Mind the gap: Mixed-Methods Approach to Investigate Transition Bottlenecks to Low-Carbon Energy Futures

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Research paper

Mind the gap: Mixed-methods approach to investigate transition bottlenecks to low-carbon energy futures

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ABSTRACT

Electrification of transport and industry, a crucial pathway for emission mitigation, may result in a large increase of electricity demand in Sweden. In this study, we investigate the transition bottlenecks for Sweden's electrification using a mixed-methods approach. We first use energy systems modeling to identify cost-efficient combinations of generation, storage, and demand-side flexibility that can meet the projected demand from electrification. Three cases are applied that differ in predetermined investments in offshore wind power and nuclear power. We then apply a multi-level perspective analysis on the three cases with the aim to map out the main characteristics of the Swedish electricity system. We base this on historical development, as well as the impacting landscape, indicating broad, long-term trends external to the system, and niche factors, referring to technological and social innovations. Drawing on these characteristics and modeling insights, we identify transition bottlenecks to Swedish electrification. We find that changes at the landscape level have been insufficient to enable a shift to an electricity system that has a high share of wind and solar power. Instead, the operational and regulatory regimes are 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, transition bottlenecks exist across all modeled futures.

1. Introduction

Electrification is a major technological measure to reduce or eliminate the use of carbon-based fuels and feedstocks in transport and industry (Victoria et al., 2022). Despite the increasing need to invest in new, low-carbon electricity generation, to meet the demand for electricity and to exploit the decreasing cost of solar and wind power (European Commission, 2024), there are socio-technical barriers to implementing these technologies, including issues with social acceptance and lengthy permitting processes for investments in wind power and transmission grids (Rinaldi, 2024).

Energy system optimization models (ESOMs) are commonly used in research and by national authorities and international organizations as part of decision-making processes related to the energy transition (Eurelectric, 2023; Lo Piano et al., 2023). ESOMs are typically used to investigate normative scenarios (Pfenninger et al., 2014), to reflect on “what-if” questions in relation to the energy transition (“what could be”), rather than predicting the future (Chatterjee et al., 2022). Since it is not possible to represent all complex and uncertain parameters with a high level of detail, each model prioritizes some elements while sacrificing others.

Understanding the challenges and opportunities of the energy transition, however, requires an analysis beyond that of ESOM to capture the social issues linked to the energy transition (Chatterjee et al., 2022; Süsser et al., 2022a, 2022b). Thus, there is growing interest in the factoring in of “the human dimension” in ESOM (Pfenninger et al., 2014), by parameterizing social factors to the models (Koecklin et al., 2021; O’Neill et al., 2017; Trutnevyte et al., 2014), soft-linking them with other models that capture social interactions with higher granularity (Hedenus et al., 2022; Krumm et al., 2022; Trappey et al., 2013), or using mixed-methods approaches in scenario analysis (O’Neill et al., 2017; Rogge et al., 2020; van Vuuren et al., 2015). These efforts have generated a body of literature on socio-technical transition scenario development, which combines qualitative socio-technical transition and quantitative modeling insights (Burger et al., 2022; Fortes et al., 2015; Foxon et al., 2013; Hughes et al., 2013; Nilsson et al., 2020). While the representation of social transformation pathways, from the actor level to the systemic level, is still in its early days, it offers a detailed scrutiny of

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the energy systems by uncovering tradeoffs and synergies beyond the realm of technical feasibility (Verrier et al., 2022). This enhances our understanding of the more nuanced ramifications of transition measures, allowing us to communicate these implications to a wider audience and ultimately foster decision-making.

Among the methods used to conceptualize socio-technical transitions through the lens of technological trajectories, the so-called multi-level perspective (MLP) system is an analytical framework that captures long-term technological evolution and diffusion over time by means of interactions at three levels: niche, regime, and landscape (Geels, 2002; Geels and Schot, 2007). There are multiple dimensions associated with each level, and change occurs when the regime is disrupted at the niche and landscape levels (Geels, 2002; Geels et al., 2017a).

The MLP framework addresses the process of transition under the umbrella of a socio-technical regime, to illustrate the patterns of regime inertia and shifts, niche momentum and landscape pressure. In contrast, ESOMs follow the logic of a social planner attempting to minimize the system cost while meeting the demand at each timestep with perfect foresight. While both instruments can be used to understand the impacts of systemic changes, they operate on different temporal scales and have different rationales, e.g., optimization algorithms for ESOM versus technological diffusion for MLP. Thus, there is potential to bring together the two research strands, although how this might be accomplished is not straightforward.

Building on the emerging literature on socio-technical transition scenarios, this work aims to identify and analyze transition bottlenecks in the low-carbon energy transition by *bridging ESOM scenarios of future electricity systems with a socio-technical MLP analysis*. Fig. 1 provides a conceptual illustration of the way that we combine MLP and ESOM in the present study. Similar to the method proposed in (Geels et al., 2020), we define transition bottlenecks as those factors that might hinder the deployment of a technology needed for Swedish electrification. We suggest and describe the required conditions, including the drivers and formats that enable technological and cost developments for each case, taking stock of existing projects and initiatives. In this methodological procedure, the modeled cases provide quantitative feedback to the MLP analysis by highlighting technical and economic constraints. Conversely, by applying the MLP framework, we provide a qualitative showcase of social and political factors that may affect the feasibility of the modeling outcomes. This approach elucidates a *socio-technical qualification of model-generated scenarios*, identifying the policies and socio-technical systems that are required to overcome the bottlenecks.

We apply the method to the case of the Swedish electricity regime. The reason for using the Swedish electricity system is that the demand for electricity in Sweden is expected to increase substantially, up to a doubling, due to the electrification of the industry and transport sectors. Sweden is a highly industrialized country with a large share of energy-intensive industries, such as iron- and steelmaking, petrochemicals, cement, and pulp and paper production. Yet, the current regime is characterized by the fact that the electricity demand has remained constant over the last three decades and, thus, has a well-established network of technologies, actors, and rules. Meeting electrification targets requires that this network undergoes a significant transformation. In the upcoming decades, while parts of the electricity system are likely to remain in the Nordic countries, such as hydropower capacity in Finland, Norway and Sweden, and some nuclear power capacity in Finland and Sweden (Kilpeläinen et al., 2019), there is a wide range of possible electrified futures with unfolding transition pathways. This makes the Swedish case highly relevant to the context of system change.

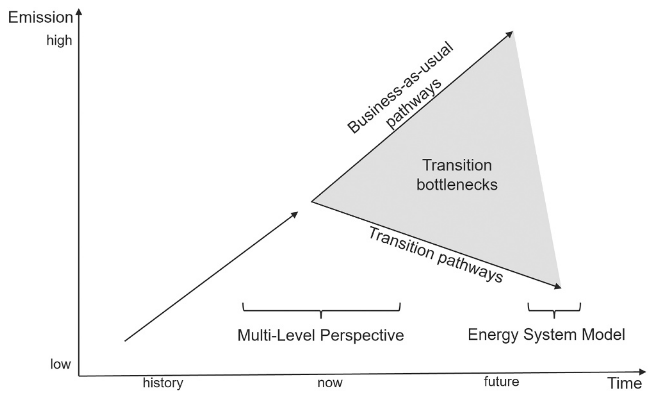

Fig. 1. A visualization of the mixed-methods approach adopted in this study. Adapted from (van Vuuren et al., 2015).

This paper is organized as follows: Chapter 2 describes the methodological procedure used in the study; Chapter 3 provides the findings derived from the analysis; and we discuss the implications of the results and policy recommendations in Chapters 4 and 5.

