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Three perspectives on challenges to the electrification of industry and transport in Sweden

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Abstract

Contemporary environmental problems have catalyzed the need for societal transitions, involving multiple actors and institutions as well as interactions across multiple sectors and scales. Given this complexity, a repertoire of methods has emerged aiming at understanding and guiding change.

Electrification stands at the core of the energy transition across numerous countries and regions and constitutes a pivotal strategy in decarbonization of the energy sector. As demand for low-carbon energy sources grows, it becomes increasingly important to examine the factors that impede and enable the energy transition.

In Sweden, the context of this work, the ambition to achieve net-zero emissions by 2045 hinges on rapid and large-scale electrification of the transport and industry sectors. However, the transition has proven more complex than technical potential alone would suggest. This thesis investigates the factors hindering electrification through two empirical studies, employing three distinct analytical perspectives: narrative analysis, socio-technical analysis, and techno-economic analysis. This is done in two papers.

Drawing on stakeholder surveys and interviews, **Paper I** applies the Q methodology, a narrative analysis to aggregate stakeholder viewpoints on challenges to electrification. Three *meta-challenges* to electrification could be 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.* From these, policy elements on how the directionality of the transition could be secured are proposed.

Paper II explores how technological developments and evolving market conditions impact different electricity futures. By combining socio-technical analysis and energy systems modeling, we identify transition bottlenecks hindering electrification efforts. The socio-technical analysis applies a Multi-Level Perspectives framework to investigate the challenges and enabling conditions of key technologies, while the energy system modeling grounds the analysis in techno-economic feasibility when analyzing three future electricity systems. It is found that landscape-level changes, which represent wider context processes, have been insufficient to promote a shift to an electricity system that has a high share of wind power. Instead, the operational and regulatory regime is strongly influenced by the existing system, which is dominated by synchronous electricity generation from hydropower and nuclear power. Yet, new nuclear power struggles to become cost-competitive in the deregulated electricity market. Thus, bottlenecks exist for all three future electricity systems investigated in this work.

By integrating insights from the three perspectives, this thesis contributes to a more nuanced understanding of the electrification challenges and offers policy-relevant implications supporting a just and effective electrification in Sweden. Together, the thesis reveals how unsettled discourse, insufficient incentives, infrastructural inertia, and fragmented governance slow transition despite stringent climate targets.

Keywords: Energy transition, Electrification, Sweden, Socio-technical Analysis, Q methodology, Sustainability, Meta-Challenges, Transition Bottleneck

Tóm tắt

Các vấn đề môi trường đương đại đã thúc đẩy nhu cầu chuyển đổi xã hội, không chỉ liên quan đến nhiều tác nhân và tổ chức khác nhau, mà còn tương tác trên nhiều lĩnh vực và quy mô. Trước sự phức tạp này, nhiều phương pháp đã ra đời nhằm giúp hiểu rõ hơn và định hướng các quá trình chuyển đổi này.

Điện khí hóa là trọng tâm trong chiến lược chuyển đổi năng lượng ở nhiều quốc gia và khu vực, đồng thời đóng vai trò then chốt trong tiến trình khử carbon của ngành năng lượng. Khi nhu cầu sử dụng các nguồn năng lượng carbon thấp tăng lên, việc nhận diện các yếu tố cản trở và điều kiện thuận lợi cho quá trình chuyển đổi năng lượng ngày càng trở nên quan trọng.

Tại Thụy Điển, bối cảnh nghiên cứu của luận án này, tham vọng đạt mức phát thải ròng bằng 0 vào năm 2045 phụ thuộc vào quá trình điện khí hóa nhanh chóng và sâu rộng của các ngành giao thông và công nghiệp. Tuy nhiên, quá trình chuyển đổi này tỏ ra phức tạp hơn so với tiềm năng kỹ thuật đơn thuần. Luận án này phân tích các rào cản đối với quá trình điện khí hóa thông qua hai nghiên cứu thực nghiệm, sử dụng ba góc nhìn phân tích riêng biệt: phân tích tường thuật, phân tích xã hội-kỹ thuật và phân tích kỹ thuật-kinh tế. Các nội dung này được trình bày trong hai bài báo khoa học.

Dựa trên khảo sát và phỏng vấn các bên liên quan, Bài báo I áp dụng phương pháp Q, một phân tích tường thuật, để tổng hợp các góc nhìn khác nhau về những thách thức trong quá trình điện khí hóa. Từ đó, ba nhóm thách thức chính được xác định là: (1) Bế tắc thủ tục làm cản trở việc mở rộng sản xuất điện có tính biến đổi; (2) Các ưu tiên chính sách cạnh tranh làm chậm tiến độ điện khí hóa; và (3) Năng lực quản lý kém ảnh hưởng đến hiệu quả thực hiện chuyển đổi. Từ đó, bài báo đề xuất một số chính sách thằm thúc đẩy quá trình chuyển đổi một cách có định hướng hơn.

Bài báo II khám phá tác động của sự phát triển công nghệ và điều kiện thị trường đến các kịch bản điện khí hóa trong tương lai. Chúng tôi nhận diện các nút thắt trong quá trình chuyển đổi bằng cách kết hợp phân tích xã hội-kỹ thuật và mô hình hóa hệ thống năng lượng. Phân tích xã hội-kỹ thuật sử dụng khung lý thuyết Quan điểm Đa cấp để phân tích các thách thức và điều kiện thuận lợi của các công nghệ chủ chốt, trong khi mô hình hóa hệ thống năng lượng đánh giá ba kịch bản điện khí hóa tương lai dựa trên các tiêu chí kỹ thuật-kinh tế. Kết quả cho thấy, những thay đổi ở cấp độ bối cảnh chưa đủ để thúc đẩy sự chuyển đổi sang một hệ thống điện có tỷ trọng điện gió cao. Cơ chế vận hành và quản lý vẫn chịu ảnh hưởng nặng nề của hệ thống hiện tại, vốn bị chi phối bởi việc phát điện đồng bộ từ thủy điện và điện hạt nhân. Trong khi đó, điện hạt nhân mới lại phải vật lộn để trở nên cạnh tranh về chi phí trong thị trường điện phi điều tiết. Do đó, cả ba hệ thống điện trong tương lai được nghiên cứu trong công trình này đều gặp phải những nút thắt riêng biệt.

Bằng cách tích hợp ba góc phân tích khác nhau, luận án này góp phần làm sáng tỏ những thách thức của quá trình điện khí hóa và đưa ra những gợi ý chính sách nhằm hỗ trợ quá trình chuyển đổi công bằng và hiệu quả hơn ở Thụy Điển. Tổng thể, luận án cho thấy sự thiếu thống nhất trong diễn ngôn, thiếu hụt các cơ chế khuyến khích, sự trì trệ về mặt cơ sở hạ tầng, và quản trị phân mảnh làm chậm quá trình chuyển đổi, mặc dù quốc gia này đã đề các mục tiêu khí hậu đầy tham vọng.

Từ khóa: Chuyển đổi năng lượng, Điện khí hóa, Thụy Điển, Phân tích xã hội-kỹ thuật, Phương pháp Q, Tính bền vững, Thách thức siêu hình, Nút thắt chuyển đổi

List of publications

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. Electrifying tensions: Stakeholder narratives to electrification of industry and transport in Sweden. Accepted for Energy Research and Social Science.

II. Phan, N.A., Johnsson, F., Göransson, L. Investigating transition bottlenecks in the Swedish low-carbon energy transition from a mixed-methods approach. Manuscript.

Nhu Anh Phan is the principal author of **Papers I–II**. Professor Filip Johnsson contributed with the discussions and editing of **Papers I–II**. Professor Hans Hellsmark contributed to the method development as well as editing and discussions in **Paper I**. Professor Lisa Göransson contributed to editing and discussions in **Papers I-II** as well as the method development in **Paper II.**

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I deeply appreciate the company of my colleagues at Energy Technology and SEE department for the many meaningful ways you have contributed to my professional growth and well-being at work.

Finally, I thank my family and friends for standing by me throughout this journey.

This thesis is not only a representation of my academic pursuits but also a reflection of the broader scholarly discussions in Energy Transition and Energy Systems research. I hope that it will inspire researchers to explore these themes further. With that, I invite you to delve into the following pages and join me in exploring the paths towards a low-carbon energy transition.

Nhu Anh Phan,
Göteborg, May 2025

“The result, therefore, of our present enquiry is, that we find no vestige of a beginning, – no prospect of an end.”

James Hutton

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1 Introduction

1.1 Low-carbon energy transition

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

Among technological pathway alternatives to the low-carbon energy transition, electrification, which comprises the replacement of fossil-based energy carriers in industry and transport with direct or indirect (e.g., via hydrogen) use of electricity, is highlighted as one key enabler. In the strategy put forth by the European Commission and in line with the climate-compliant scenarios developed by International Energy Agency, the future electricity system is envisioned to be characterized by clean sourcing from renewables and nuclear power (IEA, 2021). While electrification has a potential to limit GHG emissions, the process involves a strong increase in electricity demand of 35-150% by 2050 compared to 2020 level (IEA, 2021). This requires substantial and rapid investments in electricity generation technologies and supporting infrastructure, such as transmission grids (IEA, 2023). Given that the cost of various low-carbon energy technologies is decreasing along with the increasing deployment rates worldwide, affordable technological alternatives seem to be available.

On the other hand, it is important to understand how the transition would impact society beyond cost and technology considerations to fully account for its scope and depth. Firstly, understanding existing patterns in the electricity system is necessary to develop aligned policies. Today's electricity systems are deeply rooted in fossil fuel generation and a high level of dispatchable power. The system relies on a complex network of infrastructure and actors, making it slow to change. Transitioning to low-carbon energy means reshaping not only the technical systems but also the industries and value chains tied to fossil fuels (Bauer et al., 2022; Verbong & Geels, 2007). For example, industries could relocate to areas with more advantageous conditions for low-carbon energy, forming new value chains around clean technologies (e.g., Bauer et al., 2022; Lopez et al., 2023). However, as some industries might be fully or partially phased out, resistance to change would arise. Both support and opposition to this transition would influence regional economic development (Klaaßen & Steffen, 2023; Montrone et al., 2022) and global politics (Vakulchuk et al., 2020). This shift will also redefine the roles of consumers and producers, power market designs, institutional structures, and policymaking.

Secondly, low-carbon energy research and policy analysis involves the consideration of technological and social changes from the short- to the long-term horizons. While long-term targets are important for guiding low-carbon energy policy, the mere existence of a target does not by itself guarantee the achievement of the objective. Target setting often involves political negotiations that balance a wide range of vested interests. Furthermore, near-term concerns could substantially impact the directionality of the transition. For example, an expansion of renewable electricity could raise conflicts in local communities and between different interest groups (Devine-Wright & Sherry-Brennan, 2019; Ellis et al., 2007; van der Horst & Toke, 2010; Wretling et al., 2022). If these disputes are not resolved, they can lead to ineffective policymaking (Janssen et al., 2021).

Many decisions in the energy systems area have been assisted by energy system optimization models (Cherp et al., 2018). Although such models can provide insights into technical feasibility, they do not illuminate how these pathways are shaped within society, particularly in light of evolving actor roles and governance practices (Foxon et al., 2010; Hughes et al., 2013; Turnheim et al., 2015). Cost optimization output also considerably deviates from the actual historical development patterns of the electricity system, as shown in a case study of the UK system between 1990 and 2014 (Trutnevyte, 2016). To address this gap, adding social science perspectives, like social acceptance and energy justice, which are not captured in cost alone, can offer valuable insights that models miss. As a result, there is growing interest in more comprehensive analyses that bring together input from both modelers and other experts. For example, constraints can be defined by costs in the model (Cotterman et al., 2021), or a multicriteria analysis can accompany the modeling (Lehtveer et al., 2021; Neofytou et al., 2020). The development of indicators to support an ex-post evaluation of model results has also been proposed (Cherp et al., 2018; Lehtveer et al., 2021). These indicators can cover single sectors, technologies, or sustainability aspects. Lehtveer et al. (2021), for example, have highlighted some quantitative indicators in resource, transition dynamics and energy security that can help to understand the societal implications of results from energy system modeling in Europe, but further refinement is needed to conceptualize these indicators (Lehtveer et al., 2021).

However, while it is pivotal to ensure a feasible systemic transition that is not only cost-competitive and technologically viable but also socially inclusive and just, the literature that deals with low-carbon energy transition in a cross-disciplinary or transdisciplinary fashion is still in its early days (Joskow, 2022; Sovacool, 2017). In a state when the energy system is being transformed, integrative, interdisciplinary, and theoretically grounded methodological development is in dire need (Ford & Hardy, 2020) to support a deeper understanding of not only the technical but also the socio-technical and political challenges that an increasingly electrified energy system might bring (Cherp et al., 2018; IEA, 2021).

1.2 Aims and scope

The aim of this work is to explore the socio-technical challenges that hinder the progress of the electrification of industry and transport, with a focus on Swedish conditions. In this context, electrification is a measure to reduce or eliminate the use of carbon-based fuels and feedstock in transport and industry and, as a result, meeting a strong increase in electricity demand. This is a potential pathway for the Swedish electricity system to reach deep decarbonization due to the already low-carbon intensity in the electric grid.

We identify and characterize these challenges from discursive, socio-technical and techno-economic standpoints. Specifically, the work addresses an assessment of challenges to the electrification of industry and transport in Sweden to identify enabling conditions for the transition via two themes:

- The perceived importance of socio-technical challenges to Sweden's electrification from the viewpoints of stakeholders.
- The transition bottlenecks corresponding to plausible electricity futures.

