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Climate-friendly but socially rejected energy-transition pathways: the integration of techno-economic and socio-technical approaches in the Nordic-Baltic region

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Abstract

A framework to account for social acceptance in the modelling of energy-transition pathways is outlined. The geographical focus is on the Nordic-Baltic energy region and the technological focus is on onshore wind power and power transmission, which are considered key technologies in achieving carbon-neutral energy systems in northern Europe. We combine qualitative analysis of social acceptance with quantitative assessments of scenarios using techno-economic energy-system modelling. Key factors in and consequences of social acceptance are identified, especially environmental, health, and distributional factors, as well as costs for developers and society. The energy system analysis includes four scenarios illustrating the system effects and costs of low social acceptance. The results indicate that if low social acceptance were to restrict investments in onshore wind power, costlier solar photovoltaics and offshore wind power would step in. Greater social acceptance cost for onshore wind and transmission lines favours local solutions and a more balanced renewable energy mix. There are important distributional effects: no restrictions on transmission line investments benefit power producers while raising consumer prices in the Nordic-Baltic energy region, while very low social acceptance of onshore wind power would lead to 12% higher consumer costs. The results imply that socio-technical and political factors such as social acceptance may significantly affect transition pathway scenarios based on techno-economic variables alone. Therefore, the techno-economic, socio-technical and political layers of co-evolution of energy systems should be considered when analysing long-term energy transitions. It is important to link energy-system models with a consideration of the dynamics of socio-technical factors.

Key words: energy transition pathways; electricity transmission; energy-system modeling; onshore wind; social acceptance; socio-technical factors

1. Introduction

1.1 Background

The 2015 Paris Agreement [1] and the 2018 report of the Intergovernmental Panel on Climate Change [2] both call for the deep decarbonisation of energy systems by the middle of this century in order to limit climate change. The global temperature target of 1.5°C would in practice require carbon neutrality by around 2050 [2]. Globally this implies a major transition to clean energy, as 81% of primary energy demand is still based on fossil fuels (coal, oil and gas), which are used for generating power, heating (for homes and for industrial processes), and transport, all of which are essential for human welfare [3]. It is widely agreed that this energy transition will require a range of low-carbon technologies, as well as energy infrastructure such as power transmission lines, in order to be deployed at high speed and at scale [2–4].

The magnitude of the process of reducing emissions from the energy sector will turn the changes ahead into a major socio-economic transition, with large-scale impacts on the whole of society. For instance, existing institutions, regulations, business models and user behaviour, among other things, will need to change to achieve carbon neutrality [5]. Actually, many scenario and energy-modelling approaches overlook these aspects and focus mostly on the techno-economic optimization of the energy system by, for example, seeking solutions that minimize the costs of the energy systems under different limitations and assumptions [6–10]. For example, of the sixteen modelling studies (mainly European) of demand-side flexibility reviewed by [11], fourteen were technologically detailed optimization models for selecting technologies to minimize overall system costs while meeting the demand for energy. These traditional approaches often assume the existence of a decision-making system in which decisions are made based on economic rationale (e.g., cost minimization) and assuming full access to the information and knowledge that affect them [10,12–14]. However, the real world seldom works in such a perfect way, and nor will the energy transition [12].

To be able to describe the profound changes in energy systems that lie before us, we must therefore add two other systems or layers to the techno-economic layer, namely the socio-technical and the political layers [15]. The socio-technical perspective has been widely applied in studies of energy transitions [15–18]. It emphasizes the knowledge, practices and networks associated with energy technologies and innovation processes [15], as well as the institutions, incumbent industries, so-called niche actors, and communities involved. Socio-technical analyses of energy transitions also address issues of social justice and social acceptance (see below). Taking into account the system of political action, including the role of the state and international relations, is equally important [15], as it frames the problem and prioritizes the values and factors that shape the solutions, thus affecting the policies to be used in the energy transition [19]. For example, a neoliberal framing would focus on market logic and may favour the use of CO_2 taxes and least-cost solutions, whereas a post-market economy approach [20] emphasizing climate justice could invoke pathways based on stronger laws and enforcement, ecological debt or equity principles [21–23]. Therefore, the energy transition will be a result of the co-evolution of these three semi-autonomous interactive systems: techno-economic systems, socio-technical systems and systems of political action [15]. The co-evolution process as a whole will then provide reasons for adopting different pathways to the transition.

The Nordic-Baltic energy region, encompassing seven countries in northern Europe (Denmark, Estonia, Finland, Latvia, Lithuania, Norway and Sweden) that are all part of the northern European power market, the Nord Pool [24], provides an interesting case for studying deep decarbonisation. This is due not only to the positive political outlook for carbon neutrality in the Nordic countries [25], but also to the high technical standards achieved and the potential of alternatives to decarbonize the energy system [26–28]. For example, more than half of the electricity in Nord Pool originates from hydropower; Denmark produces half of its electricity from wind power, with Sweden also catching up in this area; and Sweden and Finland have high shares of nuclear power and bioenergy [26]. Moreover, the Nordic-Baltic region has well-developed cross-border power-transmission capacities, meaning that the capacities of all seven countries are already above the minimum target set by the European Commission for 2030, which is to have 15% of installed capacity for domestic electricity production, with countries like Denmark and Lithuania having transmission capacities above 40% and 70% respectively [29,30].

However, moving to a low-carbon (or zero-carbon) energy and electricity system would require large investments in renewables and possibly in additional power-transmission capacity, the electrification of energy systems, and increased energy storage [27]. Simultaneously, integration into and interconnections with the central European power system may need to be strengthened, which could affect electricity markets in the Nordic and Baltic countries [27]. However, there is a major gap in understanding the socio-technical and political dimensions of supplementing such techno-economic optimizations of the energy system [27,31].

1.2 Aim and research questions

The aim of this paper is to fill the above knowledge gap by analysing how socio-technical factors may affect transition pathways to a carbon-neutral energy system in the Nordic-Baltic energy region by 2050. The analysis is linked to the latest energy-system scenarios for deep decarbonisation in the region [27]. The focus here is on the power system and electricity, but there also is a link to other energy sectors through sectoral coupling in many of the deep-decarbonisation scenarios, particularly to heating, which dominates final energy use in these cold climates. Specifically, we consider the role of the social acceptance of energy technologies for transition pathways [7,32,33]. For this purpose, we develop a framework for the analysis, identifying important types of social acceptance that could, if left unnoticed, hamper the realization of the clean energy transition. We focus on the social acceptance of onshore wind power and electricity transmission lines and the potential effects on the pace, scale, and cost of deployment [8]. Both technologies play a key role in these scenarios, but they also cause considerable landscape modifications, among other impacts, they have distributional welfare effects, and their deployment has large potential impacts on the energy system in northern Europe.

Accordingly, three research questions are addressed in this paper: What are the factors and consequences of the social acceptance of energy technologies, specifically of onshore wind and electricity transmission lines? How does the social acceptance of onshore wind and transmission affect energy-system attributes in a scenario in which achieving carbon neutrality by 2050 heavily relies on these technologies? How does social acceptance affect distributional welfare across economic groups (consumers and producers) and geographical areas? Based on the outcomes of the analysis, we will then discuss the possible implications to the transition pathways toward a carbon-neutral energy system.

The paper is organized as follows. Section 2 reviews the literature on the social acceptance of energy technologies, specifically onshore wind power and transmission grids. Section 3 outlines the methodology, including the scenarios to be modelled, while section 4 presents the results of the modelling of energy scenarios for the Nordic-Baltic region. Section 5 discusses the implications for a carbon-neutral energy transition in the region. Section 6 concludes the paper.

2. Social acceptance of renewable energy technologies

2.1 The concept of social acceptance

The concept of the social acceptance of renewable energy (RE) technologies first emerged as an important issue in the early 1980s, especially in relation to wind power. Since then, wind power has been the focus of studies of the social acceptance of renewables more generally. Yet the issue is also relevant for other technologies that will be needed for the transition to a low-carbon energy system. Thus, the installation of different types of energy technology and infrastructure meets certain social acceptance issues ranging from obnoxious odours (biogas plants), health concerns related to electro-magnetic fields from overhead power lines, the noise from wind turbines, and landscape modifications caused by high-voltage transmission grids (lines and pylons), wind farms and solar photovoltaic (PV) modules [34–36]. It has also been demonstrated that, besides tangible concerns such as altered landscapes and impacts on health, the distributional effects of inadequate economic incentives, the lack of local ownership and alienating planning processes are central causes of local resistance to the deployment of RE technologies [37–40].

