Flexible Nordic Energy Systems

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Flex4RES

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Summary Report

August 2019

Nordic Energy Research

Flex4RES project summary

The Flex4RES project investigated how an intensified interaction between coupled energy markets supported by coherent regulatory frameworks can facilitate the integration of high shares of variable renewable energy (VRE) into Nordic-Baltic energy systems ensuring stability, sustainability, and cost-efficiency.

Through a holistic system approach based on coupled energy markets, the potential costs and benefits of achieving flexibility in the Nordic-Baltic electricity market from the heat, gas and transport sectors, as well as through electricity transmission and generation were identified. Flex4RES developed and applied a multidisciplinary research strategy that combined the technical analysis of flexibility needs and potentials; the economic analysis of markets and regulatory frameworks; and the modelling of energy systems, which quantifies impacts.

Flex4RES identified transition pathways to sustainable Nordic energy systems through the development of coherent regulatory frameworks and market designs that facilitate market interactions which are optimal for the Nordic-Baltic conditions in an EU context. Flex4RES will comprehensively discuss and disseminate the recommended pathways and market designs for achieving a future sustainable Nordic-Baltic energy solution with a variety of stakeholders from government, industry and civil society.

WHY: To ensure that a future decarbonised energy system is possible, in line with climate concerns, national decarbonisation targets, and the UN SDGs.

HOW: By increasing flexibility to accommodate the needs of a decarbonised system with high shares of variable renewable energy.

WHAT: Identifying and assessing regulatory and technical pathways towards coherent Nordic energy systems.

More information regarding the Flex4Res project can be found at www.Flex4RES.org or by contacting project manager Klaus Skytte at klsk@dtu.dk

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Flex4RES summary report, August 2019

Flexible Nordic Energy Systems

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Act fast and Nordic while paving the way for carbon neutrality

The energy system must undergo a deep decarbonisation by the middle of this century to mitigate the climate change and meet the targets set in the Paris Climate Accord. The transition ahead, based on several international studies, will mainly rely on renewable and efficient energy solutions. **The Nordic region is well positioned to meet this challenge** through the already high share of hydropower and district heating, well-established efficient power markets and grids, and ambitious national climate targets and policies.

Our results indicate that **large-scale deployment of clean energy needs to take place in the 2020s to hit the unique window of opportunity** in the Nordics that leads to zero CO_2 emissions in 2050. The analyses conducted in the context of the Flex4RES-project unambiguously show that, within the next ten years, most of the key policies, market mechanisms, and regulatory frameworks need to be in place to enable optimal investments required for the energy transition.

The results of the Flex4RES project show **that the Nordic electricity and heat sectors could be carbon neutral as early as in the 2030s**, leading the way towards the decarbonisation of both the other sectors of the economy and the energy systems of other European countries expected to be completed by 2050. This is supported by sector-specific decarbonisation targets, the present technology mix, and, especially, the fast deployment of wind power in the Nordics.

When following a market-based and least-cost trajectory, the **best strategy leans on a major scaling-up of renewable energy, notably wind power, and increased electrification of other sectors**. Spatial integration through increased power transmission capacities, both within the Nordic region and with third countries, supports this strategy. In addition, the Nordics have a large potential to provide energy system flexibility through sector coupling (heat, gas & transport), which enables integration of large shares of variable renewable electricity into the energy system.

To realise these opportunities, however, major policy reforms are necessary. Two present barriers stand above all, namely insufficient market signals for some stakeholders and uneven frameworks for different renewable energy resources. As a priority, a level playing field is needed for all technologies, which requires elimination of too technology-specific policies. Dynamic tariff and tax structures are also necessary to strengthen new business models needed in the change.

Our central message is though a **call for stronger collaboration in the region**. As so many times before, when facing threats, Nordic cooperation could have a unique value for the Nordic countries when tackling climate change, the most severe challenge of our time. Our analysis shows that, by combining our efforts, we can be much more effective in finding solutions than if acting alone.

Flex4RES provides a blueprint for the way forward. We need to act fast.

Recommendations

The energy transition can be conducted in different ways, with different priorities leading to different solutions. The Flex4RES project contributes with a set of important observations, conclusions, and recommendations, which are summarised in this section. Flex4RES not only touches upon deep decarbonisation of the electricity sector, but also of district heating. Extending decarbonisation efforts to the heating sector is crucial, as heat represents the largest share of final energy demand in the Nordics as well as in the rest of Europe. The analyses also consider the transport sector through the electrification of vehicles.

A CO_2-free energy sector is possible, but Nordic countries need to act fast to decarbonise them

Flex4RES results unambiguously show that a CO_2-free, least-cost, and reliable energy sector can be attained in the Nordics. However, to reach such a challenging goal, the Nordic countries **need to act fast**. Postponing measures would require even steeper emissions cuts in the coming years and would also mean missing **a unique window of opportunity** which is opening up for the Nordic countries in terms of new investments and revenue creation in the coming decade. Missing this opportunity would require much costlier solutions to be adopted in the future. In practice, a **large part of the energy transition needs to occur already in the 2020s** through more investments in clean energy production. This is also in line with many of the international recommendations for reversing the CO_2 emissions trend.

Basically, all key elements for a carbon-free energy sector would need to have been put in place in the 2020s and 2030s. The policies would need to move even faster to enable optimal framework conditions: The Nordics would need to focus already in the 2020s on sector coupling and market approaches, remove regulatory barriers and allow business cases for flexible actors.

Nordic cooperation enables more efficient solutions without ignoring national needs

The results presented here highlight the benefits of collaboration in the search for solutions for the energy sector. The evident benefits of stronger sector and geographical coupling confirm the importance of good Nordic cooperation.

Creating Nordic solutions does not exclude national specificities, but rather draws upon these to design integrated 'responses to the common energy challenges in the region. **Being different but acting together provides a comparative advantage for the Nordics**.

Norwegian and Swedish hydropower, for instance, combined with district heating in Denmark, Sweden, Finland, and the Baltics, can provide much flexibility that are needed in the system for large scale operation of wind power in Denmark and Sweden - providing cheap renewable energy from which the whole region benefits.

Nordic trust and cooperation: We reach higher standing on each other shoulders than stepping on each other toes. Exploiting differences but acting together provides a comparative advantage for the Nordics.

The policy recommendations contained here do not necessarily aim for harmonised policies, but for coherent frameworks and policies, leaving scope for individual incentives and solutions that also benefit the common targets.

Stronger Nordic cooperation would improve outcomes for our societies by increasing economic benefits and strengthening a common voice in the EU when updating joint European low- or zero-carbon policies in the coming years. Nordic solutions could also serve as global ‘lighthouse projects’ to guide other countries in their paths towards zero-carbon energy systems.

The Nordics may play an important role in decarbonising the EU and beyond

By moving fast towards carbon neutrality, the Nordic region would benefit from the **consolidation of a pioneering position worldwide**. In particular, the large-scale, cost-efficient, systemic solutions presented here create major business opportunities to pave the way towards deep decarbonisation.

Interestingly, the Flex4RES scenarios linking the Nordic and continental European energy systems indicate that, due to more cost-efficient clean-energy solutions, exporting electricity could actually be a good business opportunity for Nordic utilities. The expected revenues of electricity exports could be in the range of €5-10 billion a year in the period 2030-2040. In addition, the Nordics could, through a more flexible energy system, also provide increasing flexibility to the EU energy sector. This would facilitate the energy transition in the whole Union.

If developed early, a Nordic electricity sector based on renewables can act as a catalyst for the decarbonisation of other sectors such as heat and transport, as well as for the green transition in other European regions.

A market-based approach: unlocking flexibility through better market coupling

There are comparative advantages to combining different energy markets in the Nordic region to promote flexibility, but also to explore synergies and reduce costs. The Nordic power market has so far functioned well. Our results show that a market-based energy transition with an emphasis on market coupling is a cost effective way of unlocking flexibility to accommodate a large amount of wind and solar power. Importantly, it sends the correct signals to market actors, encouraging them to operate flexibility and invest in flexibility-enabling technology. These investments could rely heavily on sector coupling (e.g. power-to-heat). By creating a level playing field, removing regulatory barriers as proposed here would reinforce incentives to invest while ensuring that they are not distorted by technology specific measures.

In the Nordic power market, Nord Pool, we might see more trade closer to real time as the share of wind power increases. In addition, **the market participants are likely to find efficient solutions in parallel to Nord Pool, such as power purchase agreements (PPAs) and similar market-based contracts, hedging against price risk and securing investments**. With a large share of power being traded through these fixed-price contracts, the residual markets at Nord Pool are likely to be used more for flexible energy trading, with more volatile prices than we see today.

Technologies are mature, but deployment must be accelerated

The Flex4RES analyses clearly show that the transition to a zero-carbon energy sector in the Nordics can be based on well-proven and cost-efficient technologies, but will require that they are scaled up to become the foundation of the energy system. The Nordic pathway could mainly be based on existing technologies, minimising the risks and uncertainties associated with the energy transition. This represents a more realistic future option for decision-makers in the region. Using existing technology in a smarter way, as depicted in Flex4RES, eliminates the need for major technology disruptions in the Nordics to reach zero-carbon levels in the energy sector.

> *Water as storage and flexibility provider - flushing batteries away. Combining flexible (smart) operation of thermal water storage in district heating systems with water storages in hydropower dams yield large and cheap flexibility options - eliminating the need for major technology disruptions in the Nordics.*

In terms of energy production technologies, fossil-fuel-based power and heating plants must disappear from the Nordics in the 2030s to reach national energy and climate policy targets. The technical focus could be shifted to hydro and wind power, supplemented by bioenergy-based combined heat and power, which has an important local role.

The main change required in the energy sector is a stronger electrification of other sectors, notably heating, but also to some extent the transport sector. This kind of sector coupling, namely linking power to other energy sectors (referred to as power-to-X or P2X) is a key strategy for the deep decarbonisation of the energy sectors as a whole. As more than half of all final energy use in the Nordics is comprised of heat, the coupling of the power to heating plays a central role here, activating a major flexibility potential. In practice, power-to-heat (P2H) is carried out via electric boilers and heat pumps, both already in large-scale use in the Nordics. To maximise the flexibility potential, heat storage, which is a cheap and reliable way to store energy, can be utilised in much larger scale than at present and be more tightly linked to P2H schemes. Short-term heat storage is already a mature technology, but moving towards long-term storage solutions may require additional investments in RD&D to reduce uncertainties and costs.

None of the scenarios investigated in Flex4RES indicate the need to expand electricity storage (batteries) in the Nordics. The flexibility of the large amount of hydropower with dams in combination with flexible (smart) operation of thermal water storage in the district heating systems yield large and cheap flexibility options - eliminating the need for major technology disruptions in the Nordics. However, batteries may be deployed in other regions of Europe which do not have these alternatives.

Carbon capture utilization and storage (CCUS) technologies, which still encompass maturity uncertainties, are not needed in the Nordics in order to reach carbon neutrality in the energy sectors but could be needed in other sectors, e.g. industry. However, if the energy sector should be extended to move beyond carbon neutrality towards negative emissions, carbon capture would be required in the energy sector as well. This could be the case in order to obtain cost effective carbon neutrality for all sectors in total, since it could be less costly to capture CO_2 and become carbon negative in the energy sector than to decarbonise all the other sectors completely.

Stepwise Roadmap: Decarbonise the energy sectors, then expand to EU as fundament for carbon neutrality

The Flex4RES project identifies the necessary steps for a swift and cost-effective decarbonisation pathway (see Figure 1). This includes not only the necessary technological changes, but also the required reforms in markets and regulatory frameworks.

The Carbon Neutrality Roadmap comprises three distinctive phases, corresponding roughly to each of the next three decades. The first phase, which we call "Energy Transition", takes place in the 2020s. It features a sharp turn to decarbonise energy (especially wind power), simultaneously requiring massive investments in new energy and sector coupling in order to hit the unique window of opportunity for the Nordics as frontrunners. As mentioned above, we must act fast.

Optimal framework conditions for smart sector coupling and decarbonisation need to be in place in the 2020s to allow for market-based flexibility across sectors. This implies the removal of regulatory barriers and creation of level playing fields for different fuels and technologies as well as flexibility-friendly taxes and grid tariffs, enabling business models for flexible actors.

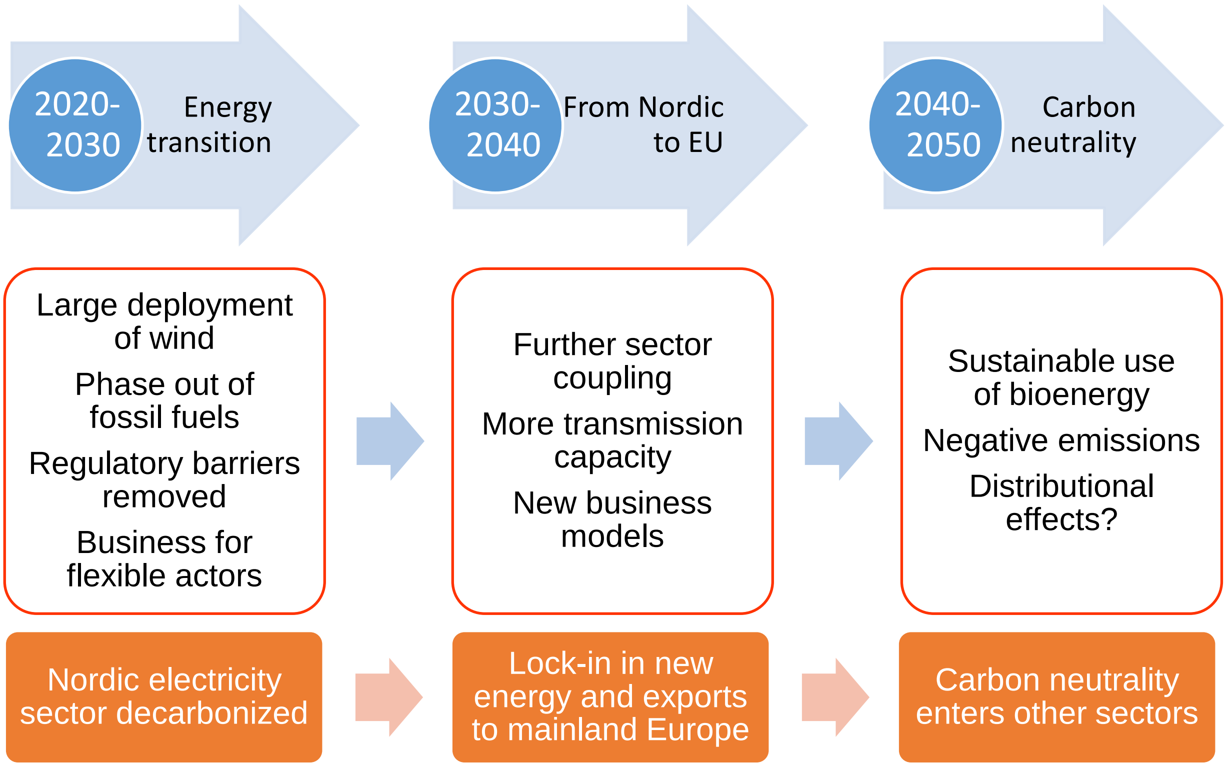

Figure 1: Stepwise roadmap toward Carbon Neutrality in the Nordics.

The second phase, which we refer to as “From Nordic to EU”, takes place in the 2030s and is characterised by a distinctive lock-in into renewable energy and flexibility technologies in the energy sector. Further transmission capacity and continued smart sector coupling enable additional wind power deployment as well as better business cases for flexible actors across sectors. This implies that the Nordic electricity and district heating sectors could be carbon neutral as early as in the 2030s - leading the way towards the decarbonisation of both the other sectors of the economy and the energy systems of other European countries, expected to be completed by 2050. The Nordics can become net exporters of energy and green energy solutions.

Due to the high magnitude of the necessary investments in installed capacity of technologies such as onshore wind power, important social acceptance and behavioural aspects that could hamper deployment must be considered. This could involve more careful siting, improved planning guidelines, and R&D efforts to further develop alternative technologies such as offshore wind power, which may face less resistance. Similar social issues may arise with the deployment of new transmission lines or large solar photovoltaic farms.

Social acceptance of wind farms and transmission lines may hamper the development.
Spatial planning, improve consumer involvement and R&D efforts in alternative technologies should be enforced.

Investments in RD&D are another important socio-political variable, which might be of particular relevance for seasonal heat storage in district heating. Our results suggest this form of storage could be expanded significantly to serve as a balancing technology linked to P2H, in combination with short-term heat storage.

Finally, in the Carbon Neutral phase (2040-2050), the Nordics have the possibility to go one step further and reach carbon negativity in the energy sector, achieving overall carbon neutrality while other sectors still have positive emissions, as well as act at a lever for the decarbonisation in other region of Europe. This could require carbon capture in biomass-based energy generation as well as the integration of natural carbon sinks (forests), among others.

Exports from the Nordics to the rest of the EU increase the revenue of Nordic electricity producers, but may also imply increased consumer prices. Likewise, carbon capture in the energy sector may imply additional costs in the energy sector and benefit other sectors of the economy. These distributional effects must be addressed by policy.

The energy sector could play a major role in a socio-economic optimal carbon neutrality pathway.
The consequent distributional effects must be addressed by policy.

As indicated in the stepwise roadmap (Figure 1), we suggest that low hanging fruit in the Nordics, namely forms of smart sector coupling, should be picked before expanding the transmission capacity to the other European regions. This will ensure business cases for P2X and accelerate the decarbonisation of the other energy sectors (heat, gas and transport) - creating a solid foundation on which to develop Nordic export potentials.

Flexibility is important on both the demand and supply sides

Both the supply and demand sides of the power market can generate flexibility. With the right incentives to act flexibly, demand has a particularly relevant role to play by exploring the energy needs of other sectors through P2X. Similarly, on the spatial dimension, flexibility can be provided by local actors as well as by other regions via transmission lines to surrounding countries. The key is to find the cheapest and most effective combination of flexibility options by exploring low-hanging fruit.

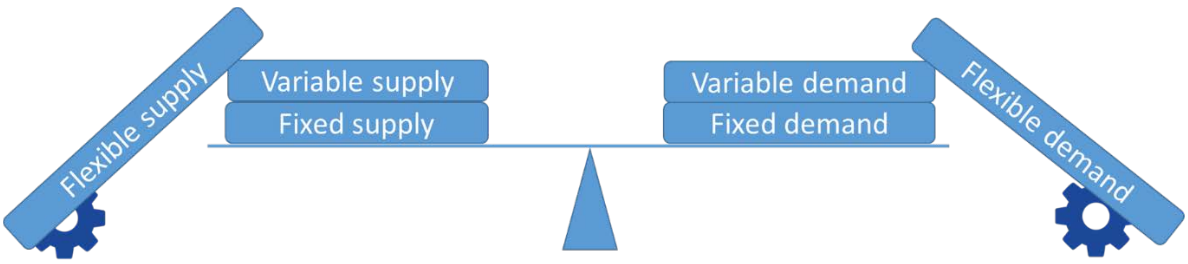

Figure 2: Flexible supply and demand balance the variability in generation and consumption.

With an increasing share of variable supply (mainly wind power) flexible demand becomes more important than today in order to have a system in balance. Power to heat (P2H) and power to gas (P2G) are flexible demand side technologies at the electricity market that can make business cases of acting flexible. It is therefore important that the regulatory and policy frameworks enable these business cases and that the market signal reach these actors.