To meet these themes, three analytical angles are applied as described in Figure 1. The findings of this work contribute to a more comprehensive understanding of factors affecting the low-carbon energy transition in Sweden and beyond. The outcome thus supports decision-making in providing foresight on the direction of the energy transition. Theoretically, it broadens the 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.

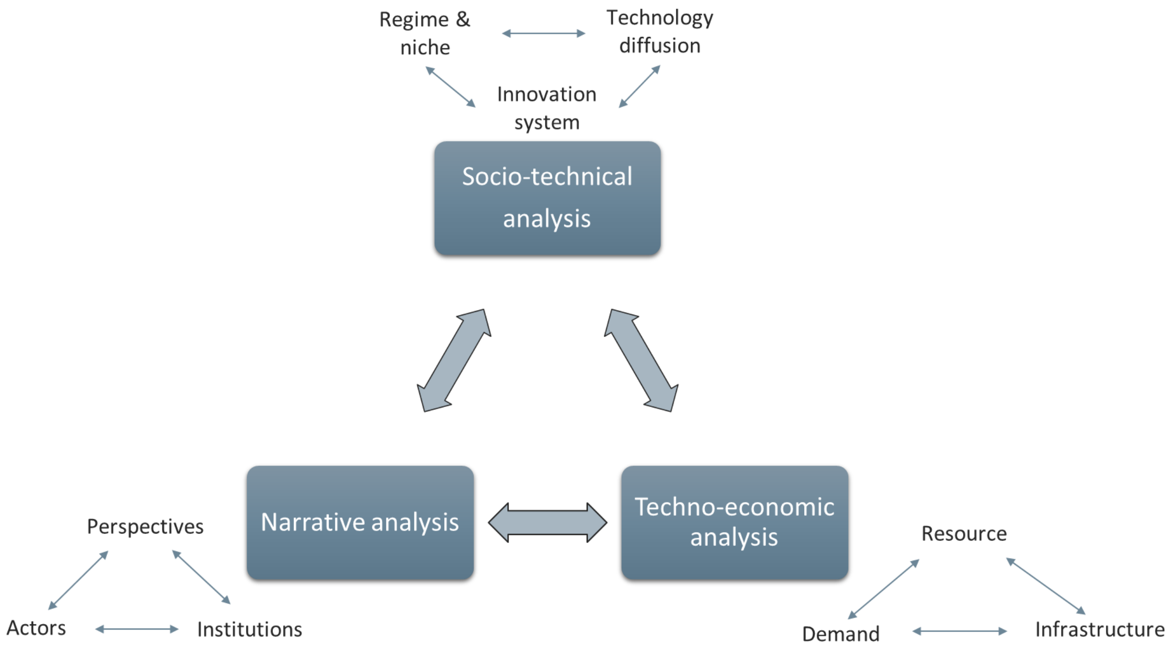

Figure 1: Three analytical angles used to describe barriers, challenges and bottlenecks of the Swedish electrification. Modified from (Cherp et al., 2018).

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. We apply the so-called Q methodology, 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 in the energy transition. We believe that a thorough understanding of how the challenge is framed is crucial for proposing credible transition policies (Faber, 2023). Beyond empirical insights, our 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 bridging between socio-technical analysis through multi-level perspectives and techno-economic analysis through energy system modeling in mapping out and articulating transition bottlenecks. Transition bottlenecks in this context refer to factors that halt or block the transition. We assume that different pathways yield bottlenecks of different strengths and attempt to analyze the strength and characteristics within and across the pathways. This paper builds upon an emerging literature that connects quantitative scenario analysis and qualitative storylines. The socio-technical analysis enables us spell out the logic driving the Swedish electricity regime, elucidating hindering and supporting factors that are difficult to quantify. We couple the analysis with results with the techno-economic analysis, which, unlike other studies, is built on not only a cost-optimal technological mix but also explores non-optimal yet politically driven options. The study serves as a building block for future socio-technical scenario development with mixed-method approaches.

Conceptually, we refer to factors hindering the transition in several terms such as barriers, challenges, and bottlenecks. While generally these terms describe things that block or halt the transition, there are slight differences in the connotations of these words which align with how our research has been developed. Barriers are meant to be specific activities or elements that must be overcome for the transition to succeed. Challenges can be driven by barriers or a group of barriers and are seen as not only factors that limit a transition but also offer opportunities to transform the system. The transition bottlenecks and their criticality instead differ depending on the transition pathways, i.e., they are linked to different electricity futures.

Methodologically, both appended papers utilize a mixed-methods approach that combines qualitative and quantitative analysis to identify socio-technical challenges in the Swedish case of electrification. The work is built on three analytical angles to address what hinders the low-carbon energy transition, including narrative analysis, socio-technical analysis, and techno-economic analysis to varying extents (Figure 1). Narrative analysis, which zooms in on the perspectives of challenges faced by key stakeholders and institutions regarding the transition, is conducted in **Paper I**. **Paper II**, instead, incorporates both socio-technical analysis and techno-economic analysis to assist in the identification of the transition bottlenecks.

The work presented in this thesis was carried out in the period of 2021–2025.

1.3 Outline of the thesis

The thesis consists of this summarizing essay and the two appended papers. The essay highlights the key outcomes of the papers and places the work in context. Following the introduction, Chapter 2 provides a background to the work, while Chapter 3 describes key methodologies used. Chapter 4 highlights and discusses selected results connected to the above-mentioned aims. A reflection on methods and findings with an emphasis on reflexivity is done in Chapter 5. Chapter 6 concludes the work with an agenda for future research.

2 Background

This chapter is divided into two sections. Section 2.1 presents existing theoretical frameworks and approaches underlying the study of challenges to transitions, with a focus on low-carbon energy transitions, as well as how we apply them into our studies. Section 2.2 contextualize the case study of the Swedish electrification.

2.1 From theory to practice: Framing our approach

In the following sections, I provide an overview of three research branches that we have taken stock of in our work, including narrative analysis (Section 2.1.1), socio-technical analysis (Section 2.1.2), and techno-economic analysis (Section 2.1.3). As shown in Figure 1, they have different focuses and elements that enable us to view the barriers, challenges, and bottlenecks from different vantage points.

2.1.1 Narratives in transitions

A narrative, which is the basic element of a discourse, consists of ideas and concepts that are strung together into coherent storylines (Dubský & Tichý, 2024; Hermwille, 2016). A narrative can be understood as a story that describes an issue, with an objective and internal logic regarding the problems and solutions to the issue. Although not used for analyzing different perspectives on barriers, studies on narratives have in recent years gained substantial traction in transition research, especially in sustainability transitions (Janda & Topouzi, 2015; Jones & McBeth, 2010). In transition studies, a narrative relates the story of the need to move from one state to another, i.e., to a more socially desirable state with specific end-points, such as net-zero carbon emissions, and it also outlines and justifies the interventions required to meet the end-state (Hermwille, 2016; Luederitz et al., 2017). Successful narratives are important in politics, as they contribute substantially to the process of legitimization of a given idea, and when effectively delivered, they can become embedded into the collective perception of an issue (Janda & Topouzi, 2015). Thus, narratives both serve to cement political power and perform a social role in connecting the inner worldviews of a narrative advocate to a collective understanding of an issue.

There are different methods to conduct narrative analysis. Given that (1) narratives are formative to the collective sense-making of a transition, and (2) a narrative is formed through the viewpoints of a stakeholder, which is then shaped by their values and norms on which problems and solutions should be prioritized, it is important to investigate the subjectivity in how stakeholders express the challenges hindering the energy transition.

In our context, to identify and analyze the meta-challenges, i.e., the key narratives on challenges, to electrification as a means to achieve net-zero carbon emissions, we apply the so-called *Q methodology*. The method is suitable for investigating and mapping out perspectives on complex topics, since it combines a mix of surveys, interviews, and statistical analyses (Brown, 1996; Watts & Stenner, 2012). Originally developed by Stephenson (1953), the Q method is commonly used in psychology and social science research to study subjectivity, and it consists of both qualitative and quantitative elements (Stephenson, 1953).

Unlike traditional survey techniques that generalize opinions by correlating variables from large, representative samples, the Q study surveys and interviews a limited, purposive set of stakeholders to identify and explore viewpoints. The individual rankings are then aggregated and statistically analyzed to extract a set of overarching perspectives or narratives. This analysis consolidates many individual viewpoints into a few narratives, i.e., in our case, meta-challenges. These elements make the Q methodology suitable for investigating and mapping narratives on complex topics, such as environmental issues and the energy transition (Brown, 1996; Watts & Stenner, 2012).

Studies have been conducted on perspectives associated with different aspects of the low-carbon energy transition using the Q methodology on both national and regional levels (Bauer, 2018; Kilpeläinen, 2022; Olazabal & Pascual, 2015). However, to the best of our knowledge, no study carried out to date has focused on identifying narratives on challenges, particularly concerning electrification in Sweden. This study focuses on key stakeholders because their viewpoints are central to many important decisions to be made in the Swedish energy transition. We believe that the outcome of this study provides a nuanced and discursive understanding of the perceived challenges related to electrification.

2.1.2 Characteristics of a socio-technical system

The developments of a socio-technical system comprise several sub-systems and interrelate technological, social, political, regulatory, and cultural conditions in understanding system-level changes (Geels, 2002; Rip & Kemp, 1998). Certain development paths or trajectories improve how the system operates within the established logic. When the changes challenge the established logic, this instead leads to regime shifts. These changes can be pushed from the niche level, where there are incubating innovations, or the landscape level, which represents the deeper structure that impacts the regime. These three levels of niche, regime, and landscape form the basis of the multi-level perspective (MLP) framework.

On explaining large-scale and long-term shifts, such as the transition of horse-drawn carriages to automobiles (Geels, 2005) or the decarbonization pathways of the German electricity system (Rogge et al., 2020), the MLP literature focuses on the analysis of rules and routines that govern specific socio-technical systems, permeate system elements, and direct the behaviors of actors within the system. As the rules become more aligned over time, socio-technical regimes are formed. This process is often characterized as complex and non-linear, akin to evolutionary processes.

Within the MLP framework, the socio-technical regime is positioned as an analytical category within a socio-technical system (Smith et al., 2005). The regime is considered "dynamically stable" and "incumbent" (Geels, 2002; Geels et al., 2017a). Landscape and niche factors can either reinforce or disrupt the existing regime (G. P. J. Verbong & Geels, 2010). Regime shifts occur when change challenges the established logic of the regime till the point of tension, which then creates windows of opportunity that lead to the eventual replacement of the regime (Geels, 2014). These changes can be pushed from the niche level, where there are incubating innovations, or the landscape level, which represents the deeper structure that impacts the regime (Geels et al., 2017b), or the interaction between these levels.

Socio-technical system studies could address the coevolution of multiple dimensions, thus elucidating emerging patterns and storylines behind pathways (Foxon, 2011; Rip & Kemp, 1998; Smith et al., 2005). Another important characteristic of a socio-technical regime is the resistance to change, the so-called path dependency (e.g., Bergek & Onufrey, 2014). This happens when existing laws, institutions, and rules disincentivize change. While path dependencies reinforce the stability of the system, they also hinder innovations and the transition to a more sustainable state, leading to lock-in phenomena. An example of that is how the fossil fuel-based energy system locks in the changes through path-dependent processes across industrial economies (Unruh, 2000).

Both papers rest on the socio-technical system theory, which highlights the multi-actor and multi-dimensional reality of a transition. In our studies, we consider the electricity system a socio-technical regime. Here, the electricity system is not only understood in terms of physical infrastructure, but as a hybrid entity that is simultaneously material, social, political, and discursive. This expands the view of the electricity system as a part of broader systems, interacting with society, politics, and technology. The electricity system is prone to path dependency due to capital intensity and often long lead times associated with changing the infrastructure. Furthermore, physical assets are often built across a wide variety of different landscapes and municipalities. Due to the high infrastructure cost and barrier to entry, electricity delivery and large-scale generation actors often operate as natural monopolies.

2.1.3 Combining quantitative computational models and qualitative socio-technical transition research

There has been a growing interest to combine qualitative social studies on energy transition and quantitative modeling approaches, which has been developed independently of each other (Hughes et al., 2013; Sovacool, 2014). While integrating social change and techno-economic representation is still in its early days (Trutnevyte et al., 2019), it would offer a more comprehensive scrutiny of the energy systems by uncovering multi-dimensional tradeoffs and synergies (Hirt et al., 2020; Verrier et al., 2022). This can raise our understanding of the more nuanced ramifications of transition measures, allow us to communicate about these implications to a wider audience, and ultimately foster decision-making under uncertainty.

With that, efforts have been made to parameterize social factors to the models (Koecklin et al., 2021), soft-link them with other models that capture social interactions with higher granularity (Hedenus et al., 2022; Krumm et al., 2022; Trappey et al., 2013), or use mixed-method approaches in scenario analysis (Koecklin et al., 2021; Süsser, Gaschnig, et al., 2022). These give rise to a stream of literature on socio-technical transition scenario development, which combines qualitative socio-technical transition and quantitative modeling insights (Burger et al., 2022; Fodstad et al., 2022; Fortes et al., 2015a; Foxon et al., 2013; Hughes et al., 2013; Trutnevyte, 2014; Trutnevyte et al., 2014; Verrier et al., 2022). Despite the differences in these research strands (Turnheim et al., 2015), several integration techniques has been emerging to complement their strengths in in scenario design (Fodstad et al., 2022; Geels, Berkhout, et al., 2016; Süsser, Martin, et al., 2022). There are three main strategies that can be considered in the integration process: bridging, iterating, and merging (Trutnevyte et al., 2019).