The study of the social acceptance of energy technology (or infrastructure) can be based on a conceptual framework with three dimensions [32,41]. *Market acceptance* concerns investors and project-developers, energy-suppliers, utilities and grid-owners, as well as energy consumers. Changes in electricity consumer costs and the distribution of producer revenues and other benefits can influence market acceptance. *Socio-political acceptance* involves potentially different opinions of the energy technology as acceptable and useful and the tone of the debate in the media, politics and national institutions. *Community acceptance* covers the opinions of those people living in the environment of specific energy projects, who must therefore bear most of the direct external impacts. Processes engaging local citizens in energy projects can contribute to community acceptance, while a lack of such processes contribute to local conflicts around such projects.

The three-dimensional framework has been developed further by Fournis and Fortin [33], who describe how the social acceptance (or 'social acceptability' in their parlour) of RE projects evolves through the interactions of three dimensions or levels: the micro-social level, which targets coordination, social interpretation, attitudes and perceptions in a local community context; the meso-political level, which addresses the multi-level governance of RE projects; and the macro-economic level, which is situated between the diverse national configurations and the globalization of economic development [33].

There are clear costs and other consequences associated with low social acceptance of RE projects, but they are difficult to quantify due to the complexity of social acceptance. Increased costs from low acceptance are partly incurred during planning and approval processes. Local people can file formal complaints to voice their concerns about the impacts of RE technologies, leading to delays and even the rejection of planned projects. Local media are also used to express concerns and influence approval decisions by local authorities, and in some cases physical threats and attacks have been reported, as illustrated by the conflicts around the Frøya wind park in Norway [42].

A study of barriers to RE deployment across Europe found evidence that non-economic barriers increase the costs of renewable electricity and reduce deployment [43]. The study identifies administrative costs related to inefficient planning and approval processes, and costs and lost revenues due to delays in deployment, as important themes [43].

Below we look more closely at the social acceptance of onshore wind and transmission lines and the costs and other consequences associated with low social acceptance.

2.2 Social acceptance of onshore wind power

In spite of the public's generally positive attitude towards RE, onshore wind-power projects have been met with growing opposition from local populations. Low acceptance has a negative impact on the development of wind power due to delays in project approval and the obstruction of ongoing projects [36,44,45]. This opposition can be observed throughout Europe, especially in countries where wind energy has experienced rapid expansion over the past decade [46], such as the United Kingdom [47], Wales [47–50], Germany and Denmark [39,51,52].

The nature of and factors behind the opposition are very case-specific [52] and depend on the economic, political and cultural context [46]. Denmark is illustrative of the multifaceted nature of the social acceptance of wind power. Comparing the social acceptance of wind projects in Denmark and Sweden, Devlin [51] associates Danish citizens' early support for wind energy with the scarcity of clean energy resources in the 1990s. Over the last decade, however, Denmark has experienced a decline in acceptance from local communities with the potential to host wind-power projects [39,40].

Impact on landscape and environment

Important factors for social acceptance are concerns about the visual impact [53–55], noise pollution and other environmental impacts, such as the impact on birds and other wildlife [53,56]. In Austria, for example, '…between 30 and 50 percent of wind projects cannot be realised due to environmental issues, mainly related to bird protection' [43].

Health concerns

Concerns about the health effects of wind turbine noise has been a recurrent and dominant issue in shaping the social acceptance of wind power. A recent study carried out by the Danish Cancer Society did not find any evidence for a connection between wind turbine noise and negative health effects [e.g. 57,58]. Negative publicity of the health effects from wind turbines may also affect life quality; yet it is probably not the wind turbines themselves that affect the quality of life, but rather a confirmation bias, that is, a cognitive phenomenon where people search for, interpret and prioritize information in ways that confirm their beliefs, which is created especially by social media [59]. This kind of impact from wind turbine noise can be understood from a psychological perspective focussing on mental functions, rather than a physical perspective that focuses on the functioning of the body [59].

Distributional effects

The mainstreaming of wind-power planning and the increased private economic interest in wind power seem to have been important factors in creating resistance to wind-power facilities in Danish communities [60]. Local resistance in this respect was found to be largely due to the hierarchical planning process itself [38,61], as well as to the unequally distributed benefits and burdens because of ownership structures, including the lack of local ownership of wind turbines and concerns about property losses [36]. Support for wind-power facilities was stronger in communities where these facilities had broad local ownership and the income from the facilities contributed to local value creation [61,62].

Danish Energy, the lobbying organisation for Danish energy companies, stresses that the early engagement of local communities is important to avoid long or failed planning processes for onshore wind power [63]. In 2017, wind projects with a total capacity of some 305 MW were stopped by municipal councils, sometimes very late in the planning process [63]. According to recent a survey [63], there is strong public support for the current Danish policy of decentralised decision-making regarding onshore and nearshore wind parks, underscoring the importance of efficient and inclusive planning frameworks and processes at the 'micro-social level'.

In many countries, wind power competes for space with other sectors in society, including transport, tourism, reindeer farming, communications and defence. We understand this as social acceptance at the 'meso-political level', a reference to the framework by Fournis and Fortin [33] outlined above. A report on non-economic barriers to RE deployment within the EU documents how the use of space for wind projects can conflict with transport, communication and defence infrastructure [43]. In Germany in 2015, 247 planned wind projects with a total capacity of 4.12 GW were blocked due to problems with both military and civil radar systems [43]. Distance requirements from weather radar systems and omnidirectional radio range systems were also important barriers in Germany [43]. In France in 2015 military considerations blocked 7 GW of wind projects. Concerns for air-traffic safety also block wind projects in many countries [43].

2.3 Social acceptance of transmission lines

While earlier fossil-fuel power plants were located near important load areas such as energy-intensive industries and major cities, the generation of renewable electricity will be much more dispersed and often far from consumption centres [64]. Hence, a large expansion of European domestic and cross-border transmission lines is needed in the coming decades to integrate renewable power plants physically into the rest of the system and thus increase flexibility [30,65], for example, from northern Germany to southern Germany and between Norway and other European countries. The investment costs of deploying the high-voltage grid infrastructure that meets European targets is expected to reach EUR 125 to 140 billion until 2030 and up to 420 billion until 2050 [30]. Of course, transition pathways relying on local self-sustained internal power balances would reduce the need for transmission grid expansion [66].

Yet, opposition to the construction of high voltage grids from populations has already been observed in many places. According to [64], the lack of public acceptance, together with an inappropriate regulatory framework, is the main barrier to network development. The literature points to several factors causing low social acceptance: landscape modification and visual impact, health concerns related to electromagnetic fields, and distribution of the costs and benefits associated with electricity transmission. We discuss each one in turn here.

Impact on landscape and environment

The main barrier to grid infrastructure is objections by local communities to having the line built in their vicinity [67]. According to Bertsch et al. [34] and Buijs et al. [68], the degree of landscape modification is the most important driver of the low local acceptance of transmission lines [34] due to their substantial size. The typical pylon used for the highest voltage of overhead transmission lines is 45 m high [69] and may need a clearance of up to 200m in width [70]. In Germany, where the *Energiewende* is accelerating grid development, the construction of the Wahle-Mecklarover overhead power line raised around 21,000 objections [71]. Several factors influence acceptance of the visual impact, such as the location of residential areas, tourism activities and the loss of value of private property [72,73]. Local populations and organisations also resist the building of transmission lines in national parks and natural areas [32,74].

The growing antagonism to these types of infrastructure is pushing project developers to hide the lines. Bertsch et al. [34] found greater public acceptance of underground cables compared to overhead power lines. Underground power cables also cause some landscape modifications [69]. These include sealing-end compounds, typically covering 1500 m^2, which are needed to connect them with overhead lines, and tree-less corridors in forested areas directly above the cable to prevent tree roots damaging the cables [34]. Local communities nevertheless prefer underground cables to overhead lines. In Denmark, 28% of the high-voltage transmission grid is buried [70] and a large part of the new connection to Germany in the southwest of the country was placed underground.