Sector coupling is only effective if it is done in a "smart way" where flexible demand and supply react to the need of flexibility. Frameworks should allow and markets should give the right signals to act flexible and to invest in flexible demand technologies, e.g. P2X.

CONTENT

1 Introduction

The Paris Climate Accord, signed in December 2015, and the UN IPPC report, published in autumn 2018, urge nations to cut their greenhouse gas emissions to limit the global temperature rise to 1.5°C by the end of this century, now regarded as the upper limit for ecosystem sustainability. In practice, reaching these goals will require the sources and sinks of carbon dioxide to be in balance by 2050, most likely calling for negative emissions thereafter. Currently, over 80 percent of all energy consumed worldwide is still based on CO_2-emitting fossil fuels. This means a radical transition must occur in the energy sector towards clean and efficient energy in the coming decades. Fortunately, markets for renewable energy are growing rapidly, driving the necessary change.

The Nordic countries have long been leaders in the development of clean energy. The region has traditionally utilised much hydropower, bioenergy, wind power, and nuclear energy, leading to lower energy-related emissions relatively to the European average. Close to 80 percent of the electricity in the Nordics is already emission-free, with hydropower alone representing half of all electricity generated in the region. In addition, district heating and combined heat and power production have considerably contributed to the efficient use of fuel in heating. The Nordic countries also pioneered the integration of national electricity markets making wise use of market mechanisms to provide cost-efficient solutions. This resulted in lower electricity prices in the region as compared to the rest of the European Union. But Nordic ambitions go even further, as demonstrated by the Nordic Carbon Neutrality declaration presented by the region's prime ministers, which calls for climate neutrality by the year 2050. The energy sector in the Nordic countries is in a very good position to rise to this call and lead the way towards carbon neutrality.

The Nordic Flagship Project "Flexibility for Variable Renewable Energy Integration in the Nordic Energy Systems", or Flex4RES for short, aims at assessing how to reach the above-mentioned political goals in the Nordic countries with maximum efficiency. The main strategy of Flex4RES to facilitate the transition towards zero emissions has been to take a holistic approach to the energy system, viewing technology, markets, and policies as intrinsically interdependent.

In practice, this has resulted in stronger coupling between energy sectors and countries across the Nordic and Baltic regions, which introduces more flexibility and resilience into the energy system, even with very high shares of variable renewable energy such as wind power.

Through a set of technical, economic, regulatory, and policy analyses, combined with comprehensive scenario modelling of the energy systems with the Balmorel tool, Flex4RES identifies a pathway to resilient, sustainable, cost-efficient, and coherent carbon-neutral energy systems in the Nordics and Baltics in 2050. Flex4RES goes beyond scenarios based on techno-economic simulations and optimisations of the energy system typical of previous Nordic studies, by incorporating social and political dimensions. In this way, the results presented in this report highlighting the key results of Flex4RES more closely reflect real world conditions than previous studies and could thus better inform future policy design in the Nordic and Baltic states.

2 Pathway towards carbon-free energy sector in the Nordics

The energy system is highly complex, comprising many actors, networks, and self-organized elements, as well as the interactions amongst them. Describing changes in a system with such interdependencies is very challenging. The comparison amongst the four scenarios developed in Flex4RES aims to identify the necessary techno-economic changes in the Nordic energy sector to reach carbon-neutrality at least-cost. However, such profound changes must also be considered in their wider social and political context. In other words, technical change cannot happen independently of the regulatory and social changes that enable it. Therefore, Flex4RES also delineates the regulatory and social pathways to zero-carbon energy systems. Only when these three dimensions – techno-economic, social and regulatory – are aligned can meaningful change be effected.

In this context, the Flex4RES scenarios represent the techno-economic systems, but they also include considerations of market design and policy change. In addition, a socio-technical analysis was undertaken in within the project to analyse the role of non-technical factors independently of the scenarios. The combined results of these analyses constitute the Nordic pathway to carbon-neutrality depicted in Figure 3.

The core of the pathway is based upon the scenario modelling, around which the other elements are built. All dimensions evolve according to individual roadmaps, all of which need to be harmonised to produce the desired outcome.

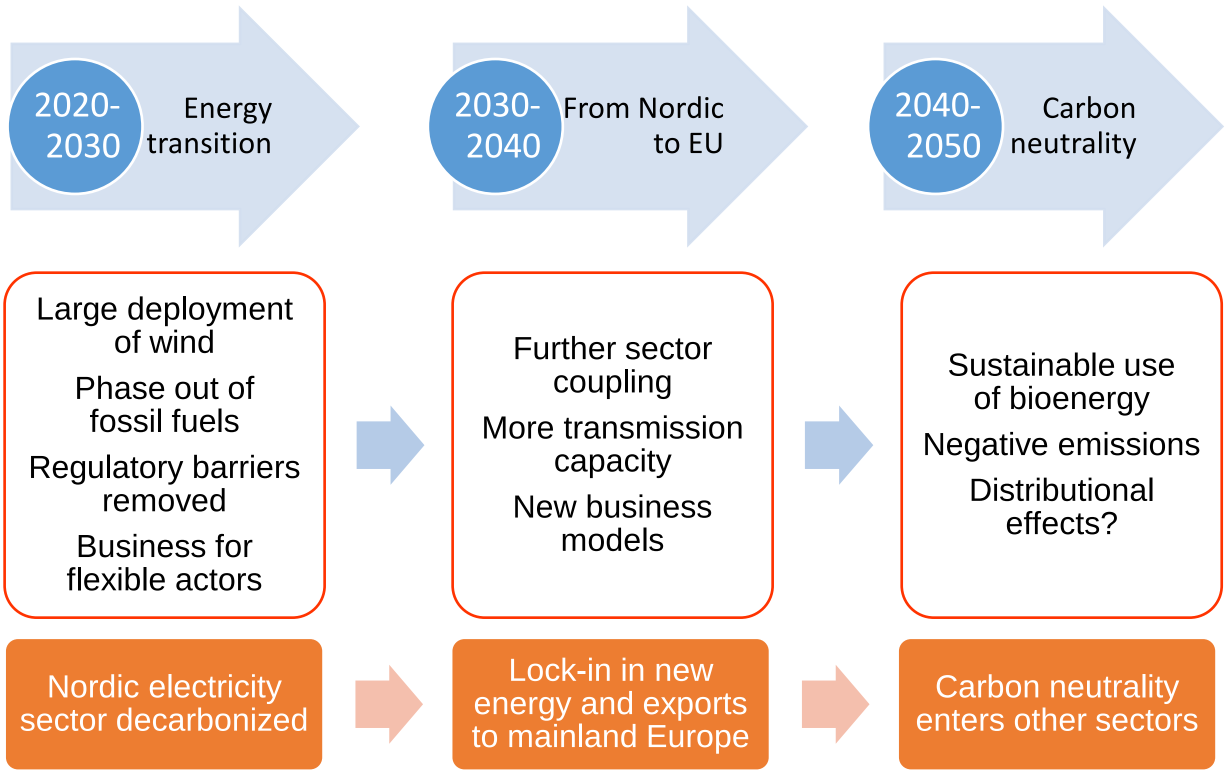

Figure 3: Stepwise pathway towards carbon neutrality.

The Carbon Neutrality Pathway comprises three distinctive phases, corresponding roughly to each of the next three decades. The first phase, which we call “Energy Transition”, takes place in the 2020s. It features a sharp turn to decarbonise energy, simultaneously requiring massive investments in new energy and infrastructure. The 2020s will be of critical importance for the whole zero-carbon transition in the Nordics, as most of the changes required need to be put into place during this decade to reach 2050 goals in time. The regulatory and political frameworks must also be reformed to remove key market barriers hindering new business models for flexible actors and new investments - especially within sector coupling.

In particular, it is necessary to establish a level playing field which guarantees technology neutrality in investment decisions. Proper signals such as dynamic electricity grid tariffs and taxes are also needed to encourage the daily flexibility at the demand-side, both in the electricity sector and in the other energy sectors using electricity.

Due to the high magnitude of needed investments in installed capacity of technologies such as onshore wind power, important social acceptance and behavioural aspects that could hamper deployment must be considered. This could involve more careful siting, improved planning guidelines, and R&D efforts to further develop alternative technologies, which may face less resistance. Similar social issues may arise with the deployment of new transmission lines or large solar photovoltaic farms.

Investments in RD&D are another important socio-political variable, which might be of particular relevance for seasonal heat storage. Shot-term heat storage is already used extensively in the Nordic district heating systems. Our results suggest heat storages could be expanded significantly to serve as a balancing technology linked to P2H.

The second phase, which we refer to as “From Nordics to EU”, takes place in the 2030s and is characterised by a distinctive lock-in into renewable energy and flexibility technologies in the energy sector. Additionally, exports from the Nordics to the rest of the EU increase once regulatory barriers are removed and new transboundary investments take place, because of the relatively higher electricity prices in the rest of Europe. This generates much higher revenues to Nordic power producers, but would also increase the electricity prices faced by consumers before reverting to previous levels by the middle of the century.

The consequent distributional effects must be addressed by policy. The strong electrification of the energy sector may also challenge its resilience to problems such as cyber-security.

In summary, all key elements for a carbon-free energy sector will need to have been put place in the 2020s and 2030s. The policies need to be enacted even faster to enable optimal framework conditions: The Nordics must focus already in the 2020s on enabling sector coupling, promoting market approaches, removing regulatory barriers and strengthening business cases for flexible actors.

In the 2040s, during the last phase, which we call “Carbon Neutrality”, the final steps are taken to ensure a fully sustainable energy sector as well as decarbonising the other sectors. Sector coupling has been strengthened when deploying high shares of renewable energy leading to higher electrification of the heating sector through P2H and reducing reliance on biomass, which can then be used for biofuels in the transport sector and other green chemicals. The adoption of new technologies peaks by 2050. There are climate indications that, after year 2050, negative emissions may be necessary to limit the temperature rise to 1.5°C. This would require the implementation of a range of other solutions such as the electrification of industrial processes, power-to-gas, and CCS, among others. It may also be necessary to limit the use of forest-based bioenergy to preserve forests as CO_2 sinks, which is not considered in the horizon 2020-2050. The export of electricity from the Nordics to the rest of Europe will start to dwindle as the price differences diminish. Though not analysed in detail, energy efficiency and the utilisation of waste heat may deserve future attention due to their large potential to decrease the demand for primary energy.

3 Increasing transmission capacity or coupling energy markets?

There are several ways to provide the additional flexibility needed in a future renewable energy based electricity sector. In Flex4RES, we mainly explore two of them: increasing transmission capacity between countries and strengthening sector coupling. The latter refers more specifically to coupling the electricity sector to the heat, gas or transport sectors, increasing the electricity demand. These other energy sectors could constitute a large flexible electricity demand segment in the future if the sector coupling is conducted in a "smart way" where demand react to price signals from the market (see chapters 4.4 and 4.5 later in this report).

With this in mind, we have defined scenarios that, in contrast to a baseline business-as-usual scenario, allow the expansion of transmission lines and/or remove the main regulatory barriers that hinder sector coupling:

1. **BAU**: Business-as-usual case resembling the Nordic Energy Technology Perspective (IEA NETP 2016) CNS scenario with present regulatory frameworks and limiting grid development to the plans laid out in Entso-e’s Ten Years Network Development Plan (TYNDP) until 2030;
2. **Connect**: As BAU, but allowing for additional investments in transboundary transmission capacity determined by the Balmoral model;
3. **Policy**: As BAU, but eliminating the regulatory barriers that hamper sector coupling and flexibility in the power sector;
4. **Combi**: Combining the Connect and Policy scenarios. In other words, as Connect, but eliminating regulatory barriers which hamper sector coupling and flexibility in the power sector.

The barriers removed in the Policy and Combi scenarios builds on studies in the Flex4RES project where we have scrutinised the enabling and constraining framework conditions for flexibility in the Nordic-Baltic region by interviews among national experts. Our main findings pointed at the Nord Pool electricity market as an efficient and homogenising enabler for flexibility at the electricity sector and highlighted a series of regulatory barriers mostly impeding sectors coupling and demand-side activation. Two of the main policy recommendations, which are implemented in the Policy and Combi scenarios, were to make grid tariffs and electricity taxes more flexibility friendly.

Comparisons between scenarios BAU and Connect reveal the effect of expanding transmission capacity while keeping regulatory barriers to stronger sector coupling in place. Comparisons between scenarios BAU and Policy, in turn, can be used to analyse the effect of removing the aforementioned barriers while limiting interconnection to the plans described in Entso-e/TYNDP for 2030.

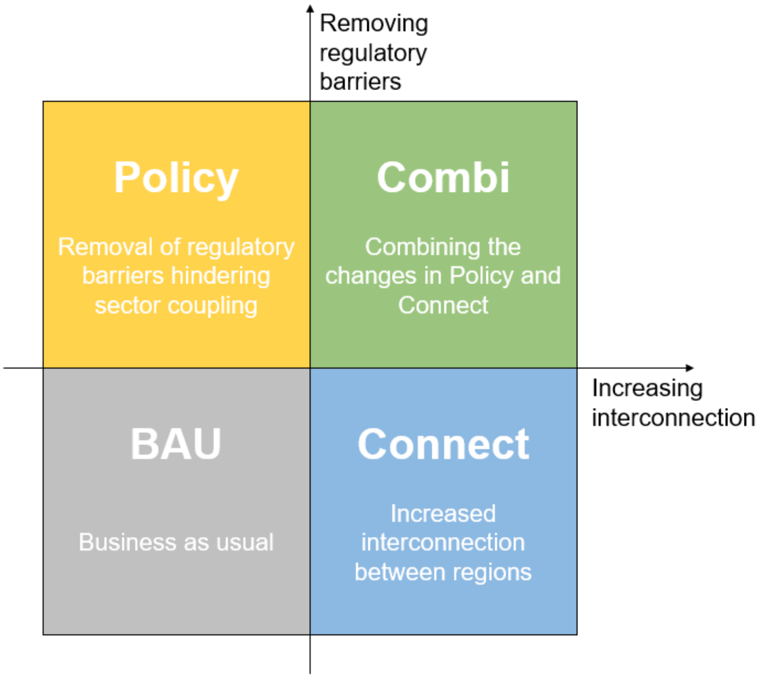

Figure 4: The Flex4RES scenarios to reach a carbon neutral energy future

Further comparisons are possible between scenarios Connect and Combi, to assess the impact of removing regulatory barriers when expanding interconnection is an endogenous decision of our model. Finally, comparing scenarios Policy and Combi sheds light on the effects of expanding interconnection when regulatory barriers have been removed.

All scenarios follow the present energy and policy targets described in Chapter 4. All results detailed in this section refer to the Nordic-Baltic region, unless otherwise specified in order to keep the Nordic focus in an EU context.

3.1 From fossil fuels to carbon neutral energy system

Although all four model scenarios reach carbon neutral energy systems by 2050, the path each scenario presents varies greatly, particularly when it comes to the cost of the transition and the time it takes to phase-out fossil fuels. Among the similarities, we can highlight the fact that wind and hydropower are predicted to dominate power production in the Nordics in 2050, responding for over 90% of electricity production. In district heating production, P2H and heat storage are predicted to represent two-thirds of all heat consumed, with the final third coming from bio-based CHP in 2050 (Figure 7).

As for the dissimilarities, larger transmission capacities and removal of sector coupling barriers are shown to increase investments in renewable electricity (Figure 5), as depicts the power capacity development over time in the different scenarios. The business-as-usual case (BAU) shows the lowest amount of renewables, whereas the scenarios with stronger market coupling between the Nordics and the mainland Europe (Connect and Combi) show higher investments in renewable electricity technologies also servicing the non-Nordic market. The removal of regulatory barriers carried out in scenarios Policy and Combi enhances local flexibility and therefore also enables higher renewable use - especially for P2H. Through better intra-Nordic power transmission capabilities in Connect and Combi, local flexibility improvements may also work within the region by enabling better exchange of power between the Nordic countries, i.e. to 'export flexibility' from one region to another, if necessary.

Figure 5 below shows the evolution of the installed capacity of different technologies to generate electricity in the Nordics and Baltics between 2030 and 2050. Hydropower, mostly located in Norway, keeps a high capacity share throughout all scenarios and years. While thermal and combined heat & power (CHP) units burning fossil fuels are decommissioned over time, wind and solar gain substantial shares. Gas plants leftover in 2050 are not used at all, but could remain in the system as a backstop since their nominal lifetime has not expired. Central power plants are replaced by highly efficient decentralised CHP plants using biofuels. The participation of nuclear power decreases over time. Sweden does not extend the lifetime of the existing plants, which means that Sweden decommissions its nuclear plants until 2050, whereas Finland maintains around 2.8 GW of installed nuclear power capacity.

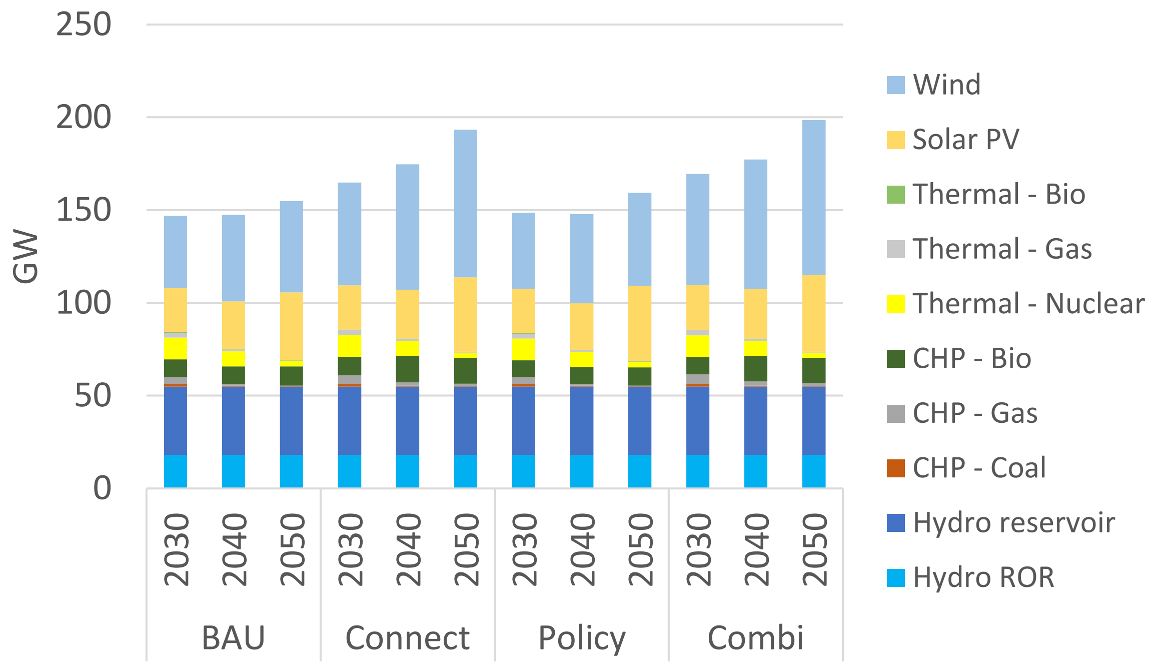

Figure 5: Installed electricity capacity by technology in the Nordics and Baltics

The largest differences in the electricity system are driven by transmission capacity expansion, as seen by comparing scenarios BAU and Policy to, respectively, scenarios Connect and Combi. The Connect and Combi scenarios see a large expansion of wind power capacities, especially in the Nordics but also in the Baltics, as compared to BAU and Policy. With additional transmission lines to central European consumption centres, the capacities in offshore and onshore wind power increase by 60-70% in Connect when compared to the BAU scenario in 2050. In particular, offshore capacities in the North Sea and onshore plants in Sweden and the Baltics are expanded and contribute to the decarbonisation of the rest of Europe through power exports.