Bridging approaches involve the exchange of shared concepts between ESOMs and socio-technical analyses, while maintaining the distinct insights of each research strand in parallel. This is a common approach to cross over insights from both socio-technical transitions and quantitative system modeling (Fortes et al., 2015b; Geels, Berkhout, et al., 2016; Nilsson et al., 2020; Turnheim et al., 2015; Venturini et al., 2019). It has for example been used in the identification of transition bottlenecks and transformative policy mixes in the low-carbon energy transition (Geels et al., 2020; Rogge et al., 2020).

Merging approaches combine the two methods in forming a single model or framework, allowing for an in-depth integration between ESOM. This has been seen in, for example, the BLUE model, which incorporates the MLP framework in the system dynamic modeling setup (Verrier et al., 2022) in exploring both cost-optimal and non-optimal behaviors (Li, 2017).

An iterative approach allows for back-and-forth dialogues between the socio-technical frameworks and energy system models, or between modelers and decision-makers. The former can also be exemplified with the quantification of narratives. Here, researchers first elicit the visions or narratives pertaining to the transition from relevant actors, then quantify them into various pathways described by the narratives (O'Neill et al., 2017). This technique has been used for example in the Shared Socio-Economic Pathways (SSP) in the IPCC report (O'Neill et al., 2017). In some cases, the model output can be used to revisit the narratives (Alcamo, 2008). The latter, i.e., the exchanges between modelers and decision-makers, has been applied to the MARKAL energy system model family in the UK (Strachan et al., 2009). It is worth noting that both bridging and merging approaches can be iteratively refined to achieve better alignments, as has been done with the transition bottleneck identification (Geels et al., 2020; Rogge et al., 2020).

Table 1 provides a comparison of ESOM and MLP. Both methods broadly capture change, although through different lenses. Specifically, ESOM provides cost and technology mix through optimization algorithms, while MLP describes historical and recent developments in the system in articulating the ways forward. Considering the different time horizons and transition logics underlying the two analyses, a high level of integration would require the simplification of both methods. As the bridging strategy recognizes the complexity and the context specificity of the transition (Trutnevyte et al., 2019), while aligning insights yielded by the two methods where they meet, this is our preferred integration strategy.

Table 1: Comparison between ESOM and MLP. Based on author's own compilation from various sources (e.g., Geels, Berkhout, et al., 2016; Hofman et al., 2004; Sovacool, 2014; Süsser, Martin, et al., 2022; Turnheim et al., 2015).

	ESOM	**MLP**
Actors	Social planner with perfect foresight	A variety of actors, including businesses, government, academia, civil societies, and local communities
Logic of transition pathways	Optimization algorithms Attention to system interactions	Regime inertia and shifts Niche momentum Landscape pressure
Technology characteristics	Investment and operational parameters	Innovations and diffusion
Institution (rules of the game)	Supply meets demand at each timestep Cost-minimized investment and operations	Decision-making procedures Governance frameworks Cultural practices
Temporality	Overnight investment on an arbitrary future year, resolution depends on the model	Historical analysis to near future, resolution is typically a few decades
Questions to address	What are the trade-offs among different technological mixes? What are the extreme limits of technological deployment under a variety of circumstances?	What are the patterns of technological diffusion in society? What are the opportunities and challenges?
Policy instruments	Meeting economic and technical feasibility Broad, long-term targets	Meeting social feasibility Broad, long-term targets

In our work, we apply 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) proposed to use the concept of transition bottlenecks as a "methodological aid" to mediate the "tension" between energy system modeling and multi-level perspective analysis due to their different focuses (on technical and operational feasibility for ESOM versus social and political feasibility for MLP) and timeframes (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, institutional structures such as decision-making traditions, organizational routines, cultural norms, 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 the characteristics and drivers of transition bottlenecks could contribution to, for instance, a more concrete and differentiated identification of the typology of transition pathways or transition policy (Rogge et al., 2020) when it comes to the electricity system in Sweden, including the timings of deployment of different technologies along the value chain and multi-level interactions among stakeholders.

2.2 The Swedish case of electrification

In this section, the Swedish case of electrification is described in detail. The institutional changes in the Swedish electricity regime before and after the deregulation of the electricity market, as well as the shifting roles of key technologies in the regime are charted in Section 2.2.1. Section 2.2.2 zooms into the commitment of the electrification of industry and transport to meet climate targets in the country. Section 2.2.3 offers a foray into the potential impact of electrification on future Swedish electricity regimes.

2.2.1 From the first line to a society electrified: The Swedish electricity regime development

In Sweden, the first electrical network was built in the south in the early 20th century. By 1902, the first Electricity Law in the country was created, which included the terms for area concessions and line concessions were laid out. This guaranteed a monopoly of electricity network by regional electricity companies for a certain region, corridor, or line (Högselius &

Kaijser, 2010). These companies started to operate independently to produce and distribute electricity. However, in 1909, Vattenfall was established by the Energy State Board (Statens Energiverk) which acted as a wholesale power supplier that harnessed power from waterfalls and provided electricity to industry. This was the start of the formation of the electricity supply sector in Sweden, with Vattenfall and regional companies responsible for the generation and transmission of power, and municipal companies responsible for distribution to end users. As transmission lines connecting different Swedish regions were built in the 1930s by independent grid owners (Myhr, n.d.), the joint cooperations gradually took shape and Vattenfall took on the additional responsibility of a transmission network owner by 1947 (Högselius & Kaijser, 2010). Grid contracts were drawn up between Vattenfall and power generators to secure access. Transmission and distribution grids were also linked, enabling extensive power exchange in the country. In 1952, the first 400 kV line to deliver the electricity from the north of the country to the industry and cities in the south was put in operation (Myhr, n.d.; Sonnsjö, 2024). The 12 largest electricity companies then formed a power "club" in the mid-60s, which was then considered "the Swedish system" (Högselius & Kaijser, 2010). They accounted for 90% of the electricity produced, with Vattenfall generating half of the electricity, receiving a special status. With ample governmental support, nuclear power plant projects were also initiated in the 60s (Faber, 2023), alongside growing negative public opinions (Sonnsjö, 2024).

In the next decades, Vattenfall increasingly lobbied for a corporatization of its enterprise, which means a transition from a commercial state agency (affärsverk) to a joint-stock company. The issue became contentious and politically charged, for example, with the Social Democrats and Left party opposing this change (Högselius & Kaijser, 2010). However, in 1992, the generation part of Vattenfall was declared a joint-stock state-owned company, while the electricity transmission ownership was handed to Svenska Kraftnät, a new state agency finalized in 1993. This required a change in the institutional framework (Swedish Parliament, 2018).

Around the same time as the discussion regarding the corporatization of Vattenfall, a discussion on the deregulation of the electricity market was initiated, in line with the rising popularity of neo-liberal economic thinking (Högselius & Kaijser, 2010). Several investigations were conducted on the impact of the deregulation on the electricity system by different state agencies, including concerns over oligopoly, increasing vertical integration (with multiple mergers and acquisitions of regional companies as a reaction to the possible deregulation), the impact of increasing competition and possibilities from membership in the European Commission. The opposition came from the left-leaning parties for concerns of the privatization of Vattenfall and the subsequent loss of control over the domestic system, and from companies from the original power club that felt threatened by the increased competition expected with the deregulation. It was not straightforward how the transition could impact the Swedish system, which was perceived to be highly efficient and low-cost at the time (Högselius & Kaijser, 2010; Lindblom & Andersson, 1998).

There were also generally challenging times for the Swedish economy due to the economic crisis in 1990 and the currency crisis in 1992, and consequently the government had to roll out two crisis packages in 1990 and 1992, respectively. It was seen that the corporatization of Vattenfall could only be effective if paired with a deregulated electricity market. A new government bill on a competitive electricity market was approved in 1992 which reached a broad consensus, and a new electricity law was drafted in 1993 (Högselius & Kaijser, 2010; Lindblom & Andersson, 1998). Accordingly, the construction of a new electricity network for competition was not allowed, but new entrants had the right to use the network of concession holders at a fee. A report was created on electricity competition given a network monopoly (Högselius & Kaijser, 2010). As an outcome of these tumultuous events, the Swedish system officially started the deregulation process of the electricity by 1996 after joining the European Union in 1995 (Högselius & Kaijser, 2010).

To sum up, the bumpy road toward a deregulated market of electricity within a regulated system of electricity delivery was characterized by ideological differences that led to changing stances and affected by other events in the electricity sector, such as the nuclear phaseout discussion, and external macroeconomic and political factors, such as the economic crisis, changing political affiliation between the ruling governments, and membership in the EU.

Given the development trajectory, the electricity supply in Sweden has been historically dominated by large-scale, dispatchable and synchronous generators. In the 20th century, both the production and consumption of electricity have increased exponentially, doubling its capacity virtually every 12 years. This is similar to the characteristics of the electricity generation and distribution regime in European societies portrayed in the literature (Sataøen et al., 2015; Smith et al., 2005; G. P. J. Verbong & Geels, 2010). However, the electricity demand stalled in the country since 1987 (Högselius & Kaijser, 2010), and electricity demand has been constant over more than the last 30 years at around 140 TWh (Swedish Energy Agency, 2022).

At present, the largest share of electricity in the Swedish electricity generation are from hydropower and nuclear power, accounting for 40% and 30% of the supply share, respectively (Statista, 2023a). Hydropower acts both as a supplier and a load balancer. Future expansion of hydropower is greatly limited due to water regulations (Jakhmola, 2022). Although nuclear power plants have become of age and 6 out of 12 reactors have been phased out, there is currently a renewed interest in nuclear power to meet the burgeoning demand in electricity (World Nuclear Association, 2024).

With the constant domestic demand, the deregulation of the electricity trade market and the integration into a common EU energy market, it has been profitable to build more electricity capacity and export, leading to a net export volume of around 20TWh per year (Swedish Energy Agency, 2022). While investments in electricity generation with high upfront investment costs, such as hydropower and nuclear power, have been absent, the global reduction in the cost of renewables has enabled an increase in installed capacity, especially in the form of wind power. Onshore wind power has rapidly and substantially expanded since the turn of the century, currently attaining a 20% share in the system (Swedish Energy Agency, 2022). On the other hand, despite Sweden’s long coastline, offshore wind power is more or less non-existent, only marking 193MW in 2023, with no new capacity built since 2013 (Fernández, 2024; WindEurope, 2022). There are, however, revisions being made to the maritime spatial plans to enable 120TWh of offshore wind buildup (Swedish Wind Energy, 2024). In addition, there is currently a strong interest in solar photovoltaics, with both rooftop installations and solar parks, although the total contribution currently stands below 1% in the electricity generation mix (IEA, n.d.).

In addition to electricity supply technologies, there have been some innovations in flexibility solutions and planning for changes in grid infrastructure. The last years have seen large investments in batteries driven by attractive conditions for using them to support the grid (by providing fast frequency reserves). Nevertheless, the implementation level in terms of capacity has so far been low (Energinet et al., 2023; Svenska Kraftnät, 2024b).

Figure 2 summarizes the main characteristics of the Swedish electricity regime, alongside landscape and niche factors impacting it.

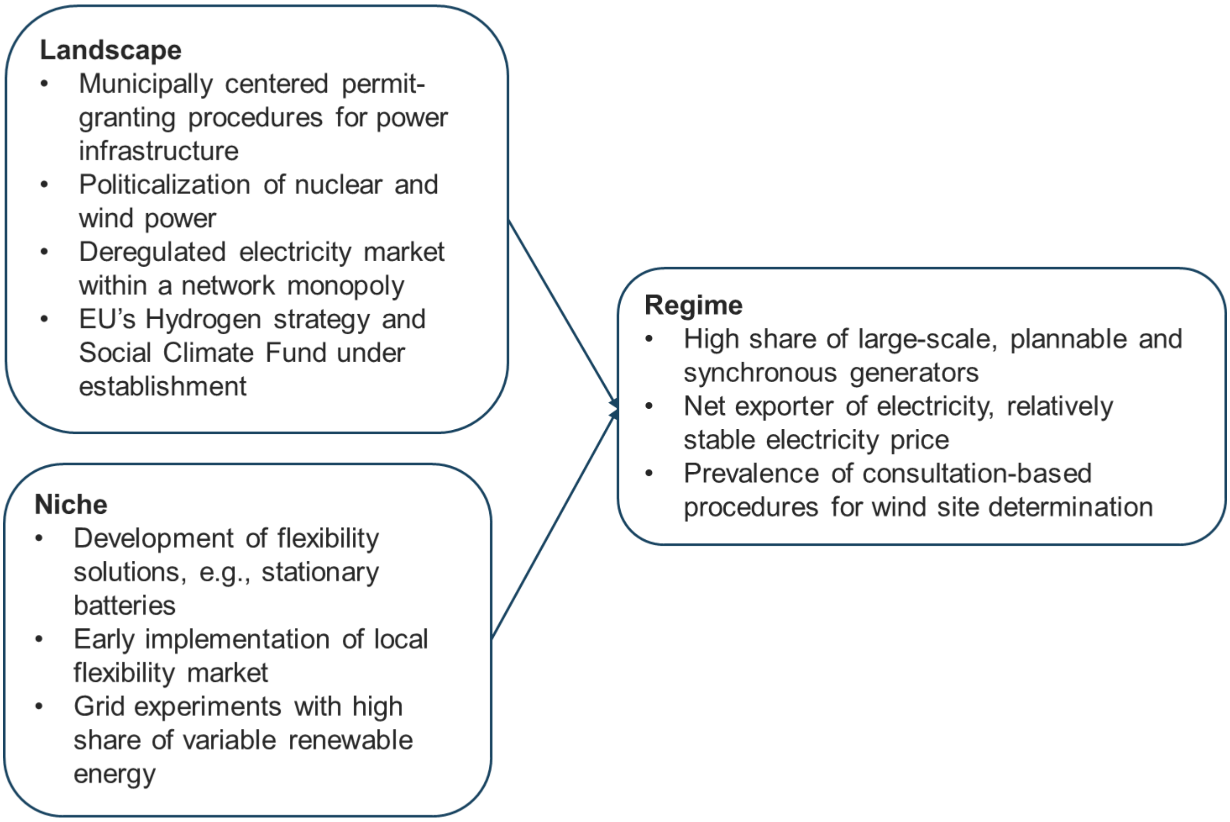

Figure 2: Characteristics of the Swedish electricity regime.