2. Research design

We combine the above-described combination of ESOM and MLP analyses, as also proposed by Geels et al. (2020), with the focus on Swedish electrification, as illustrated in Fig. 2. The ESOM provides three cost-optimal, demand-satisfying technology mixes of future low-carbon electricity systems in Sweden. These three cases differ in terms of their predetermined levels of investment in offshore wind and nuclear power. Basing the analysis in one country allows us to explore the empirical conditions specific to that country. In this case, the choice of modeled cases follows the current discourse in Sweden, which is steeped in an ambiguity of possible directions for the transition. Accordingly, while the MLP framework provides important insights into how technologies evolve and diffuse over time, ESOM generates cost-optimal technological mixes under different scenarios.

To understand the current electricity systems regime, the MLP analysis charts the important historical events and processes that led to the current technology mix (applying the niche, regime and landscape levels (Geels, 2002). The analysis is based on literature reviews. As the ESOM part provides the operational and economic constraints of the system for one year in the future (2050), and the MLP analysis provides insights into what constitutes the system as it is today, their combination bridges the two scholarly strands in eliciting possible bottlenecks. From this exercise, we map out the transition bottlenecks connected to each modeled case.

We make a few modifications to the original study of Geels et al. (2020). First, while we perform the modeling and MLP independently, our combined approach uses the MLP framework to provide a qualification of the modeled cases. From the identification of transition bottlenecks, we elaborate on enabling conditions to realize each case, rather than a description of socio-technical storylines. This is because we want to structure the key differences between future scenarios that can meet the requirement of electrification of the Swedish industry and transport sectors, with and without the expansion of nuclear power. Furthermore, the original study developed two pathways for technological substitution and broader regime transformation from the bridging of the two methods. However, in our case study we retain a cost-optimal case as reference, and two more costly but politically motivated cases for the comparison. The details of each step are described in the following sections.

2.1. *Energy systems modeling*

We apply the ENODE model, which is a greenfield, bottom-up, technology-rich investment model of the electricity system, to conduct a techno-economic analysis. The model formulation was first presented in (Göransson et al., 2014) then further developed to evaluate the impact of thermal plant cycling (Göransson et al., 2017), variation management (Johansson and Göransson, 2020), and thermal energy storage (Holmér et al., 2020) on cost-optimal electricity and heating

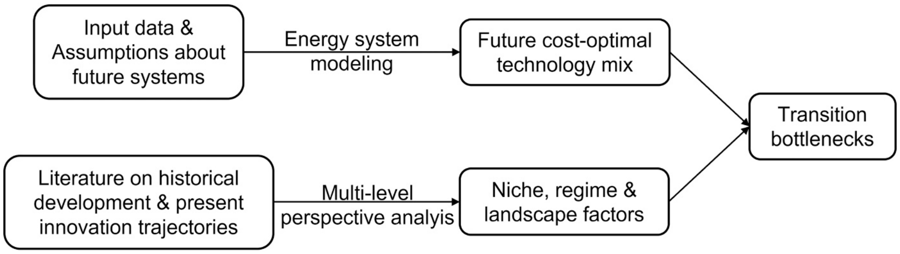

Fig. 2. Overview scheme of the energy system optimization model and multi-level perspective analysis combined method to investigate energy transition bottlenecks on the deployment of each technology.

systems. The technical details and cost properties of selected technologies are detailed in (Göransson, 2023).

The model minimizes the annualized investment and operational costs, while meeting the demands for electricity, heat, and electricity-generated hydrogen in 2050. The model has a 3-hour resolution and is applied to the northern European regions shown in Fig. 3, to account for electricity trade between Sweden and the surrounding countries. Several key constraints in the model are described in Eqs. (1) – (4), while the key sets, variables and parameters used are described in Table 1. The full model formulation is detailed in earlier studies (Göransson et al., 2017; Holmér et al., 2020; Johansson and Göransson, 2020).

The objective function of the model is expressed in Eq. (1). It minimizes the total system cost and includes the annualized capital costs, fixed and variable operational costs.

$$\min \sum_{r \in R} \left(\sum_{p \in P} i_{r,p} * C_p^{inv} + \sum_{p \in P} i_{r,p} * C_p^{fixOM} + \sum_{t,p \in T, P^{gen}} g_{r,t,p} * C_p^{OPEX} \right) \tag{1}$$

Demand for electricity must be met at every time step, as expressed in Eq. (2)

$$\sum_{p \in P^{gen}} g_{r,t,p} + \sum_{p \in P^{storage}} \left(s_{r,t,p}^{discharge} - s_{r,t,p}^{charge} \right) - \sum_{r', p \in R, P^{tran}} x_{r,r',t}^{netexport} \geq D_{r,t}, \quad \forall r, t \in R, \quad T \tag{2}$$

Generation must stay below installed capacity weighted by profile. This is expressed in Eq. (3).

$$g_{r,p,t} \leq i_p W_{p,t}, \quad \forall t, p \in T, P \tag{3}$$

Fig. 3. Regions studied in the model.

Table 1
Key sets, variables, and parameters used in the mathematical description of the model used in this work.

Sets		
R	Regions, {1,.,r}	
T	Time-step, {1,.,t}	
P	Technology	
P^{gen}	Electricity-generating technologies, $\forall P^{gen} \in P$	
$P^{storage}$	Energy storage technologies (Li-ion battery, hydrogen storage), $\forall P^{storage} \in P$	
P^{trans}	Transmission technologies (OHAC and HVDC), $\forall P^{trans} \in P$	
Variables		
$i_{r,p}$	Investment in technology p in region r	[GW]
$g_{r,t,p}$	Generation, or storage level, for technology p at time-step t in region r	[GWh/h]
$x_{r,r',t}^{netexport}$	Electricity net export from region r to region r' during time-step t	[GWh/h]
$s_{r,t,p}^{charge}$	Charging of storage p in region r at time-step t	[GWh/h]
$s_{r,t,p,y}^{discharge}$	Discharging of storage p in region r at time-step t	[GWh/h]
Parameters		
$\eta_p^{storage}$	Charging and discharging efficiency of technology p	[-]
$C_{p,y}^{inv}$	Investment cost for technology p	[k€/GW]
$C_{p,y}^{OPEX}$	Running cost (fuel, CO_2 and variable O&M cost) for technology p in year y	[k€/GWh]
C_p^{fixOM}	Fixed yearly O&M cost for technology p	[k€/GW]
$D_{r,t}$	Electricity demand during hour t in region r, including existing electricity demand, electricity demand for industry and battery-vehicle transports	[GWh]
S_p^{rate}	Storage (dis)charge rate as a fraction of storage per hour	[-]
$W_{p,t}$	Hourly profile for VRE (value of 1 for dispatchable technologies)	[-]

The storage balance in Eq. (4) ensures that the energy balance for the different types of energy storage is not violated.

$$g_{r,t+1,p} \leq \quad g_{r,t,p} + s_{r,t,p}^{charge} \bullet \eta_p^{storage} - \frac{s_{r,t,p}^{discharge}}{\eta_p^{storage}}, \quad \forall \quad r, t, p \in R, T, P^{storage} \tag{4}$$

We apply the model to three different cases with respect to Sweden, applying the assumptions listed in Table 2. The three cases differ with respect to the minimum investment for nuclear power and offshore wind power capacity in Sweden. The scenarios with 9 GW of nuclear power and 22 GW of offshore wind are close to the projections commonly discussed by various political groups in Sweden. These cases reflect a strongly polarized national debate about the future of the Swedish electricity system, framing the issue as a choice between renewables and nuclear power as the primary technology.

- A "cost-optimal" case, without constraints as to the minimum capacity of any generation technology.
- A nuclear case for which 9 GW of nuclear power in Sweden are exogenously 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 that exogenously prescribes 22 GW of offshore wind in Sweden, corresponding to 120 TWh of offshore wind production (using the assumed 2050 offshore wind power technology). This level corresponds to an offshore planning exercise performed by Swedish governmental agencies (Swedish Energy Agency, 2023).