Electricity generation from solar photovoltaic (PV) matches well with the hours of larger demand, which drives the installation of large amounts of solar panels in the Nordics and Baltics. Denmark and Sweden are the major markets for this technology. Overall, the installed capacity close to doubles from 2030 to 2050 in all scenarios from around 23GW to approximately 37-41GW. However, due to a lower capacity factor, solar PV does not contribute nearly as much in electricity production as wind power does (Figure 6).

When changing electricity taxes and grid tariffs to remove barriers to sector coupling in scenario Policy, while the optimal system composition and size remain similar to those in BAU, differences can be spotted looking at capacities for flexible and variable renewable technologies. Due to larger utilisation of flexibility, 5% (0.5 GW) less biomass based CHP (CHP-Bio) is needed in 2050. It is exchanged with 10% (4 GW) more solar PV and 2% more wind turbines. Only 0.01 GW of additional peak capacity in the form of bio-fuelled condensing units (named Thermal-Bio in the figure) needs to be installed to serve system peaks as compared to BAU.

When comparing scenarios Connect and Combi, a similar pattern can be observed. While less CHP-Bio is installed and marginally more Thermal-Bio, the market share of variable renewable technologies grows. The model chooses to invest 5% more into wind energy in the Nordics and Baltics in Combi as compared to Connect. Solar PV only increases by around 2.5% (1 GW). The difference driven by the additional transmission lines in the scenarios in question is that wind energy is the technology which grows in the process.

In order to assess the actual contributions of different technologies to electricity production, Figure 6 shows the actual production by commodity in the Nordics and Baltics for all scenarios from 2030 to 2050.

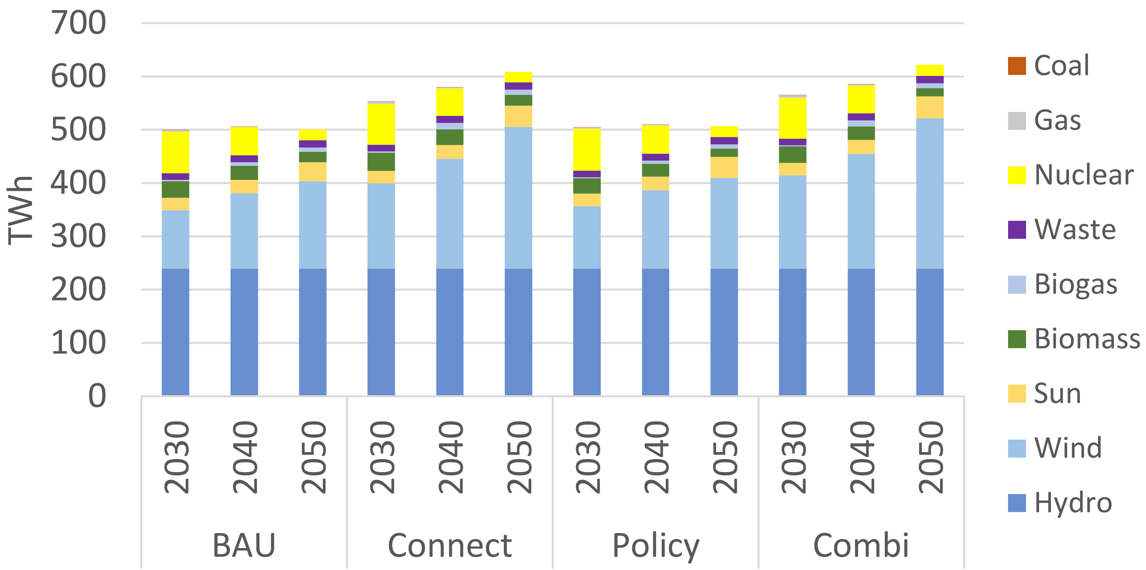

Figure 6: Electricity generation by fuels in the Nordics and Baltics

Hydropower is still the main contributor in the electricity system in the Nordics and Baltics when looking at actual electricity generation, with wind taking second place (see Figure 6). Coal and gas are barely used in 2030 and have been entirely pashed out by 2050. The share of nuclear-generated electricity declines due to the decommissioning of plants in Sweden, whereas biomass, biogas and waste energy only shrink marginally over time in all scenarios. Although electricity production from solar power increases over time in all scenarios, its contribution is smaller than the installed capacity shown in Figure 5 would suggest.

The largest differences are still observed when the transmission system is expanded. When installing additional lines in the Connect scenario, total generation increases by 21.9% in 2050 as compared to scenario BAU. Combi yields the largest increase in the production of electricity: about 24.2% or 622 TWh in the Nordics and Baltics as compared to BAU. The lion's share of that increase is used to export electricity to central Europe.

Changing the grid tariff and tax scheme in the Policy scenario has further positive effects on reducing the amount of biofuels required by the system. There is a reduction of around 0.5 TWh worth of biogas and 3.4 TWh of biomass in the Policy scenario as compared to the BAU, while solar power produces 11% more and wind power sees an increase of 3.6%. This development is stronger when transmission line expansion is allowed in the Combi scenario. From Connect to Combi, solar PV capacity rises by 1 GW, whereas wind energy capacity grows by around 16 GW, boosted by the flexibility from market coupling and smarter sector coupling. Changing the tariff and tax structure also yields larger VRE generation. While wind power contributes 164 TWh and solar power approximately 36 TWh in BAU, the Policy scenario sees these numbers increase to 170 TWh and 40 TWh, respectively due to the enhanced demand-side flexibility from smart sector coupling.

Increased market coupling through transmission line expansion stands out as the key variable determining the technology mix in the Nordic and Baltic energy systems. The more exchange of energy is allowed by transmission lines, the more generation capacity is installed in the Nordics and Baltics to send cheap green energy to central Europe. While hydropower is still a major factor in the energy mix, it serves further the flexibility on the production side. The wind sector is the main beneficiary of increased interconnection when looking at the rise in installed capacity. CHP plants will still be an important part of the future energy mix, albeit to a smaller degree than today. The fuel used in these plants will rapidly change from gas and coal to renewable fuels such as biomass. Moreover, solar PV installations will see a rapid increase. Even though solar power's actual contribution in energy production will not reach the same levels as wind due to lower capacity factors, it will still play a significant role in the Nordics.

Key messages at a glance

- **Each country specialises in a set of energy solutions, resulting in a well-balanced energy generation portfolio at the Nordic level.**
- **Hydropower remains a main energy deliverer and source of flexibility.**
- **Increased transmission in the Connect and Combi scenarios yields significantly more investments in production capacities in the Nordics and Baltics, with wind energy becoming the dominant resource.**
- **Additional transmission lines trigger substantial offshore wind investments in Denmark and onshore investments in Sweden and the Baltic countries.**
- **Biomass-based CHP displaces gas and coal, but less overall CHP capacity is needed in 2050.**
- **Even though installed solar capacities are large, their contribution to actual production is limited by low capacity factors.**

3.2 Coupling of electricity and district heating

When all energy resources compete on a level playing field for heat production (Policy and Combi scenarios), the district heating sector becomes partly electrified. The larger participation of power-to-heat (P2H) and combined heat and power (CHP) shows the active role these technologies play in the electricity market, respectively as electricity consumption/conversion and energy storage to absorb peak production in windy periods, and as suppliers, when wind energy is scarce.

Figure 7 summarizes the installed capacity of heat generation in the Nordic and Baltic district heating sectors over time in all four scenarios.

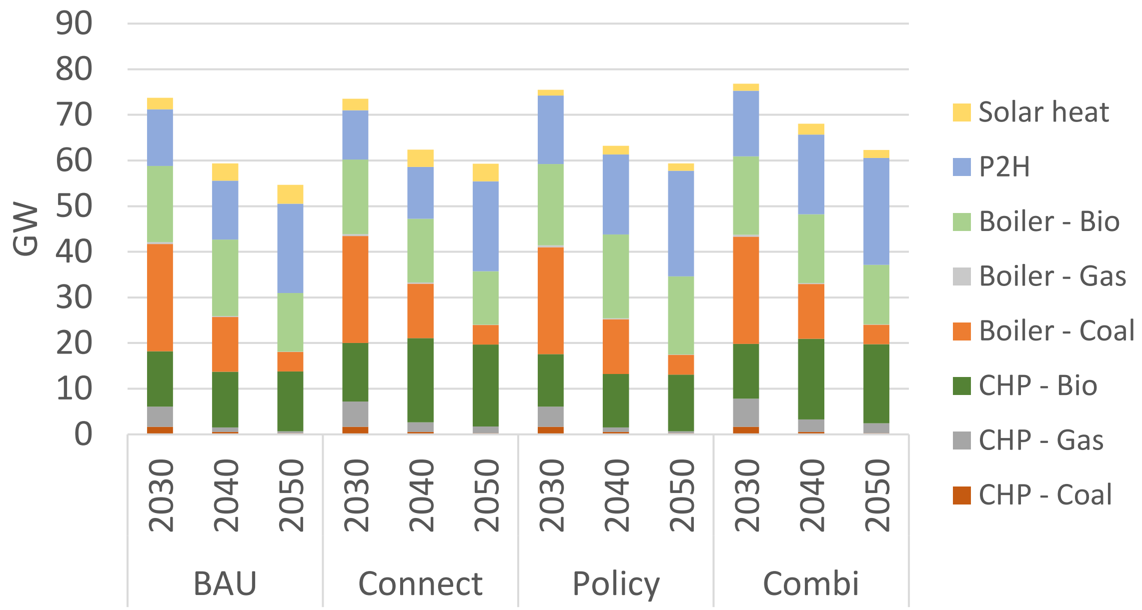

Figure 7: District heating generation capacities in the Nordics and Baltics by technology

Due to increased efficiency of the operation of the heat generation plants and thermal storages as well as decreasing heat demand stemming from increased energy efficiency and better use of waste heat (industrial excess heat/process heat) for district heating, the overall installed capacity is reduced over time in all scenarios. Boiler and CHP capacities using coal and gas are rapidly declining until 2050. Few of the existing CHP-Gas and Boiler-Coal remain idle in the normal operation of the system: they are not used, but the capacities are kept as reserves if their technical lifetimes have not expired. The presence of P2H increases over time, as does that of CHP-Bio. The installed capacity of boilers using biofuels stays mostly constant from 2030 to 2050. Solar heat is present in small quantities in all scenarios, particularly in Denmark, although this technology is stronger in BAU and Connect than in Policy and Combi.

The most notable result is the growth of P2H technologies with the change of the tax and grid tariff scheme in the Policy scenario. When capacity taxes and tariffs are applied, P2H grows by 18.5% and 19.5% in Policy and Combi, respectively, when compared to BAU. The changes are especially large in Denmark and Sweden, while differences in the Baltics and Finland are less pronounced.

Significant changes in the optimal heating technologies are also seen in Norway, where additional interconnection in Connect and Combi and the consequently higher electricity prices result in a substitution away from P2H and towards CHP-Bio in 2050. In BAU and Policy, boilers using biofuels and P2H dominate the technology mix. Similar developments are observed in the Baltics. With more transmission lines to central Europe, Lithuania and Latvia invest more in CHP-Bio in detriment of Boiler-Bio, which dominates without additional interconnections.

Figure 8 summarises the generation of heat in the district heating sector by fuel from 2030 to 2050.

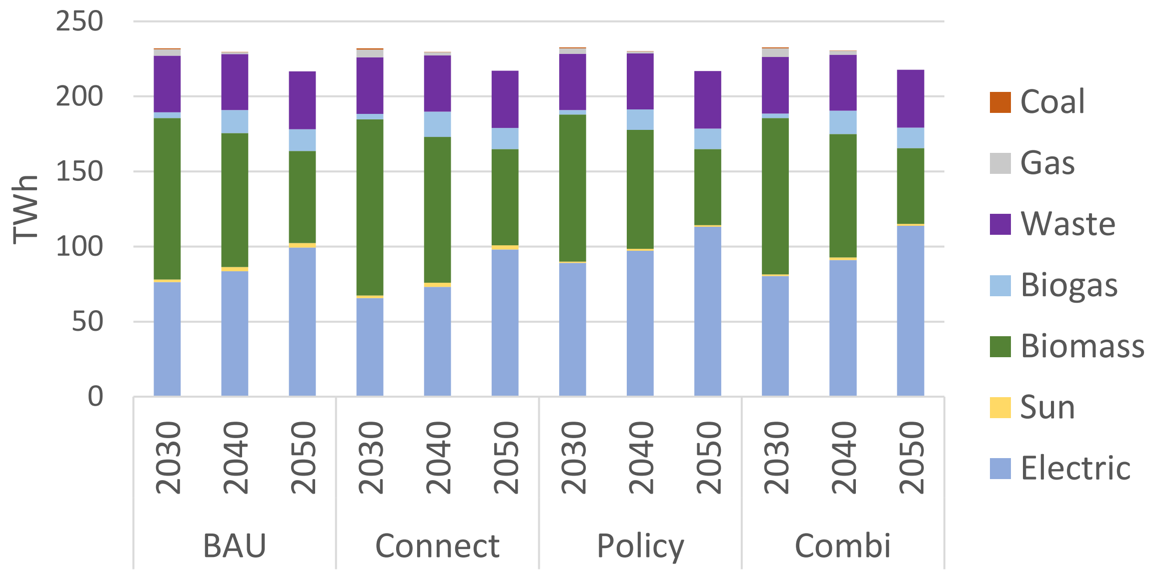

Figure 8: District heating generation in the Nordics and Baltics by fuels

In general, heat generation from electricity (P2H) is predicted to dominate the district heating sector in the future in all scenarios. Furthermore, it is visible that, compared to the reduction in installed generation capacity in Figure 7, the total production is not declining as much. For example through digitalization and energy trading closer to real time the technologies will operate more efficient on market signals. Thus efficient utilization of capacities will rise in the future.

The figure also provides clues as to how different technologies are used. Heat pumps are used in many hours, but electric boilers are in the mix to serve flexibility (few operating hours). I.e. of the P2H technologies, heat pumps are mainly operated as base-load whereas electric boilers are used more flexible. Biomass still serves a considerable portion of the heat demand in 2050, but its share is reduced by 43%-51% over the decades, depending on the scenario. Biogas, on the other hand, has significant gains. In Combi, for example, it goes from 3 TWh in 2030 to approximately 14 TWh in 2050. Municipal waste and process heat remain more or less constant throughout the period, whereas the use of coal and gas is reduced from small amounts in 2030 to zero in 2050.

Interconnections have negative effects on the usage of electricity for heat generation (P2H) in Norway and Sweden due to higher prices. This effect is more than offset, however, by the increase of P2H in other countries like Denmark and Finland. Policy changes have stronger effects in Sweden, Denmark, and Finland, when compared to the Baltics. Nonetheless, Estonia has the largest share of P2H in its fuel mix in 2050. With capacity taxes and tariffs, biomass usage decreases by approximately 6-8 TWh when comparing scenarios BAU to Policy and Connect to Combi.

Biogas is especially used in Finland in boilers, while Denmark specialises more in CHP in all scenarios. The use of biomass, however, declines over time while the use of more flexible biogas grows. Waste represents half of the production in Latvia and Lithuania, while Sweden and Finland rely more heavily on P2H.

In summary, changing the electricity tax and grid tariff scheme from energy-based to capacity-based enhances the coupling of the electricity and heat sectors by strengthening the business case for P2H. With this change, the Nordic and Baltic district heating systems do not require additional support in order to increase electricity usage. Furthermore, the coupling increases the amount of flexibility, even though fewer CHP plants are available. This occurs even though the changes improve the business case for CHP in the Nordics and Baltics. With smaller transmission capacities, CHP plants are largely substituted by boilers.

Electricity is projected to represent around 50% of the overall heat generation. The other half is expected to rely mainly on biomass, biogas, waste, and recovered industrial process heat as fuels. Solar heating systems will only play a minor role in the Nordics, restricted to Denmark and southern Sweden.

Key messages at a glance

- **The sector coupling is driven by electricity market prices that fully transmit the need for flexibility and allow for business models for flexible P2H actors.**
- **The introduction of flexibility friendly electricity grid tariff and tax schemes expands the business opportunities of P2H and heat storage.**
- **P2H will evolve as the main heat source in the Nordics and Baltics in 2050 emphasizing the synergies of sector coupling (low hanging fruit).**
- **Waste as well as biomass and biogas are the main fuels for CHP.**
- **Biogas/-mass based heat-only boilers will especially be used when no additional flexibility in the power sector is needed from the heat sector.**
- **Increased transmission improves the business case for CHP plants as they can sell electricity to central European prices while bio-boilers are their substitute for fixed interconnections.**
- **Solar heating systems will play a role in Denmark and Sweden.**

3.3 Flexibility from heat storage in district heating

Our model runs reveal that heat storage systems will play a major role in the Nordic and Baltic energy systems. Figure 9 summarises the development of heat storages in the Nordics and Baltics. Short-term heat storage refers to hourly and daily storage in hot water storage tanks as well as in the district heating grid itself. Seasonal heat storage, in turn, refers to thermal storage between seasons - often with a slower filling and draining speed than for the short-term storage technologies but with the possibility of storing thermal energy for longer periods.

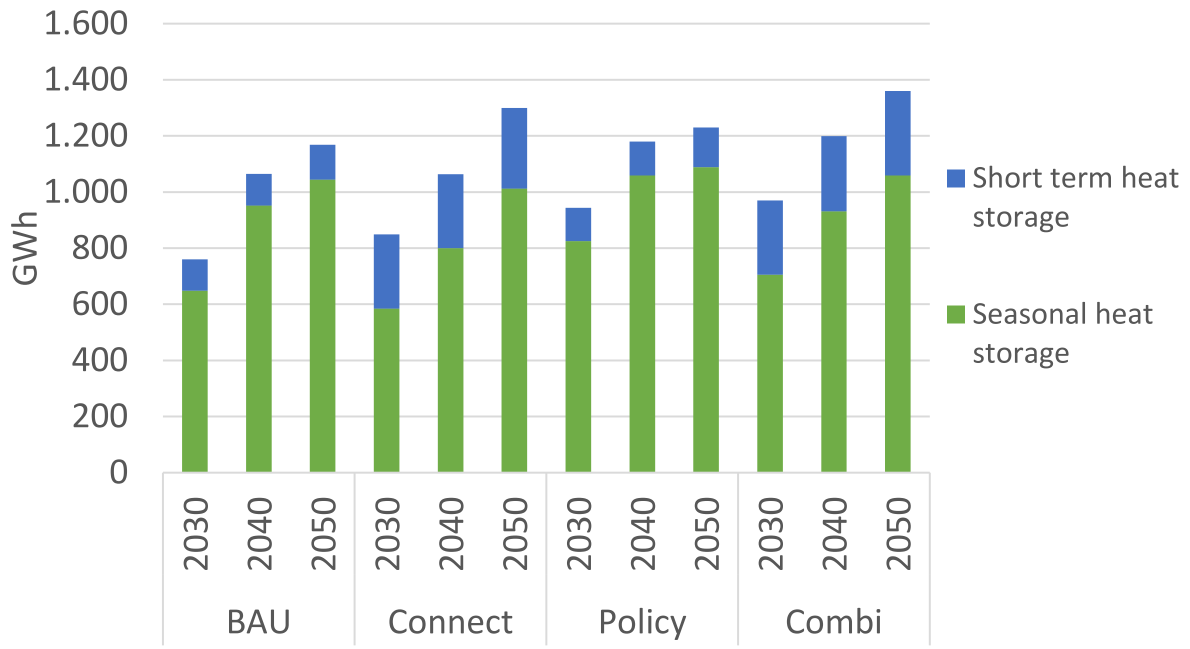

Figure 9: Evolution of the use of storage in district heating

All scenarios show that there is a large need for seasonal heat storage to store the energy produced in the summer to be consumed in the winter. Between 1,169 GWh and 1,360 GWh of heat storage capacity are optimal in 2050, depending on the scenario. This storage capacity serves a large amount of flexibility to the system, as it allows P2H to follow price signals by uncoupling it from the heat demand. Furthermore, storage discharges actively, covering peaks in heat demand in wintertime, thus reducing the required heat generation capacity.

