industrial value chains, and levels of social acceptance. These questions warrant further research.

### 6.3. Considerations for future work

When it comes to future research, this section echoes the longstanding social science debate between agency and structure: To what extent are societal transitions shaped by the actions of individuals and organizations, and to what extent by the institutional rules, resources, and norms that structure those actions (Koistinen & Teerikangas, 2021; Kok, 2023)? Although parts of this research, particularly the Q methodology studies, engage directly with stakeholder perspectives through surveys and interviews, the thesis primarily focuses on identifying the conditions and constraints that shape energy transitions.

While the Q methodology in **Paper I** generates clusters of perspectives that are shared by stakeholders, it would be useful to understand the key lines of discourse that emerge during the critical moments of change in the Swedish electricity regime. While work has been conducted on the roles of the state and markets in climate policy (Haikola & Anshelm, 2023; Högselius & Kaijser, 2010; Niskanen et al., 2023) and in the framing of wind power (Bjärstig et al., 2022; Niskanen et al., 2024) and nuclear power (Edberg & Tarasova, 2016; Sonnsjö, 2024), policy change is usually preceded by and co-evolves with public debates. Given its potential to reshape norms and reframe storylines, it could be considered a change element in the energy transition. Such a discourse analysis could be carried out, for example, by textual analyses of different media outlets and policy documents. This would serve to explain how stakeholders construct and contextualize their views on different technologies in the energy transition during the critical moments of change, and how transition storylines get manifested in the process. A recent example of this is a report on the anti-wind movements in Europe published by WindEurope, in which Sweden ranks highest in terms of content generation associated with negative perceptions of wind power but ranks lower in the level of engagement with such content (WindEurope & CASM Technology, 2026).

The bridging exercise between MLP and ESOM, as implemented in **Paper II**, could be combined with further studies that create a dialogue between the envisioned futures and modeled futures. Several studies have drawn attention to this line of research (Burger et al., 2022; Sgouridis et al., 2022; Trutnevyte, 2014). Such approaches could enable qualitative aspirations to inform model interpretation while using model outputs to ground and refine future visions. This would broaden many of the perspectives on governing transitions that link both techno-economic feasibility and socio-technical insights within different empirical settings,

thereby enabling the exploration of re-conceptualizations (Wise et al., 2014), turning points, and the co-existence of future pathways (Trutnevyte, 2014).

From a modelling perspective, it would be relevant to investigate how lifetime extension and retrofits influence the configuration of low-carbon technology portfolios and the evolution of energy systems over time. While **Papers II-IV** evaluate technologies within a broader energy system context, future work could assess the readiness of the system itself to accommodate different technology pathways, as proposed in system-readiness frameworks (Xydas et al., 2026).

Regarding technological growth implementation in ESOMs, which is addressed in detail in **Paper III**, the endogenization of technology diffusion could be considered in future modeling practices, for example by linking the installed capacity with the knowledge stock associated with a technology in a certain region over time, to capture the spillover effect when technological diffusion occurs from one region to another (Leibowicz et al., 2016). For nascent technologies with limited historical observations, such as offshore wind power, Small Modular Reactors (SMRs), and carbon capture technologies, it is difficult to infer empirically or replicate the temporal and spatial diffusion processes observed for more-mature technologies within ESOMs. Rather than attempting to calibrate the diffusion dynamics from sparse historical data, it may be more fruitful to represent the technology-specific mechanisms that are expected to shape future deployment. For example, models could endogenously capture cost reductions through learning-by-doing (DeCarolis et al., 2017; Rubin et al., 2015). Moreover, models could account for lumpy investments associated with large-scale infrastructure, such as nuclear power plants or transmission networks, which cannot be deployed incrementally (J. DeCarolis et al., 2017).

When addressing uncertainty in energy systems optimization models, future research should first assess which uncertainties have the strongest relevance for the research objectives and the empirical context. Diagnostic frameworks such as NUSAP can help to evaluate how model inputs and assumptions influence the results (Van Der Sluijs et al., 2005). To capture these uncertainties more effectively, researchers could engage stakeholders in the development of normative scenarios and in discussions about future technological pathways. In this context, the extensive literature on integrating qualitative and quantitative methods offers useful guidance (Clemen & Winkler, 1999; Kann & Weyant, 2000; O'Hagan, 2019).

## 6. Discussion

Previous studies have suggested that stakeholder involvement should occur early and throughout the research process, allowing the inputs to shape the research questions, assumptions, and outcomes, rather than being limited to later stages when the model structures are already established (Copeland et al., 2022; Strachan et al., 2016). Multi-criteria decision-making approaches can support this process by providing both elicitation methods and statistical foundations for incorporating stakeholder perspectives (Afsordegan et al., 2016; Gosling, 2017).