Economic and technical input data for the selected technologies are taken from the Danish Energy Agency's technology catalogue (Danish Energy Agency, 2025). The cost of nuclear power applied in this work corresponds to large-scale nuclear power (Generation III) of the same size as is in place in Sweden today. The assumed cost is based on industry expert estimates and is lower than the costs given by the IEA (IEA n.d.). Small modular reactors (SMR) are excluded due to the lack of information on cost and expected time of commercial viability.

Renewable resource profiles are taken from two historical years (1991 and 1992), corresponding to high and low rates of water inflow to hydropower reservoirs. Wind and solar power production potentials are derived from the ERA5 climate model (European Centre for Medium-Range Weather Forecasts, 2018) and the Global Wind Atlas (Technical University of Denmark n.d.). Wind power is represented with constraints on deployment that differ with regards to geographic position (Table 2). The existing hydropower capacity is assumed to continue. Climate change impact is represented by the extent of altered water flows, reduced heating demands, and increased extreme weather events (Göransson, 2023).

Flexibility refers to the ability of the power system to balance supply and demand over various timescales on both the supply and demand sides. Storage and other flexibility solutions are part of the optimization and, therefore, differ according to the electricity mix. The model includes three types of demand-side flexibility: strategic charging of electric vehicles; flexible operation of heat pumps in district heating grids; and flexible operation of electrolyzers. The two latter types are only possible at the cost of overcapacity of heat pumps and electrolyzers, respectively, as well as investments in thermal tank storage units and line-rock caverns for hydrogen storage.

2.2. *Multi-level perspective framework application*

We base the socio-technical analysis with MLP framework on a literature review, which primarily consists of scientific publications and gray literature sources for regulatory and policy documents, as well as reports from state agencies, and EU-level documents and international organizations. We conduct the analysis on a similar set of technologies as done in the techno-economic analysis, however, we exclude technologies that have limited possibilities for expansion, such as hydropower, as well as those that contribute marginally to our modeled results, such as solar power. This means that we focus on four groups of key technologies, including wind power, nuclear power, flexibility measures, and ancillary service of the power grid.

On a *regime level*, the analysis entails a description of the current electricity system, including the underlying characteristics of the institutions, infrastructure and market that shape its present state (Geels, 2002; Geels et al., 2017a). The regime consists of several sub-regimes, including the supply, grid and demand-side regimes. Our focus on the regime incorporates both tangible elements, such as infrastructure and targets, and intangible elements, such as administrative and operational norms (Geels, 2011).

Table 2
Assumptions made for the three cases modeled in this work.

Case	Cost-optimal	9 GW of Nuclear Power	22 GW of Offshore Wind
% of suitable land	Onshore: 4 % Offshore: 33 %dddss		
Flexible demand	30 % of cars charged flexibly, possibilities to store heat and hydrogen		
Transmission	According to projection scenarios for 2040 by TYNDP (ENTSO-E and ENTSOG, 2023)		
Storage options	Hydrogen storage, stationary batteries, thermal energy storage		

The *landscape level* analysis comprises long-term systemic factors that impact both the regime and the niche levels internalized by regime and niche actors, though usually outside of their control. This includes socio-economic situations, infrastructure delays, and extreme weather events, among others (Geels et al., 2017b). Exogenous factors, such as technological breakthroughs or political struggles in other countries, may be translated into landscape pressures if they are perceived as relevant by the regime and niche actors. Since landscape factors could be wide-ranging, we limit our focus to factors that directly impact on the energy sector. In particular, the focus is on norms and values that are embedded in the development of government regulations and procedures in the electricity sector.

On the *niche level*, the momentum of low-carbon niche innovations is detailed. The term *niche* is defined in the literature as an element of novelty or innovation (Petrovics et al., 2022) that requires a protected environment for development until it reaches a certain market share or some other indicator of maturity, with the focus on new technologies. In this paper, we operationalize this concept by applying three heuristic criteria for niche identification. Specifically, an element has niche properties when; (1) the element has not been implemented in the regime and has the potential to challenge the existing Swedish electricity regime; (2) the development of the element requires a protected environment (Geels, 2011); and (3) the introduction, development or implementation of the element involves or is driven by new institutional arrangements or the emergence of actors and networks (Geels, 2011). We do not address in depth the developments of the demand-side regime, instead flexibility solutions and ancillary service are explored through the lens of supply and grid actors.

We structure the analysis by first articulating the present context for each of the key technologies, including historical development patterns of the technology in question and the role it plays in the electricity regime in Sweden. This is followed by key challenges to further expand or implement the technology on a higher level. Next, key enabling conditions for the technology are identified based on levers to address key challenges. Here, we analyze enabling conditions not only in Sweden but also bring up countries and regions with similar or comparable conditions to the Swedish electricity regime. This approach also corresponds to our modeling scope, which takes out Sweden's results from a Northern European model setup.

2.3. *Identification of transition bottlenecks*

We showcase transition bottlenecks for each key technology and modeled case, linking the modeling and MLP analysis results iteratively. The three modeled electricity systems are characterized by their technology mix, annual production and electricity prices. With the socio-technical analysis, we discern the niche and landscape factors that enable regime shifts through the lens of the key technologies obtained from the technoeconomic analysis. The three modeled systems can then be realized within contexts that are quite distinct in terms of culture, institutions, and political arrangements, while still sharing the common traits of the system. The gap between the future-state and today's situation, identified by combining the modeling and the MLP analysis, reveals transition bottlenecks. The criticality of each bottleneck is highlighted with regards to the level of deployment of each technology shown in the energy system optimization model (Table 3).

3. Results

This section presents the results from: (i) the techno-economic analysis (through ESOM) in Section 3.1; (ii) the socio-technical analysis (through MLP) in Section 3.2; and (iii) the integrated analysis of transition bottlenecks in Section 3.3.

3.1. Techno-economic analysis

Fig. 4 shows the annual level of electricity supplied by each technology for the three cases: the cost-optimal case, the 9 GW nuclear case and the 22 GW offshore wind case in 2050. Since the Swedish electricity system is small in the northern European context, the differences between the three cases are modest on the north European level. Wind power is the dominant electricity supplier in northern Europe under the conditions investigated. In Sweden, wind power supplies a substantial share of the electricity demand in all three cases. On the other hand, the addition of nuclear power or offshore wind power capacity reduces the levels of investment in onshore wind power and solar power capacity. In the cost-optimal case and in the 9 GW nuclear case, a significant part of the electricity demand is covered by imports. Electricity is primarily imported from Finland, which has a lower level of land restriction for onshore wind power, and from Denmark, which has slightly better conditions for offshore wind power.

When it comes to strategies to handle variations in the electricity system, Fig. 5 presents the investments in hydrogen, battery and heat storage in each of the modeled cases. Hydrogen and heat storage units are part of demand-side flexibility measures, whereby the storage units decouple the operations of the electrolyzers and heat pumps from the demands for hydrogen in industry and for heat in district heating systems. There are significant investments in hydrogen storage in all cases, as shown in Fig. 6. Heat storage capacity is also present in all cases, albeit at much lower levels in the nuclear power case compared to the cost-optimal and offshore wind cases. The motivation for investing in storage technologies is the variable value of electricity in all cases, due to the major part of the electricity supply in northern Europe being supplied by wind and solar power.