In addition to seasonal storage, there is a need for short-term storage to help cover the aforementioned peaks in demand, especially in the Connect and Combi scenarios. Slightly more than twice as much capacity is required to balance short-term variations in demand in scenarios Connect and Combi as compared to BAU and Policy, respectively.

Two additional effects arise as interconnection is expanded and flexibility triggered through new policy. Market coupling through transmission lines increases the business case for additional storage systems in district heating. Denmark, Sweden, and Finland, with their large district heating networks, are particularly affected. Capacity-based taxes and grid tariffs for electricity use in the Policy scenario causes storage systems to serve flexibility more efficiently due to decreased price distortion. This effect, however, is weaker than that of increased interconnection.

The overall heat storage capacity of 1,169 GWh and 1,360 GWh in 2050 can be challenging to achieve due to spatial barriers such as increasing land prices and restrictions on land usage - especially for large-scale seasonal storage. If these constraints prove to be binding, other technologies able to serve the same kind of flexibility with fewer land requirements might be favoured. However, it is as of yet unclear what alternative technologies could fit the bill.

Key messages at a glance

- **Increased business model for heat storage in district heating, as a response to the relatively scarcer cheap electricity available to cover the domestic demand**
- **Flexibility friendly tax and grid tariffs promote hourly storage, but to a lesser extent than the market price variations trigger by the cross-border exchanges of electricity**
- **Restrictions on land-use, public acceptance and other socio-technical parameters may limit the deployment of large-scale seasonal heat storages.**

3.4 Increased transmission benefits renewables in the Nordics, but pose distributional challenges

Expanding transmission lines improves the competitiveness of wind power. Better export opportunities mean that windy periods have less of a depressive effect on area prices, improving the business case for wind. However, there are significant distributional effects of increasing transmission capacity, as different stakeholders in different countries are affected unevenly. This process hurts European fossil-based power producers and Northern consumers and benefits Northern hydro and wind power producers, as well as Western European consumers. Asymmetrically distributed benefits might be the biggest barrier to increased cross-border transmissions, but national and international efforts to improve the distribution of benefits might prove effective in addressing these concerns.

From the perspective of the Nordic countries, the increased producer revenues are much larger than the increased consumer costs, so there is a net socio-economic benefit to investing in more transmission lines. This also means that a redistribution of benefits could make both consumers and producers better off than in the BAU scenario. Figure 10 illustrates the annualised system cost in the Nordics and Baltics for selected years in each of the four scenarios.

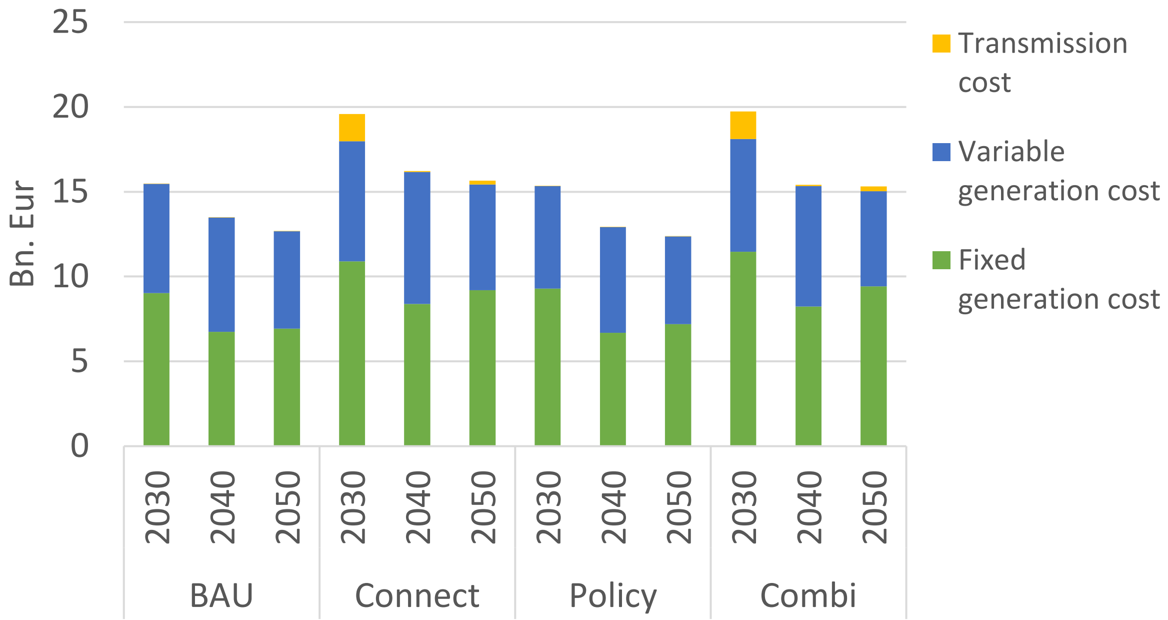

Figure 10: Total system cost development by scenario for the Nordics and Baltics

The transmission costs included in this graph encompass both investment cost and the cost of running the grid. This figure depicts a pronounced increase in system cost in the aforementioned countries with the expansion of transmission lines. Note that the additional costs do not stem solely from the investment in transmission capacity itself, but are mostly due to higher generation costs as both generation capacity and actual generation increase in the Nordics in the Connect and Combi scenarios. This is true both in the presence of existing electricity taxes and grid tariffs – comparing scenarios

BAU and Connect – and with more flexibility friendly tax and grid tariffs – comparing scenarios Policy and Combi. This increase is due to the reinforcement of the role of the Nordic and Baltic countries as providers of electricity to the rest of the system with expanded transmission capacity.

As the model provides a socio-economic optimal outcome, expanded generation capacity in the Nordic-Baltic region indicates that it is cheaper to produce electricity there and that increased transmission capacity can contribute to the efficiency of the overall European electricity system. The revenues for each technology and the consumer costs shown in Figure 11 complete this story: increased interconnection benefits Nordic producers by increasing their revenues. Wind and hydro reservoir producers emerge as the biggest winners with expanded transmission capacity. Finally, consumers in the Nordics face higher prices, while consumers in other regions of Europe benefit from lower prices.

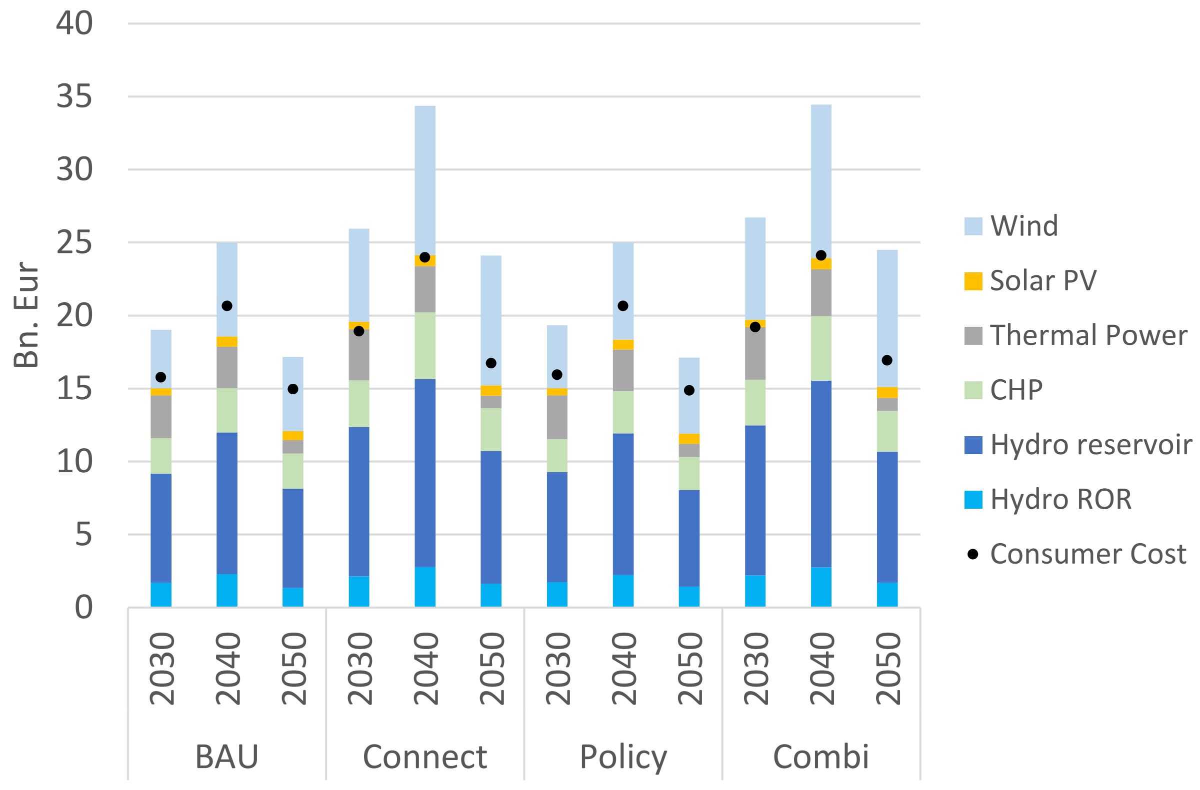

Figure 11: Producers revenues and consumer cost in the electricity sector in the Nordics and Baltics

Policy reform is shown to cause a moderate decrease in overall system costs both with additional transmission capacity – comparing scenarios Connect and Combi – and without it – comparing scenarios BAU and Policy. This indicates that current grid tariff designs still represent a barrier to the optimal operation of the energy system, justifying the need for reform.

Key messages at a glance

- **Export from the Nordics to the rest of EU increases the revenue to the Nordic electricity producers but may also imply increased consumer prices.**
- **The consequent distributional effects must be addressed by policy.**
- **Nordic renewables - especially wind producers - improve their business case with increased transmission and are able to expand their capacity.**

3.5 The Nordics as lever for EU decarbonisation

As mentioned in the early sections of this report, increasing transmission capacities between countries, particularly between the Nordics and the rest of Europe, can foster the more rapid decarbonisation of European energy systems. This result is illustrated in Figure 12- Figure 14, which shows the evolution of the carbon intensity of electricity consumed in each of the countries included in our model for two scenarios: Policy and Combi. As transmission capacities are the key variable here, the picture in scenario BAU is essentially the same as that shown for Policy. The same is true of scenarios Connect and Combi.

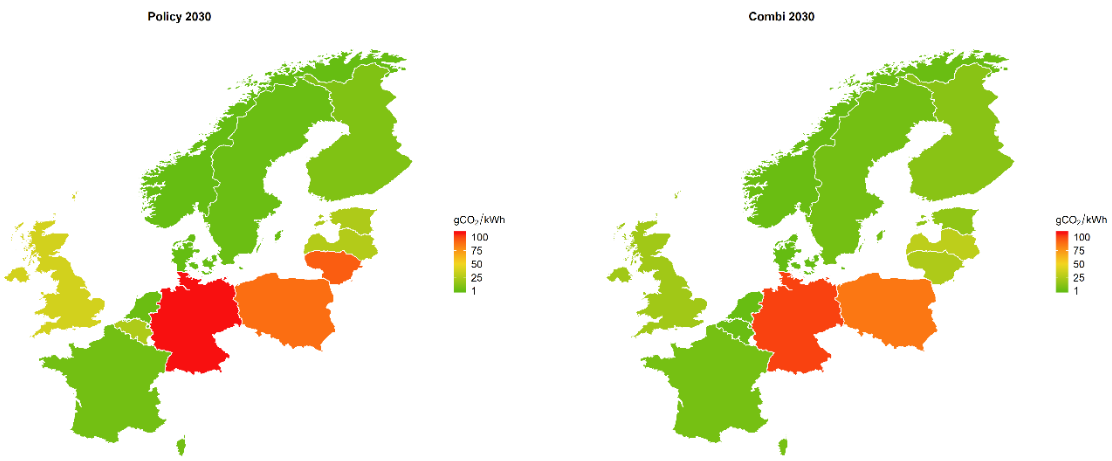

Figure 12: CO_2 emissions per unit of electricity consumed in scenarios Policy (left) and Combi (right) in 2030.

As we can see from Figure 14, both scenarios lead to a complete decarbonisation of energy systems by 2050, which is what the model is designed to do. The speed of the transition, however, varies according to how well interconnected the countries are. As compared to Policy, in scenario Combi we observe accelerated decarbonisation in Belgium (completed in 2030 as opposed to 2050); Lithuania (completed in 2040 as opposed to 2050); the UK (completed in 2040 as opposed to 2050); and Germany (with a steeper decline in carbon intensity between 2030 and 2040).

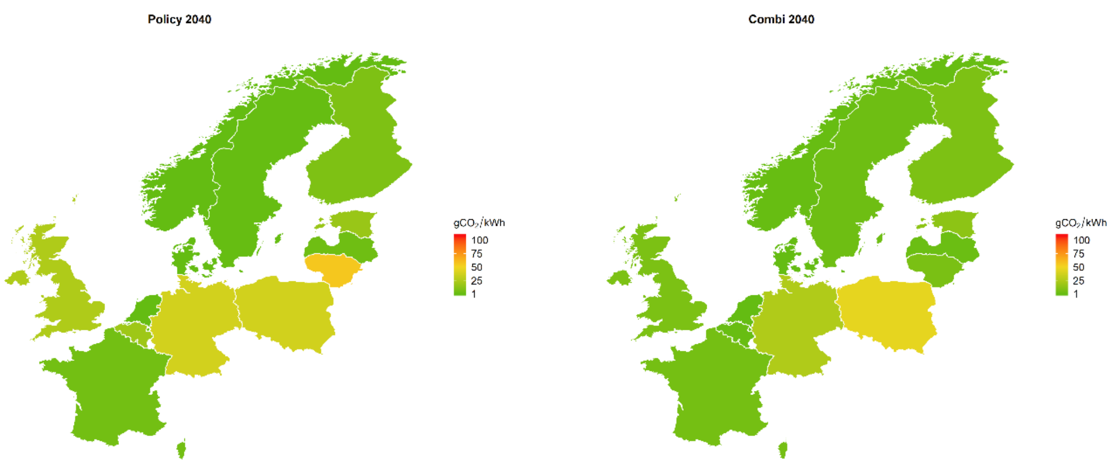

Figure 13: CO_2 emissions per unit of electricity consumed in scenarios Policy (left) and Combi (right) in 2040.

This can, in large part, be attributed to stronger coupling of the aforementioned countries to the Nordics, which provide a large amount of cheap renewable energy, displacing the fossil generation in other European countries. The main message of this analysis is that Nordic leadership in renewable energy can spread its benefits beyond the Nordic region to the rest of the continent, supporting the EU's decarbonisation goals, as long as there is adequate investment in transmission lines.

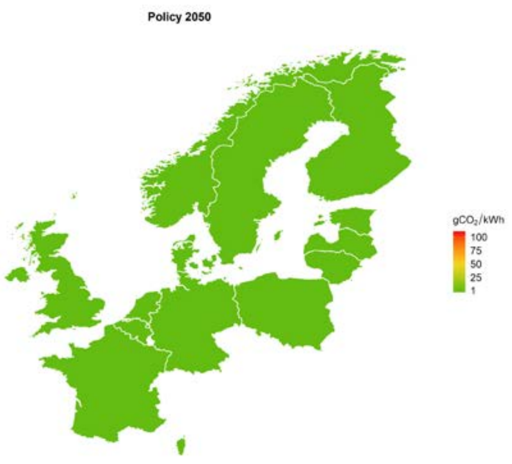

Figure 14: CO_2 emissions per unit of electricity consumed in scenarios Policy (left) and Combi (right) in 2050 - a carbon neutral energy sector in Northern Europe.

In addition to the role of interconnection, carbon taxation is the other key factor driving the decarbonisation of the European energy systems modelled in Flex4RES. In all scenarios it is assumed that the carbon tax would increase during the 2020s to 65 €/tCO_2 and double to 130 €/tCO_2 by 2050, similarly to what is assumed in other international studies. This assumption is key to guarantee the swift move away from fossil fuels predicted by our model, albeit less so in the scenarios with limited transmission capacity.

Key messages at a glance

- **A Nordic electricity sector based on renewables can act as a catalyst for the decarbonisation of other sectors such as heat and transport, as well as for the green transition in other European regions.**
- **Transmission lines and high CO_2 prices accelerate this.**

4 Thematic chapters

Our findings affect the overall energy system. In what follows, we compile our results by thematic chapters, covering the main techno-economic, market design, policy and regulation, and social aspects of the energy transition.

4.1 Nordic emphasis on carbon neutrality

The Paris Agreement of 2015 sets the scene for the reduction of greenhouse gas emissions worldwide. The aim of the Agreement is to keep global warming well below a 2ºC increase compared to pre-industrial levels and if possible to stay below 1.5ºC. This creates a strong pressure to quickly reduce greenhouse gas emissions.

The Nordic countries have a strong agenda for reducing GHG emissions and have set ambitious carbon neutrality targets for the next thirty years. Therefore, Nordic policies and measures can serve as an example of the actions required to effectively reach carbon neutrality by 2050. In Flex4RES, we have extended the focus to the Nordic-Baltic region. This means that, in addition to the four Nordic countries – Denmark, Finland, Norway, and Sweden – we also included the three Baltic countries – Estonia, Latvia, and Lithuania – in our analyses. The combined region, located in Northern Europe, covers a vast area, but is only home to about 30 million people.

The Nordic region in Europe is ahead of most other regions in the world with respect to reducing carbon emissions in the electricity sector. The present carbon intensity of Nordic electricity is under 60 gCO_2/kWh, compared to the global average of over 500 gCO_2/kWh. According to IEA's 2-degree scenario (IEA Energy Technology Perspective ETP 2017, and Nordic Energy Technology Perspective NETP 2016), the world needs to match the current Nordic level by 2045. In other words, the Nordics are around 30 years ahead of the global average. One of the main reasons for this is the unique power supply mix in the Nordic-Baltic region with almost half of all electricity produced from hydropower.

By extending the use of electricity in the heat and transport sectors, the Nordic-Baltic region can provide an interesting case for deep decarbonisation pathways and policies with large-scale deployment of wind power and other variable renewable electricity (VRE).

In addition to a strong political will to reduce emissions, past experience in using energy markets as an instrument to reach energy policy goals is very positive. The Nordic countries were amongst the first in the world to open their electricity markets. They established a unified market and a common electricity exchange in the 1990s, the Nord Pool power exchange. It became a pioneering example for many other countries and regions.