Using the seabed to lay cables can be an alternative to land-based overhead lines and can facilitate technical connections at the interconnection nodes for international lines. This is the case with the Cobra cable, which connects Denmark to the Netherlands by sea without passing through Germany. The acceptance of submarine power cables has been subject to much less research compared to that of land-based transmission lines. However, some studies identify possible risks, such as harm to the local fishing industry or to recreational fishing and boating [75,76]. An analysis of the Baltic Sea by Wójcik [77] illustrates well the many overlapping interests between different maritime activities that may cause opposition to the construction of submarine cables.

Health concerns

Emissions of electromagnetic fields (EMF) affect peoples' attitudes towards high-voltage power lines [69]. While the negative health effects of EMF exposure are scientifically disputed, a survey from 2010 showed that 70% of European citizens believed that their health had been affected by high-voltage power lines [69]. This has a critical impact on large pan-European transmission grid projects, where one third of the 32 European Priority Interconnection Plan (PIP) projects encountered local objections due to the perceived health risks of EMF [78]. High-voltage underground power cables also emit electromagnetic fields (but not electric fields, as do overhead lines), and these are stronger at short distances from the cable than those emitted by overhead lines [69]. DC lines also have better characteristics than AC lines when it comes to EMF due to their shielding [71]. They can therefore mitigate objections due to health factors in specific cases, for example, the connection of a distant single node such as a wind farm to the network.

Distributional effects

Because of its national strategic importance, the expansion of the transmission grid is often perceived as an expert-driven, top-down process with only limited possibilities for the local population to influence it [79]. Moreover, transmission lines and interconnectors create collective benefits (country- or region-wide) while the disadvantages are mainly felt locally, resulting in feelings of unfairness.

Disproportionate distributional effects are of two kinds. One relates to the perception (potential or proven) of local costs (e.g. reductions in property values, the deterioration of tourism activity etc.) and of serving collective welfare in a way that is often unclear and seems distant from local concerns. In spite of the payments made to the affected municipalities and landowners, a lack of acceptance is generated if the apportionment of costs and benefits is perceived as unfair. It is interesting to put this argument in a historical perspective. Authors such as Furby et al. [80] point out that, in a society free from blackouts, the advantages linked to electrification could no longer positively influence the attitudes of the population, who therefore focus on the less positive aspects of power infrastructure instead.

The second kind of effect is linked to the economics of electricity markets, where the development of interconnectors may undermine the situation of some stakeholders, as shown by the discussions over the cross-border line that will connect the United Kingdom to Norway. The increased transmission capacity for exports of renewable electricity from Norway to the United Kingdom has encountered opposition from the Norwegian power-intensive industry and from households who argue that the connection will increase domestic electricity prices and so threaten competitiveness and raise electricity bills [74]. The construction of the interconnector has also been criticized by British electricity producers, who fear a drop in market prices.

2.4 The consequences of low social acceptance

It is well documented that low social acceptance significantly affects the construction of new wind turbines and wind parks, causes delays in project approval and in some cases blocks ongoing projects [36,44,45]. Yet a comprehensive assessment of the costs to society and to developers associated with low social acceptance seems to be lacking.

The European Commission has estimated the costs of so-called ‘non-economic barriers’ for wind projects [43]. They found that on average such costs were a small part of the overall development costs at 1.5-4.5%, the main problems resulting from these barriers being project delays and potential failures [43]. Non-economic costs were incurred in all phases of project development: pre-audit, planning and obtaining permissions. The costs in the planning and approval phases were the largest and of similar magnitude. Delays in permitting wind projects not only increase costs, they can also lead to reduced revenues if remuneration is reduced over time [43]. Grid-access costs were generally higher than administrative costs [43]. There were large variations in costs between projects, countries and regions. In France, for example, the non-economic barriers accounted for around 15% of the overall project development costs [43]. This included ‘the effect of the constraints imposed by the military, the high number of appeals from wind power opponents, the cost burden resulting from the administrative procedures, and the delay for grid connection’ [43].

Low social acceptance has significant effects on the establishment of high-voltage transmission lines. According to Ciupuliga and Gibescu [81], compared to other factors, the most serious consequence of the lack of acceptance by local populations is delays in the planning and construction of grid projects. An illustrative example of how low acceptance can affect project development is the 1.4 GW underground power cable connecting France and Spain in the Pyrenees, which has increased the export capacity of RE from Spain [82]. Thirty-five years passed between the first planning steps and the project’s realization in 2015, of which seven years were spent in stakeholder dialogues [83]. The long delays put at risk the market targets to which policy-makers had committed themselves [83].

The lack of social acceptance can also affect the costs of grid projects in different ways. The costs are difficult to generalise as they depend on specific network architecture and land topologies. For example, Thomas et al. [71] estimated the costs associated with land use (payment to municipalities and property owners) in a 380kV overhead line project in a rural part of Germany at 4M€/km, or 5%

of the construction costs. Project rejection may result in more costly path profiles for the line, the burying of cables, or the use of more expensive technologies, as well as extra planning costs. According to the Energy Regulators Cooperation Agency [84], the burial of overhead lines could multiply project development costs by a factor of 4 to 8, with the financial benefits being the lower risks of project rejections and delays and lower compensation payments.

2.5 Reducing the costs of low social acceptance

What can key stakeholders such as utilities and policy-makers do to increase the social acceptance of energy technologies, which is so crucial for achieving a low-carbon energy system? For RE projects such as wind farms it is possible to include some kind of economic compensation. According to the Danish law on onshore windfarms, for example, local populations must be offered the opportunity to become partners in the project [85]. However, in many cases the shares are left unsold or are purchased by legal entities out side the local community [86]. Support for wind power is stronger in communities where wind turbines have broad local ownership and where the income from the facility contributes to local value creation [87].

The inclusion of local people in the planning process through co-creation or similar approaches seems crucial in obtaining their support [61]. Social acceptance may be enhanced through a comprehensive approach that includes education, information and knowledge about energy technologies [88], combined with minimal landscape modification, and which facilitates the co-production of energy and other types of value creation, such as crop-farming, animal husbandry and fisheries [34,89]. The concept of energy citizenship could be part of such an approach, as it can facilitate citizens' engagement in energy projects based on trust and notions of justice [37,90]. Along these same lines, it has been argued that community energy initiatives and shared ownership models could receive higher levels of public support [91].

High-voltage transmission lines are pivotal to a low-carbon energy transition, but they pose specific challenges for social acceptance. Achieving local acceptance is complicated by the fact that the technology itself does not create local value, making it difficult for local populations to benefit through value co-creation. Hence, studies across diverse contexts emphasise the need to engage local residents and other stakeholders in all stages of planning new transmission lines (and other energy infrastructure projects) in order to address stakeholder concerns and build up trust [35,83,92,93]. In this regard, Lienert et al. [69] compared local perceptions of overhead and underground transmission lines in Switzerland and found that providing information about impacts on health, landscape, the environment and property values reduced differences in the perception of the two technologies. Yet, even when consultations are held, stakeholders may consider them non-inclusive, as shown by cases in France, the United Kingdom and Norway [83,94], suggesting that local populations lack trust in project developers and institutions. New technologies such as superconducting transmission lines may support the greater acceptance of interconnectors, as they minimize the visual impact and lower the EMF due to their underground locations and the much smaller size of the grid components [71]. Finally, the transmission company can expropriate the necessary areas according to the law on projects of public interest such as infrastructure projects. Although the financial compensation of property owners may be obligatory, it is no guarantee of social acceptance.

3. Methodology

The present study builds on a review of articles from the social-science literature on sustainability transitions and energy systems, with a focus on the social acceptance of energy technologies and their possible effects on transition pathways. This material was identified through a search of key words, using search machines such as Google Scholar, ScienceDirect and DTU Findit. Furthermore, we searched websites and documents to identify recent events and non-academic reports on social acceptance and RE deployment in the Nordic and Baltic countries.

Table 1 outlines the analytical framework derived from the analysis of the specific factors in and consequences of social acceptance of energy technologies based on the literature review in section 2. For each type of social acceptance, it notes the expected effects on the energy system, especially regarding flexibility, and their implications for transition pathways. We also suggest how the factor may be handled in energy-system models. Here the framework is limited to considering onshore wind power and power transmission, the technologies that are the focus of this paper, but it can be expanded to cover other technologies prone to low social acceptance, such as solar photovoltaic parks, biogas plants and demand-response technologies (e.g. smart appliances).