In terms of uncertainty approaches, while stochastic programming, as performed in **Paper IV**, provides a single hedging strategy across all states of the world, model processing time increases significantly as the number of uncertain parameters and stages increase (Yue et al., 2018). The analysis could be combined with other approaches, such as robust optimization, which is more computationally efficient, depending on how reliable and for which factors the probabilities could be obtained. When some levels of confidence in the probabilities, alongside the bounds and ranges of the uncertain factors, can be determined, robust optimization could be developed within or in parallel with a stochastic programming framework. New modeling techniques should also be considered, taking stock of decision theories and uncertainty treatments in other fields, such as info-gap decision theory modeling, which has been applied in power systems research (Nojavan et al., 2017; Soroudi et al., 2017).

Further research is also needed to assess the compatibility of alternative electrification pathways with climate targets under shifting geopolitical and societal conditions, as highlighted by others (Li & Pye, 2018). Several policy and technological uncertainties are pertinent to the energy transition, such as grid investments, price elasticity of demand, and biomass availability and storage or import possibilities, and these could merit further model development. The approaches presented in the thesis could be complemented with security of supply analyses that account for the risks along material and fuel value chains, including potential supply disruptions. For example, stochastic techno-economic analyses could be used to examine the impacts of hydrogen import disruptions in Central Western Europe (Blanchard, 2024) or the impacts of oil supply constraints on an Irish energy system (Glynn et al., 2014).

## 7. Conclusions

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In the context of the electrification of energy systems, this work explores the factors that hinder the low-carbon energy transition. The overarching research question is: How do different transition barriers influence the ability of the energy system to handle large-scale electrification? For this, there are three supporting research questions:

- How are challenges to electrification perceived and framed by stakeholders? (**Paper I**)
- What bottlenecks emerge across alternative electrification pathways? (**Paper II**)
- How do supply growth constraints and varying demand trajectories shape future electricity system development? (**Papers III and IV**)

The research presented herein spans from barriers to uncertainties in the electricity system, from Sweden to Europe, and from a snapshot of reality to a multi-year model setup. Within the scope of the thesis, two papers focus on Swedish case studies and elucidate contemporary electrification challenges, while the other two papers adopt a European perspective and investigate long-term electricity system development. Collectively, the papers move from understanding how transition challenges are perceived and manifested at the present time (**Papers I and II**) to examining how key supply deployment constraints and uncertainties influence future electricity system pathways (**Papers III and IV**).

## 7. Conclusions

The first question is answered through a Q analysis that aggregates stakeholder viewpoints on the challenges (**Paper I**). Three Meta-challenges are identified from the work, namely Procedural Deadlocks, Competing Political Preferences, and Poor Governance. All Meta-challenges highlight the importance of systemic transformation, albeit with different orientations. The Procedural Deadlock Meta-challenge underscores the delays and inefficiencies in scaling up variable electricity production, which hinder the deployment of technologies that are critical for achieving net-zero carbon emissions. The Competing Political Preferences Meta-challenge highlights how divergent political priorities, particularly regarding carbon policies and flexibility incentives, slow progress toward electrification. The Poor Governance Meta-challenge emphasizes inadequate grid investments and distributive justice concerns, particularly the perceived uneven allocation of transition-related benefits and burdens across stakeholder groups and regions, including communities that are hosting energy infrastructure. These findings underscore the need for integrated and adaptive policy frameworks that move beyond technology-centered debates, such as those surrounding wind and nuclear power, and that instead focus on addressing broader systemic challenges.

For the second question, **Paper II** examines how technological development and policy conditions shape alternative futures for the Swedish electricity system. By combining energy system modeling with a socio-technical analysis based on the Multi-Level Perspective, the study identifies transition bottlenecks across three electrification cases. The results indicate that all of the pathways face significant challenges. Wind- and solar-based systems are constrained by operational practices, regulatory frameworks, and institutional arrangements that have evolved around a synchronous generation regime, while new nuclear power faces difficulties in achieving cost-competitiveness within a deregulated electricity market. Thus, rather than identifying a single preferred pathway, the study highlights how each transition pathway gives rise to distinct challenges.

With the third question, **Papers III and IV** investigate how supply constraints and demand trajectories shape the future European electricity system. These papers consider deployment constraints on wind, solar, and nuclear power and demand pathways that differ in size, pace, and uncertainty level. The results show that supply constraints imposed at the national level strongly affect the scale and geographic distribution of variable renewable electricity deployment. Wind and solar power display divergent deployment patterns in the long term due to differences in cost-competitiveness, resource quality, and growth limits.