Political drivers of the green transition

The Nordic-Baltic region, with the exception of Norway, belongs to the European Union (Norway is part of the European Economic Area), which determines a common energy and climate policy framework for its member states. In December 2018, the new revised Renewables Energy Directive (2018/2001) entered into force, establishing a new binding renewable energy target for the EU of at least 32% in 2030 (Figure 15), with a clause for a possible upwards revision by 2023. Likewise, in December 2018, the revised Energy Efficiency Directive established a headline EU energy efficiency target for 2030 of at least 32.5% (compared to projections).

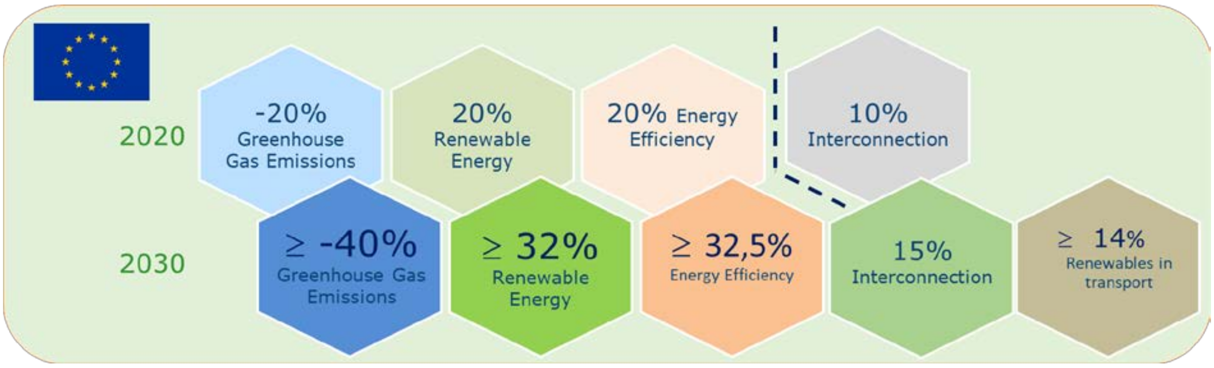

Figure 15: EU climate and energy goals for 2020 and 2030.

The renewable energy target refers to total final energy use. The electricity sector should be decarbonised faster. For the EU electricity sector, a 50% renewable electricity target has been set for 2030 and it should be fully carbon-free by 2050.

In addition, goals for better power transmission interconnections between members states are established (Figure 15). In the 2020 targets, the European Council called for all EU countries to achieve interconnection of at least 10% of their installed electricity production capacity by 2020. In 2030, the target is raised to 15%. This means that each country should have electricity cables in place that allow at least 15% of the electricity produced by its power plants to be transported across its borders to neighbouring countries. 17 countries are already on track to reach that target by 2020, or have already reached it, but more interconnections are needed in some regions. The Nordics are among the countries that are already fulfilling the 2020 interconnection target.

In particular, the four Nordic countries (Norway, Sweden, Denmark and Finland) have more ambitious CO_2 reduction targets and policies than the EU. In January 2019, the Nordic countries issued a Nordic Carbon Neutrality declaration that calls for carbon neutrality by 2050, and the countries already have policies in place to bring carbon-neutrality by year 2050 or earlier (Table 1).

The Finnish Government has recently (June 2019) announced to strengthen its climate policy by requiring full net-carbon-neutrality by 2035 and becoming carbon-negative by 2050. Norway has also recently agreed on a 2030 target to cut net greenhouse gas emissions to zero, 20 years earlier than the previous deadline (2050). Sweden plans to achieve net carbon neutrality in 2045 and become carbon-negative in 2050. Swedish electricity generation must be 100% renewable by 2040. However, so far there is no limit date for the use of nuclear power. The new government in Denmark has bid to achieve a 70% reduction in greenhouse gas emissions by 2030 and to be independent of fossil fuels by 2050. Danish electricity supply should be 100% renewable and 90% of the district heating supply should be fossil-free by 2030.

Table 1: Renewable energy and CO_2 reduction targets in the Nordic-Baltic region.

Country	Share of RES by 2030 (%)		CO_2 target
	Of final energy	Electricity	
Denmark	55	100	Carbon neutrality by 2050
Finland	>50	*	Carbon neutrality by 2035
Norway	67.5 by 2020	100	Carbon neutrality by 2030
Sweden	45	100 by 2040	Carbon neutrality by 2045
Estonia	42	30	-80% by 2050
Latvia	45	-	-80% by 2050
Lithuania	45	45	-80% by 2050

*Both Finland and Sweden have considerable amounts of nuclear power (see Table 3) that is expected to continue after 2030.

The renewable energy and emissions goals of the Nordic-Baltic region are presented in Table 1 (see also Table 5 in the appendix), which shows a much higher level of ambition than the EU goals mentioned above (Figure 15). This is demonstrated by all countries planning to achieve the 2020 and 2030 EU targets early and, in several cases, to exceed them by a large margin. The Nordic countries (Denmark, Norway, Finland and Sweden) have declared more ambitious targets for reduced carbon emissions, and full carbon neutrality by 2050 should be an achievable goal for the region as a whole. The Nordic countries (Norway, Sweden, Denmark and Finland) already fulfil the EU 2030 target for the electricity sector with more than 50% renewables, and intend to be carbon-free already by 2030 or 2040. Much of the deep decarbonisation will be based on electrification, with extended deployment of renewable electricity sources including VRE such as wind and solar power.

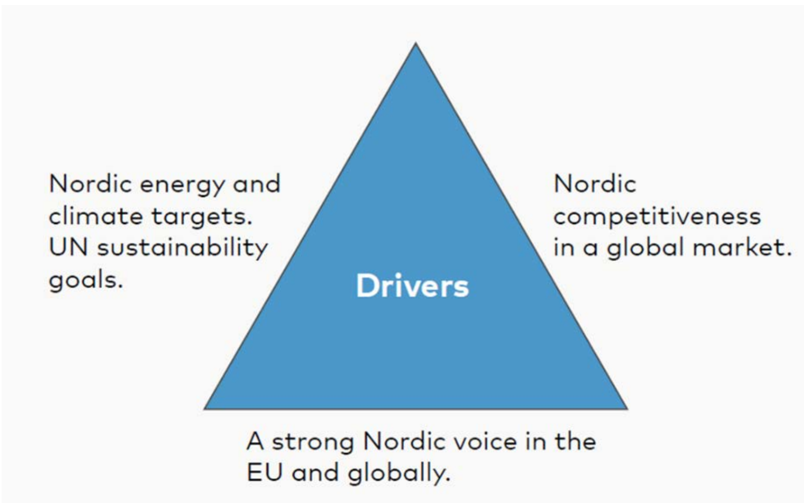

Figure 16: Policy drivers for enhanced energy cooperation in the Nordics.

As indicated above, the Nordics are pioneers in the EU green transition. A position that is revealing business opportunities for Nordic green solutions and technologies as well as green energy and flexibility providers in the decarbonisation of other regions of the EU and beyond. Each of the countries are relatively small in a EU context, but standing together as a region with around 30 million people, a common Nordic voice can be strong in leading the international energy and climate debate (Ollila, Nordic Energy Co-operation: Strong today –stronger tomorrow. 2017). These political drivers are summarised in Figure 16.

Energy trends

Due to the cold climate, vast area, low population density, and many energy intensive industries, the availability and use of energy has always been an important issue in the Nordic-Baltic region. In addition, the countries in the region possess large energy resources, both fossil and renewable. The main indicators related to energy and CO_2 emissions in the Nordics and Baltics are presented in Table 2, showing that the energy mix is less carbon-intensive than the average EU mix – energy use in the region represents slightly less than 8% of the total for the EU, while emissions represent just over 4% of those of the whole Union. Norway is a major exporter of oil and gas, with exports totalling over 15% of the EU's entire primary energy demand.

Estonia, Finland, Latvia, and Lithuania are more energy-intensive than the average member state, which stands at 0.09, measured in thousand tonnes of oil equivalent per 2010-dollar of GDP. Estonia and Finland surpass even the USA, which has an energy intensity of 0.12, measured in the same unit. Finland is the country in the region with the highest total carbon emissions, but Estonia is the most energy- and carbon-intensive economy. Estonia is also the country in the Nordic-Baltic region with the lowest share of RES and the largest difficulties in achieving ambitious climate goals.

Table 2: Present energy and emission situation (2016).

Country	**TPES** (Mtoe)	**Energy/GDP** (toe000/2010$)	**Emissions** ($MtCO_2$)	**Emissions** (tCO_2/cap)	**Emissions**[2] (tCO_2/cap)	**RES share** (%)[3]
Denmark	16.5	0.05	33.5	5.84	8.8	32.8
Finland	34.0	0.13	45.5	8.28	10.9	34.7
Norway	27.2	0.06	35.5	6.78	10.5	45.7
Sweden	49.2	0.09	38.0	3.83	5.6	41.2
Estonia	5.5	0.23	16.4	12.44	15.1	18.4
Latvia	4.3	0.15	6.8	3.47	6.1	42.5
Lithuania	7.2	0.16	10.8	3.75	7.3	21.2

[2] man-made emissions of the 'Kyoto basket' of greenhouse gases, EU average 8.4 tCO_2/cap (2016); [3] 2017 data

As shown in Table 3, renewable energy responds for a high share of energy supply in the Nordic-Baltic countries, which is far beyond the EU average of 13.9%. In Latvia, Norway, and Sweden, this figure is as much as three times higher than the EU average.

All countries except Denmark have large forest resources (biomass). Just over half of the total Nordic-Baltic land area (129 million hectares) is classified as forest (65 million hectares) by FRA 2000 (Global Forest Resources Assessment 2000). The two countries with the highest electricity consumption, Norway and Sweden, have plenty of hydropower (see Table 3). The share of wind energy is increasing and most of the countries have good or very good wind resources. The low population density means that there is ample space for onshore wind turbines where there is little conflict with other human activities.

As can be seen in Table 3, renewable energy sources – hydro, wind, and biomass – now account for close to 70% of total electricity supply. In contrast to that, fossil-fuel-based power production only accounts for a little more than 10%, which is less than a quarter of the average share in the EU. When it comes to variable renewable energy (VRE) such as solar and wind power, the Nordic-Baltic region is still below the EU average. The large share of hydropower creates less of a need for new power generation capacity. However, large differences exist among the seven countries – Denmark is the country with largest share of wind energy in the world (almost 50%), and therefore has much experience with large-scale integration of VRE into the power system. Sweden also has a significant and increasing supply of wind power.

Table 3: Electricity mix in the Nordic-Baltic region in 2016 (TWh).

Country	Fossil	Nuclear	Hydro	Biomass	VRE	Production	Consumption
Denmark	11	0	0	4	14 (47%)	30	35
Finland	13	22	16	11	3 (5%)	66	85
Norway	3	0	143	1	2 (1.4%)	149	133
Sweden	3	61	61	10	16 (11%)	152	140
Estonia	9	0	0	1	1 (10%)	11	9
Latvia	1	0	0.5	0.5	1 (25%)	4	7
Lithuania	3	0	3	1	0 (0.5%)	7	12
TOTAL	44	83	223	27	36	416	419
Share(%)	10.5	21.1	53.6	6.5	8.7		
EU-28(%)	48.9	25.7	12.1	in fossil	13.4	3100 (TWh)	2786 (TWh)

Renewable energy and the power sector should play a major role in a clean energy transition in the future, but energy efficiency measures also have a large potential due to the high energy intensities in several of the countries in the region. The power sector in the Nordic-Baltic region is already almost free of fossil fuels (~90%) and has a large potential for expanding power production from renewable sources. Therefore, expanding the electrification of other sectors such as heat and transport can foster the decarbonisation of the entire energy system. In other words, as deep decarbonisation pathways and policies are expected to increase both the role of electricity and the share of VRE, the region has an obvious potential to serve as a test case for the future European energy system.

Technology development

Electricity is expected to become much more central for the energy system to achieve the targets outlined in Section 2, supplying an increasing share of the energy needs of the heat and transport sectors. As there are only limited possibilities for expanding hydropower and nuclear power has limited political support, the increasing amount of electricity will primarily come from renewable energy sources: either biomass or VRE. The Nordic-Baltic region, with large and sparsely populated forest areas and huge both onshore and offshore wind resources, has plenty of both. However forest biomass is very sensitive in terms of its sustainability and the EU's Land Use, Land Use Change, and Forestry (LULUCF) legislation. It is therefore likely that the largest sustainable potential for new renewable energy sources in the Nordics and Baltics can be found in solar and, especially, wind power.

The increasing share of VRE (primarily wind energy) will create a number of flexibility needs that must be satisfied to keep the very high power quality that is common in the Nordic-Baltic region and reduce the cost of achieving climate policy goals. The major VRE technologies – wind and solar – are close to grid-parity. Once parity is attained, it will provide new and cheaper conditions for expanding these technologies without support - outcompeting investments in fossil fuel technologies. However, it will also bring new technical and regulatory challenges for keeping a stable power system. Some, although not all, flexible technologies that are necessary to handle an increasingly variable electricity supply coupled to heat and transport are expected to be commercially viable in the early twenties. Table 4 lists the main technologies in a future energy system with much more VRE and indicates when they are expected to become commercial.

Table 4: When are different technologies expected to become commercial (grid-parity)?

Technology	2020-2025	2025-2030	2030-2035
Wind power	commercial		
Solar PV	commercial		
Electric vehicles	commercial		
Power-to-heat	commercial		
Power-to-gas			commercial
Long term storage		commercial	
Interconnections	commercial		
Smart grid		commercial	

Increasing amounts of wind and solar power will challenge the stability of the power system by increasing the variability of supply. The three demand technologies – electric vehicles, power-to-heat, and power-to-gas – as well as storage can, if used flexibly, help to balance the power system. Here, the question of barriers is crucial.

Related Flex4RES publications

Flex4RES reports:

C. Bergaentzlé, L. R. Boscán Flores, K. Skytte, E. R. Soysal, and O. J. Olsen, ***Framework conditions for flexibility in the electricity sector in the Nordic and Baltic Countries.*** 2016. ISBN: 978-87-93458-46-8

L. R. Boscán Flores *et al.*, ***Framework conditions for flexibility in the Gas–Electricity interface of Nordic and Baltic countries: A focus on Power-to-Gas (P2G)***. 2017. ISBN: 978-87-93458-50-5

F. Karimi, P. D. Lund, K. Skytte, and C. Bergaentzlé, ***Better Policies Accelerate Clean Energy Transition. Policy brief - Focus on energy system flexibility***. 2018. Available: https://www.nordicenergy.org/article/better-policies-accelerate-clean-energy-transition/ ISBN: 978-87-93458-56-7.

D. Møller Sneum, D. Blumberga, J. Katz, and O. J. Olsen, ***Framework conditions for flexibility in the individual heating-electricity interface***. 2017. Available: http://www.nordicenergy.org/publications/framework-conditions-forflexibility-in-the-individual-heating-electricity-interface/ ISBN: 9788793458499

D. Møller Sneum, E. Sandberg, E. R. Soysal, K. Skytte, and O. J. Olsen, ***Framework conditions for flexibility in the district heating-electricity interface***. 2016. ISBN: 978-87-93458-42-0

L. Sønderberg Petersen, R. B. Berg, C. Bergaentzlé, S. Bolwig, and K. Skytte, Eds., ***Smart grid Transitions: System solutions and consumer behaviour***. Department of Management Engineering, Technical University of Denmark, 2017. ISBN: 978-87-93458-51-2

Published conference articles:

L. R. Boscán Flores, K. Skytte, and E. R. Soysal, ***Flexibility-friendly support policies: A Nordic and Baltic perspective***, in 2017 14th International Conference on the European Energy Market (EEM), 2017, pp. 1–7. DOI:10.1109/EEM.2017.7981856 ISBN: 978-1-5090-5499-2

Podcasts:

P. Lund, D.M. Sneum, ***Policies for flexibility: A Flex4RES perspective. What have violins to do with flexibility and sector coupling?***

K. Skytte, D.M. Sneum, ***The future Nordic energy system. Water as storage and flexibility provider - flushing batteries away***.

4.2 Flexible energy systems

To reach the ambitious energy and climate goals of a carbon-neutral energy system in the Nordic and Baltic countries, a large share of variable renewable energy sources (VRE) will be deployed, especially wind power, in addition to other traditional, storable renewable energy sources such as biomass and hydropower. By nature, the temporal supply of wind power is highly variable because it is determined by weather conditions; it is uncertain due to forecasting errors, and it is location-specific, as the primary energy carrier cannot be transported like coal or biomass.

Such properties imply major integration and interfacing challenges for wind power in the energy system. The quantity of wind power produced depends heavily on available wind resources, implying that other parts of the energy system have to act flexibly to counteract this variability in order to ensure a reliable and cost-effective energy system.

In Flex4RES, electricity supply or demand is considered flexible when it is possible to regulate the increase or the decrease of generation or consumption in response to system conditions (market signals). That means flexibility is used as a measure to keep the balance between generation and consumption of electricity, balancing out the variability from variable supply and demand (Figure 17).

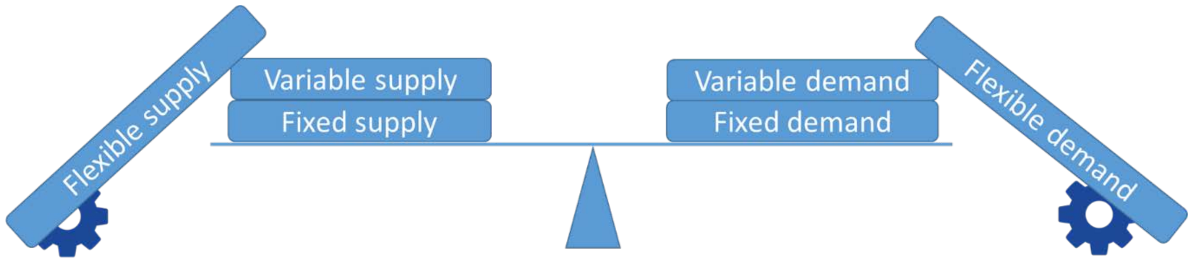

Figure 17: Flexible supply and demand balance the variability in generation and consumption of electricity

Flexibility can be obtained locally or it can originate from other regions through transmission lines to surrounding countries. Furthermore, the supply and demand of electricity can satisfy final electricity consumption directly or be coupled to the heat, gas, or transport sectors, or even storage facilities.

Although flexibility is relevant from a level of seconds to an annual level, in Flex4RES the analyses are limited to flexibility on an hourly level.

VRE generation variability and needs for flexibility

The CorRES (Correlations in Renewable Energy Sources) tool, which combines meteorological time series and stochastic simulation, was used to simulate wind and solar generation (*variable supply, VRE*) time series in the Flex4RES project. The tool can be used to model both current and future scenarios, and it provides hourly VRE generation time series, taking into account the weather-dependent spatiotemporal dependency structures. As VRE generation is becoming the norm, these generation patterns drive the flexibility needs of the system.

Aggregate load and VRE generation for an example scenario year are shown in Figure 18. The figure shows what the scenario VRE installations would have generated in a meteorological year similar to 2012.