Table 1. The implications of social acceptance for energy-system models and transition pathways.

Type of social acceptance	**How the factor can be handled in energy-system models**	**Expected effects on energy system**	**Expected effects on flexibility**	**Implications for transition pathways**
Acceptance of onshore wind power.	Higher cost of investment in onshore wind. Constraints on new onshore wind deployment. Delayed investments in onshore wind.	Higher system costs. Less wind power, more solar PV, more off-shore wind.	Less / slower take-up of power-to-x technologies.	Slower deployment. New business models. Local engagement. Innovation for 'acceptable' onshore wind parks.
Acceptance of power transmission.	Higher cost of investment in transmission capacity. Preference for cabled transmission technology. Constraints on new transmission capacity.	Higher system costs. More decentralised power production. Lower exports of electricity.	Increased need for other sources of flexibility within countries and regions.	Innovation in decentralised systems. Innovation in below-ground (cabled) transmission technologies.

3.1 Energy-system modelling in Balmorel

General model design and assumptions

We perform energy modelling using Balmorel, an open-source energy-system model programmed in the GAMS language [10]. Balmorel applies a bottom-up approach simulating electricity and district heat generation by partial equilibriums. The model does not include individual heating technologies, only district heating. In addition to technical equations, the model also makes it possible to include economic and regulatory constraints. The objective of the model is to find the least-cost solution that balances energy supply and demand. The model source code and data are available on GitHub [95] . This study adopts the model version developed by the Flex4RES project [96].

The period studied covers every decade from 2020 to 2050. The modelled time series includes seven weeks throughout a year, with 76 hours in each week. The modelled countries are the Nordics (excluding Iceland), the Baltics and neighbouring European countries (Belgium, Netherlands, France, Germany, Poland and the United Kingdom). In this analysis, most of our discussion focuses on the Nordic and Baltic sub-regions.

Assumptions about costs and the technical data of technologies, existing capacity and planned changes, energy demand, and fuel and emission prices are determined exogenously. Table 2 lists key price assumptions, the NETP 2016 project [31] being the main reference for fuel prices. For long-term CO_2 prices, we apply the prices from the Current Policy Scenario in the World Energy Outlook 2016 [85] with the 2020 price adjusted to the same level as in 2030. We assume constant annual energy demand throughout the modelling period. Unless otherwise stated in the scenarios, the model can invest in new generating and storage capacities from 2020. The investment decisions relate to predictions for the next decade.

Table 2. Assumptions regarding fuel and emission prices from 2016 to 2050.

	Fuel prices				Emission prices
	Coal	Lignite	Natural gas	Biomass	
Year	€/ MWh				€/ t CO_2
2020	8.3	2.7	20	22– 31	27
2030	9.6	3.7	30	30– 38	27
2040	9.9	3.6	33	37– 45	40
2050	10.1	3.5	37	39– 47	54

Transmission modelling

Countries in Balmorel are further modelled as regions to simulate power transmission. Regions in the Nordic and Baltic countries follow the classification of Nord Pool bidding areas [86]. Germany is divided into four regions, while the other countries are modelled as one region each. This study models the transmission grid in a simplified manner by depicting aggregated transmission capacities between regions. Existing lines are modelled using the flow-based approach, approximating to physical power flows by power-transfer distribution factors (PTDF) from real line capacities. New lines are simply modelled in terms of their net transfer capacities to avoid physical power-line constraints. The investment cost assumptions of new transmission capacities are in principle estimated from established projects, assuming a payback period of forty years with a 3.25% discount factor. Details of transmission modelling methodology and investment cost assumptions can be found in [97], and Table A1 also lists the costs of each new transmission link. All transmission lines have operation and maintenance costs of 0.1 EUR per MWh and an efficiency of 95.8%, plus a capacity rating of 90% to simulate potential power-line outages.

Scenarios accounting for socio-technical factors

This study assesses the influence of socio-technical factors, specifically the acceptance of onshore wind energy and transmission lines, which may significantly change the configuration of transition pathways to a carbon-neutral energy system by 2050. To investigate this in a quantitative framework, four scenarios were run in the Balmorel model to illustrate how variations in social acceptance might influence such pathways. The scenarios are defined by the assumptions about investments in onshore wind-power and high-voltage electricity transmission lines connecting regions and countries in northern Europe, as follows:

1. **HighHigh (BAU).** This scenario represents a 'business as usual' situation in which investments in new transmission lines or wind-power plants are generally socially accepted. Hence, we do not model any additional costs for new transmission lines or onshore wind-power investments in this scenario. Northern Sweden serves as an example of such a scenario, with many wind-power projects under construction. The BAU costs of new transmission lines and onshore wind power are found in Tables A1 and A2.
2. **LowWind.** The LowWind scenario represents a situation in which onshore wind-power expansion experiences low social acceptance, but transmission line investments are generally accepted. An additional social cost for wind power is thus added to the investment cost to account for measures for tackling low social acceptance, such as suboptimal turbine placement, expensive compensation schemes, or greater use of small-scale turbines. We could not identify an example of this scenario in the study region, as areas with low acceptance of onshore wind power often also experience resistance to new (overhead) transmission lines (see the LowLow scenario below).

3. **LowTransmission.** In this scenario, investments in transmission lines experience low social acceptance, but wind-power investments are generally accepted. An additional social cost for transmission lines is thus added to the investment cost. The Norwegian power-intensive industry illustrates this situation, opposing increased cross-border power transmission capacity due to the risk of increased power prices.
4. **LowLow.** The LowLow scenario represents a situation in which both onshore wind power and transmission lines experience low social acceptance. Additional costs are added to the investment costs to represent the social cost. Norway, Denmark and Germany serve as examples of this scenario, with loud public debates and opposition to infrastructure investments of this kind in recent years.

In those scenarios with additional social acceptance costs, we investigate three levels of a social cost factor that is multiplied by the techno-economic investment cost (Table A1 and A2) of onshore wind and transmission lines:

Medium (**M**): 1.25
Large (**L**): 1.5
Extra Large (**XL**): 2

The system attributes considered are: investment in generating capacity (generation mix), the power price, the consumption cost of electricity, and producer revenues. The distributional welfare effects are assessed in terms of electricity producer revenues and consumer costs. We report the indicators for different geographical regions, namely the Nordic and Baltic countries and, when relevant, other northern European countries (Belgium, Germany, the Netherlands, France, Poland and the United Kingdom) that are connected to the Nord Pool electricity market. The next section presents the results of these model runs.

4. The system-wide impacts of low social acceptance

Here we present the results of modelling the four scenarios, as described in the previous section. While the model was set at up to 2050, all the results refer to 2030, for which the findings are most profound.

4.1 Generating capacity investments

Nordics and Baltics

Figures 1a-1c display the modelled investments in 2030 for the Nordic and Baltic countries in LowWind (Figure 1a), LowTransmission (Figure 1b) and LowLow (Figure 1c) scenarios. The HighHigh (BAU) scenario, in relying exclusively on techno-economic parameters and ignoring the social costs, depicts a future Nordic energy system with high investments in onshore wind. The excellent wind resources are exploited for export to other northern European countries with less favourable wind conditions.

In the scenarios with restrictions on onshore wind power (LowLow and LowWind), we observe more investments in solar power, offshore wind and biomass-based combined heat and power (bio-CHP). Fossil-based technologies are not competitive and thus attract hardly any investments, even in the LowLow scenario. The modelled solar PV investments (small in scale, behind the meter) are relatively high in all scenarios. Note, however, that we assume no grid tariffs for this technology, meaning that consumers do not pay grid costs for using the electricity generated from small-scale PVs. This increases the competitiveness of solar PVs. In the scenario with lower transmission investments, LowTransmission, we observe lower investments in wind power, but also a slight increase in solar power. In all cases, higher social costs lead to changes in the mix of RE supply.