In terms of the total cost to meet the demands for electricity, heat and hydrogen, the nuclear power case yields the highest system cost for Sweden, which is 1650 MEUR-2020/year higher than the cost-optimal case, while the cost for the offshore wind case is 480 MEUR-2020/year higher than the cost-optimal case. If these costs are evenly distributed across all consumers in Sweden, they correspond to 6.5 EUR-2020/MWh in the nuclear case and 2 EUR-2020/MWh in the offshore wind case. The varying electricity supply at the northern European level also gives rise to a varying marginal cost for electricity in all the cases investigated. Fig. 6 shows the marginal electricity cost in southern Sweden for each of the modeled cases and indicate the presence of both high and low electricity prices in all cases investigated. The number of high-price hours is slightly higher in the cost-optimal case than in the nuclear and offshore wind cases, resulting in an annual average marginal cost for electricity of 33 EUR-2020/MWh in the cost-optimal case compared to 24 EUR-2020/MWh in the other cases.

3.2. Socio-technical analysis

In the following sub-sections, we provide a socio-technical analysis of each key technology and infrastructure component. This includes a description of the development of the technology or component, the current challenges pertaining to the development of the technology or component, and the enabling conditions for further expansion.

3.2.1. Wind power

3.2.1.1. Context. Onshore wind power has expanded substantially in Sweden since the turn of the century, reaching an approximately 20 % share of electricity generation by 2023 (Swedish Energy Agency, 2022). Besides the global drop in production cost and the availability of large land areas with favorable wind conditions, the expansion of onshore wind power was greatly enabled by the electricity certificate system in Sweden, which was in force from 2003 to 2021 (Holmberg and Tangerås, 2023). Thus, wind power has moved from being a niche technology to being a part of the regime. To further increase wind power penetration level, the Government of Sweden has proposed an economic

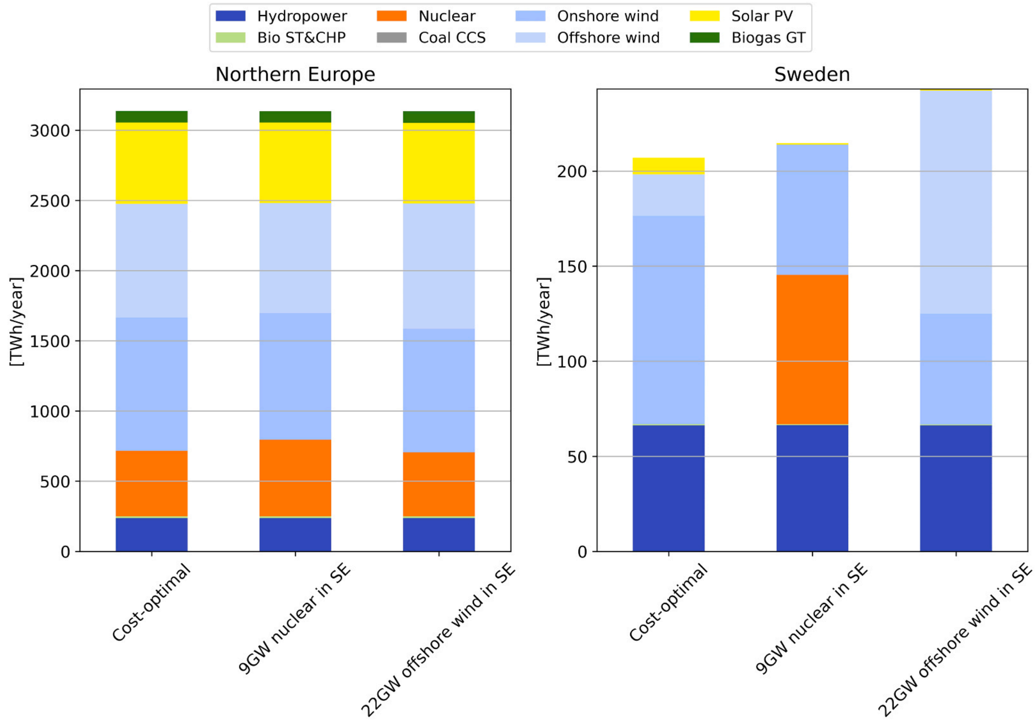

Fig. 4. Annual generation levels of different low-carbon energy supply technologies in northern Europe (left) and Sweden (right) in each of the modeled cases in TWh per year in 2050. Biogas GT: Biogas gas turbine, Bio ST&CHP: Biomass steam turbines and combined heat and power, Coal CCS: Coal Carbon Capture and Storage, Solar PV: Solar photovoltaics.

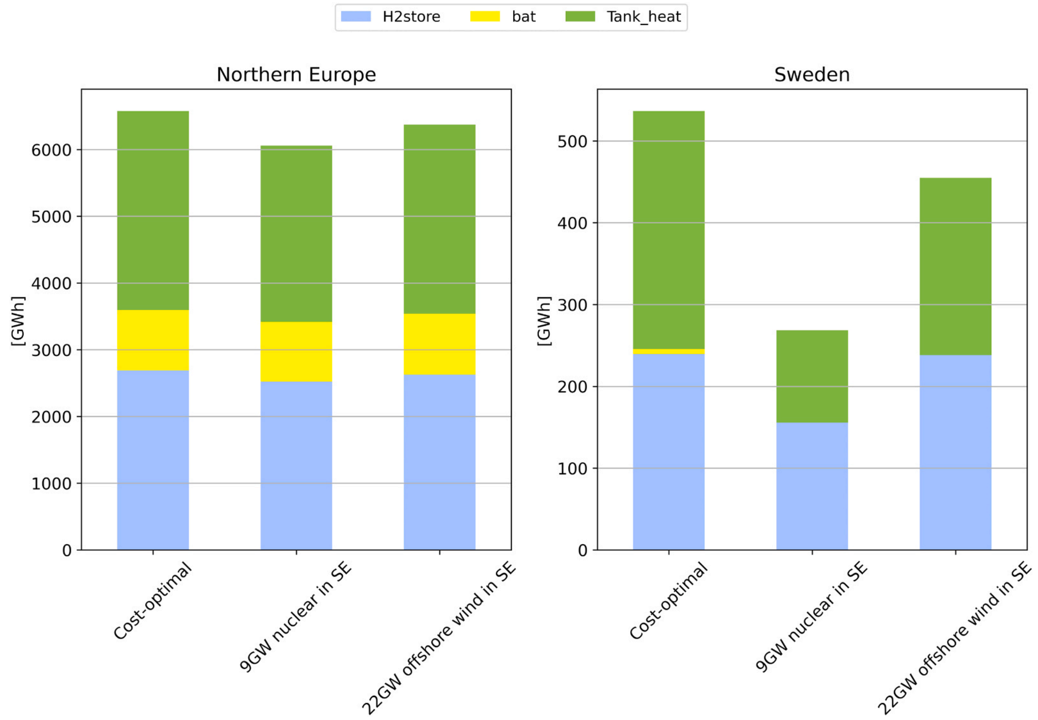

Fig. 5. Installed capacity of energy storage in northern Europe (left) and Sweden (right) in each of the modeled cases in 2050. H2store: Hydrogen storage, bat: Battery, Tank_heat: Tank heat storage.

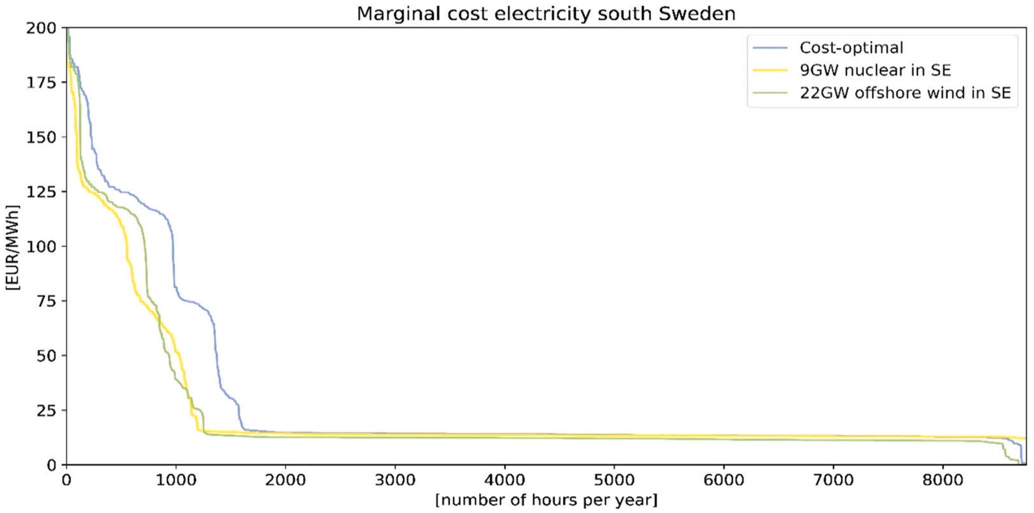

Fig. 6. Marginal cost of electricity in Sweden in each of the three modeled cases in 2050.

compensation scheme for local communities in the form of revenue sharing and property price compensation (Government Offices of Sweden, 2023a).