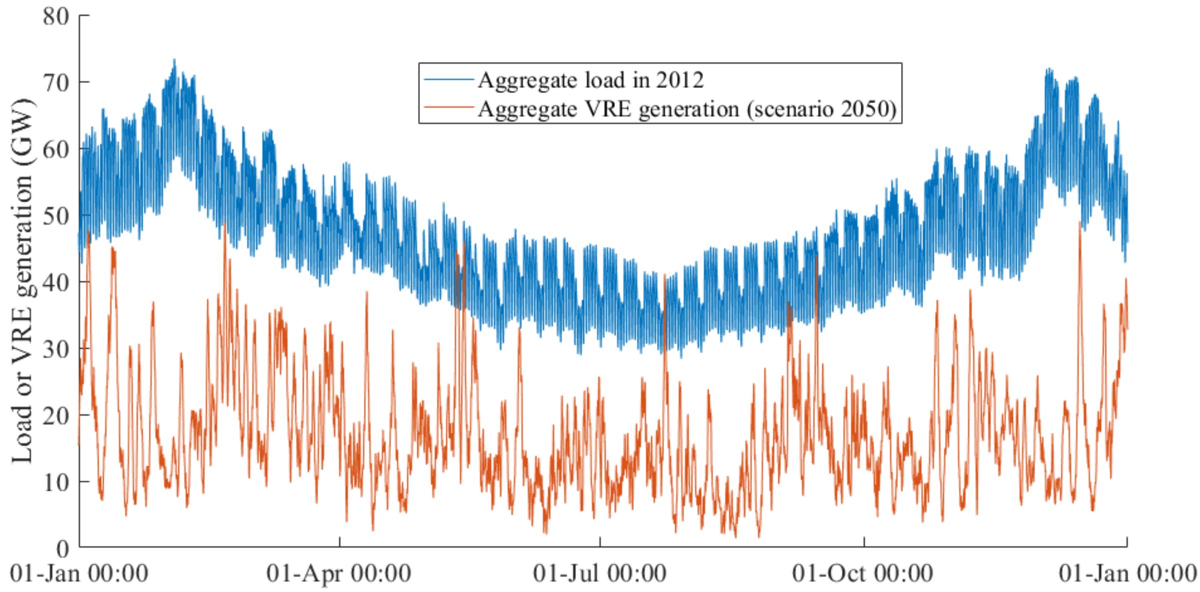

Figure 18: The aggregate load time series of 2012 and the aggregate VRE generation of the 2050 scenario for the analysed Nordic and Baltic countries. The VRE generation is simulated for the VRE installation scenario 2050 using historical meteorological year of 2012.

In all Flex4RES scenarios, the standard deviation (SD) of the aggregate hourly residual load (load minus VRE generation) increases notably in 2050 (Koivisto, Das et al., 2019). At the same time, average residual load decreases. Thus, on average, less energy will have to be generated by the other technologies, while the need for flexibility increases. Alternatively, the variability in residual load can be managed by flexible demand (demand-side response), flexible supply (e.g. hydropower with reservoirs), transmission of power to or from surrounding countries, or energy storage.

With more VRE generation capacity installed, the probability of very high residual load decreases (as some VRE generation is usually available during peak consumption). However, there is always the possibility that aggregate VRE generation is zero, and thus the highest possible residual load is determined by peak consumption. This may raise questions considering the incentives to retain enough dispatchable/flexible generation capacity to meet a rare but possible peak residual load (Koivisto, Das et al., 2019).

CorRES allows the impacts of the ratios of wind and solar power, geographical distribution of the installed capacity and VRE technology development to be studied at the system level. When considering a large geographical area, it becomes important to model the spatial correlations in VRE generation, as can be seen in Figure 19: generation from more geographically spread installations are on average much less correlated. The optimised scenarios in Koivisto, Maule et al., 2019 show that a mixture of offshore wind, onshore wind and solar PV leads to lower variability. The negative correlations between solar PV and wind generation make a mixture of wind and solar valuable.

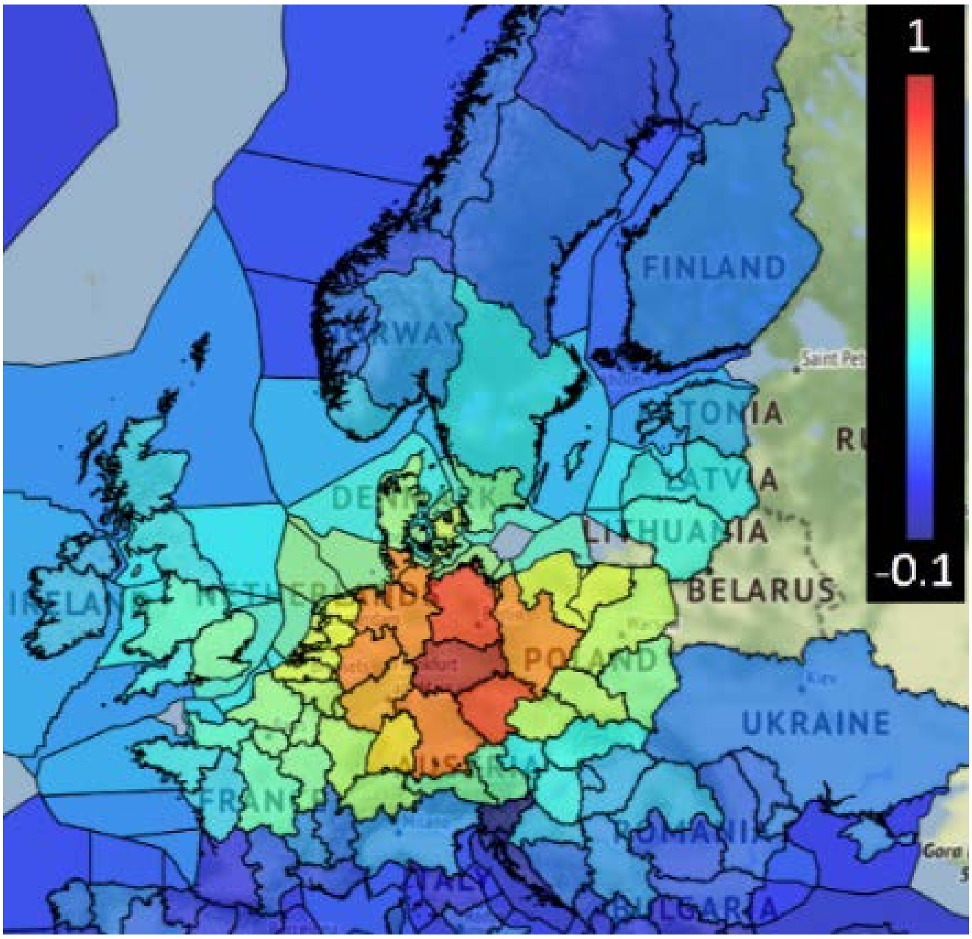

Figure 19: Spatial correlations in wind generation looking from an example German onshore region based on CorRES simulations (Koivisto, Maule et al., 2019).

The results in Koivisto, Maule et al., 2019 highlight the importance of considering expected VRE technology development when assessing the variability of large-scale VRE generation in the future. Also, the results on the optimal geographical distribution of VRE installations highlight the importance of analysing larger geographical regions rather than single countries when planning future energy systems. The results identify benefits to the integration of large geographical areas as VRE shares increase.

Based on the CorRES runs, increasing VRE generation is not expected to significantly increase hourly ramp rates in aggregate residual load in the analysed scenarios towards 2050. However, VRE ramping may still cause challenges locally and, as VRE generation is usually less predictable than load, increasing VRE generation is expected to require more intraday and intra-hour balancing.

Electricity prices and flexibility

The price in the wholesale market Nord Pool indicates the system need for flexibility. Simply put, flexibility in the electricity market can be understood as the ability to react to market signals by increasing or decreasing production and consumption in response to situations of abundance or scarcity. Flexibility is coordinated by prices: high prices signal scarcity, encouraging producers to ramp up generation and consumers to curtail load. Low prices, in turn, indicate abundance, nudging producers to slow generation and consumers to expand demand.

The mechanism described above ensures that both supply and demand work to achieve balance in the market if they act flexibly. To do so, both supply and demand act to minimise price variations: low prices cause supply to fall and demand to rise, pushing prices back up to their previous level; high prices drive supply up and demand down, driving prices back down to their previous level.

This realisation is useful for measuring present flexibility in the electricity market: the more flexibility there is in both supply and demand, the more they act to minimise price variation and the more stable the prices will be. Therefore, price variation is a simple way of measuring flexibility in the electricity market, abstracting it from its more complex technical aspects.

With this in mind, we have developed an indicator that uses the coefficient of variation of prices, a standardised measure of variation given by the ratio between the standard deviation and the mean, to measure flexibility in the electricity market. The indicator is given by the formula $\frac{1}{1+CV[P]}$ in which $CV[P]$ is the coefficient of variation of electricity prices.

The indicator is bounded between zero and one. A value of zero indicates that there is no flexibility in the market and prices are infinitely volatile. A value of one, on the other hand, indicates that there is enough flexibility in the market to completely smooth out price variations: flexibility is perfectly adequate to the needs of the market. For this reason, we have called this measure the Adequate Flexibility Indicator (AFI).

Using hourly data from the Nord Pool database, we have constructed the AFI for each Nord Pool price zone in the Nordics and Baltics. An illustrative map is presented in Figure 20, comparing flexibility across zones.

Before comparing the adequacy of flexibility among zones, it is important to highlight that, given the definition of the AFI, all values calculated for the region are relatively high (minimum of 0.74), indicating that there is no ‘flexibility emergency’ in the Nordics and Baltics as of 2018. Having said that, it is interesting to find out how flexibility is distributed among different Nord Pool zones and what drives that distribution.

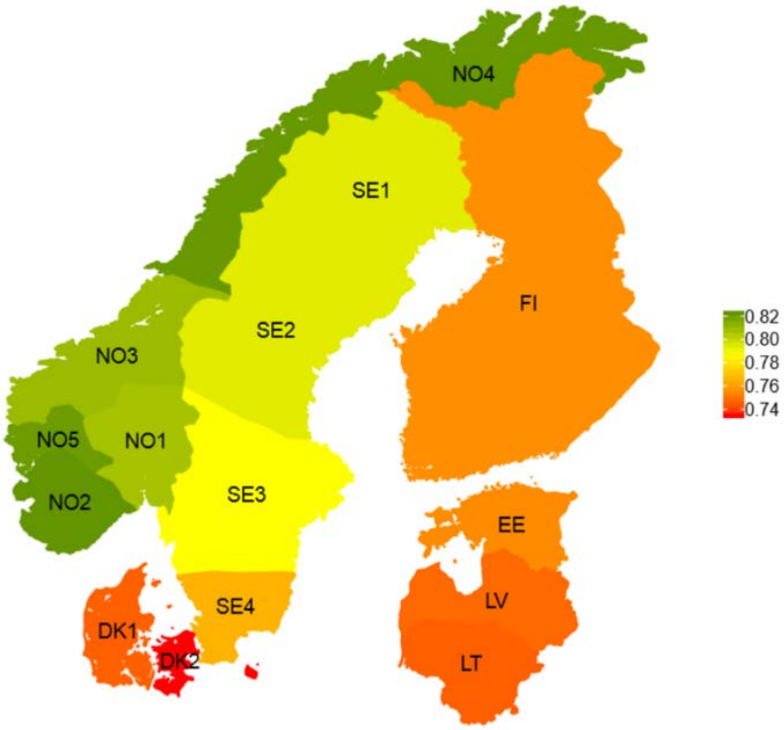

Figure 20: Adequate Flexibility Indicator (calculated using 2018 Nord Pool data).

From the figure, we can see that Norway is the great source of flexibility in the Nordics and Baltics, exhibiting the most stable prices in the region. This is largely due to a very high share of dispatchable hydropower and a prevalence of large industrial consumers who are able and willing to respond to prices.

On the other end of the spectrum we find Denmark, particularly the eastern region DK2; Finland; and the Baltics. In all cases, variable demand is a big contributor to the flexibility challenges experienced in these countries. For Denmark, the high shares of wind energy also increase the volatility of supply and likely increase the need for flexibility.

Sweden lies somewhat in the middle, with the populous southern zones with large amounts of wind power, SE3 and SE4, displaying slightly less adequate flexibility than their hydropower-rich and relatively sparsely populated northern counterparts, SE1 and SE2.

For a more detailed picture of flexibility, we can zoom in on supply and demand separately, analysing how they correlate with price variations. This can be done by calculating the correlation between prices and respectively supply or demand. On the supply side, a positive correlation indicates flexibility: production is ramped up in times of scarcity, when prices are high. The correlation between supply and prices can therefore be used directly as an indicator of supply flexibility. On the demand side, flexibility is indicated by a negative correlation: demand is curtailed in times of scarcity, when prices are high. This means the negative of the correlation between demand

and prices can be used as an indicator of demand flexibility. In this case, a positive value indicates demand flexibility, while a negative value indicates inflexibility. These two measures, of supply and demand flexibility, are shown for the Nordics and Baltics in the year 2018 in Figure 21.

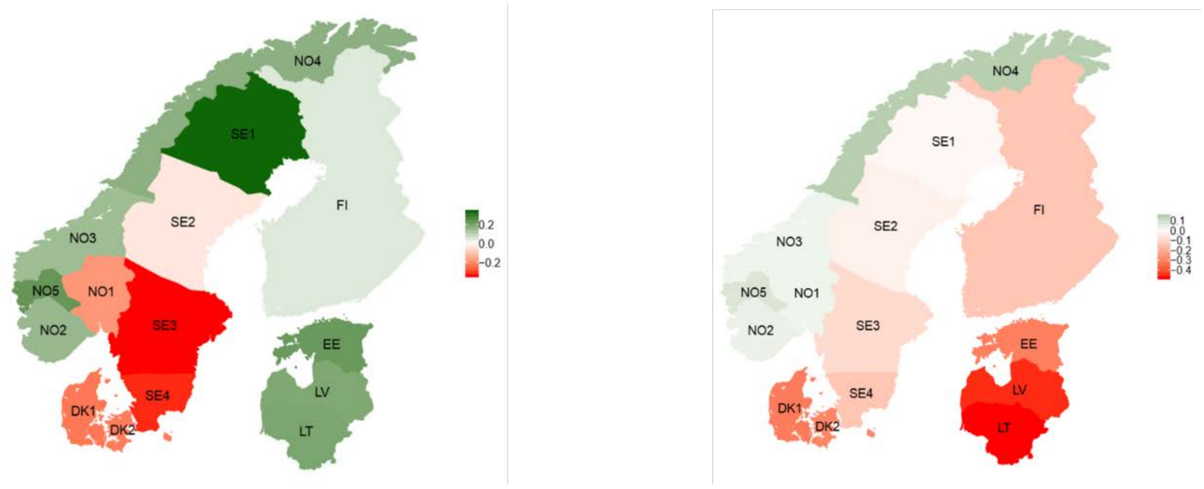

Figure 21: Supply (left) and demand (right) flexibility - year 2018.

This figure complements the stories told by the adequate flexibility indicator (Figure 20). On the supply side (map on the left), inflexibility mainly concentrates in regions with a high share of wind energy, which tends to set prices rather than react to them. This is the case in both Denmark and Southern Sweden. Hydropower is also confirmed as a major provider of flexibility on the supply side, with regions rich in the technology presenting the highest degrees of supply flexibility, notably Norway and Northern Sweden (SE1).

On the demand side (map on the right), perhaps the most noteworthy fact is that inflexibility is far more widespread than on the supply side. Norway is the exception, particularly in the sparsely populated northernmost zone NO4. As noted above, demand inflexibility is largely responsible for the low scores of the AFI in the Baltics and in Denmark, with wind also playing a role in the latter case.

This exercise, in addition to providing a quick overview of the adequacy of flexibility in the Nordic-Baltic region, can be used to evaluate where flexible technology and strategy would find stronger business cases. The lower the AFI, the higher the need for additional flexibility and the stronger the business case for flexibility strategies. An analysis of supply and demand flexibility helps pinpoint on which side improvements are needed. The easiest example to illustrate this point is perhaps that of electricity storage. A battery has a stronger business case the more hours with very low prices it finds to charge and the more hours with very high prices it finds to discharge. In other words, price variability strengthens the business case for batteries. The same is true of other technologies and strategies such as P2H or demand-side management.

Related Flex4RES publications

Flex4RES reports:

E. Blom, and L. Söder. ***Including Hydropower in Large Scale Power System Models***. KTH, 2018. Available from http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1320598&dswid=-4766

A. Crosara, E. Tomasson, and L. Söder, ***Generation Adequacy in the Nordic and Baltic Region: Case Studies from 2020 to 2050***. KTH, 2019. Available from http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1336561&dswid=-9620

M. Koivisto, P. Sørensen, P. Maule, E. Nuño, ***Needs for Flexibility Caused by the Variability and Uncertainty in Wind and Solar Generation in 2020, 2030 and 2050 Scenarios***. DTU Wind, 2017.

K. Skytte, L. Söder, N. Mohammad, ***Methodology of Determine Flexibility Costs and Potentials and major flexibility potentials in the Nordic and Baltic countries***. DTU/KTH, 2018.

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J. Ekström, M. Koivisto, I. Mellin, R. J. Millar, and M. Lehtonen, ***A statistical modeling methodology for long-term wind generation and power ramp simulations in new generation locations***, Energies, vol. 11, no. 9, Sep. 2018. DOI:10.3390/en11092442

J. Ekström, M. Koivisto, I. Mellin, R. J. Millar, and M. Lehtonen, ***A Statistical Model for Hourly Large-Scale Wind and Photovoltaic Generation in New Locations***, IEEE Trans. Sustain. Energy, vol. 8, no. 4, pp. 1383–1393, Oct. 2017. DOI:10.1109/TSTE.2017.2682338

M. Koivisto et al., ***Using time series simulation tools for assessing the effects of variable renewable energy generation on power and energy systems***, Wiley Interdisciplinary Reviews: Energy and Environment, vol. 8, no. 3. John Wiley and Sons Ltd, 01-May-2019. DOI:10.1002/wene.329

E. Nuno, M. Koivisto, N. Cutululis, and P. Sorensen, ***On the Simulation of Aggregated Solar PV Forecast Errors***, IEEE Trans. Sustain. Energy, vol. 9, no. 4, pp. 1889–1898, Oct. 2018. DOI:10.1109/TSTE.2018.2818727

K. Skytte and L. Bobo, ***Increasing the value of wind: From passive to active actors in multiple power markets***, Wiley Interdisciplinary Reviews: Energy and Environment, vol. 8, no. 3. John Wiley and Sons Ltd, 01-May-2019. DOI:10.1002/wene.328

K. Skytte and P. E. Grohnheit, ***Market prices in a power market with more than 50% wind power***, in Studies in Systems, Decision and Control, vol. 144, Springer International Publishing, 2018, pp. 81–94. DOI:10.1007/978-3-319-74263-2_4

L. Söder, ***Requirements for Strategic Reserves in a Liberalized Market with Wind Power***, in Electricity Markets, Renewable Generation and Software Agents: Traditional and Emerging Market Designs, Springer, Cham, 2018, pp. 165–185. Available: http://link.springer.com/10.1007/978-3-319-74263-2_7 DOI:10.1007/978-3-319-74263-2_7

E. Tomasson and L. Soder, ***Generation Adequacy Analysis of Multi-Area Power Systems with a High Share of Wind Power***, IEEE Trans. Power Syst., vol. 33, no. 4, pp. 3854–3862, Jul. 2018. DOI:10.1109/TPWRS.2017.2769840

Forthcoming articles:

J. Ekström, M. Koivisto, I. Mellin, R. J. Millar, M. Lehtonen, ***A Vector Autoregressive Based Methodology for Wind Generation and Power Ramp Analysis in New Locations***. Submitted for publication.