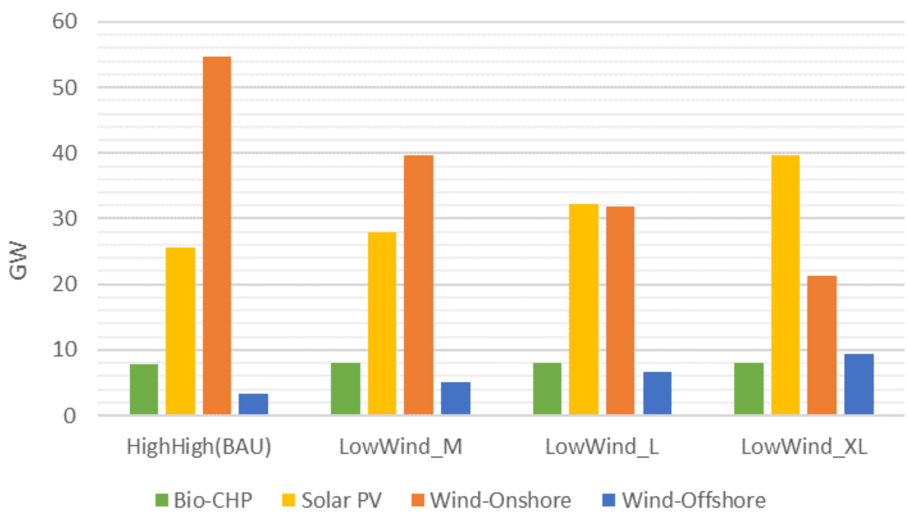

Figure 1a. Installed capacity of selected RE technologies (GW), Nordic and Baltic countries, in 2030 (LowWind vs. HighHigh).

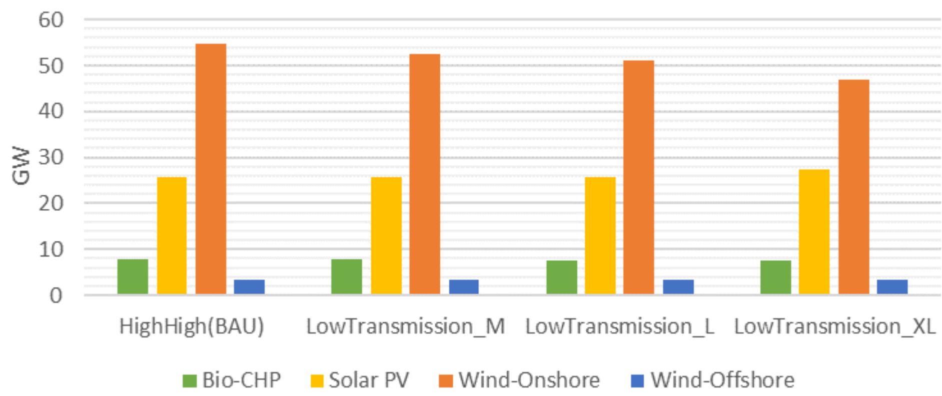

Figure 1b. Installed capacity of selected RE technologies (GW), Nordic and Baltic countries, in 2030 (LowTransmission vs. HighHigh).

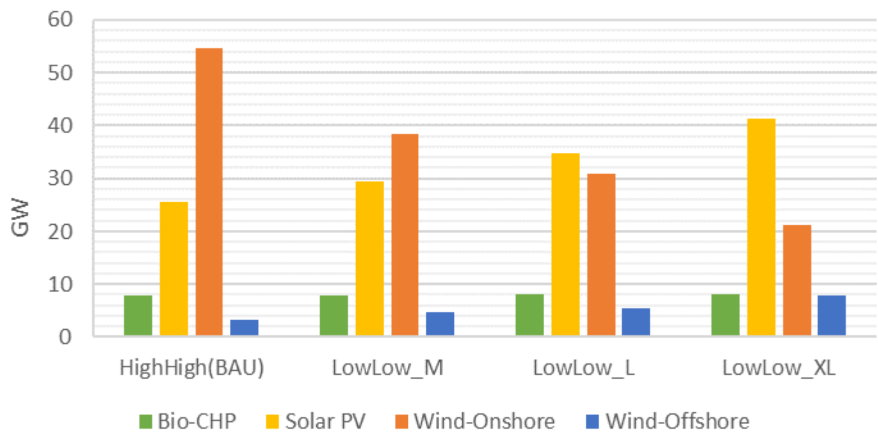

Figure 1c. Installed capacity of selected RE technologies (GW), Nordic and Baltic countries, in 2030 (LowLow vs. HighHigh).

All modelled countries

Figures 2a-2c display the modelled investments in 2030 for all modelled countries, while Table 3 presents the data underlying the three figures. The total installed onshore wind-power capacity is affected by increased social costs assumed for onshore wind in the Nordics and Baltics (LowWind and LowLow), but the effect is smaller for the whole model region, as some onshore wind investments are located further south in these scenarios.

Table 3. Installed capacity of selected RE technologies, all modelled countries, in 2030.

Scenarios	**Bio-CHP**	**Solar PV**	**Onshore Wind**	**Offshore Wind**
HighHigh(BAU)	18	294	234	56
LowWind_M	18	297	222	61
LowWind_L	18	301	215	64
LowWind_XL	18	309	205	68
LowTransmission_M	18	293	232	57
LowTransmission_L	18	292	231	57
LowTransmission_XL	18	291	227	59
LowLow_M	18	297	221	61
LowLow_L	18	302	215	63
LowLow_XL	18	309	205	67

As expected, offshore wind investments are higher in scenarios with a social cost for onshore wind investments in the Nordics and Baltics (LowWind and LowLow). The results for wind development between the scenarios are inverted for the other northern European countries compared to the Nordics and Baltics. This suggests two distinct effects of market prices on wind investment decisions in the south-west versus the north and the east. In the LowWind scenario, the increase in transmission capacities increases the average wholesale electricity price in the Nordic-Baltic region and creates new business opportunities for wind developers. In the south-west, however, the situation is the reverse, as here more transmission lines provide access to cheaper resources such as hydropower, lower the spot price and limit profitability for producers.

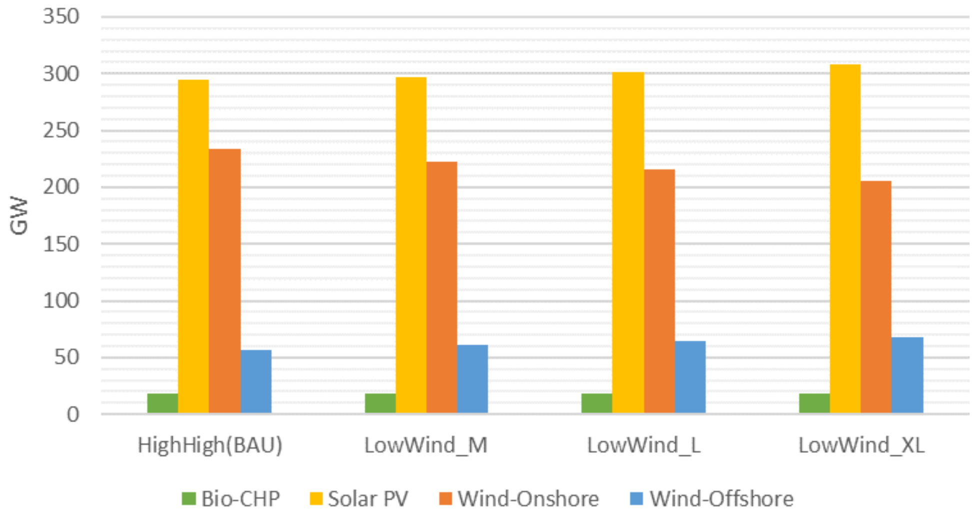

Figure 2a. Installed capacity of selected RE technologies, all modelled countries, in 2030 (LowWind vs. HighHigh).

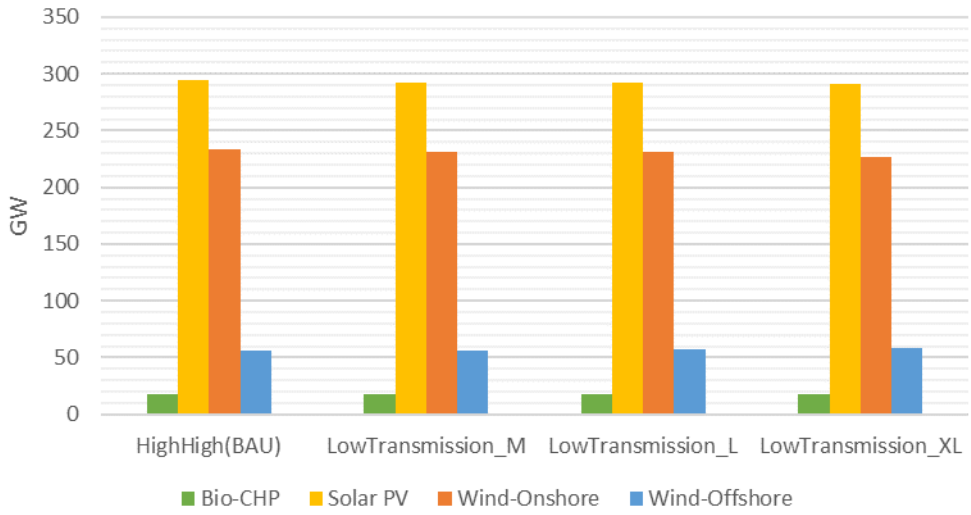

Figure 2b. Installed capacity of selected RE technologies (GW), all modelled countries, in 2030 (LowTransmission vs. HighHigh).