Meanwhile, despite Sweden's long coastline, offshore wind power is practically non-existent, with only 193 MW of installed capacity by 2023, with no new capacity built since 2013 (Fernández, 2024; WindEurope, 2022). Between onshore wind and offshore wind power, the main differences in the permit-granting processes lie in the involved actors and jurisdiction with regards to the location of the wind turbines in the permit-granting procedure. As part of the site selection procedures, offshore wind farm developers are responsible for proposing suitable locations in their applications. Furthermore, the permitting process is principally different between projects conducted within and outside the territorial border, where municipal vetoes and government rulings, respectively, apply.

3.2.1.2. Challenges to expansion. The challenges to wind power expansion are primarily related to social acceptance and the complicated implementation of permit-granting procedures for wind power.

With respect to social acceptance, the development of wind power has over the last years been heavily politicized in Sweden, where there is a specific pattern of party support (Isaksson and Gren, 2024), in which wind power opposition coincides with nuclear power support (Holmberg, 2022).

Regarding the permitting of wind power, as is the case in some other European countries, the planning and approval processes are lengthy and complex (IEA, 2024). Swedish municipalities have a planning monopoly, i.e., sovereignty over how their space is used. A municipal veto is implemented with the intention of streamlining the permit-granting processes for onshore and offshore wind power within their geographic area (Wretling et al., 2022). In practice, the municipal governments can veto the introduction of wind power throughout the municipality at any point in time during the process of consultation and permitting, without any need to justify their decision (Liljenfeldt and Pettersson, 2017; Mels, 2016). Due to these factors, the time to reach a decision on an onshore wind permit application can be up to 10 years (European Commission, 2020) with a high rate of rejection (Swedish Wind Energy, 2023).

For offshore wind establishments, the siting and permit-granting processes are heavily dependent upon the interactions between multiple actors at different levels (Mels, 2016). Siting conflicts often arise because the proposed sites overlap with the interests of the armed forces or marine activities (WindEurope, 2022). There are no clear criteria for approving an application, increasing the risks for investors and project developers (Swedish Wind Energy, 2024). Despite efforts to coordinate the relevant governmental bodies involved in the identification of areas, so as to develop new offshore wind power facilities (Swedish Wind Energy, 2024; WindEurope, 2022), the planning of offshore wind generation remains ambiguous.

Besides the regulatory challenges associated with site selection, since offshore wind power development still belongs to the niche phase in Sweden, significant financial challenges are foreseen, particularly with respect to the upfront costs. Meanwhile, Sweden lacks a system that buffers the economic vagaries of offshore wind power projects. As there is neither a relevant state support system nor revenue stabilization model operating in the country, there are problems with risk allocation, and this causes insecurity among project developers and investors. On top of that, since the financial support for the grid connections for offshore wind parks (Svenska Kraftnät, 2024a; TT, 2023) has been removed, this shifts the responsibility for investment in offshore transmission lines to the wind power investor.

3.2.1.3. Enabling conditions for expansion. To expand wind power while still preserving the self-governing feature of the Swedish municipalities, one possibility for the municipal veto tool is to pair it with some mechanism for political accountability. For example, making the permit decision legally binding within a specific timeline could reduce the uncertainty for the industry and wind power actors (Government Offices of Sweden, 2021). Beyond the veto tool, stronger integration between spatial planning and environmental permits would enable a more-effective permit-granting process (Larsson et al., 2014).

For offshore wind power, successful cases can be observed in Denmark where selected sites for offshore wind power are permitted in a process that combines government tender calls at pre-determined sites (Danish Energy Agency, 2024). Sweden could institute something similar to reduce the current ambiguity in site selection procedures. Other procedural solutions to streamline permitting process for both onshore and offshore wind power plants should be explored (Government Offices of Sweden, 2021). In addition, the failure to attract bids in the auction rounds in Denmark and the UK highlights the importance of providing financial support to mitigate the risks for investors and project developers (WindEurope, 2024, 2023).

To address the negative attitudes towards wind power, the motives for support for different actors, including investors, local communities, municipal politicians and bureaucrats, should be understood, to enable conditions that allow acceptance. For example, if the main concern is decreased property values (Bergek, 2010), the implementation of property price renumeration schemes could be advanced (Government Offices of Sweden, 2024). It would also be beneficial for the government to further develop some system of economic incentives to municipalities that are hosting wind power (Government Offices of Sweden, 2023a). When it comes to implementation, Sweden could learn from Finland, which has established a system in which the wind power plant property tax is paid to the wind power-hosting municipalities (Renewables Finland n.d.). The tax rate is determined as a proportion of the investment cost of the wind turbine, and the municipalities have the possibility to adjust the rate. Furthermore, many landowners in Finland also receive land lease payments from hosting wind turbines (Renewables Finland n.d.).

3.2.2. *Nuclear power*

3.2.2.1. Context. Nuclear power has been integral to the Swedish electricity regime; together with hydropower, it has as acted as the backbone of electricity generation in Sweden for the last 40 years. There were originally 12 nuclear reactors, of which 6 have been phased out (World Nuclear Association, 2024a). Despite an ambivalence in nuclear energy policy, Sweden recently joins the bandwagon of countries reaffirming their commitment to nuclear power in light of energy security concerns (European Commission, 2025; Heim, 2025; Szulecki and Kusznir, 2018), which is often referred to as a nuclear energy renaissance (Andersson, 2024).

Over the last decades, there has been a political tug-of-war between the anti- and pro-nuclear power factions in the country, fueled by various international events such as oil crises and nuclear reactor meltdowns. Triggered by the Three Mile Island accident, for instance, there was a referendum on the future of nuclear power in 1980 with an ambivalent outcome, which stated that nuclear power was to be phased out once alternatives became available (World Nuclear Association, 2024a). The impact of the result of that referendum has diminished as time has passed (World Nuclear Association, 2024a). In 2010, the Swedish Parliament voted for the possibility to build new nuclear reactors, but this was limited to replacing old ones on existing sites (making it possible to have a maximum of 10 reactors corresponding to the number of reactors in 2010).

The Government of Sweden in the 2021–2025 term is highly in favor of nuclear power and set a target for two new nuclear reactors to be in place in 2035 (World Nuclear Association, 2024a). In addition, an investigation of the financing of nuclear power was commissioned by the government, which proposed a three-pillar financing regime, involving governmental loans, guaranteed electricity sales price in the form of contracts for difference, and a profit-sharing mechanism (Government Offices of Sweden, 2023b).

3.2.2.2. Challenges to expansion. While the public support for nuclear power increased between 2019 and 2021 (Holmberg, 2022), political struggles related to nuclear power have persisted (Edberg and Tarasova, 2016; Faber, 2023; Wiwen-Nilsson, 2006), which could undermine the long-term stability of energy politics needed by investors. The energy policy for nuclear power in Sweden is characterized not only by political shifts but also by changing market conditions and conflicting priorities, ultimately leading to policy reversals that now favor nuclear power as part of a fossil-free future (World Nuclear Association, 2024a).