H. Koduvere, S. Buchholz, and H. Ravn, ***Constructing aggregated time series data for energy system model analyses.*** Submitted for publication.

Published conference articles:

M. Koivisto, N. Cutululis, and J. Ekström, ***Minimizing Variance in Variable Renewable Energy Generation in Northern Europe***, in 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), 2018, pp. 1–6. DOI:10.1109/PMAPS.2018.8440369 ISBN: 978-1-5386-3596-4

M. Koivisto, P. Maule, N. Cutululis, and P. Sørensen, ***Effects of Wind Power Technology Development on Large-scale VRE Generation Variability***, in 13th IEEE PES PowerTech Conference, Milan, Italy, June 2019.

M. Koivisto, P. Maule, E. Nuño, P. Sørensen, and N. Cutululis, ***Statistical Analysis of Offshore Wind and other VRE Generation to Estimate the Variability in Future Residual Load***, in Journal of Physics: Conference Series, 2018, vol. 1104, no. 1. DOI:10.1088/1742-6596/1104/1/012011

E. Nuño, M. Koivisto, N. Cutululis, and P. Sorensen, ***Simulation of regional day-ahead PV power forecast scenarios***, in 2017 IEEE Manchester PowerTech, 2017, pp. 1–6. / DOI:10.1109/PTC.2017.7981155 ISBN: 978-1-5090-4237-1

D. Risberg and L. Soder, ***Hydro power equivalents of complex river systems,*** in 2017 IEEE Manchester PowerTech, 2017, pp. 1–6. DOI:10.1109/PTC.2017.7981057 ISBN: 978-1-5090-4237-1

4.3 A renewable-energy-friendly design for the power market

As mentioned in the previous chapter, operation and investment decisions should be driven by sound market signals that accurately reflect the need for flexibility and capacity. Using a well-designed numerical electricity system model makes it possible to identify an efficient electricity supply system, i.e. a system that supplies the demanded electricity at least cost. But the least-cost configuration of such an electricity system model implicitly assumes a possibly large number of transactions between different producers as well as between producers and users of electricity. However, for these transactions to be realised in the real world, there must be suitable trading arrangements. These include market places, trading rules and definitions of the traded products. In addition, the model solution implicitly assumes that the market in which the trading takes place is competitive, i.e. that no single producer or user can significantly affect the market price of electricity.

After major electricity market reforms in Norway, Sweden, Finland, and Denmark in the 1990s, there is a well-functioning, integrated, multi-country market for electricity, Nord Pool, although there is still a national TSO (Transmission System Operator) in each Nordic country responsible for balancing the system in real time. However, the design of the Nordic electricity market reflects the conditions prevailing at the end of the 20th century. Thus, the market is designed for an electricity supply system dominated by a significant amount of dispatchable hydropower (flexible supply) and a fair amount of nuclear power producing base-load electricity.

In contrast, the expected future electricity production in the Nordics will have a very significant share of variable supply from wind power and some solar power. As a result, the properties of the electricity supply system will change in a very significant way. The key words are increased variation and increased uncertainty on the supply side of the market. This development, to be described in some detail below, calls for minor and possibly major changes of both the overall design of the electricity market and various aspects of the trading practices. Part of the Flex4RES project has been devoted to these issues. The analysis, findings, and recommendations are briefly presented in this section of the report.

Current electricity market design and trading patterns in the Nordics

The current electricity market in the Nordics is designed as a sequence of forward markets and a real-time market (also called Regulating Power market) as illustrated in Figure 22 below. The day-ahead ("Elspot") and intra-day ("Elbas") markets are in general designed and operated by the company Nord Pool, while the real-time markets are operated by the national TSOs. The traded product is MWh of electricity per hour, i.e. hourly contracts for delivery at a specific future hour. However, Nord Pool is soon (by end 2020) to implement 15 minutes imbalance settlement periods, implying that both the Regulating Power as well as the Elbas markets will be settled with 15 minutes time resolution.

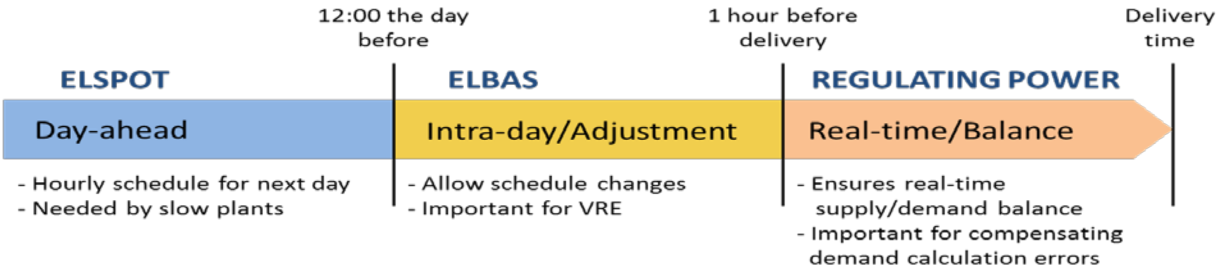

Figure 22: Sequence of physical power markets at Nord Pool.

In addition, transactions in the market for financial derivatives, i.e. forwards, futures, options, etc., take place before the energy markets shown in Figure 22. This market is operated by the company Nasdaq Commodities. These instruments allow market participants to hedge price risks and thus "lock in" the price of sold or bought electricity several years before delivery.

More than 95% of the total supply of electricity is currently traded on the day-ahead market (Elspot), while the quantities traded on the intra-day and real-time markets are quite small. Substantial day-ahead trading in general leads to a largely fixed hourly production schedule for the following day. That, in turn, means that predictions about market conditions (demand and supply conditions) one day ahead are generally quite accurate. If that were not the case, there would be more intra-day and even real-time trading.

However, wind and solar power output predictions are uncertain until only a few hours before delivery. Thus, one likely effect of increased shares of wind and solar power is that intra-day trading will increase, while day-ahead trading will decrease. However, this will not be a result of regulations, but the outcome of the choices made on commercial grounds by the market participants.

The impact of a high share of wind and solar power

The impact of a large-scale introduction of intermittent power can be illustrated by data for Sweden. According to current projections, around 40% of the produced electricity in Sweden will be generated by wind and solar power in 2045. Below, ENSTOE data and TYNDP scenarios are used to simulate supply and demand conditions in January 2045. The time pattern of demand is assumed to be the same as in 2017, while the level of demand is somewhat higher. In the figure, demand is represented by the dark line, while the coloured areas show the hourly production levels for each technology.

Figure 23 shows the supply and demand conditions in January 2017, i.e. in a year when hydro and nuclear power still dominated electricity production in Sweden. Thus, the production in hydro and nuclear power plants supplied most of the load, while the contribution of wind power was quite small. The category "other" includes solar power and CHP plants. As always, demand varied significantly and systematically between day and night, between workdays and holidays, and between summer and winter. Note that there was an almost constant level of nuclear power production, never below 8,000 MWh/h, while hydropower production was following load to balance the system. A similar pattern prevailed during the other months of the year.

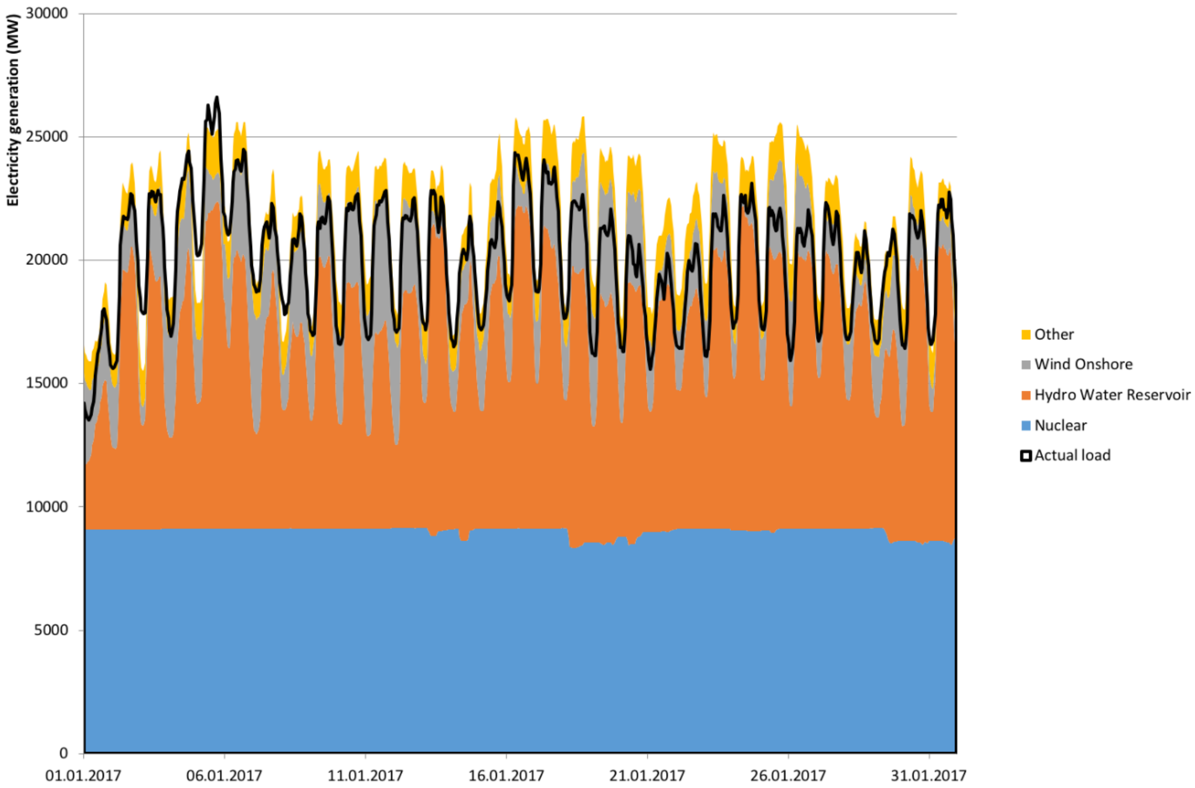

Figure 23: Actual electricity supply and demand in January 2017. Source: Calculations presented in Bergman & Le Coq (2019)

When the nuclear power plants are phased out (in accordance with current plans) and wind and solar power capacity continues to grow the situation becomes much different. Figure 24 shows the projected situation in January 2045, i.e. a point in time when all the Swedish nuclear power plants are expected to be shut down. As in Figure 23 the dark line represents demand while the orange represents hydropower and the grey wind power production. The key assumption here is that nuclear power is fully phased out, while significant additions of wind and solar power capacity have been made in accordance with current plans.

As shown in Figure 24, the level of wind power production varies between approximately 2,000 MWh/h and 15,000 MWh/h (in January there is almost no solar power production in Sweden). Thus, the production in hydro and CHP power plants will have to vary equally as much in the opposite direction to balance the system. To induce flexible supply from hydro and CHP power production to increase, the day-ahead and/or intra-day prices must increase. If, in the opposite case, production should decrease, so must prices. Thus, the large-scale introduction of intermittent wind and solar power will be accompanied by increased electricity price volatility.

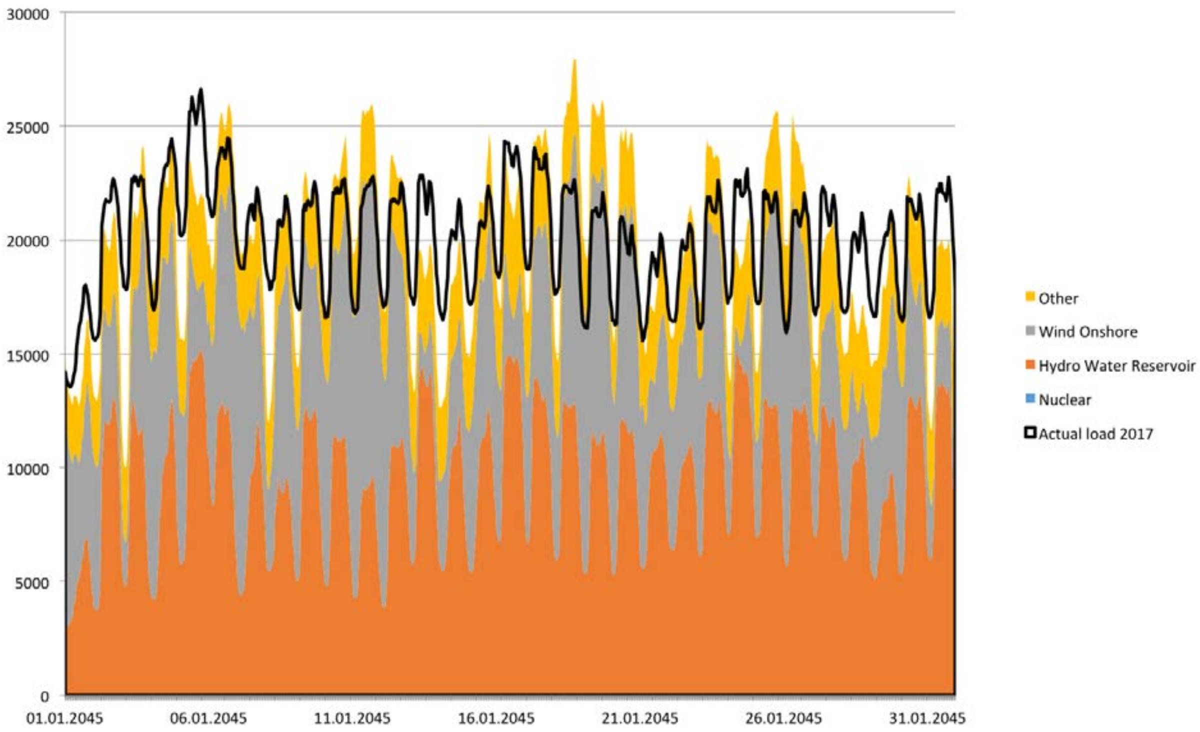

Figure 24: Projected electricity supply and demand conditions in January 2045. Source: Calculations presented in Bergman & Le Coq (2019).

The extent of price volatility, however, depends on several factors. One is access to flexible hydropower, where more flexible hydropower means less price volatility. Another factor is the short-run price sensitivity of demand, where higher price sensitivity means less price volatility. A third factor is access to storage facilities and/or cross-border trade options, where more storage capacity and/or cross-border trade options means less price sensitivity. In the long term, technological change enabling customers to participate in the market in (near) real time and the development of cost-efficient, large-scale storage facilities may significantly reduce the price volatility resulting from high shares of wind and solar power. However, to be profitable, these technologies rely on a certain amount of price volatility.

Another issue related to increased electricity price volatility is whether liquid markets for electricity-market financial derivatives, which allow market participants to hedge price risks, will continue to exist. There are two types of trading in the market for such derivatives. One is trading by power producers, retailers, and major consumers of electricity wanting to hedge electricity price risks. The other is so called ‘proprietary trading’ by market participants, normally without direct connection to power production or electricity-intensive industries, who merely seek to benefit from electricity price volatility.

Thus, if the movement of electricity prices is negatively correlated with the prices of one or several other assets, electricity derivatives help to stabilise the value of certain portfolios of financial assets. Proprietary trading is important, as it adds liquidity to the market for electricity-related derivatives, and is a key factor for the functioning of electricity markets with high shares of renewable electricity.

Safeguarding security of supply

Like most European electricity markets, the Nordic market is an energy-only market (EOM), i.e. a market where generators are paid for the energy (MWh) they deliver but not for the capacity (MW) they keep available. In effect, this means that economic incentives (such as high peak-period prices and imbalance penalties) rather than regulations are expected to ensure that available peak-load capacity is enough to maintain desired levels of security of supply. Figure 24 shows that wind power production can be quite low for several consecutive days. As demand response primarily has the function of shifting demand by a couple of hours or so, the safeguarding of security of supply would have to be based on imports, storage, or additional domestic production capacity.

One of the key issues in the context of increasing shares of wind and solar power is whether the current system will continue to work in an acceptable way or if a capacity mechanism or some other arrangement will be needed to ensure security of supply. The current discussion on this topic is focused on the so-called 'missing money problem'.

The missing money problem in a nutshell

An increase in wind and solar generation (with zero marginal cost) is likely to reduce the general price level as well as the yearly number of operating hours of more flexible power plants. Unless prices are sufficiently high during these hours, the annual revenues of e.g. thermal peak-power plants will not cover their capital costs - preventing investments in new capacity.

Due to regulations and lack of public acceptance, peak period prices may not be allowed to be high enough to compensate for the lower number of operating hours. Thus, from the point of view of investments in peak capacity, increased shares of intermittent power will be associated with increased risk for capacity shortage during peak-demand periods.

The missing money problem is the key argument for adding a capacity mechanism, i.e. a mechanism for paying generators to keep capacity available during peak demand periods. The mechanism may also remunerate operators of storage facilities and major consumers who are prepared to reduce their consumption when capacity shortage is imminent. Thus, in a market design with a capacity mechanism, generators are paid not only for the MWhs they deliver, but also for the MWs they keep available.

However, while the addition of a capacity mechanism is a regulatory approach to the security of supply problem, there may alternatively be a market-based solution in the form of power purchase agreements (PPAs). In short, PPAs are bilateral agreements between a buyer and a seller of energy to trade a specific amount of energy in the future for a fixed price.

If designed properly, these contracts can serve as a means for demand to express its preference for reliability: if consumers are willing to pay a higher price to support more capacity, and therefore increase reliability, that preference will result in higher PPA prices. On the supply side, this means a higher price guaranteed by the PPA, which provides the needed incentives for investment into capacity.

This eliminates the missing money problem by obviating the need to cap prices to protect consumers from the very high prices needed in peak hours to support capacity: the PPA accomplishes that through its fixed price. At the same time, the PPA also ensures generators do not depend on these few peak hours by providing them with a steady stream of revenues. In return, producers commit to selling energy at a lower price (the fixed PPA price) during peak events. This way, it protects demand from high prices and producers from low prices, revealing an average price that is able to sustain the required capacity.

Despite being a valuable instrument, these contracts, as suggested above, must be designed carefully. The risk is that PPAs designed to minimize price risk might erase the incentives needed to activate flexibility in the system. If consumers who sign PPAs face a fixed price on the margin, there is no incentive to reduce consumption at times of scarcity (when the market price is high) or increase it in times of abundance (when it is low). The same is true of producers. In a system dominated by variable renewable energy, however, flexibility is key to balancing demand and supply at every moment.

To preserve incentives for flexibility while also providing a hedge to price variation, it is therefore important that PPAs offer a fixed price for the units covered by the contract all the while maintaining exposure to the market price on the margin.

This is achieved by a rather simple design: the consumer pays a fixed price for a fixed quantity of energy every period. If their consumption is below this level, they can sell the spare kWhs on the market. The producer, in turn, receives the fixed price for a fixed quantity of energy and has the obligation to deliver it every period. If they are unable to produce it, they have to purchase the remaining kWhs on the market.