Accordingly, solar PV deployment continues throughout the modeled period, while onshore wind expands until mid-century, followed by investment in offshore wind once cost-effective onshore wind and solar resources are exhausted within a region. On the other hand, demand developments primarily influence investments in solar PV and offshore wind power, while nuclear power investments are concentrated to a few countries with limited renewable resources relative to electricity demand, notably Germany, Poland, and Italy. The possibility to hedge against future uncertainties is limited due to the prevalence of technologies that have high upfront costs. Instead, rapid demand increases lead to geographically distributed electricity generation investments. Overall, the findings highlight the importance of jointly considering supply-side limitations and demand evolution when planning future electricity systems.

Taken together, this thesis shows that across the Swedish and European analyses, governance structures, institutional capacity, and infrastructure readiness emerge as critical determinants of transition outcomes. While large-scale expansion of wind and solar power consistently represents the most cost-effective pathway to electrification, realizing this pathway requires overcoming barriers related to permitting, grid adaptation, and system flexibility. The findings further demonstrate that future electricity systems are shaped by the interactions between technological deployment constraints and evolving electricity demand. Ultimately, the challenge of electrification extends beyond technology and economics to one of societal transformation, necessitating institutions and governance arrangements that are capable of enabling rapid and large-scale decarbonization.



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# Glossary

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## **Barriers, challenges, meta-challenges, and transition bottlenecks**

*Barriers:* Specific factors that block or halt a goal from being achieved.

*Challenges:* General factors that hinder the achievement of something. They can be driven by single barriers or a group of barriers.

*Meta-challenges:* Aggregated stakeholder perceptions of energy transition challenges, encompassing issues with differing levels of perceived importance associated with **Paper I**.

*Transition bottlenecks:* Barriers to energy transition pathways, linked to different electricity futures and key technologies in **Paper II**.

## **Scenario, case, and pathway**

*Scenario:* A plausible, technically consistent modeled future state. This concept is used most extensively in **Paper IV** to explore the impact of uncertainty in demand levels and nuclear deployments and demand developments on future systems.

*Case:* Case is similar to a scenario in the concept of modeled future systems but specific to the context of the case study. **Paper II** explores two cases in addition to the cost-optimal case that are anchored in the contemporary energy discourse of the country with the government term of 2022-2026.

*(Transition) pathway:* The process, sequence of developments, and dynamics by which a future (such as a low-carbon energy transition of the electricity system) is reached. **Papers III** and **IV** model multi-year evolutions of the electricity system, which enables the analysis of the system developments. The pathways to reach the three cases in **Paper II** are also articulated via transition bottlenecks.

## **Growth, deployment, and diffusion of technology**

*Growth:* The net change in capacity, the difference between the capacity of new investments and that of retirements of a technology.

*Deployment:* The physical installation of a technology in specific locations.

*Diffusion:* The spread or adoption of a technology across a country or market over time.



# Appendix

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Table A.1 presents a list of 52 statements (s1 to s52) on socio-technical barriers to electrification in Sweden used in Paper I. The compilation was done so that each statement is independent and mutually exclusive in content from the others.

Table A.1: List of statements on socio-technical barriers to electrification in Sweden used in the Q survey.

| Statement Number | Statement                                                                                                                                                                                   |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| s1               | Prioritizing land for biodiversity and recreation over land for energy production hinders the deployment of new low-carbon electricity infrastructure.                                      |
| s2               | Concerns regarding the health and safety of local people hinder the deployment of new low-carbon electricity infrastructure.                                                                |
| s3               | Security risks linked to the supply chain for critical materials will limit the scale-up of low-carbon electricity infrastructure.                                                          |
| s4               | The idea that financial compensations to local communities with new wind power developments are considered bribery will hinder the deployment of new low-carbon electricity infrastructure. |
| s5               | Concerns regarding reduced local property values hinder the deployment of new low-carbon electricity infrastructure.                                                                        |
| s6               | Existing support schemes for solar photovoltaic installations prioritize people who own their properties over people who live in multi-family houses.                                       |
| s7               | There is too much investment in demonstration projects for new technologies, and not enough in market implementation.                                                                       |
| s8               | Return on investment designed to increase shares of renewables is too uncertain for end-use sectors.                                                                                        |
| s9               | There is too little support for the development of new nuclear technologies, such as small modular reactors (SMRs).                                                                         |
| s10              | There is too little support for grid connections to offshore wind turbines.                                                                                                                 |
| s11              | Expectations on cost reduction for solar photovoltaics are overly optimistic.                                                                                                               |
| s12              | Large companies are locked into outdated technologies.                                                                                                                                      |
| s13              | Consumers will oppose the increased volatility of electricity prices when the shares of renewables increase within the electricity system.                                                  |
| s14              | Lengthy legal appeals prolong the processing time for permits to develop new electricity infrastructure.                                                                                    |