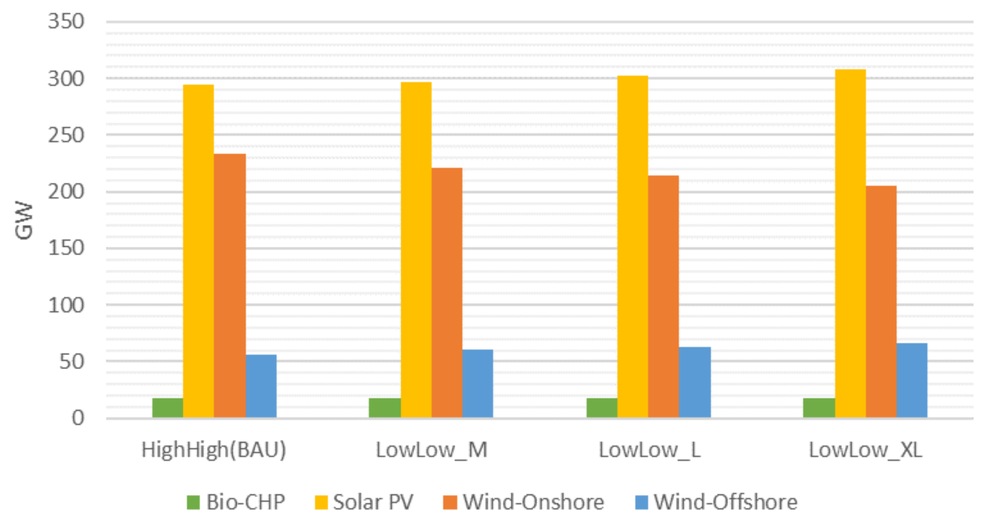

Figure 2c. Installed capacity of selected RE technologies (GW), all modelled countries, in 2030 (LowLow vs. HighHigh).

4.2 Power price impacts

Figure 3 illustrates how the increased investment costs of wind and/or transmission affect power prices in the Nordic and Baltic countries. The prices shown are annual simple average prices. In the case of low acceptance of onshore wind (LowWind), electricity prices are higher because there is less installed onshore wind, which has low long-term marginal costs. In the cases of low acceptance of transmission lines (LowTransmission), electricity prices can be kept low because the affordable hydropower is not shared with northern European countries, and the onshore wind also contributes to low prices. In the case of low acceptance of both technologies, limited onshore wind power leads to high electricity prices, while local hydropower counters the price increase slightly. Among the Nordic countries, Denmark stands out in having a quite similar price for all scenarios. The interpretation is that onshore wind development in Denmark is saturated compared to other Nordic and Baltic countries, which reduces the price impact from onshore wind. This is also a result of Denmark being geographically close to the European continent with a power market that is closely linked to both the other Nordic and Baltic countries and to northern Europe [29]. For northern European countries, prices are also quite similar for the different scenarios.

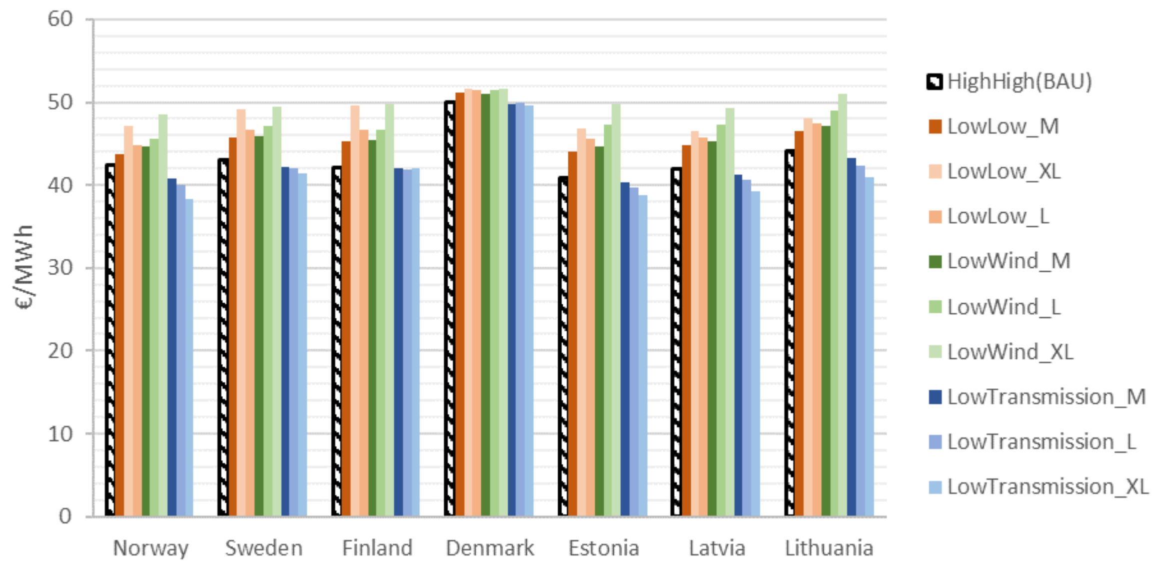

Figure 3. Modelled wholesale power prices (annual averages in €/MWh), Nordic and Baltic countries, in 2030 (all scenarios).

The relative changes in power prices from the HighHigh (BAU) scenario to the other scenarios are already substantial for some countries in 2030 (Figure 4). Restrictions on onshore wind (LowWind) increase prices in the Nordics (except Denmark) and Baltics, by as much as 18.2% in Finland and 21.7% in Estonia. In Denmark, Germany and the other northern European countries the price effect is small. Restrictions on transmission capacity (LowTransmission), conversely, lower prices significantly in the Nordics and Baltics (except in Denmark), while other northern European countries experience a slight increase in prices or none at all. It is also interesting to note that, when investments are opened up for both wind and transmission (HighHigh), power prices fall in the entire region, for example, by as much as 18% in Finland compared to the LowLow scenario.

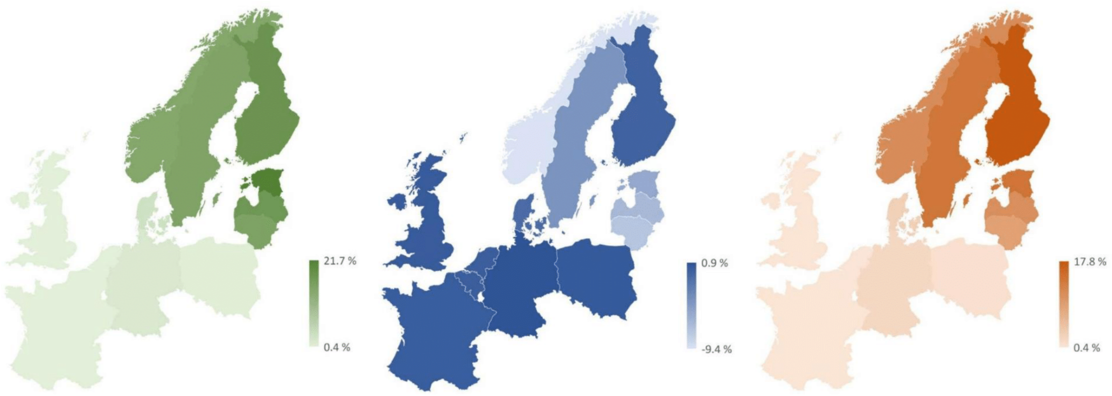

Figure 4. Changes in the modelled power price (annual averages in %), in 2030, in the LowLow_XL (red), LowWind_XL (green) and LowTransmission_XL (blue) scenarios compared to BAU.