2.2.2 Powering the transition: Electrification as a part of the climate policy

While Sweden has one of the highest levels of electricity consumed per capita in the world and has been a net electricity exporter (Statista, 2023b), its emission intensity in the electricity sector is quite modest in comparison (Statista, 2023a). Sweden has the lowest emission intensity in electricity generation in the EU (European Environment Agency, 2023). Fossil fuel has made up less than 5% of the energy mix in the last three decades, mostly in the transport sector (IEA, n.d.). This is possible due to a heavy dependence on low-carbon technologies such as hydropower and nuclear power, accounting for 40% and 30% of the supply share, respectively (Statista, 2023a). Hydropower acts both as a supplier and a load balancer, but its contribution has stagnated over the years. Future expansion of hydropower is greatly limited due to water regulations (Jakhmola, 2022). Although nuclear power contribution was slowly in decline due to various political decisions, there has been a nuclear renaissance discourse in recent years that may foresee future expansion to meet the burgeoning demand in the electricity system (Edberg & Tarasova, 2016).

While the historical regime of operating electricity system is dominated by large-scale, plannable and synchronous generators, the conditions for new investments in electricity generation on a landscape level have changed. Notably, since the deregulation of the electricity market, investments in electricity generation with high upfront investment costs and long lifetimes, such as hydropower and nuclear power, have been absent. Meanwhile, renewables, especially wind power, have been on the rise. Onshore wind power has rapidly and substantially expanded since the turn of the century. While onshore wind power has now attained a 20% share in the system, offshore wind power is on the cusp of a growing phase, marking 2% of installed capacity off the coast (Jakhmola, 2022). At the same time, solar photovoltaics has seen remarkable growth in both residential and commercial arrays, although the total contribution just currently constitutes under 1% in the mix (IEA, n.d.).

Since 2017, a legally-binding climate policy framework to reach net-zero emissions by 2045 (Swedish Government Office, 2021) has come into force in Sweden. Sweden targets to curb 59% of its greenhouse gas emissions in 2030 compared to the level in 2005, and to achieve net-zero carbon emissions by 2045. To meet these goals, several projects aiming to electrify industrial processes (Heidelberg Materials, 2018; Vattenfall, 2021b), produce fossil-free hydrogen (Vattenfall, 2021a) and electrofuel (Vattenfall, n.d.), as well as directly electrify road transport (Preem, 2024; Volvo Cars, 2024; Volvo Trucks, 2025) have been set in motion by big industry actors. For example, the country is home to one of the world's first major projects for hydrogen-based steel production (Vattenfall, 2021b). Such changes in energy use and energy carrier are estimated to double the Swedish electricity demand over the next two decades (Swedish Energy Agency, 2023b).

The change of government in the end of 2022 has led to a turning point in the Swedish energy and climate policies. The previous, short-lived cross-party energy agreement set forth by the previous ruling party was replaced by the so-called "Tidö Agreement", which includes a revision of the overarching energy policy goals to meet net-zero emissions in 2045 after the right-wing bloc of the Swedish government came into power (Swedish Parliament, n.d.). The agreement consists of two main components. Firstly, the vision of 100% renewable power is modified to be 100% fossil-free power. This entails an increased support of dispatchable electricity generation, and in particular nuclear power has been in focus of the discussions. The support for nuclear power, among other generators, is greatly strengthened both in terms of financial support, where the new government is considering establishing a state credit guarantee for nuclear power investments (World Nuclear Association, 2024). The debate between the role and optimal level of dispatchable versus weather dependent electricity generation in the energy mix has strongly influenced the Swedish energy politics (Bjärstig et al., 2022). The increase in demand and the expansion of electricity supply technology options challenge the stable and established energy policy landscape and makes the transition pathways more ambiguous. Although Sweden has reduced its domestic greenhouse gas emissions at a faster pace than the EU average (European Parliament, 2021), the Swedish Climate Policy Council concluded in their latest assessment report that the efforts to reduce emissions must increase substantially to meet the 2045 target (Ministry of the Environment, 2020; Swedish Climate Policy Council, 2023).

In addition to supply technologies, there have been some innovations on flexibility solutions and planning for changes in grid infrastructure, but the implementation level has been low in the country (Bergaentzlé et al., 2017; Energinet et al., 2023; Svenska Kraftnät, 2024a).

2.2.3 A regime in flux: The impact of electrification on the Swedish energy system

Electrification pathways require new or existing actors, including consumers from manufacturing and transport sectors, to provide system flexibility. On the one hand, this aligns with a running assumption in sustainable development that more collaborations among affected and interested actors in decision-making have a net benefit to the regime (ref). On the other hand, the involvement of more actors increases the complexity of interaction, which could lead to conflicts of interest and objectives. These conflicts can be about where the new generation capacity would be placed, how the consent process is handled with regards to various stakes and concerns, for instance, local environmental impact vs climate impact. Ultimately, in striking a balance of interests among actors, some values or interests would be more prioritized than others.

It could be seen in practice that most of the announced electrification projects (mentioned in Section 2.2.2) are limited to large actors who have access to more financial, physical, technological, and social resources compared to small-scale entrepreneurs and other social groups. Similar behaviors could be observed in the transition to deregulate the Swedish electricity market, where there was little participation of households and environmental groups. Since niche developments that spread into mainstream markets are largely dominated by incumbent regime actors, who possess greater bargaining power and access to resources, fringe actors have more limited opportunities to pursue transformative change.

While the electricity regime is already populated with more actors and a more complex value chains after the deregulation, the electrification plans will once again raise the questions of ensuring the competitiveness of Swedish industries and utilities in an increasingly globalized world. After a period of stalling demand, it is unclear how the rising electricity demand will be met.

Looking into the future, while parts of the energy system are likely to remain in the upcoming decades in the Nordics, such as hydropower capacity in Finland, Norway and Sweden, and some of the nuclear power capacity in Finland and Sweden (Kilpeläinen et al., 2019), the quest for a low-carbon energy future is largely open, particularly on the demand side.

In Figure 3, a schematic diagram of two representative electricity systems with and without flexibility is displayed. The traditional schematic with single electric flow delivered from producers to wholesale and retail consumers is shown on the left figure. In juxtaposition is the system that considers flexibility resources with storage solutions. With the new system complexifying the interactions between actors, new actors or existing actors with new roles would be introduced. There are multiple options to enact the schematic, from market design to technological choices. The challenge for policymakers and other decision-makers is then to harness such windows of opportunity effectively, anticipating the numerous possibilities and constraints as well as the broad interest of different actors (Kilpeläinen et al., 2019). This requires a high-level view of multi-system dynamics (Köhler et al., 2019).

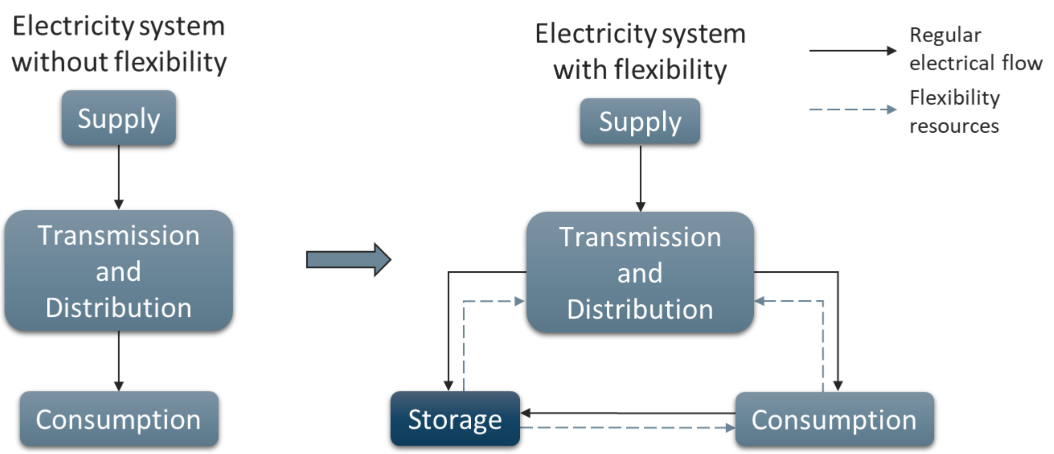

Figure 3: An overview of the power system with and without flexibility consideration. Full line: Regular electrical flow, dotted line: Flexibility resources.

3 Methodology

In this chapter, I present an overview of how the methods are applied to my research before delving into the nuances of each work. The overview of mixed-methods approaches is presented in Section 3.1. This is followed by the design of the Q methodology applied in **Paper I** in Section 3.2. The transition bottleneck identification applied in **Paper II** is described in Section 3.3, including the application of the socio-technical analysis in Section 3.3.1 and the techno-economic analysis in Section 3.3.2. Finally, the approach to the barrier prioritization workshop is explained in Section 3.4.

3.1 Mixed-methods application

Table 2 presents an overview of methods utilized and the dimensions explored in each of the methods applied in this work to investigate socio-technical challenges to the electrification of industry and transport in Sweden. The categorization used in the Q methodology, the workshop, and the literature each describe the content of the barriers and challenges within each group, with some variations depending on the approach. The variations are due to both different contexts the method was applied to and how our understanding developed over time. For example, the literature-derived barrier categories enlist ”other” barriers that include cybersecurity and resource constraints, while justice issues are categorized under the social group. As the Q methodology was operationalized, there was a need to expand on contested norms, governance, justice, and security and reliability as stand-alone groups rather than captured under the broad spectrum of social and political issues. The politics group was brought back for the workshop since stakeholders were anticipated to view security and reliability through political lens, e.g., political dispute, geopolitical risks, or volatility, rather than technical challenges associated with security and reliability, e.g., access to converters or disturbance management. It is noteworthy that these categories only describe the content of the barriers and do not prescribe the root causes of these barriers or their impact on the system. These barriers in practice interrelate with one another and change over time. However, the way they reinforce or suppress each other is out of the scope of the research.

On the other hand, to identify transition bottlenecks via the multi-level perspectives, coupled with the results from energy system modeling scenarios, it became more straightforward to implement technology-based categories. This is because these technologies have different development trajectories both historically and in terms of diffusion dynamics, leading to distinguished factors that become elusive should they follow the descriptive categories of the Q methodology and workshop.

Among the methods applied, the Q methodology and the workshop involve stakeholder input. While the Q methodology application focuses on socio-technical challenges to the Swedish electrification in general, the workshop was built on the three scenario results from the energy system modeling to capture stakeholder views on broader challenge categories.

In addition to empirical approaches, the multi-level perspectives framework was applied as a theoretical model for identifying the transition bottlenecks through three levels, similarly through linkages with modeled scenario results. Employing the modeled results was useful in clarifying the cost and technical feasibility space where pathways could take shape, hence providing an anchor between the abstract levels of the MLP and the empirical insights provided by the energy system model.

Table 2: Overview of the applied methods and dimensions.

Approaches	Dimensions					Insights	Paper addressed
Q methodology	Contested norms	Economics	Security and Reliability	Governance	Justice	Meta-challenge identification	**Paper I**
Multi-level perspectives and energy system modeling	Wind	Nuclear	Flexibility	Power Grid		Transition bottleneck identification	**Paper II**
Workshop	Contested norms	Economics	Politics	Governance	Justice	Stakeholder prioritization of challenges	Supplement
Literature	Social	Economic	Political	Other		Foundation knowledge on barriers	Supplement

The Q methodology was applied to the analysis of **Paper I**, while the multi-level perspectives framework was linked with energy system modeling to identify transition bottlenecks in **Paper II**. The results from the workshop and the literature review supplemented the analyses of these two studies.

3.2 Q methodology

We used the Q methodology to explore how key stakeholders perceive and prioritize the socio-technical challenges to electrification in Sweden. The Q methodology in general has five steps: 1) Identifying the concourse and selecting statements; 2) Selecting participants; 3) Conducting the Q survey and interviews; 4) Performing Q analysis; and 5) Interpreting results from the factor analysis (Cuppen et al., 2010). The steps in the analysis are summarized in Figure 4 and described in detail in **Paper I**.