Moreover, the building and operation of new reactors are imbued with economic uncertainty. Nuclear power is characterized by a high fixed cost to variable cost ratio, which together with the high-cost level results in high financial risks for nuclear power investments. The cost estimation is also specific to where and how a reactor is built, and the three ongoing nuclear projects in Europe, including Hinkley Point C in the UK (Lawson, 2024), Flamanville 3 in France (World Nuclear News, 2024), and Olkiluoto 3 in Finland (World Nuclear Association, 2024b), have seen large cost overruns and delays. For instance, an audit of the Flamanville 3 project by the French National Audit Office concluded that the electricity cost from Flamanville 3 will be around 176 €/MWh (French Court of Auditors, 2025) which can be compared to the levelized cost of energy (LCOE) for nuclear power of 40–180 €/MWh, as given by the IEA (IEA, 2022). There have also been further delays to the project after this audit. In addition, Sweden last completed a nuclear reactor construction project in 1985, which happened under a vertically regulated electricity market.

On the regulatory side, the installation of new nuclear power could also face long lead times and a lack of administrative experience. It should be mentioned that the siting of new nuclear power will also require municipal approval, since in practice municipalities also have a planning monopoly for nuclear power.

3.2.2.3. Enabling conditions for expansion. A key enabling condition is to limit risk for investors and operators. A number of financial models for nuclear power have been developed and applied in recent years to facilitate investment, combining a long-term power purchase contract, to reduce revenue risk, and a means to cap investor exposure, for example through loan guarantees. For example, in the UK, a contract for difference mechanism was established to incentivize investments in low-carbon electricity infrastructure, which unlocked investments in new nuclear power expansion (UK Department for Energy Security and Net Zero, 2016; Watson and Boston, 2024). In the Czech Republic, where a strong increase in nuclear capacity is part of the country's long-term energy strategy, low-interest state loans are guaranteed (World Nuclear Association, 2025). In Finland, a collaboration between industrial and utility companies has allowed for the development of new nuclear capacity (World Nuclear Association, 2024b).

To ensure long-term governmental commitment to a nuclear power program, political stability is critical. This could be secured through a cross-party energy agreement or a similar instrument that recognizes multi-partisanship in sustaining the conditions for nuclear power development. In Denmark, a cross-party energy agreement was established and implemented between 2020 and 2024 for the development of renewable energy, especially wind power (Government of Denmark, 2018). If nuclear power is to be expanded, similar arrangements must be in place.

While standards for reactor design and licenses are not harmonized globally (Bredimas and Nuttall, 2008), there have been some proposals regarding a regulatory framework to license new nuclear reactors (Swedish Radiation Safety Authority, 2023). To streamline the licensing process, further refinement of such a plan, which anchors safety and environmental concerns, must be made.

3.2.3. Flexibility measures

3.2.3.1. Context. While the share of wind and solar power increases and new loads are introduced from the electrification of industry and transport, the flexibility measures applied in Sweden are still mainly limited to supply-side flexibility in terms of hydropower and gas turbines, stationary batteries for ancillary service provision, and tank heat storage units for district heating.

Sweden's basic industries have significant potential to use hydrogen (Svenska Kraftnät, 2024b), which could be produced from water using electricity and offer flexibility through hydrogen storage systems. Similarly, there are extensive district heating systems in Sweden which could offer flexibility through power-to-heat and heat storages.

Flexibility is mainly procured by transmission and distribution operators. When balancing resources fall short, Swedish Transmission System Operator (TSO) *Svenska Kraftnät* (SvK) activates strategic power reserves, including 20 gas turbines across 10 sites, which can respond within 15 min (Svenska Kraftnät, 2024c). On the DSO level, different solutions to incentivize investments in and utilization of flexibility have been implemented, and these have gradually incorporated niche innovations into the regime.

To enable demand-side flexibility trade and reduce local congestion, several local flexibility markets have been introduced as pilot projects in Sweden, the biggest of which are Sthlmflex and CoordiNet (Palm et al., 2023; Power Circle, 2022). Following these pilot projects, two local flexibility markets have been established (E.E.ON Energy Distribution, 2025; NODES Market Platform, 2024). These markets create incentives for new participants, such as aggregators and forecasting service providers, while also broadening the roles of traditional operators and consumers by transforming them into providers of flexibility and purchasers of electricity (Power Circle, 2022).

3.2.3.2. Challenges to implementation. Ancillary service and local flexibility markets currently offer the strongest economic incentives for flexibility. These markets act as niches where aggregators can establish themselves and use digital platforms to efficiently collect and manage distributed flexibility sources. However, the broad implementation of flexibility services has not broken through into the regime. The regulatory framework to facilitate and support such services is still missing.

The electricity system in Northern Europe operates under an energy-only market, where price volatility reflects the growing share of wind and solar generation. While the price volatility feature could stimulate investments in flexibility, it raises concerns as to the socially acceptable level of such variations as the share of variable production of electricity increases (Mays, 2021). If investments in flexibility do not go hand in hand with investments in new generating capacity and increased demand, there is a risk that electricity price peaks will occur more often and be more severe than what is considered appropriate by different actors.

Compared to the stable pricing of ancillary services, which are procured on more-long-term contracts, volatile energy prices offer weak investment signals for flexibility investment (Mays, 2021). This is a hindrance for emerging storage technologies such as electrolyzers and line-rock cavern projects, which lack clear niche applications to bridge the gap to large-scale implementation. Meanwhile, small-scale flexibility uptake is hindered by the lack of a market for standardized load control equipment (Swedish Energy Markets Inspectorate, 2017) and a narrow legal definition of flexibility (Ruwaida et al., 2023).

3.2.3.3. Enabling conditions for further implementation. To enable different types of flexibility in the electricity market without hindering long-term investment, one option would be to expand the power reserve and local flexibility markets to cover different patterns of variability in future systems (Hirth and Ziegenhagen, 2015). The incorporation of demand-side resources would require grid operators to adopt different standards for determining resources that qualify for flexibility payments and that are attuned to the specific flexibility characteristics of such resources (Mays, 2021). Furthermore, since the appropriate level of volatility could vary significantly between different actors, it is necessary to couple volatility exposure with protective measures for vulnerable social groups, as in the EU's Social Climate Fund, which aims to cover renewable energy integration and storage among other measures (European Commission n.d.).

To enable flexible hydrogen production a reduction in cost for electrolyzers is needed, which could be achieved by scaling up the production of electrolysers (IRENA, 2020). In addition to the economies of scale, the performance of electrolyzers could be enhanced through the optimization of plant design, stack design, and efficiency improvements (IRENA, 2020). This requires a holistic approach to the entire value chain of the emerging renewable hydrogen economy (IRENA n.d.).

To incentivize flexible consumption practices and flexibility of trade from small-scale resources, standardization and large-scale implementation of load control equipment must be advanced to deliver real-time data that can be applied in developed control algorithms, for example, by aggregators. The entry barrier could also be lowered, with higher levels of engagement between the grid operators, aggregators and flexibility service providers (Ruwaida et al., 2023).

3.2.4. Ancillary services of the power grid

3.2.4.1. Context. As more electricity is generated from wind and solar power, connected via converters with different electrical properties, new ancillary services are needed to maintain grid stability. Frequency control strategies are shared across the Nordic synchronous system and frequency control, therefore, relies on market-based services where companies provide balancing support. In contrast, voltage control is local and regulated through grid codes, which set rules as to how power plants must handle reactive power. Thus, a shift from less synchronous generation to more converter-connected generation implies redefining products for frequency control as well as the updating of grid codes.