4.3 Consumer costs and producer revenues

Nordics and Baltics

Figure 5 shows the relative change in consumer costs for each scenario when compared to the HighHigh (BAU) scenario for the Nordic-Baltic region. The consumer costs increase substantially with high social costs for wind and not for transmission (LowWind), as power prices rise with less wind power. The opposite effect, but weaker, is seen when we assume higher social costs for transmission lines (LowTransmission). Here, less energy is exchanged with continental Europe and the United Kingdom, which do not have the same access to low-cost RE. Assuming high social costs for both onshore wind power and transmission (LowLow), consumer costs increase, as the cost-driving effect from high wind-power costs here outweighs the cost reduction effect observed when only modelling social costs for transmission.

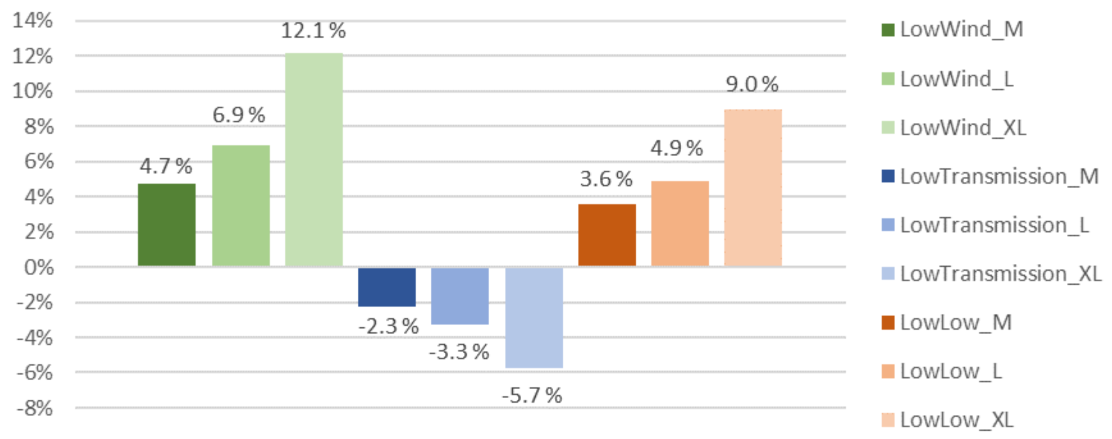

Figure 5. Consumer cost, Nordics and Baltics, 2030, relative change from the HighHigh (BAU) scenario (%).

Figure 6 displays the relative change in producer revenues for each scenario when compared to the HighHigh (BAU) scenario for the Nordic and Baltic region. Like consumer costs, producer revenues increase with higher social costs of wind power and decrease still more with higher social costs for transmission investments (LowTransmission). Contrary to consumer costs, in the LowLow scenario producer revenues are reduced when compared to BAU. This is because reduced producer revenues from the low transmission levels dominate compared to their increased revenues from low onshore wind levels (LowLow). Hence, the LowLow scenario is unfavourable for both consumers and producers in general.

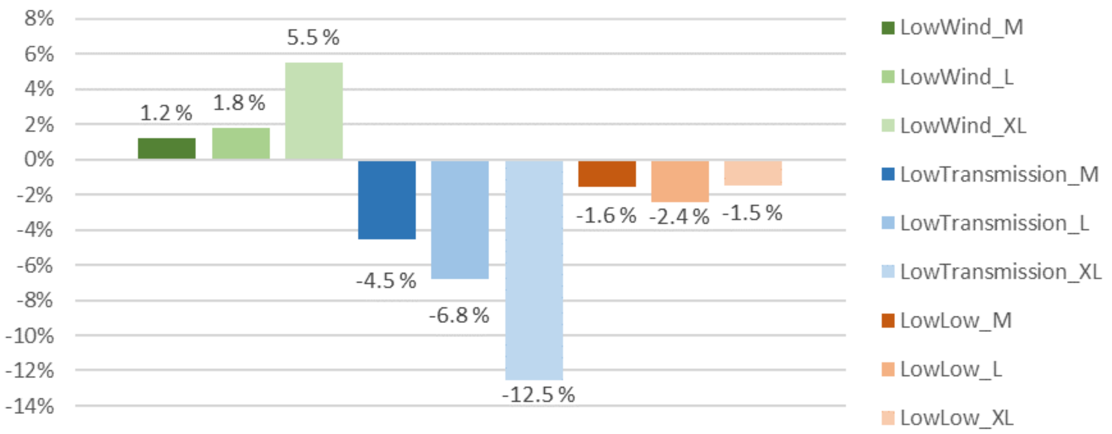

Figure 6. Producer revenue, Nordics and Baltics, 2030, relative change from the HighHigh (BAU) scenario (%).

Figure 7 gives more insights into how revenues for each generation technology are affected. A distinction can be made between new onshore wind generators, alternative investment options such as solar PV, offshore wind and natural gas, and existing generators such as nuclear, thermal power and hydropower. For the LowWind scenario, existing generators and alternative investments benefit from higher prices. For the LowTransmission scenario, existing generators and wind power experience lower benefits. In the LowLow scenario, alternative investments benefit, while onshore wind power is disadvantaged. Existing generators also benefit, but not as much as in LowWind, due to the lower benefits from transmission.

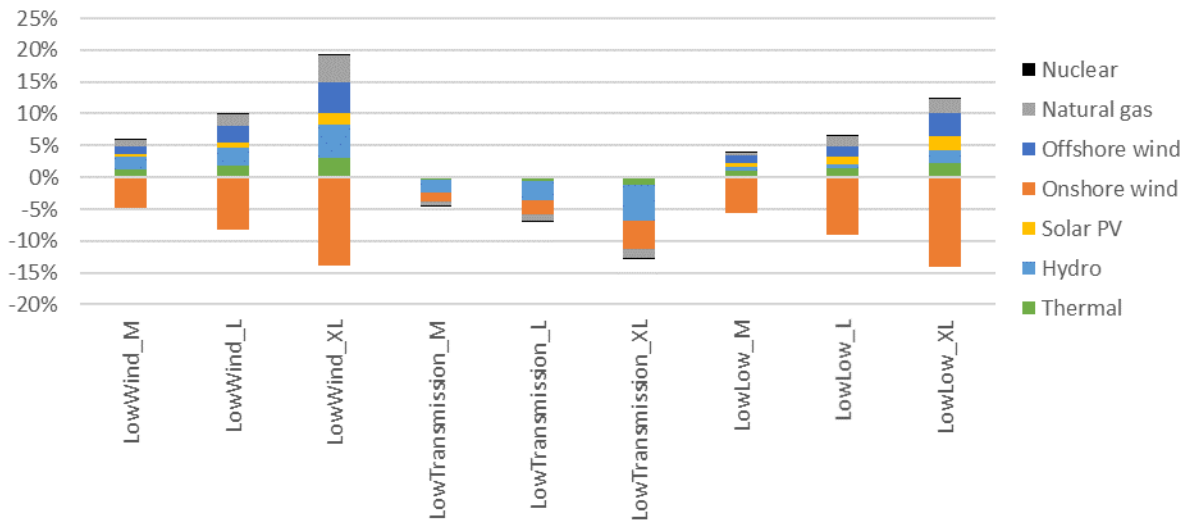

Figure 7. Producer revenue per generating technology, Nordics and Baltics, 2030, relative change from the HighHigh (BAU) scenario (%).

4.4 Summary of model results

The Balmorel model results confirm that the Nordic and Baltic countries have onshore wind resources capable of contributing significantly to the cost-efficient decarbonisation of the northern European energy system. In the cost-optimal model solution, using the techno-economic approach, the Nordic and Baltic countries will have installed roughly 55 GW of onshore wind power by 2030. If low social acceptance were to restrict onshore wind-power investments, as recently seen for example in Denmark and Norway, solar PV and offshore wind power would replace much of the investment in onshore wind, assuming moderate carbon prices. If we assume low carbon prices, gas power would take a large share of the investments.