For our study, we invited stakeholders from various organizations associated with the energy sector, as well as those affected by the strategy of using electrification as a means of decarbonizing the energy sector, to rank statements about potential challenges in order of their perceived importance.

Qualitatively, a limited number and carefully chosen stakeholders are surveyed and interviewed, ranking their viewpoints on a topic of interest on a scale from -5 (most unimportant) to +5 (most important). Quantitatively, the individual stakeholder rankings were aggregated and statistically analyzed to extract overarching themes that we here call meta-challenges.

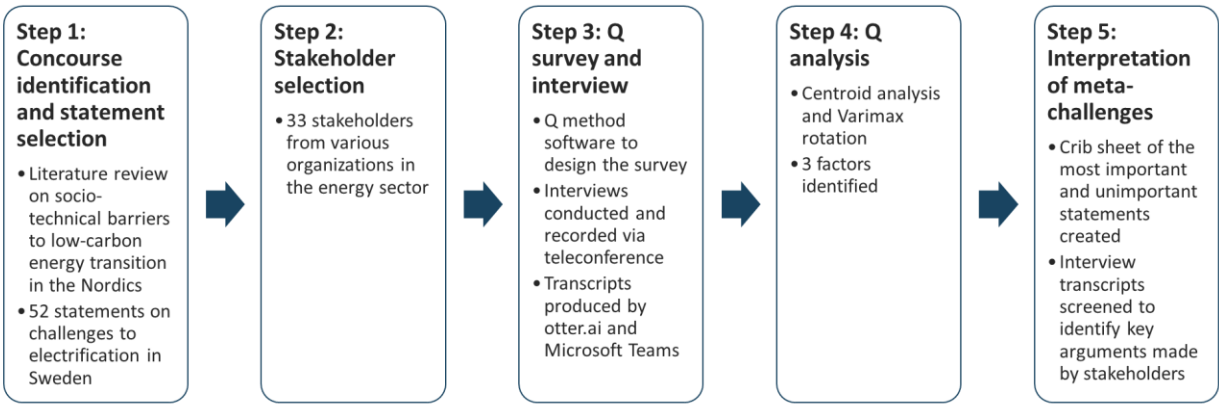

Figure 4: Application of the Q methodology. Source: **Paper I**.

We formulated the statements from the categories of barriers derived from the literature review on the socio-technical challenges to the Nordic energy transition. The categorization of these statements can be viewed in Figure 5. As mentioned in Section 3.1, we added the group of security and reliability, justice, governance, and systemic transformation since statements in this group have specific characteristics that overlap with other groups, and at the same time represent important topical issues that should be treated distinctly and on the same structural levels as economic barriers, for instance. Given that there are 52 statements (from s1 to s52), the distribution across the groups is quite even, with higher concentrations of statements in contested norms (27%), economic (25%), and governance (17%). There was only one statement explicitly looking at the lack of systemic transformation. It should be noted that the statements were generated iteratively, resulting in the distribution rather than being pre-determined.

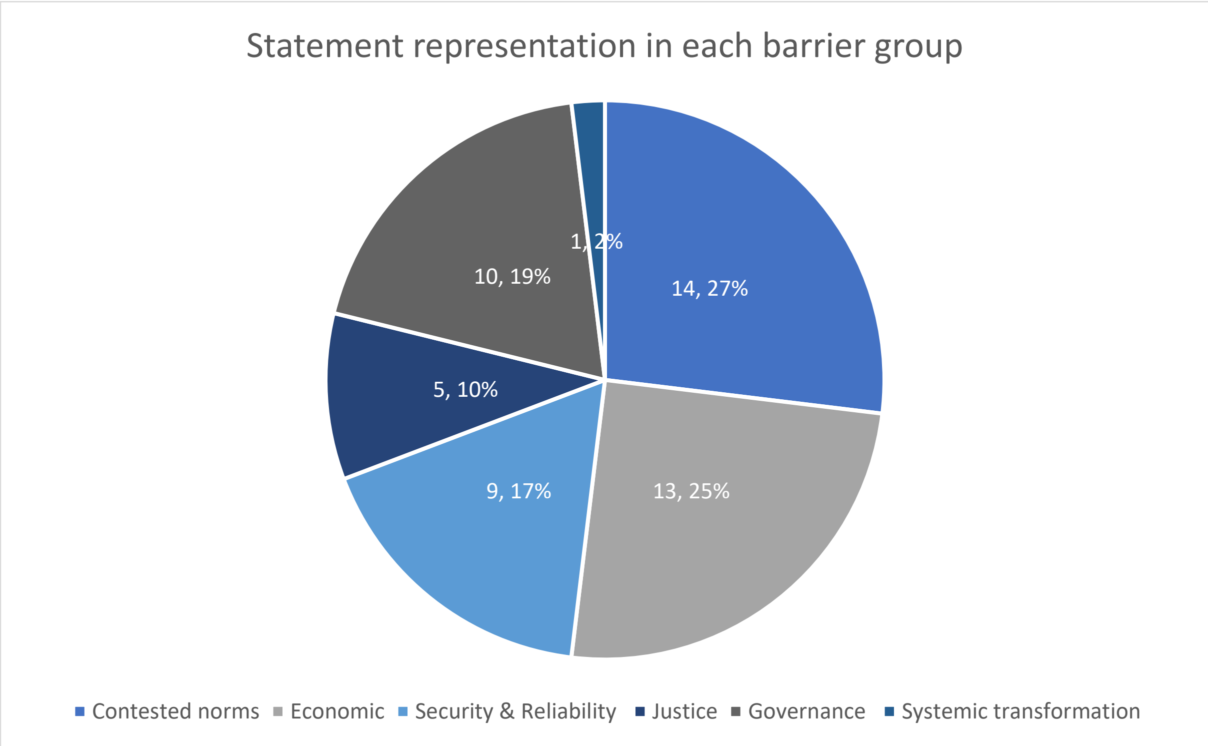

Figure 5: Statement representation in each barrier group. Based on the data used for **Paper I**.

3.3 Identification of transition bottlenecks

We combined the above-described combination of ESOM and MLP analysis as also proposed by (Geels et al., 2020), with a focus on the Swedish electrification, illustrated in Figure 6. The ESOM provides three cost-optimal, demand-satisfying technology mixes of future low-carbon electricity systems in Sweden. The preconditions for the three cases differ mainly in terms of pre-determined investment levels in offshore wind and nuclear power. Basing the analysis on one country also allows us to explore in-depth the conditions specific to that country and its possible levers for change. In this case, the choice of modeled cases follows the Swedish current discourse, which is steeped in an ambiguity of directions for the transition. Accordingly, while the MLP framework provides important insights on how technologies evolve and diffuse over time, ESOM generates cost-optimal technological mixes under different scenarios.

To map out transition bottlenecks connected to each modeled case, we first described the context that the key technology creates, followed by the challenges and enabling conditions for the expansion of the technology, using both techno-economic analysis through ESOM and socio-technical analysis through the MLP framework. The socio-technical analysis charts significant historical events and processes that led to the current technology mix (applying the niche, regime, and landscape levels). The enabling conditions are also illustrated by successful cases from other countries. As the ESOM part provides operational and economic constraints of the system for one year in the future, and the MLP analysis gives insight into what has formed the system as it is today, their combination bridges the two scholarly strands in identifying possible bottlenecks related to what needs to occur for each modeling case to be implemented. Finally, the transition bottlenecks can be elucidated from the gap between the enabling conditions and the current challenges from both analyses. The criticality of each bottleneck is highlighted based on the level of deployment of each technology demonstrated in the model.

We made a few modifications compared to the original study by (Geels et al., 2020). Firstly, while we did the modeling and MLP independently, our combinatory approach uses the MLP framework to provide a qualitative analysis to the modeled variables of cost and technologies. From the identification of transition bottlenecks, we elaborated on drivers and formats to enable the transition in each case, rather than transition storylines. This is because we wanted to structure key differences between future scenarios that can meet the requirement of the electrification of the Swedish industry and transport sectors, with and without the expansion of nuclear power from existing data. Furthermore, the original study developed two pathways of technological substitution and broader regime transformation through the bridging between the two methods. In our case study, however, we kept a cost-optimal case as the reference and two more expensive but politically motivated cases to compare. The details of each step are described in the following sections.

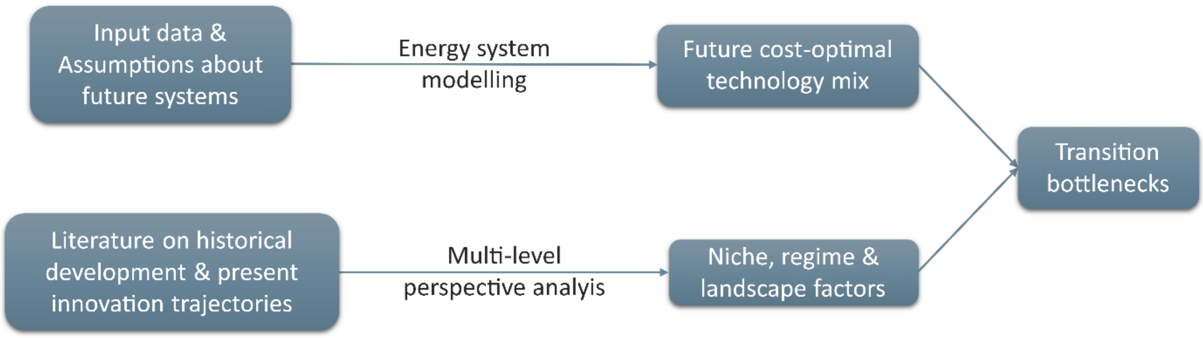

Figure 6: Overview scheme of the energy system optimization model and multi-level perspective analysis combined method to investigate energy transition bottlenecks on the deployment of each technology. Based on the data used for **Paper II**.

3.3.1 Multi-level perspective framework as socio-technical analysis

For the socio-technical analysis, we implemented the multi-level perspective framework to characterize social and political factors associated with the Swedish electricity production and delivery regime based on our literature review. We conducted the analysis on a similar set of technologies as the ESOM, but excluded technologies with limited possibilities for expansion, such as hydropower, along with ones where there is limited information available, such as solar power and small modular reactors.

Specifically, we described the context that led to the contemporary development of these selected energy technologies and power infrastructure. We have addressed this by document studies as our main method. In addition to scientific literature reviews, data consists primarily of official regulations and regulatory guidelines, policy documents, and reports.

On a regime level, this entails a description of underlying characteristics that shaped the current electricity system. Our focus is on historical trajectories, planning and licensing systems, consulting procedures, and arguments for the development of a certain technology. We also analyzed landscape factors, comprising the policy-making traditions that have a bearing on the current development of government regulations and procedures in the electricity sector. For niche-level analysis, we focused on innovations yet to enter the regime. This includes technologies that are in different development phases as well as institutional arrangements that require protected environments and will lead to the emergence of new actors.

3.3.2 Energy system modeling as techno-economic analysis

We applied the ENODE model for our case study investigating three different cases for a net-zero carbon-emitting electricity system in Sweden. The ENODE model is a greenfield bottom-up, technology-rich investment model of the electricity system. Technical details and cost properties of selected technologies, as well as main equations are given in (Göransson, 2023). The model minimizes the annualized investment and operational costs while meeting demand for electricity, heat, and electricity-based hydrogen. We apply the model with a three-hourly resolution and time horizon of two years, corresponding to high and low water inflow to hydropower reservoirs. The model is applied to the north European regions to account for the effects of import and export between Sweden and the surrounding countries. We apply the model to three different cases with respect to Sweden with the assumptions given in Table 3.

The three cases differ in terms of the minimum required nuclear power capacity and offshore wind power capacity in Sweden:

- A "cost-optimal" case, without constraints on minimum level of capacity of any generation technology.
- A nuclear case for which 9-GW nuclear power in Sweden is prescribed in the model. This case is aligned with one of the long-term scenarios of the Swedish transmission grid operator (Svenska Kraftnät, 2024a).
- An offshore wind case prescribing 22-GW offshore wind in Sweden, corresponding to 120TWh of offshore wind production (using assumed Year 2050 offshore wind power technology) – applying Year 2050 offshore wind power plants - which has been proposed in an offshore planning performed by governmental agencies (Swedish Energy Agency, 2023a).

Table 3: Assumptions on the three cases modeled in the transition bottleneck study. Source: **Paper II**.

Case	**Cost optimal**	**9-GW Nuclear**	**22-GW Offshore wind**
% available land	Onshore: 4% Offshore: 33%		
Flexible demand	30% 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		

3.4 Barrier prioritization workshop

To facilitate cross-scenario comparisons of barriers, we organized a workshop with stakeholders from different parts of the energy sector, many of whom also participated in the Q study. The main difference between the stakeholders joining the workshops and the ones joining the Q study is the absence of stakeholders from political parties and civil societies in the workshop, making the participants in the workshop a focus group of representatives from utility companies, electricity-consuming industry, academia, and national agencies. During the workshop, we presented the three cases (explained in Section 3.3.2) and key socio-technical barriers to the decarbonization of the electricity system in Sweden. These barriers were grouped into 5 categories, including governance, contested norms, politics, justice, and economics. The dimensions associated with these groups are given in Table 4. The purpose of the grouping was to understand how stakeholders prioritized different barriers across the modeled cases. Although these barriers interrelate with and impact on each other across different groups, we tried to synthesize these groups qualitatively based on their functional characteristics, not their drivers or their impact on other transition barriers. We are also aware that the strength of each barrier changes over time depending on the implementation of solutions, for instance, barriers to coordination can be mitigated with the negotiation of coexistence and facilitation instruments.