Most converters today follow the grid's frequency and voltage and adjust accordingly. However, in areas with high shares of wind and solar power or weaker grid connections, converters may need to have the capability to control the frequency and voltage. Such "grid-forming" converters have been introduced in recent years, although most converters still rely on the traditional "grid-following" approach on the regime level (Musca et al., 2022).

In terms of frequency, SvK has standardized the procurement of a variety of frequency products with different time horizons to accommodate balancing the needs within the country (Svenska Kraftnät, 2024c). On a regional level, to improve the level of coordination as the renewable energy share grows, the four Nordic TSOs (SvK, Energinet, Fingrid and Statnett) are integrating their balancing market into a single Nordic Balancing Model (Nordic Balancing Model n.d.). SvK is responsible for securing 35 % of the fast frequency reserve needed in the Nordic countries and stationary batteries have emerged as the leading source of this service (Energinet et al., 2023; Svenska Kraftnät, 2025). Similarly, most energy storage projects in the Nordic countries currently focus on frequency regulation, largely though Li-ion batteries (Svenska Kraftnät, 2024b).

Unlike frequency control, voltage control is local and there are few possible providers of voltage control at specific locations where it is needed. Voltage control is built into grid codes, requiring both thermal power plants and converter-based wind and solar power to help maintain stability. Wind and solar power have been capable of supporting voltage control for over a decade (Energinet et al., 2023). However, grid code requirements for voltage control provision vary between TSOs in the Nordic countries, with lower requirements in Sweden than in neighboring countries.

3.2.4.2. Challenges to implementation. The establishment of FFR instruments (Svenska Kraftnät, 2024c) and the development of grid-forming converters (Energinet et al., 2023) indicate that what is needed for regime change is available at the niche level, and that the landscape around these technologies is about to be formed. However, the experience of adjusting the operations of the power grid on a national level to accommodate a high share of variable electricity generation remains limited. For example, large-scale testing of power grids where 80 %–100 % of the load is supplied by converter-based generation is still lacking, and a grid-forming concept is absent from the national grid code system (Musca et al., 2022). This creates a disparity between the current mode of operation and the requirement of future systems to ensure continued stability and reliability. Meanwhile, on the distribution grid level, DSOs are tightly regulated to protect customers and limit the levels of grid fees (Johansson et al., 2020), which undermines their role in managing voltage control locally. Moreover, Sweden currently lacks long-term strategies for grid operations under conditions of high shares of variable electricity generation.

3.2.4.3. Enabling conditions for further implementation. To resolve the operational disparity, the development of both flexibility and ancillary services necessitates more-active roles for DSOs in the management of two-way power flows at the local level, e.g., in peak-load management, procurement of voltage support, and investment in smart grids or distributed energy solutions (Flammini et al., 2019; IRENA, 2019).

To advance large-scale testing of the grid behavior during mainly converter-based generation, pilot tests in which multiple grid-forming converters interact are needed, in order to close the gap between research and real-life operations (Musca et al., 2022). Furthermore, Sweden could learn from the examples in other countries in terms of setting a long-term plan as to which grid features are required to meet an increasing share of converter-based electricity generation. For example, Germany has set out a plan with a detailed timeline that addresses the steps that need to be taken to achieve a high share of wind and solar power in the production mix by 2030. The plan includes large-scale testing, as well as updates of grid codes and new ancillary service products. It also addresses the issue as to which actor is responsible for the changes that need to be made (German Federal Ministry for Economic and Climate Action Affairs, 2023)

3.3. *An integrated analysis of transition bottlenecks*

Following the techno-economic and socio-technical analysis, in this section we present the identified transition bottlenecks based on the gap between the current regime setup and conditions which would be needed to operate the modeled systems. A summary of the niche and landscape factors that could leverage these bottlenecks for the main technologies in the three modeled cases and on a system level is provided in Table 3 and Sections 3.3.1 and 3.3.2. Here, we also highlight the criticality of addressing these bottlenecks, presuming that the more capacity that needs to be built per technology, the more critical it is to address the bottlenecks.

3.3.1. *Transition bottlenecks for individual technologies*

3.3.1.1. Wind power. Despite the increase in onshore wind power production, further expansion suffers from key bottlenecks, such as procedural uncertainty in the permit-granting process and the absence of local incentives to stimulate acceptance. For offshore wind, which is in the early growth, conflicts between governmental actors and the lack of financial support also form a bottleneck in the transition.

All three modeled cases show a need for expansion of wind power, albeit to varying extents, highlighting the criticality of this transition bottleneck to electrification in Sweden. To remove the bottlenecks to onshore wind power would be most critical for the cost-optimal case where the level of onshore wind power is the highest, but highly relevant to the other two cases. For offshore wind, the bottlenecks are the strongest in 22 GW offshore wind case, followed by the cost-optimal case, while the 9 GW nuclear case has no investment. The results highlight the needed landscape push to resolve conflicts of interest, increase clarity in the permitting process and systematize economic support for offshore wind power.

3.3.1.2. Nuclear power. Nuclear power development in Sweden, while receiving a high level of support from the government during the period of 2021–2025, carries heavy political weight and economic uncertainty. The key bottlenecks here lie in the absence of financial support, the challenges of sustaining political support, and procedural uncertainty. Although in the modeling we apply a lower cost of investment for nuclear power than those listed by the IEA, our modeling shows that the cost-optimal case is without nuclear power. Thus, the bottlenecks for nuclear power are only present in the 9 GW nuclear case.

It can be foreseen that a large expansion of nuclear power capacity will require the development of financial support schemes, such as those in Finland, the UK, the Czech Republic, alongside political stability and regulatory learning. This necessitates largely landscape pressures that could sustain support for nuclear power beyond economic motivations.

3.3.1.3. Flexibility measures. There are many flexibility resources in the electricity regime of Sweden that remain unlocked. The main transition bottlenecks to do this pertain to an overall undervaluation of flexibility

Table 3
Transition bottlenecks identified per key technologies in the Swedish electricity regime. The criticality of addressing transition bottlenecks for each modeled case is shaded based on new capacity needed compared to the other two cases (Light blue: low criticality, blue: medium criticality, dark blue: high criticality).

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

measures on both large-scale and small-scale flexibility resources. This includes the lack of coordination between system operators at different voltage levels, the lack of measures to increase protection against price volatility to ensure long term acceptance of the energy-only market, the lack of niche application of electrolyzers, and the lack of investment support for flexibility.

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

On a landscape level, the current energy-only market, together with an extended power reserve, could create a cost-efficient combination of flexibility measures. However, policymakers should consider how different approaches may impact investment signals for flexible resources, such as the ability of energy prices to reflect the value of flexibility (Prakash et al., 2023) and the price-smoothing effect with flexibility installations on a large scale which lower revenues (Loschan et al., 2024). It is also important to time flexibility entering the market with renewable expansion to avoid high price variations. Measures to reduce risks with long-term investment in flexibility for energy-intensive industries are also needed, such as with power purchase agreements and long-term contracts.

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

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

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

There are several niche factors that support the adjustments of frequency control and voltage control of the power grid needed to meet a high level of converter-based electricity generation. In addition, the lack of large-scale converter-based experimentation will be a growing bottleneck if left unaddressed. As other countries and technology developers take the lead, grid codes and ancillary service markets have begun adapting to accommodate systems with a higher share of converter-based generation, though further changes will still be necessary. As Sweden has not yet set out a plan as to how to implement these changes, such as that presented by Germany, Sweden may experience a delay in advancing its electrification targets.

3.3.2. Transition bottlenecks for each modeled future

Considering bottlenecks for each technology, different patterns of the regime shifts required for the three modeling cases can also be observed if they are to be realized.