|     |                                                                                                                                                                |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| s15 | Efforts to resolve competing interests in land and sea areas relevant for renewable electricity generation are insufficient.                                   |
| s16 | Poor communication between new consumers, producers, and grid operators hinders effective grid expansion planning.                                             |
| s17 | The stigma around nuclear power safety hinders its continued deployment.                                                                                       |
| s18 | There is too little faith in emission reductions by means of electrification.                                                                                  |
| s19 | Electricity producers prioritize grid access for new projects over other key features, e.g., wind speed.                                                       |
| s20 | A high share of renewables in the power mix will fail to meet "just-in-time" demand from consumers.                                                            |
| s21 | The expansion of energy storage capacity will be inadequate to accommodate a high renewable share in the electricity system.                                   |
| s22 | It is overly optimistic to expect people to consume electricity in a more flexible manner at home.                                                             |
| s23 | It is too costly to fully electrify some sectors like heavy-duty vehicles.                                                                                     |
| s24 | The installation of fast-charging stations is occurring too slowly for the electrification of road transport.                                                  |
| s25 | Difficulties in finding reliable storage sites for nuclear waste will limit the expansion of nuclear power needed for electrification.                         |
| s26 | Limitations in grid capacity between Sweden and continental Europe hinder an efficient electrification.                                                        |
| s27 | Discussions of the costs and benefits of electrification fail to consider people with low incomes or ethnic minorities.                                        |
| s28 | The pace at which the prices of end-use technologies, such as solar photovoltaics and electric vehicles, are decreasing is too slow for most people to afford. |
| s29 | Rapid electrification of industry will put people without the right skillsets out of job.                                                                      |
| s30 | The deployment of new electricity infrastructure in the north of Sweden will disrupt the Sami people's traditional way of life.                                |
| s31 | Electrification will make society more sensitive to cyberattacks.                                                                                              |
| s32 | A large fraction of the population is poorly informed about electrification and energy transition.                                                             |
| s33 | Too much emphasis is placed on nuclear power by the media and politicians.                                                                                     |
| s34 | Electrification will likely deepen or perpetuate regional and urban-rural divisions.                                                                           |
| s35 | State-owned firms such as Svenska Kraftnät and Vattenfall are not leading the transition.                                                                      |
| s36 | The mindset of private consumers in relation to electricity services hinders an increase in the share of renewables in the energy mix.                         |

|     |                                                                                                                                                        |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| s37 | The mindset of industrial actors in relation to electricity provision hinders electrification in end-use sectors.                                      |
| s38 | Local people are concerned with losing their place identity when new electricity infrastructure is built close to where they live.                     |
| s39 | Current carbon pricing levels are too low for electrification to be implemented in industries.                                                         |
| s40 | The prominent number of actors that have a veto on new developments hinders the deployment of new low-carbon electricity infrastructure.               |
| s41 | Electrification will ultimately create more fuel dependence on geopolitically sensitive areas.                                                         |
| s42 | The integrated EU electricity market and the impact that it has on Swedish electricity prices represent a barrier to electrification.                  |
| s43 | Polarized mindsets on climate actions at the international level limit the progress of electrification in Sweden.                                      |
| s44 | Broad system transformations, and not just technological substitutions, are needed for electrification.                                                |
| s45 | The lack of coordination between authorities involved in the permitting processes hinders the deployment of new electricity infrastructure.            |
| s46 | Free emissions allowances disincentivize heavy industry from implementing electrification.                                                             |
| s47 | Low-income households and small companies lack the means to adapt to changes in electricity prices.                                                    |
| s48 | Widespread political claims without sufficient evidence mislead citizens about the impact of electrification.                                          |
| s49 | Project developers fail to take the interests of the locals into account during the consultation process of new low-carbon electricity infrastructure. |
| s50 | Political disputes, such as those related to nuclear power vs wind power, become a barrier to electrification.                                         |
| s51 | Market instruments for flexibility to adapt to a higher level of renewable penetration are insufficient.                                               |
| s52 | There is not enough investment in measures that alleviate grid capacity constraints needed for electrification.                                        |