Table 4: Barrier group characterization for the workshop.

Barrier group	**Dimension**
Governance	Challenges associated with a multi-actor presence in the transition, such as challenges to coordinate and collaborate between different tiers of government in site planning for wind power, leading to delays in permit or license application procedures.
Contested norms	Public acceptance of low-carbon electricity technologies. Norms and values associated with variable and firm capacity contribution to the power system.
Politics	The political divide between left-wing and right-wing blocs on energy supply undermines the stability of the energy landscape.
Justice	Difficulties in determining who bears the cost for the transition. This ranges from who bears the cost for the possible increase in electricity price, and the existing and potentially ongoing uneven geographical spread of the electricity infrastructure. It includes justice in procedures and outcomes and recognition aspects.
Economics	Challenges to secure finance for the grid and the new electricity supply. Lack of market instruments, for example, for variation management.

In the workshop, we asked stakeholders to rank how critical it was to address the different barriers to meet decarbonization targets on a scale of one (least critical) to five (most critical) for each scenario. This degree of criticality or importance is relevant to gauge since the perspective of these stakeholders will influence the decision-making process both on a national and organizational level.

4 Selected results

In this chapter, the main results from the two papers are described. Section 4.1 describes the findings from **Paper I**, while Section 4.2 and Section 4.3 highlights the key insights from **Paper II** and the workshop, respectively. The summary of the findings can be found in Section 4.4.

4.1 Meta-challenges to the Swedish electrification

From the application of the Q methodology described in Section 3.2.1, there are three main meta-challenges to electrification in **Paper I**:

1. Procedural Deadlock. This refers to the procedural deadlock associated with expanding variable electricity generation and is concerned with the scaling up of the demand for new electricity generation on time

2. Competing Political Preferences, which highlights carbon prices, flexibility instruments, and political disputes as the main issues hampering the transition

3. Poor Governance, which focuses on multi-stakeholder coordination and is especially concerning an increased grid capacity, hinders an effective electrification process

To compare the abovementioned meta-challenges, Figure 7 displays in a Venn diagram the concerns that are common to and differ for each meta-challenge. The overlapping areas highlight issues that are viewed similarly, while the formulation process of the 52 statements can be viewed in Section 3.2. All three meta-challenges share as 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) is regarded as critical for Meta-challenges 1 and 2. In contrast, **fuel dependence** on other countries (s41) was seen as unimportant for Meta-challenges 1 and 3, similar **to support for small modular reactors** (s9) for Meta-challenges 2 and 3.

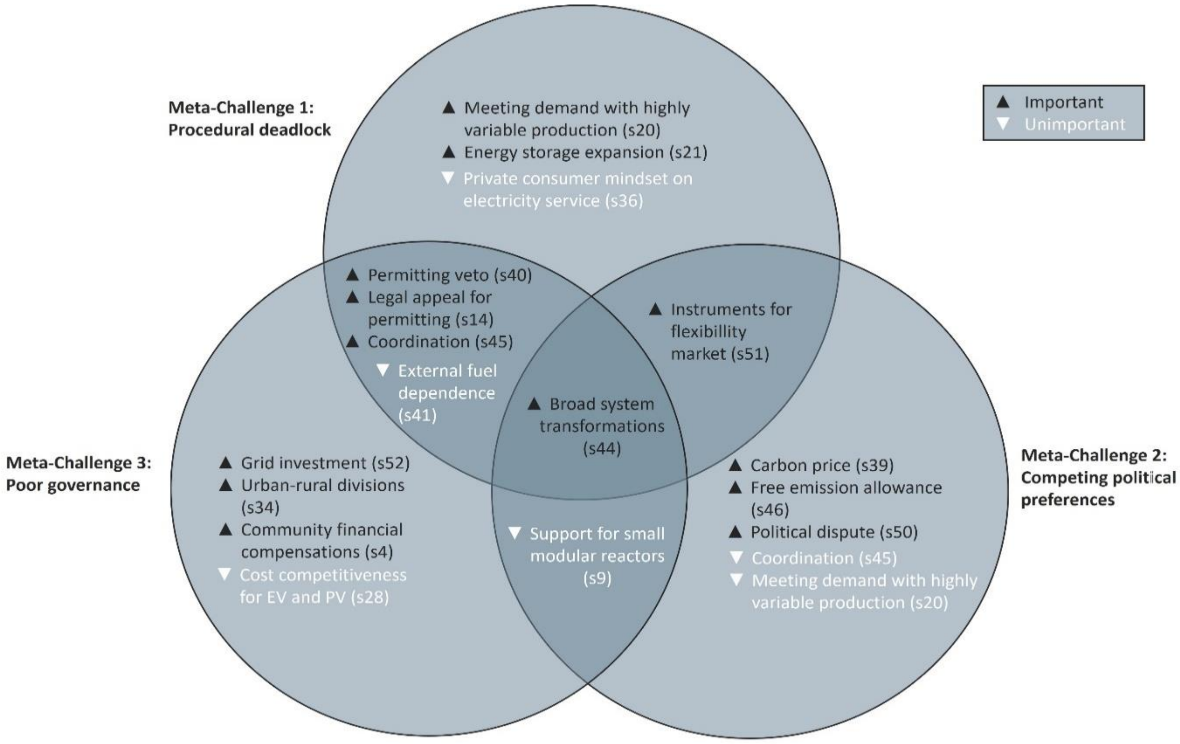

Figure 7: Issues that are shared and unique in the rank-order of the three identified meta-challenges, each linked to its original statement in brackets. Texts are colored according to their ranks, from the most important to the most unimportant. Black text with upward arrows: issues ranked as important; white text with downward arrows: issues ranked as unimportant. Source: **Paper I**.

The remaining part of the circles in the Venn diagram constitutes what is unique for each meta-challenge. These include concerns regarding **increasingly variable electricity production** (s20 and s21) for Meta-challenge 1 on Procedural Deadlock, **carbon instruments** (s39 and s46) and **political disputes** (s50) for Meta-challenge 2 on Competing Political Preferences, and issues related to **grid capacity** (s52) and a just transition, including the **urban-rural division in the transition and community compensation** (s34 and s4) for the meta-challenge 3 on Poor Governance. Regarding issues considered unimportant, Meta-challenge 1 consists of **the mindset of private consumers on electricity service** (s36), while Meta-challenge 2 devalues **coordination** (s45) and **meeting electricity demand with a high level of variability** (s20) in the electricity system. Meta-challenge 3 instead regards **cost competitiveness for EV and PV** (s28) as unimportant. These issues have different characteristics and reflect different priorities that stakeholders associated with each meta-challenge hold.

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 Preference 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.

It should be noted that the issues that have common sort values may be interpreted differently for each meta-challenge. For instance, the statement regarding **the lack of broad system transformation** (s44) is unanimously ranked as the most important in all three meta-challenges. The stakeholders associated with each meta-challenge offered various interpretations as to why they considered this aspect to be most important. For Meta-challenge 1 on Procedural Deadlock, the statement was meant to explore different solutions beyond the electricity infrastructure, such as paying greater attention to non-electricity infrastructure or the distribution side of the value chain. Strengthening the market-based approach for wind power, e.g., in the permitting process, was suggested as an explanation concerning Meta-challenge 2 of Competing Political Preferences. With regards to Meta-challenge 3 of Poor Governance, stakeholders remarked on the need for a more techno-neutral approach to electricity generation, as well as the need for a broad energy agreement to enable stable investment conditions for electrification.

When it comes to the narrative analysis, the similarities and differences across the meta-challenges suggest that stakeholders aligned with different meta-challenges prioritize different issues. For example, those associated with the meta-challenge of **Procedural Deadlock** emphasized the need to overcome permitting and infrastructure delays in expanding the electricity supply mix, while those associated with **Competing Political Preferences** focus on policy disputes, particularly around carbon pricing and technology-neutral incentives. Stakeholders associated with **Poor Governance**, on the other hand, place emphasis on future grid planning and just transitions.

The shared importance of deep system transformations across the meta-challenges identified indicates a broader consensus that structural change is necessary to achieve electrification, echoing findings from transition literature that stress the need for alignment between technical systems and institutional reforms (Geels, Kern, et al., 2016; Wanzenböck et al., 2020). However, this consensus does not imply uniformity in understanding what is feasible.

As noted in previous studies on socio-technical systems, stakeholder perceptions are shaped by differing assumptions about system performance, energy security, and governance (Wolsink, 2007). Hence, underpinning the meta-challenges in this study are key discourses related to energy security, democratic values, regional disparities in energy provision, and the tension between large-scale industrial electrification and local community interests (Devine-Wright & Sherry-Brennan, 2019).

4.2 Transition bottlenecks to the Swedish electrification

From the identification of the transition bottlenecks in **Paper II**, we could observe different patterns of the regime shifts required for the three modeling cases if they were to be realized.

In the cost-optimal case, while the total system cost is economically favorable, a large capacity of onshore wind power and an ancillary infrastructure, i.e., transmission grid for connecting the wind power or other power electronics supporting converter based generation need to be deployed. This is currently hindered by the absence of measures to stimulate wind power and enhance municipal benefits linked to hosting wind power infrastructure. Furthermore, there would be a change in regime in the power grid, which in this case rely primarily on converter-based generation for frequency and voltage control.

The 9-GW nuclear case presents the least severe changes to the electricity mix and power grid infrastructure. However, rolling out nuclear power would drive up the system cost, and the financing of nuclear power, the long lead times, and the lack of updated nuclear licensing and safety and environmental regulations remain as bottlenecks. Furthermore, a certain level of variation management is still needed, although this level is lower than those in the cost-optimal case and the 22-GW offshore wind case. 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.

The 22-GW offshore wind case necessitates extensive development of the offshore wind infrastructure. Currently, the infrastructure is not in place for the subsequent development of offshore wind, as compared to the infrastructures for nuclear power and onshore wind power. The major barriers relate to how governmental actors can resolve conflicts regarding the process of approving offshore siting, and the lack of systems to attract offshore wind investors and allocate financial risks.

In addition to these landscape factors, technological experimentation to support variable electricity production and system integration are needed to leverage the changes in generation capacity. This is relevant to all three cases, albeit less so in the case of nuclear power.

From our transition bottleneck analysis, we demonstrate that while the system is undergoing significant changes, such as those that accompany the increasing penetration of weather-based renewables, the testing of local flexibility markets and converter-based generation, and the rollout of Nordic balancing services with multiple flexibility products, the existing momentum is not sufficient to enable a regime shift in which deep emissions cuts from electrification of industry can be realized. While the current regime is largely fossil-free, it remains unclear as to how the transition process will unfold to meet the climate targets.

4.3 Workshop results

The rankings obtained from the workshop were sorted into different barrier categories, namely governance, contested norms, politics, justice, and economics, and are shown in Figure 8. The figure reveals the average weighted importance with respect to the five categories (*cf.* Table 4) as ranked by the workshop participants. In general, the stakeholders concurred that tradeoffs occur in all cases, and that politics and governance are the most important barriers to tackling in all cases, but to different extents. Governance seems to be more challenging for the cost-optimal and 22-GW offshore wind cases, as wind planning involves a variety of public actors from multiple tiers of government. A discussion was raised on site determination for wind power that accounts for different societal interests. The general standpoint was that the municipal and military veto cannot be abandoned but must be aligned with shared visions that can be integrated into the municipal planning process and motivate compromises with other military interests. As such, the importance of partnership (on a local level) was highlighted to make the process more streamlined. On the other hand, nuclear and offshore wind scenarios were also observed to possess political barriers since these cases are not technology-neutral but include technology-specific subsidies.

Economic factors were seen as minor in the cost-optimal and 22-GW offshore wind cases. The stakeholders agreed that access to capital is not a big issue for the energy transition in Sweden when it comes to investment in new generation capacity, except if there is new nuclear capacity to be introduced. Nevertheless, the uncertainty about investment conditions should be reduced to attract investors. For the 9-GW nuclear case, however, economics were perceived as equally challenging as governance. This is due to the larger uncertainties in the investment cost of new reactors compared to wind turbines, as Sweden last built a reactor in the 70s in a regulated market, and cost estimation is specific to where and how a reactor is built. Nevertheless, the risk associated with investment costs and permitting is expected to be reduced, in case new reactors are built on existing power plant sites. With a high penetration of wind power, the participants argued that securing finance depends on who bears the cost of transmission offshore, the cost of delays in the permitting process, and the regulation on financial compensation. The final aspect of economic consideration is the changes in electricity price across these three scenarios. The participants also consider stability in electricity prices very important. However, results from the techno-economic modeling show that price volatility is present in all three scenarios due to the high share of electricity supplied by wind power in northern Europe as a whole, i.e., including in the scenario with nuclear power.

When it comes to contested norms, a higher ranking was observed for the cost-optimal case due to public acceptance issues connected to onshore wind power. On a socio-political level, the participants stated that social resistance can be expected for cost-optimal and 9-GW nuclear scenarios because it changes the image of Sweden from a net exporter to an importer.

In terms of justice, it can be seen that the cost-optimal and 22-GW wind scenarios have almost the same rankings, while the 9-GW nuclear scenario stood out with lower ranking in justice. This can perhaps be explained by the lower number of sites for nuclear power, the greater distance of site to residential areas, and the more availability of local job opportunities compared to those of wind power.