Investments in more transmission and onshore wind would not only affect land use and the environment, it would also have diverse economic impacts on power market actors, highlighting the significance of the distributional effects. Overall, no restrictions on investments in transmission lines would benefit producers in the Nordics and Baltics, while consumers in the same region would have an economic incentive to oppose such expansions, as has recently been the case in Norway. Limited expansion of onshore wind would be beneficial for existing power generation and alternatives to onshore wind such as solar power and offshore wind, while an expansion of onshore wind would benefit consumers through lower electricity prices. Neither consumers nor producers in general would benefit from a scenario with high social costs for both onshore wind and transmission investments.

The modelling results also show that there is a trade-off between investments in onshore wind and transmission lines on the one hand, and the more expensive alternative of de-centralized solar PV and offshore wind on the other. Finally, we stress that the modelling results are based on many important assumptions. While the direction of the effects mentioned above is robust, their magnitudes may differ depending on these assumptions. We would need more nuanced analyses of the most important assumptions if we were to draw stronger conclusions regarding the magnitude of the effects.

5. Discussion

Several factors and specific circumstances affect the social acceptance of new energy installations such as wind turbines and transmission lines, analysed here. These factors are not static but interact at different levels of society and also vary spatiotemporally. This kind of complexity and contextuality implies that broad, flexible and inclusive approaches could be more successful in enabling a timely and affordable transition.

After a qualitative discussion of such issues, we simplified the analysis by modelling the systemic consequences of social acceptance for the Nordic-Baltic region. This exercise is mainly illustrative, as it relies on simple cost assumptions applied uniformly across the model region. The scenarios illustrate the kinds of effects that the low (compared to a least-cost solution) deployment of certain technologies can have at the system level. It suggests that, if investment decisions were driven by costs only – that is, by unrestricted conditions and least-cost solutions – project developers would install huge amounts of additional onshore wind in the Nordic and Baltic countries, meeting not only the demand for power in the region, but also supplying electricity to mainland Europe and the United Kingdom. This would involve additional investments in transmission capacity as well.

The simple assumptions on social acceptance included in our energy-system modelling approach cover only a fraction of the many factors influencing social acceptance that were discussed in earlier sections. In our four scenarios, we operationalized these factors by simple cost adders, which assumes that a lack of social acceptance can be directly translated into a cost figure. There are large differences between the cost estimates of different studies. The extra costs can reflect both project costs due to delays and the cost of coping with social acceptance through various measures. In addition to the challenge of representing the complexity of social acceptance in a meaningful way, there is also the problem of strongly varying impact within a large region as the Nordic-Baltic one. For example, onshore wind is strongly resisted in Denmark and Norway, but accepted in large parts of (northern) Sweden.

Further research could address such limitations through three main avenues. First, in-depth empirical research is needed to provide more accurate estimates of the social acceptance costs associated with different technologies, accounting for place-specific conditions. Second, energy models should be refined to be able to account in a realistic way for the systemic effects created by social acceptance and other socio-technical factors [12] in terms of choice of technology, costs and delays, quantitative restrictions, and how these factors vary across model regions. Third, energy modelling should take into account the dynamic information feedback loops that affect energy demand and investment decisions, and impact not only on regulations and policy, but also on environmental awareness within society [12]. Here optimisation models such as Balmorel have clear limitations; other modelling approaches, such as system dynamics modelling or agent-based modelling, could prove more promising if their limitations in, for example, technological detail and geographical coverage could be overcome [12].

These efforts should be followed by analyses identifying more sophisticated ways of responding to declining social acceptance and its expected impact. Here it is important to draw on both social-science research addressing the distributional, institutional, sociological and psychological aspects, e.g. [7,37,39,69,88,98], and studies of the impacts on health ([e.g. 99]) and environment (e.g. [56]). Such work would make important contributions to the broader research agenda on the synergies and trade-offs between greenhouse gas emissions reductions and the other sustainablility criteria that are involved in the low-carbon energy transition.

Revisiting the idea outlined in Section 1 that energy transitions result from the co-evolution of interactive systems [15], then our analysis of the social acceptance of selected energy technologies in the Nordic-Baltic context indicates that socio-technical and political factors may significantly affect energy-transition pathway scenarios based on techno-economic variables alone. Therefore, the techno-economic, socio-technical and political layers of the co-evolution of energy systems should be considered when analysing long-term energy transitions. One strategy for achieving such an integration, also applied in this paper, is to couple energy-system model scenarios with analyses of the dynamics created by socio-technical factors.

6. Conclusion

In this paper we have demonstrated the importance of the social acceptance of technologies for the energy transition, through both a literature review and energy-system modelling. In the energy system modelling part, we codified restrictions on the energy-system model in the form of simple cost adders with respect to two central technologies in the Nordic-Baltic energy region – onshore wind power and electricity transmission lines, which are likely to experience the highest barriers to social acceptance in the coming years. These barriers have important system-wide effects, notably distributional effects regarding electricity prices and revenues, effects on the installed capacity of different RE technologies and effects on the consumer costs of electricity. Though most of the impacts of low social acceptance described above may have turned out as expected, the magnitude of them, as well as their spatial spread, were not self-evident, which helps to assess the weight of the different consequences of social acceptance.

This analysis therefore well demonstrates the importance of considering the constraints arising from social acceptance and of measures to overcome them in energy-system modelling, policy and planning. The analyses add an important quantitative and systemic dimension to existing knowledge on social acceptance, which has mainly been qualitative in nature. Avenues for future research into the social acceptance of energy transition pathways have also been outlined.

Acknowledgements

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Table A1: Investment cost assumptions of new transmission lines (links) applied in the study (1000 Euro/MW)

	NO2	NO2	SE4	SE4	DK1	DK1	DK1	DK2	BE	BE	BE	BE	DE4-S	DE4-S	DE4-E	FR	NL
Link	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|
	DE4-N	UK	DE4-N	PL	NL	UK	DE4-N	DE4-N	DE4-S	FR	NL	UK	NL	FR	PL	UK	UK
k€/MW	1186	1215	725	862	843	1196	568	568	539	568	451	402	568	568	568	735	872

	NO1	NO2	NO3	NO4	NO4	NO4	SE1	SE3	SE3	SE3	SE3	SE4	SE4	FIN	EE	LV	LT
Link	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|
	SE3	DK1	SE2	SE1	SE2	FIN	FIN	FIN	DK1	EE	LV	LT	DK2	EE	LV	LT	PL
k€/MW	568	696	568	490	539	568	568	794	774	1000	1000	990	421	676	451	451	568

	NO1	NO1	NO1	NO2	NO3	NO3	SE1	SE2	SE3	DK1	DE4-E	DE4-E	DE4-E	DE4-W	DE4-W
Link	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|
	NO2	NO3	NO5	NO5	NO4	NO5	SE2	SE3	SE4	DK2	DE4-N	DE4-W	DE4-S	DE4-N	DE4-S
k€/MW	510	568	519	490	568	510	568	568	568	510	568	568	568	568	568

Table A2: Investment cost assumptions of wind turbines

Technology group	Standard size (MW)	Investment cost (MMoney/MW)(default value)	Annual operating and maintenance costs (kMoney/MW)(default value)	Variable operating and maintenance costs (Money/MWh)(default value)	Technology available for investments from this year	Economic lifetime (years)	Technology investment expires from this year
WINDTURBINE_OFFSHORE_FAR	8	2.2543881	43.414	3.234	2020	27	2029
WINDTURBINE_OFFSHORE_FAR	8	1.952953985	37.044	2.646	2030	30	2049
WINDTURBINE_OFFSHORE_FAR	8	1.674972678	31.458	2.156	2050	30	2050
WINDTURBINE_OFFSHORE_NEARSHORE	6	1.956143023	39.0726	2.9106	2020	27	2029
WINDTURBINE_OFFSHORE_NEARSHORE	6	1.713652137	33.3396	2.3814	2030	30	2049
WINDTURBINE_OFFSHORE_NEARSHORE	6	1.469910277	28.3122	1.9404	2050	30	2050
WINDTURBINE_ONSHORE	3	1.158736	23.422	2.45	2020	27	2029
WINDTURBINE_ONSHORE	3	1.066037	21.854	2.254	2030	30	2049
WINDTURBINE_ONSHORE	3	0.980754	20.776	2.058	2050	30	2050
WINDTURBINE_ONSHORE	0.025	4.4688	93.1	0	2020	20	2029
WINDTURBINE_ONSHORE	0.025	4.24536	88.2	0	2030	20	2049
WINDTURBINE_ONSHORE	0.025	4.033092	83.3	0	2050	20	2050