In the cost-optimal case, while the total system cost is economically favorable, a large capacity of onshore wind power and flexibility measures need to be deployed and the ancillary service infrastructure updated. This is currently hindered by the absence of measures to enhance municipal benefits linked to hosting wind power infrastructure and a detailed plan for changes in markets and grid codes to 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 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 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 siting in the sea, 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 9 GW nuclear power case.

4. Discussion

Our analysis shows that, despite significant differences in supply mix, the three cases investigated share several key transition bottlenecks. The existing momentum is thus not sufficient to enable a regime shift in which deep emissions cuts from electrification of industry can be realized. While the current electricity system regime is largely fossil-free, it remains unclear as to how the transition process will unfold to meet the climate targets with increasing electricity demand. The regime shift will be distinct for each modeled future, although deeper changes can be envisaged for the cost-optimal case and the 22 GW offshore wind case. By identifying critical transition bottlenecks across scenarios, our findings contribute to the literature on socio-technical transitions and provide a basis for designing strategies that accelerate the transformation toward a sustainable and resilient energy system.

Across the three modeled cases, we show that transition bottlenecks are present in all future systems. The techno-economic analysis demonstrates that an increase in wind power installations from the current levels is cost-efficient in all cases. Results show that to facilitate the electrification of industry and transport requires continued investments in wind power in Sweden. This suggests that the transition, regardless of the pathways followed, will necessitate a system transformation from a high level of firm capacity to a system with large investments in variable capacity over the next decades, given the long lead time of nuclear power. The extent of change however will be most pronounced in the cost-optimal case and the 22 GW offshore wind case, compared to the 9 GW nuclear case.

Most transition bottlenecks occur on a landscape level across all key technologies, with regards to the lack of permitting fast-tracking, economic support, updated regulations with increasing renewable penetration, and a stable political environment. Niche factors affect transition bottlenecks for flexibility measures in stimulating small-scale distributed flexibility resources, while stronger niche-regime interactions are necessary for large-scale experimentation of converters considering the ancillary service of the power grid.

Compared to (Geels et al., 2020), who proposed the concept of transition bottleneck, the distinction of technological substitution and broader system transformation based on previous work on transition typologies (Geels and Schot, 2007; Smith et al., 2005) can be translated to a higher share of thermal versus variable electricity generation, respectively, in ESOM. In our study, we did not define how electricity system futures could look like in advance but use insights from both ESOM and MLP to juxtapose each future case with today's context and identify the resulting transition bottlenecks. This is closer to the analytical framework presented in (Savvidou and Nykvist, 2020), who look into the Swedish heating system and to the work by (Nilsson et al., 2020), who also add a local action analysis. Our approach allows us to articulate the tension between long-term climate targets and near-term concerns in deriving transition bottlenecks. While it is limited in actor representation, which could collectively generate different future pathways if included (de Bruijn and Herder, 2009; Grünewald et al., 2012), the study closely follows the political debate in Sweden, where electricity futures are actively discussed vis-à-vis the role of nuclear (Kan et al., 2020; Sonnsjö, 2024) and wind power (Bjärstig et al., 2022; Niskanen et al., 2024), as well as flexibility markets (Palm et al., 2023). In addition, we find it useful to develop two non-optimal cases where nuclear power, which was established in a regulated market, and offshore wind power, which is currently nascent in development in Sweden, alternatively take the lead in the model setup, in comparing cost and technology mix. These outputs then provide the basis for identifying the bottlenecks given a development in any of these directions.

Moreover, we also measure the criticality of the bottlenecks based on how much capacity or investment is needed, which gives an indication of different feasibility levels. However, the measures required to overcome the identified bottlenecks for the respective case vary in nature, prohibiting an objective ranking.

The combination of ESOM and MLP approach in our study allows the modeling results to be interpreted in a socio-technical context (Table 3) as well as to bring to light the bottlenecks of technologies of significant shares across the modeled cases. Bridging as an integration technique is meaningful in the exchange of shared concepts between techno-economic and socio-technical analyses, while maintaining the distinct insights of each research strand in parallel. The study thus contributes to a growing literature that aims to cross over insights from both socio-technical transitions and quantitative system modeling (Fortes et al., 2015; Geels et al., 2016; Turnheim et al., 2015; Venturini et al., 2019).

There are different possibilities to further develop the bridging strategy used in the study. This could be done, for example, in the scenario creation stage with stakeholder involvement, where the socio-technical analysis could be utilized to define potential transition pathways, taking stock of existing work (Foxon et al., 2013; Geels et al., 2020), or transformative policy mix, as done in (Rogge et al., 2020). In addition, the qualitative feedback from a socio-technical analysis could be translated to a modeling formulation that would allow consideration of the feasibility of the current regime in the modeled cases (Fortes et al., 2015; Venturini et al., 2019). Finally, while we consider the criticality of the bottlenecks as a function of the deployment levels in the modeled cases, the extent of change, the difficulty of making changes, and the available knowledge vary greatly across different technologies and development stages.

Overall, the study draws attention to the impact of path dependency and context sensitivity to the energy transition, via an integrated analysis of transition bottlenecks in the Swedish electricity system. To address the transition bottlenecks on the landscape level, state agencies and local planners will likely have to diversify their roles and responsibilities to accommodate the foreseeable technological and operational changes, such as those in the permitting and licensing procedures. On the niche level, the emergence of new actors, such as those involved in the provision of flexibility and grid-forming converters, has been supported by incumbent actors to a certain extent. This suggests that the transition requires not only niche and regime interactions, but also with substantial pressure at the landscape level, such as with the pronouncement of EU-wide support for renewable hydrogen economy such as with electrolyzer investment takeoff. The findings can also be relevant for the low-carbon energy transition in other countries that are decarbonizing the electricity system with expected rising demand and experiencing the polarization between nuclear and wind power (Sovacool et al., 2020; Verbruggen, 2008).

5. Conclusions

A mixed-methods approach combining energy system optimization modeling and multi-level perspectives is applied to analyze transition bottlenecks to investigate future electricity systems in Sweden subject to electrification of the industry and transport sectors. Three techno-economic cases are investigated; one in which the demand for electricity is met to the lowest cost to society resulting in a high share of onshore wind power, one with economic support for nuclear power and one with economic support for offshore wind power.

Results show that the transition to all three future electricity systems is subject to bottlenecks and that these bottlenecks mainly arise on landscape level. Key technologies deployed in the cases are either relatively mature, or niches exist but adaptations of rules and regulations enabling the new technologies to contribute to the Swedish electricity system is lagging. Interactions between niche and regime levels are needed for emerging technologies such as electrolyzers and grid-forming converters to be established.

Furthermore, results show that even though bottlenecks for all electrification cases exist, they vary in nature and which actors are involved. The two wind power dominated systems require a transformative change in terms of electricity system operation for which the system operators play a central role. The new nuclear dominated system instead requires changes in market structure which need to be led by governmental actors. Both a change to the system operation and the market will change the conditions for the technologies in electricity system.

All three cases also impact society and face social acceptance issues, but the decision to accept the impacts or not are taken at different levels. The nuclear system comes with higher cost to society and the decision whether to accept this is taken by the state while the wind dominated systems come with higher local impact and the decision whether to accept this is taken by the municipalities. While the state represents both those benefiting and suffering, consequences of the decision the local municipalities mainly represent those facing consequences and it is clear that some of the benefits of accepting wind power needs to be returned to these municipalities to alleviate this bottleneck.

Statement on the use of AI

In the preparation of this manuscript, the authors used artificial intelligence tools, specifically generative pre-trained transformer (GPT) large language model, to support aspects of the writing process regarding grammar and language improvement. The use of AI did not replace any scholarly analysis, interpretation, or original contributions of this work, and the authors take full responsibility for all content.

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Lisa Göransson: Writing – review & editing, Supervision, Methodology, Conceptualization. **Nhu Anh Phan:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Filip Johnsson:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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