Overall, it can be seen that the cost-optimal and 22-GW wind cases have almost overlapping rankings across all barrier categories despite the differences in the electricity mix and cost. Meanwhile, the 9-GW nuclear case stood out with lower ranking in justice barriers, which can be derived from the differences between nuclear power and wind power site features, and significantly higher ranking in economic barriers, indicating a greater challenge, which can be explained by the higher investment cost and electricity price in the 9-GW nuclear case relative to other cases.

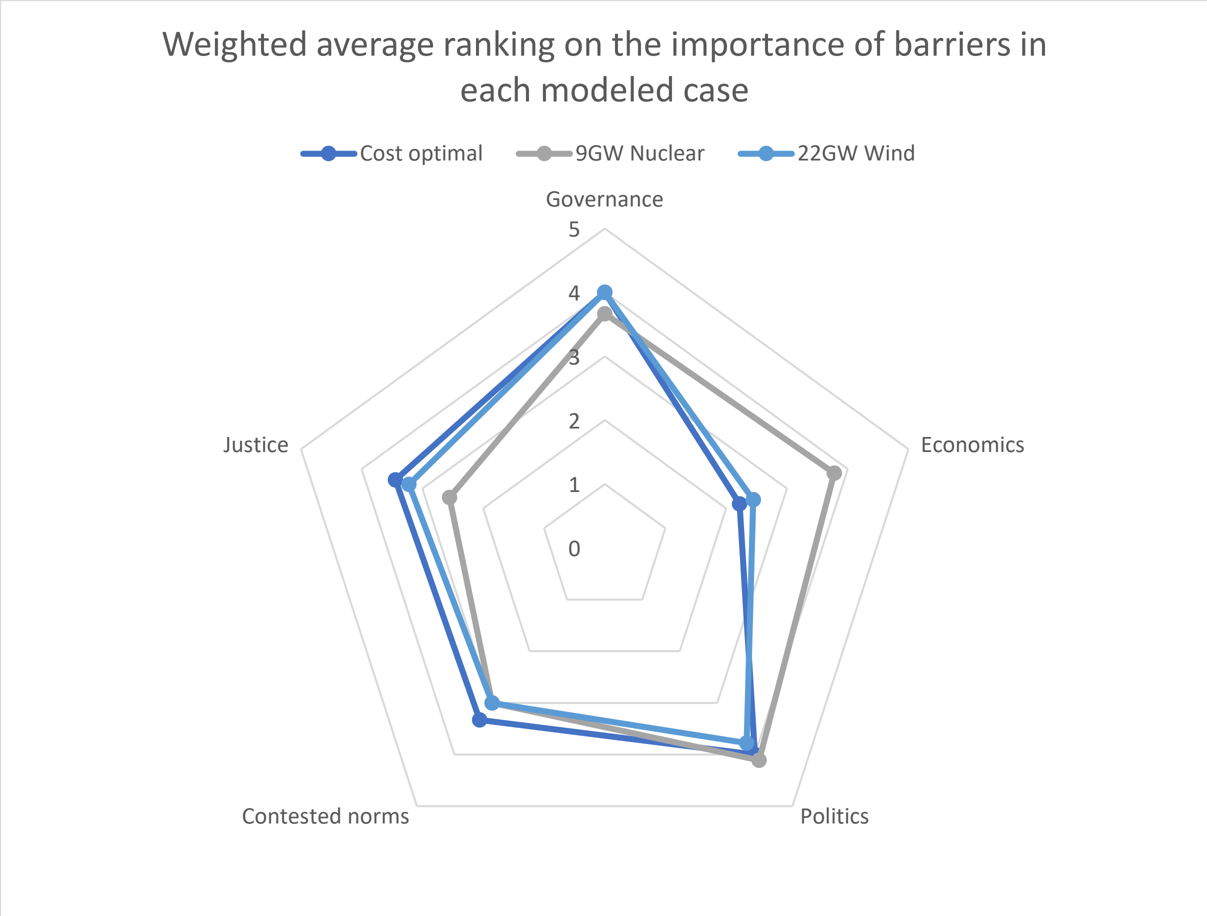

Figure 8: Stakeholder rankings on the barriers corresponding to each of the modeled cases. Dark blue: Cost-optimal case, Grey: 9-GW Nuclear case, Light blue: 22-GW Wind case.

4.4 Synthesis of findings

From the results, the main challenges for the Swedish electrification are:

The effectiveness of the permit-granting process for new electricity infrastructure representing the crux of governance challenges. **Paper I** focuses the veto and appeal process, as well as coordination challenges. Meanwhile, **Paper II** highlights the unpredictability of the process for wind power. Its impact becomes more critical for the cost-optimal case and 22-GW offshore wind, for high deployment of onshore and offshore wind, respectively. Yet it is also relevant for the 9-GW nuclear power case should new nuclear capacity be built on new sites.

The permit-granting issues of new electricity infrastructure receive traction both from the stakeholders participating in the Q study and the workshop, and in the transition bottleneck study in terms of practice, length, and characteristics. In the literature, many studies have explored the institutional, legal, and social factors contributing to the permit-granting process in Sweden (Bergek, 2010; Bjärstig et al., 2018; Mels, 2016; Wretling et al., 2022) as well as in other countries (Bell et al., 2005; Goetzke & Rave, 2016; Kungl, 2015), and contrary to the perception of stakeholders, it is not conclusive whether the length of the process leads to lower deployment rates of certain technologies. Rather, wind deployment, for example, seems to be determined by experience in deployment, which contributes to the readiness in infrastructure (Goetzke & Rave, 2016), institutional setup (Bergek, 2010; Ek et al., 2013; Wretling et al., 2022), and economies of scale (Goetzke & Rave, 2016). Nuclear power also requires a license to build (World Nuclear Association, 2024), but as the plants are concentrated in a few locations rather than extensively spanning across different regions, it is unclear how much of a hindrance licensing will be (Michanek & Söderholm, 2009; Sam et al., 2023).

Secondly, financing challenges will also hinder the low-carbon energy transition. **Paper I** emphasizes the effectiveness of carbon policy, the need for grid investment, and instruments to incentivize flexibility. **Paper I** stresses the importance of the availability of financing support for offshore wind power (due to low diffusion in the Swedish system and lack of experience), nuclear (due to long lead time and high upfront cost) and electrolyzers (due to the lack of economics of scale to drive down the cost). Economic concern, which was ranked highly by the participants of the workshop, was also identified as a more prominent bottleneck for the nuclear case, followed by the offshore wind case due to the lack of diffusion and experience of this technology, while the cost-optimal case receives the lowest ranking, suggesting that cost is perceived to be the least concern in this case compared to the other two. Furthermore, the accepted level of electricity price volatility required for efficient uptake of flexibility service was also brought up in the identification of the transition bottlenecks in **Paper II**. These results are in line with the literature, which suggests the need for financial instruments for handling high upfront costs for electricity infrastructure in the energy transition (IRENA, 2020; Kan et al., 2020; Klaaßen & Steffen, 2023; Rosner & Fields, 2021; WindEurope, 2022, 2024), especially for transformative technologies (Hörbe Emanuelsson et al., 2025).

Thirdly, socio-political issues are perceived as important in the Q study in **Paper I**, especially when it comes to the presence of political disputes in the energy debate, while the presence of varying mindsets, concerns, and priorities leading to social acceptance of certain technologies or pathways is considered broadly unimportant. It can be interpreted that while the energy transition might deepen the divide between different social groups, social acceptance is not a hindrance per se, if compensation schemes are in place for the electricity infrastructure. In the literature, the clash between nuclear-dominant and wind-dominant regimes (Sonnsjö, 2024; Sovacool et al., 2020; Verbruggen, 2008) and the framing tensions they ensue (Bjärstig et al., 2022; Edberg & Tarasova, 2016; Faber, 2023) increase the uncertainty in how the two regimes can coexist or cross over. **Paper II** stresses the importance of policy stability, which is relevant across all three cases, but especially important for the 9-GW nuclear case.

The transition bottleneck study in **Paper II** identifies structural and regulatory aspects that are not addressed within the Q study in **Paper I**. For example, the possible incentives of flexibility instruments could be developed more substantially within the MLP framework and backed by the results from ESOM in **Paper II**. While flexibility service remains a niche-level innovation at the moment, the uptake of it would require the interactions between niche and regime level. Similarly, operational disparity between power grids, mainly tailored to synchronous generation and not adapted for converter-based generation, necessitates more niche-regime interactions and was more scrutinized in **Paper II**. This is because of both the hierarchical ontology embedded in the MLP framework and the state of development of research in which the Q study was done, when flexibility was less well understood.

On the other hand, the discursive elements in the energy transition in focus in **Paper I** contextualize the challenges and cluster them based on the ranks of priority. Highlighting diverse perspectives on the challenges provides a robust foundation, while the stakeholder surveys and interviews enabled a co-construction of the processes through which certain challenges are prioritized. Exploring normative views is also done in the workshop, but the Q methodology takes a step further by providing a structure to systematize the varied narratives into meta-challenges. This kind of analysis with the Q methodology is essential for examining politically contested issues—such as the tension between nuclear and wind power in Sweden—where relying solely on numerical data and scientific literature is insufficient.

In summary, the findings highlight the evolving discourse on what hinders the energy transition in Sweden. It emphasizes how the electrification progress could be undermined by infrastructural lock-in, insufficient incentives addressing financing challenges and the development of flexibility solutions, as well as fragmented governance practice, notably in permit-granting procedures. These challenges are mutually reinforcing and further complicated by political contestation between technological pathways.

5 Reflections on Methods and Findings

This section offers a reflexive account of how methodological decisions and analytical framings have shaped the findings of this thesis. Rather than separating methods from results, I reflect on how knowledge was developed throughout the process, and what this implies for the robustness and limits of the insights gained.

5.1 Framing and positionality

The focus on the Swedish electrification as a lens for understanding energy transition debates foregrounded actors from policy and industry, and specific framings, such as technological innovation and its impact on society. The studies included in the thesis are concerned with the viewpoints of decision-makers in a broad sense, similar to Faber (2023), rather than solely the government and its public administration. This scope seems to be aligned with Swedish modern energy policymaking traditions. Uba (2010), for example, shows that while energy policy development in Sweden is predominant by politicians, civil servants, and state authority representatives, industry representatives also has a strong presence in the process, especially from thermal generation actors compared to renewable actors (Uba, 2010).

On the other hand, the studies in the thesis reflect a tendency to prioritize certain non-state actors, focusing on the viewpoints of stakeholders representing utilities, industrial coalitions, and policymaking. This inevitably shapes which tensions are made visible and which are left in the background. For example, the analysis orients towards perspectives of established stakeholders who contribute to the stability of the regime rather than emerging actors with less access to resources but who may prioritize more transformative solutions to meet climate targets. Furthermore, this orientation also leans the analysis towards generation-side technologies compared to demand-side technologies, although elements of flexibility solutions and ancillary service of the power grid were also covered in **Paper II**. Furthermore, the analysis lends itself to niche innovations that are emerging on a regime level rather than the very new niche technologies.

In both studies, there is a high level of interpretative activities in the method application. In the Q study (**Paper I**), to derive meta-challenges from the statistical analysis of the rankings and the interview transcripts also requires us to make sense of the participating stakeholders' perspectives. In the transition bottleneck study (**Paper II**), modeling future systems inevitably involves assumptions due to uncertainty. Similarly, within the MLP framework, the placement of elements across niche, regime, and landscape levels relies on researchers' interpretations as these are heuristic levels and not fixed categories. In both cases, the researcher's situated perspective plays a central role in shaping the analysis.

Rather than undermining analytical rigor, this underscores the need to broaden what rigor entails—to include transparency in judgment and thoughtful engagement with context. As Elliott and Lukeš (2008) note, knowledge production in case studies involves both *general* insights shaped by interpretive traditions and more *universal* elements derived from the act of inquiry itself. They argue that readers and policymakers must critically assess how research aligns with the specific contexts where decisions are made (Elliott & Lukeš, 2008).

5.2 Methodological comparison

The similarities and differences of the methods for the three perspectives applied in the thesis are presented in Table 5. These approaches applied in this thesis are built on *specific cases* (of Swedish electrification of industry and transport), *local dynamics* (national energy system), and *historically situated processes.*

The **MLP, Q methodology, and workshop approaches** share several key similarities, particularly in their recognition of the **normative complexity** of sustainability transitions. All three aim to explore how transitions are shaped not only by technical and institutional factors but also by social processes, including values, perceptions, and contested meanings. Each method provides a platform, either explicitly or implicitly, for **stakeholder engagement**, recognizing that understanding the perspectives of diverse actors is essential for navigating complex transition pathways (Hermwille, 2016; Janda & Topouzi, 2015; Luederitz et al., 2017). Additionally, all approaches acknowledge the importance of **context**, whether through systemic analysis (MLP), subjective meaning-making (Q methodology), or facilitated interaction (workshops). As such, they each contribute to a more holistic understanding of transitions by emphasizing the **interplay between structures, agency, and discourse**, albeit through different methodological entry points. The sensitivity to the who, when, and where characteristic of the method provides an in-depth, context-specific understanding of complex change processes.

Each of these applied methods underscores the normative dimensions of transition processes, though they do so through distinct lenses and with varying emphases. The **Multi-Level Perspective (MLP)** approach conceptualizes transitions within a systems framework, focusing on institutional, regulatory, and infrastructural dimensions. It offers analytical strength in 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. Being paired with the output from energy system modeling to identify transition bottlenecks, it lends itself to a more top-down analysis, leading to certain types of agency enacted by different social groups being less developed. This means that while its strength lies in systemic comprehensiveness, it may inadequately capture the interpretive and discursive elements of transition, particularly the evolving values and viewpoints of stakeholders.

In contrast, **Q methodology** is grounded in capturing subjectivities. It brings to the surface 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 in both data collection and analysis.

The **workshop approach** serves as a more expedient exploratory tool, well-suited to gauging stakeholder opinions across broad thematic categories in a time-efficient and resource-conscious manner. While valuable for identifying preliminary patterns and fostering discussion, it typically lacks the methodological depth and analytical rigor of more structured approaches.

Table 5: Similarities and differences among the applied methods.

Methods	Multi-Level Perspective (MLP) and Energy System Optimization Model	Q Methodology	Workshop Approach
Focus	Institutional, regulatory, and infrastructural aspects	Norms, values, narratives	Broad stakeholder opinions
Strengths	Systems thinking, policy relevance	Reveals diversity of perspectives	Efficient for preliminary engagement
Normativity handling	Implicit through system roles	Explicit through stakeholder framings	Surface-level insight into normative views
Temporal scope	Long-term transition processes	Mid to long-term narrative analysis	Short-term engagement
Stakeholder role	Regime actors	Stakeholders as co-constructors of meaning	Participants as feedback providers
Limitations	May miss discursive elements	Interpretation can be subjective	Limited depth and analytical rigor

5.3 Analytical generalizability

Given that **Paper I** applies a participatory approach and **Paper II** applies an interdisciplinary and integrative approach, while both studies combine qualitative and quantitative elements, the thesis strikes a balance between rigor and relevance, influencing both academic understanding and policy relevance.

While the Q analysis does not lead to a sharply delineated insight among the three meta-challenges, it shows that stakeholders are greatly aligned in their perspectives on what hinders the energy transition. This contributes to the literature by mapping the ambiguities, overlaps, and tensions within the discursive landscape of Sweden's electrification efforts. This lack of clear dominance of a single narrative is itself analytically meaningful, as it points to a transitional phase where meanings are still being negotiated, and where multiple logics coexist without being fully resolved. Rather than challenging existing transition theories, the study refines existing understandings by showing how policy and industrial actors navigate competing imperatives and unsettled visions. In doing so, it supports a more nuanced, layered view of discourse in socio-technical transitions—one that emphasizes uncertainty, contestation, and the provisional nature of meaning-making. While the specific results are context-specific, the way we use the Q study to group challenges into meta-challenge could be more generally applied. This provides a canvas to unpack why certain challenges persist and which actionable knowledge could be derived.

Bridging between the modeling results and the multi-level perspectives analysis in identifying transition bottlenecks grounds the regime configurations to what is technically feasible and cost efficient from an investment and operation points of view. The three future electricity systems (the so-called three cases) could be realized within contexts that are quite distinct according to culture, institutions, and political arrangements, while still sharing the common traits of the system. Such analysis allows us to discern the context dependency of the research elements, e.g., socio-technical system of electricity production and distribution and further highlighting the similarities and differences of each case, both from techno-economic and socio-technical standpoints. The integration level between the two methods is thus proved effective in both interdisciplinary learning and increasing realism in the findings, which also paves the way towards actionable insights (Hirt et al., 2020).

When it comes to our theoretical contributions, one way to visualize how meta-challenges and transition bottlenecks could advance theories on transitions in the making is shown in Figure 9. The figure indicates that meta-challenges work on the level of discourse, which is influenced by both policy and institutions and actor perspectives. Actors form values based on the deep societal structures they are embedded in, yet they can also influence these structures and shift their perspectives with their agency. Meanwhile, transition bottlenecks are operational on the level of decision arena, which considers and interprets available discourse in the decision-making process. This makes both the discourse and decision arena potential analytical entities in transition research. Previous work has brought up the contribution of both deep structure and actors to discourse (Geels & Verhees, 2011), charted transitions through decision-making arenas (Högselius & Kaijser, 2010), and experimented with narratives as an analytical category (Hermwille, 2016). However, the process in Figure 9 clarifies the connections between discursive elements and decision-making and how the concept of meta-challenges and transition bottlenecks could shed light on such dynamics, e.g., political steering in a discourse to influence a certain decision.

Based on the insights from **Paper I**, we also see that the study of meta-challenges could be combined with existing transition frameworks like MLP to advance the understanding of discursive elements in socio-technical transitions. While some efforts to incorporate narrative or discourse study to transition frameworks have been made (Geels, 2011; Geels & Verhees, 2011; Hermwille, 2016), this remains an understudied area of research.

In addition, based on the insights from **Paper II**, we suggest a clarification of different levels in MLP framework. **Paper II** includes multiple innovations at different stages in the development and we found it useful to include both technical innovations and novel institutions to describe how these innovations impacted the regime. Furthermore, while regime can be broadly understood as the social elements of the current state and system is understood as the infrastructural elements (Geels, 2011), the distinction between the two concepts became superfluous in the application of the method.

As a whole, the studies in the thesis provide fertile grounds to reframe what is important for a transition. Both studies show that the transition is not simply about meeting climate targets through selecting the "right" pathway with the most cost-effective technological mix, but also about how social relations and justice issues could be highlighted in the process of change. This makes the transition not solely to replace fossil fuel with low-carbon electricity but also about how energy is produced, distributed, and governed. With **Paper I**, we suggest that narratives are relevant entities to understanding and enabling systemic changes. With **Paper II**, we highlight the nature of energy systems as multi-level socio-technical arrangements that entangle infrastructure, regulations, institutions and cultural practices, rather than silo technological or economic subsystems.

Furthermore, this thesis supports transdisciplinary and interdisciplinary approaches that address energy challenges by incorporating political, social, and cultural dimensions of change. Both studies highlight that knowledge about the energy transition is not objective or detached, but *situated*, e.g., shaped by values, power relations, and forms of expertise. The use of participatory methods, such as in Q study and the barrier prioritization workshop, further enables the co-production of knowledge in light of normative goals, such as carbon neutrality. Engaging stakeholders helps reveal how challenges are framed and represented in public discourse, showing that decisions on future systems could be guided by perceived legitimacy rather than actual problem-solving effectiveness. The findings also underscore the importance of aligning methodological choices with the specific problems being addressed, rather than combining methods for their own sake. While methodological integration can be valuable, it is most effective when it is guided by clearly defined research aims.

Both studies offer policy-relevant input although in different ways. **Paper I** highlights the importance of considering narratives and context sensitivity in transition policy making, such as in the development of fair but differentiated policies across technologies. On the other hand, the policy suggestions in **Paper II** offer specific point-by-point levers where the transition bottleneck could be overcome, depending on the deployment of key technologies that are linked to each modeled case.

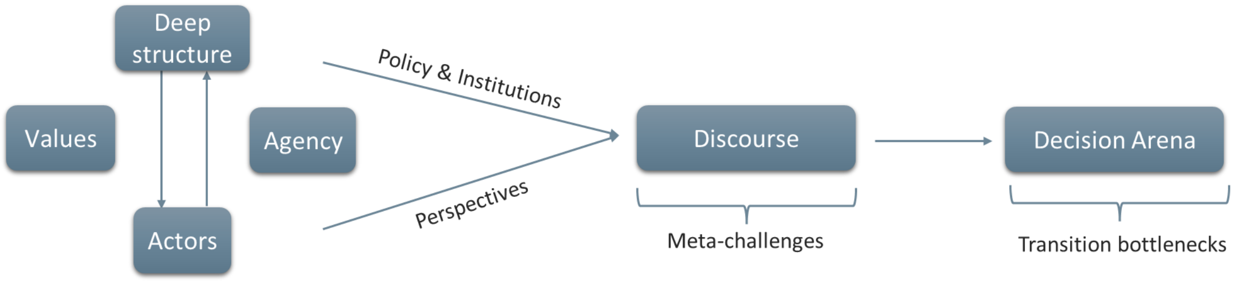

Figure 9: Schematic illustration on how meta-challenges and transition bottlenecks fit into the transition discourse and decision-making.

To sum up, this reflexive account has shown that ambiguity and interpretive uncertainty are not flaws to be corrected but features of socio-technical transitions worth exploring. By embracing the coexistence of competing narratives and pathways, this study contributes to a more reflexive and critical understanding of how transitions are imagined and narrated in real-world contexts.

6 Conclusion and Future work

6.1 Concluding remarks

In the context of the Swedish electrification, this work explores what hinders the low-carbon energy transition through two aims: 1) the perceived importance of a variety of socio-technical challenges from the viewpoints of stakeholders and 2) the transition bottlenecks corresponding to plausible electricity futures.

The first aim is answered through a Q analysis aggregating stakeholder viewpoints on challenges. Three meta-challenges are identified from the work, namely Procedural Deadlocks, Competing Political Preferences, and Poor Governance. All three meta-challenges highlight the importance of systemic transformation, albeit with different orientations. Procedural Deadlock underscores delays and inefficiencies in scaling up variable electricity production, which hinder the deployment of technologies critical for achieving net-zero carbon emissions. Competing Political Preferences highlights how divergent political priorities, particularly regarding carbon policies and flexibility incentives, slow progress toward electrification. Poor Governance emphasizes grid capacity constraints and equity challenges, particularly in ensuring fair access to electrification across diverse stakeholder groups. Such results further reveal the coexistence of evolving discourse in cost efficiency, justice, and path dependency, suggesting that the discursive landscape remains unsettled.

The second aim is met by bridging the output from socio-technical analysis and techno-economic analysis. Transition bottlenecks are linked to each of the key technologies in the energy system models, namely wind power, nuclear power, flexibility solutions, and ancillary services of the power grid. The impact of the bottleneck on each of the modeled cases, including the cost-optimal case, the 9-GW nuclear case, and the 22-GW offshore wind case. The results show that different patterns of regime shifts are required for the three modeled cases if they were to be realized, with the nuclear-dominant case foreseeing the least changes compared to the system today. Despite differences in the electricity supply mix, transition bottlenecks nevertheless exist in all three cases pertaining to uncertainty in cost, timing, procedures, and social acceptance issues. Furthermore, while landscape factor changes are necessary to stimulate investments in key generation technologies such as wind power and nuclear power, incentives to stimulate flexibility solutions and ancillary services require both adjustments on the deeper structures of the landscape level as well as niche and regime interactions.

Overall, the findings of the thesis unveil how, despite the potential for electrification and ambitious net-zero emission targets, the current pace of electrification is not on track with climate commitments in Sweden. By integrating discursive, socio-technical, and techno-economic insights, these findings highlight the ongoing debate, as well as lacking incentives, infrastructural inertia, and inconsistent governance efforts. They underscore the need for integrated, adaptive policy frameworks that move beyond polarizing debates toward solutions that address systemic challenges and advance the directionality of the energy transition in Sweden.

6.2 Future work

Several research questions can be further developed from this work. From the Q study in **Paper I**, we add a narrative-sensitive perspective to existing transition research by capturing the dynamic interplay of socio-political and cultural factors that influence transitions.

As the transition progresses, the development of the narratives should be explored. For example, what makes a narrative more long-lived and robust than others, and how they interweave with transition processes from an analytical standpoint. One potential ground to anchor this is to pair Q methodology with theoretical transition frameworks, such as Technological Innovation Systems (TIS) and the Multi-Level Perspective (MLP), to explore how discursive elements can contribute to systemic changes. Integrating Q studies with these frameworks can make interpretative activities more explicit in these frameworks. This helps illustrate, for instance, how supporters or opponents of a technology or pathway justify their positions by modifying their framings, which in turn resonate with certain cultural norms. Meta-challenge analysis with MLP can reveal how landscape pressures like climate change are translated into regime-specific challenges, or how niche actors make use of landscape-level narratives to break into the regime. Finally, the study highlights the potential for longitudinal Q studies to track changes in stakeholder perspectives over time, offering a deeper understanding of the evolving dynamics of energy transitions. As noted by ten Berge (2023), combining discourse analysis with Q methodology can also help trace the historical and theoretical roots of transition debates, further enriching insights into the social and political configurations underpinning regime change. Together, these approaches provide a robust framework for exploring and addressing the challenges of decarbonization.

From the transition bottleneck identification exercise in **Paper II**, further work could be done in uncertainty treatments and scenario co-creation. One way to do this is to model key uncertain parameters in the model from the identified transition bottlenecks to capture divergent futures and explore the conditions for robust decision-making. Additionally, stakeholder input on energy futures can be gathered through elicitation exercises, helping to shape qualitative narratives grounded in normative visions. The input can then be quantified in scenario analyses to reveal the impact of path dependency on new investments, niche scaling under different scenarios, or the cost of delayed actions. Furthermore, the narratives could be used to examine the typology of transition pathways (Geels, Kern, et al., 2016; Geels & Schot, 2007). This also calls for the development of metrics in energy systems beyond cost-effectiveness and technical feasibility to assess transition scenarios, such as from the point of resilience or legitimacy.

On the other hand, as the electricity regime could be divided into multiple regimes such as generation, distribution, and consumption, future studies could look into the multi-regime dynamics to identify the interactions in addition to key tradeoffs and dependencies from a socio-technical perspective. Moreover, considering the Swedish case, some comparisons could be drawn between the electrification case and the deregulation of the electricity market in the 90s in the country. Such analysis could reveal the changes in structure and agency as well as key patterns that remain stable despite the emergence of new actors.

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