To visualize the functioning of this contract, Figure 25 below depicts a load profile and the payments realized under the PPA:

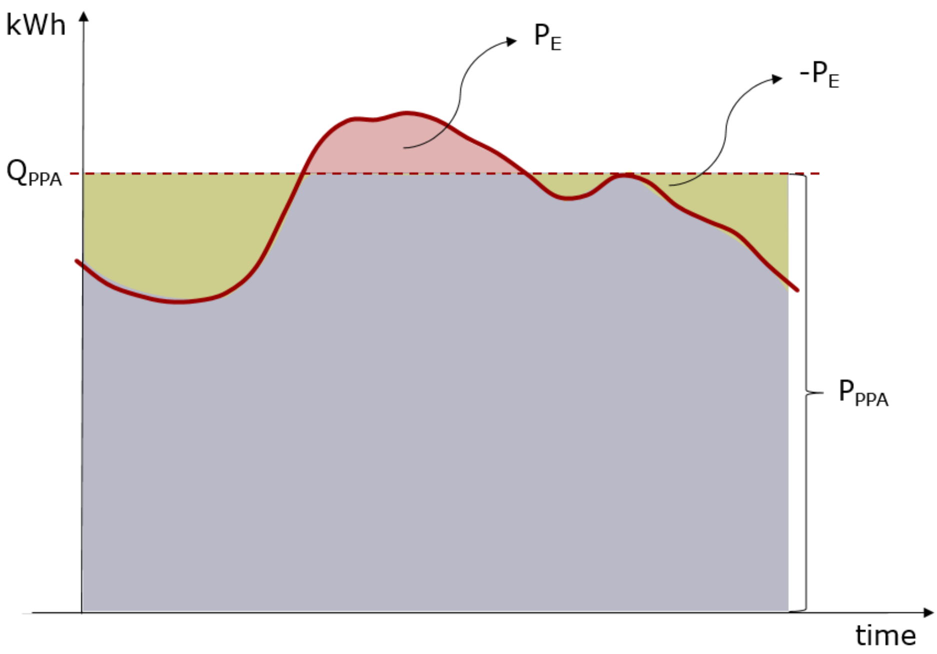

Figure 25: Load profile and prices under a simple PPA. Figure constructed by the authors.

The consumer pays the contracted price (P_{PPA}) for the contracted quantity (Q_{PPA}). For the energy consumed under the limit of the contract (shaded in blue), the consumer only pays this fixed price. For the units contracted but not consumed (shaded in green), the consumer can resell the units and receives the market price (P_E) after having paid the PPA price. For all units above the limit of the contract, the consumer simply buys them on the market and faces the market price. The working of the contract for producers is analogous.

This simple structure ensures that whatever energy producers generate up to the quantity specified in the PPA is bought for the fixed price specified on the contract. If they fail to produce the quantity they have committed to supply, they have the onus of procuring the remainder on the market. Therefore, producing one more unit of energy always implies either receiving the market price or not having to pay it.

For consumers, there is also a fixed price for all energy consumed up to the contracted quantity. Reducing consumption, however, implies being able to sell that unit on the market, which means the decision to reduce consumption is also taken looking at the market price rather than the PPA price.

This way, in spite of having fixed prices guaranteed for units produced and consumed under the limit of the PPA, all actors face the market price on the margin. This ensures that all actors benefit from acting flexibly to balance supply and demand while also protecting consumers and producers from price volatility.

Market Related Policy Recommendations

Overall, the expected development of the electricity sector in the coming years is more likely to alter the way in which existing market arrangements are utilized (e.g. higher volumes being traded closer to real time) rather than precipitating more radical changes in the rules of the game.

That being said, minor adjustments such as expanding the availability of PPAs and other futures/forward contracts, as well as ensuring that their design does not compromise flexibility, might be required. It would also be beneficial to reduce trading time from one hour to fifteen minutes, which would facilitate the maintenance of equilibrium between supply and demand in real time.

Another important consideration is that the relative stability of market arrangements is contingent upon the continued availability of hydropower on the supply side to balance the fluctuation of increasing shares of variable renewables. As nuclear power and CHP plants are decommissioned, particularly in Sweden, hydropower might be called upon more often to serve as base-load generation, compromising its availability to compensate for the relative scarcity or abundance of variable renewable energy.

It is thus important to safeguard enough base-load generation or to ensure more demand-side flexibility (e.g. by smart sector coupling) in the system to allow hydropower plants to absorb these supply fluctuations. This becomes acutely important if deepening European energy integration relies upon Nordic hydro reservoirs to balance variable renewables in the rest of the continent as well.

Finally, if well-regulated markets are likely capable of dealing with energy trade, ancillary services are a different story. With more variable renewables coming online, guaranteeing high power quality and stability is likely to become more challenging. This might require creating or expanding markets for ancillary services or otherwise guaranteeing their adequate provision.

Related Flex4RES publications

Flex4RES reports:

C. Bergaentzlé, L. R. Boscán Flores, K. Skytte, E. R. Soysal, and O. J. Olsen, ***Framework conditions for flexibility in the electricity sector in the Nordic and Baltic Countries***. 2016. ISBN: 978-87-93458-46-8

Published journal articles and books:

A. Roos and T. F. Bolkesjø, ***Value of demand flexibility on spot and reserve electricity markets in future power system with increased shares of variable renewable energy***, Energy, vol. 144, pp. 207–217, Feb. 2018. DOI:10.1016/j.energy.2017.11.146

K. Skytte and L. Bobo, ***Increasing the value of wind: From passive to active actors in multiple power markets***, Wiley Interdisciplinary Reviews: Energy and Environment, vol. 8, no. 3. John Wiley and Sons Ltd, 01-May-2019. DOI:10.1002/wene.328

K. Skytte and P. E. Grohnheit, ***Market prices in a power market with more than 50% wind power***, in Studies in Systems, Decision and Control, vol. 144, Springer International Publishing, 2018, pp. 81–94. DOI:10.1007/978-3-319-74263-2_4

Forthcoming articles:

F. Fausto and K. Skytte, ***Power Purchase Agreements and the Energy Only Market: A Hybrid Design for Future Decarbonized Power Markets,*** Submitted for publication.

Published conference articles:

K. Skytte, C. Bergaentzlé, J. K. Sekamane, and J. Katz, ***Flexible electricity markets for a decarbonised energy system***, Eurelectric-Florence Sch. Regul. Conf., no. June, pp. 20–26, 2017. DOI:10.2870/420547 ISBN: 9789290845775

E. R. Soysal, O. J. Olsen, K. Skytte, and J. K. Sekamane, ***Intraday market asymmetries — A Nordic example***, in 2017 14th International Conference on the European Energy Market (EEM), 2017, pp. 1–6. DOI:10.1109/EEM.2017.7981920 ISBN: 978-1-5090-5499-2

Podcast:

F. Fausto, ***Power Purchase Agreements - Good for the energy system – and for old ladies.*** Available at https://www.nordicenergy.org/flagship/flex4res/flex4res-podcasts/

4.4 Flexible sector coupling to district heating

Sector coupling may expand the potential for flexibility in the power market at a low cost while simultaneously decarbonising the adjacent sectors. A flexible resource of considerable magnitude is district heating (DH), which is widely used in most of the Nordic and Baltic countries. With the right coupling of the Nordic power market to the underlying national and local DH markets, a large amount of flexibility can be cost-effectively generated, enabling the integration of a larger amount of wind and solar power into the system.

Large potentials for DH sector coupling

The Nordic and Baltic countries have a long heating season that makes DH an economical option. DH networks were constructed a long time ago and now account for around half of the total heat supply in most Nordic countries. The exception is Norway, where DH only serves 8% of the heat demand, as individual electric heating has long dominated heat supply (Figure 26).

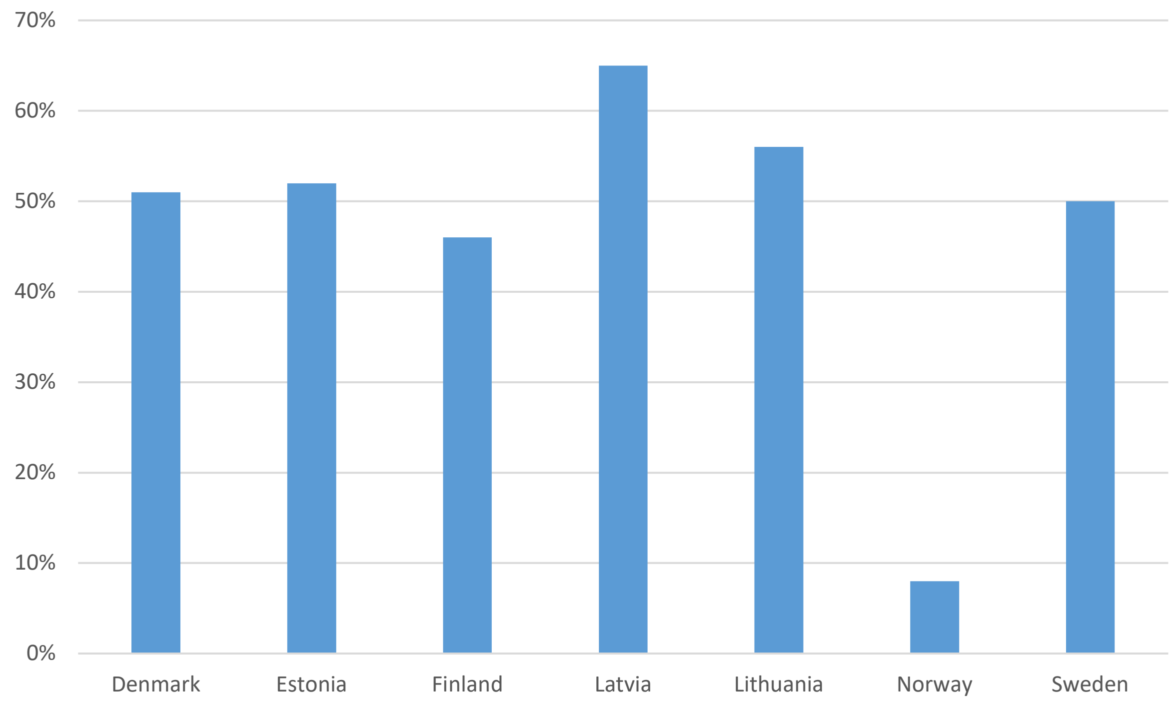

Figure 26: Percentage of DH in the total heat supply in the Nordic and Baltic countries. Source: Euroheat 2015

The average amount of energy generated in DH systems is around half of the electricity supply in the Nordic and Baltic countries (see also Figure 6 and Figure 8 at pages 13 and 16). However, this ratio is higher if Norway is not included in the comparison – with DH consumption per capita in Denmark, Estonia, Latvia, and Lithuania being similar or higher than the per capita consumption of electricity.

In the six countries with a large amount of DH, combined heat and power (CHP) currently contributes with a very large share of the supply (between 41–73% of DH heat supply), whereas the remaining part is mostly supplied by heat-only boilers. Power-to-heat (P2H), heat pumps and electric boilers, account for a non-negligible part of supply of district heating only in Norway (9% and 13% for electric boilers and heat pumps respectively) and Sweden (0.5% and 9%), but are so far insignificant in the other countries.

DH is coupled to the electricity system either through CHP, which sells electricity on the power market, or through power-to-heat plants (P2H; electric boilers and heat pumps) that convert electricity bought on the power market to heat. Such plants can be dispatched and, therefore, are potential providers of flexibility services.

Heat storages add flexibility options to the operation of DH systems. However, the use of thermal storage is presently mainly limited to Denmark, Finland, and Sweden, with limited prevalence in the Baltic countries and absence in Norway.

DH systems with several fuel options or with thermal storage can thus provide flexibility in the following ways:

1) P2H technologies can absorb wind production peaks to serve heat demand and store cheap surplus electricity through energy conversion.
2) Thermal storage or biomass boilers can generate heat in periods with no need for additional flexibility in the power market.
3) CHPs can serve electricity demand when wholesale electricity prices are high due to low wind generation.

Figure 27 illustrates these three cases of the flexible operation of DH.

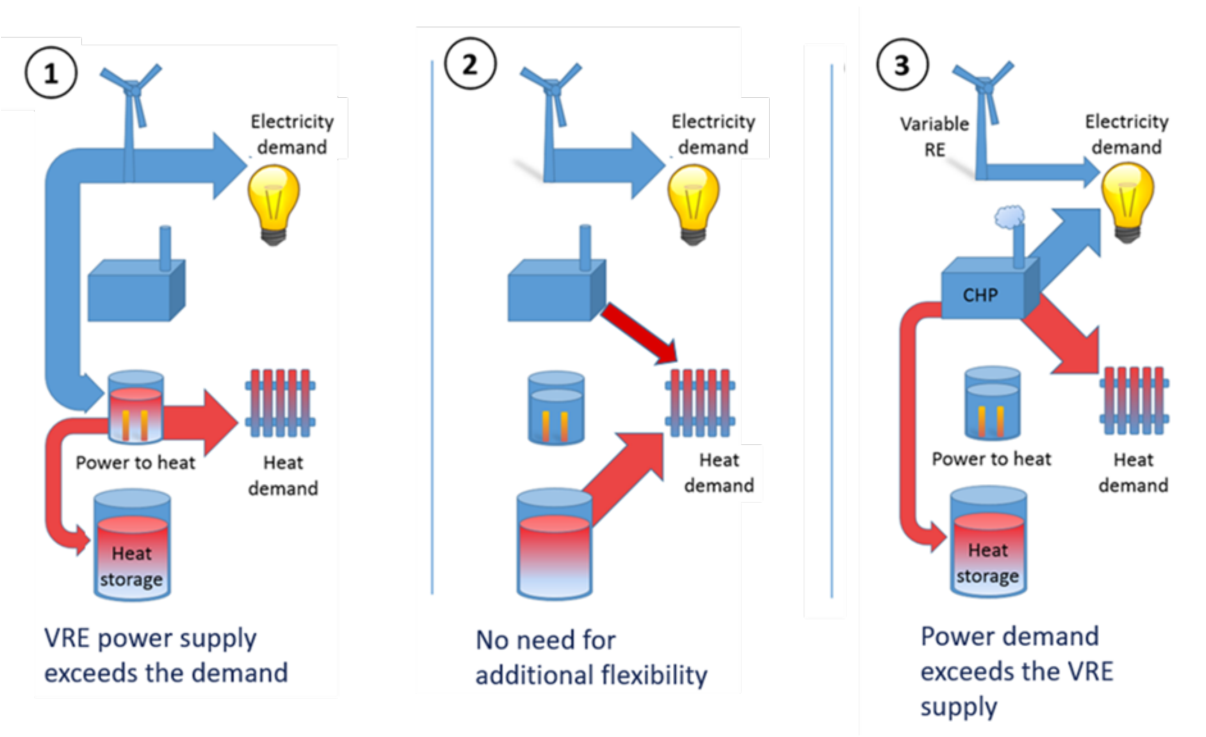

Figure 27: District heating-electricity interface and flexible operation.

Case 1 in Figure 27 illustrates a situation with high wind supply and low electricity prices. Case 3, in contrast, illustrates a state with low wind and high electricity prices.

The flexibility potential in operation of a DH system is determined by two main factors: the set of technologies being used and the costs (e.g. the fuel cost and electricity price). Figure 28 illustrates the relationship between electricity and heat prices in district heating.

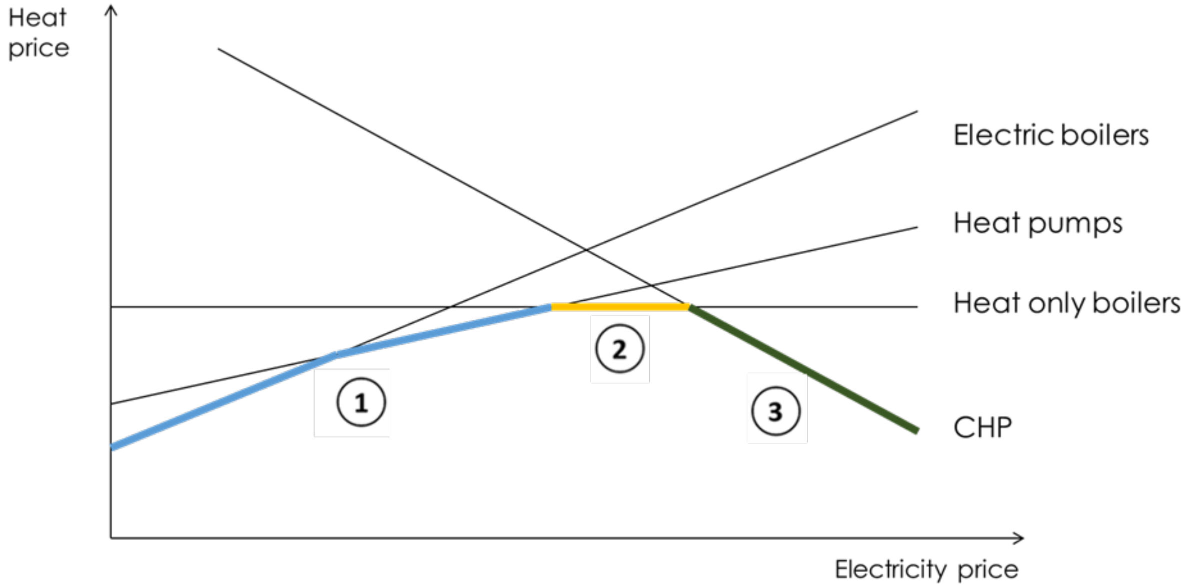

Figure 28: Optimal technology dispatch of DH according to electricity prices and marginal cost.

The figure illustrates the relationship between the marginal cost of heat generation and electricity prices. P2H technologies have an upward sloping cost function – the higher the electricity price, the higher the cost of generating heat. Conversely, CHP plants have higher revenues with higher electricity prices and can therefore generate heat at lower cost – downward sloping function. Finally, the marginal cost of heat-only boilers does not depend on the electricity price and is hence represented by a horizontal line in the graph. The lower bold lines indicate the economically optimal choice of generation technology. P2H is dispatched at low electricity prices - corresponding to case 1 in Figure 27. CHP is dispatched at high electricity prices - corresponding to case 3.

Regulatory barriers to smart energy systems coupling

At present, DH is often organised by local monopolies and regulated within a national framework that can differ much even between historically and politically similar countries such as the Nordic countries. However, as there are large interdependencies between electricity and DH, changing conditions in one sector greatly affects the conditions in the other.

For this reason, improvements in the regulatory frameworks of the DH sector must accompany the growth in VRE in the electricity sector in order for coherent energy markets to develop. This strategy will require well-thought-out market designs and framework conditions implemented in a timely fashion. Otherwise, diverging framework conditions (e.g., heat vs. electricity) may prevent the transition to integrated energy systems and increased flexibility.

In implementing a more suited regulatory framework, special attention must be paid to allowing DH operators to decide which energy resource to use and which future investments to make based on sound market-price signals. While some regulatory frameworks are rather easy to identify and modify, other barriers require further examination.

In Flex4RES, we conducted a survey (Sneum et al. 2016; Karimi et al. 2018) that identified regulatory barriers in the Nordic and Baltic countries. There are several barriers with varying importance, but two stand out:

B1: Insufficient market signals for some stakeholders;

B2: Uneven frameworks for different energy resources.

B1: Insufficient market signals for some stakeholders

Wrongly designed policy and regulatory measures can mask price signals and hinder flexibility across sectors (Skytte et al. 2017). For instance, present inflexible use of storage and P2H can mainly be attributed to unsuitable regulatory frameworks that prevent the transmission of flexibility signals and erase the economic value of operating flexibly. More specifically, most of the current electricity grid tariffs and tax scheme applying to electricity dilute the price signals sent by the power market.

Electricity grid tariffs are the fee paid by the electricity grid users for the transmission and distribution of electricity. Despite the fact that electricity grid costs are mainly driven by fixed, capital costs, current tariff design is to a large extent based on the volume of energy consumed. Similarly, an electricity consumption tax results in an additional charge paid by the final user counted for each kWh of energy consumed, regardless of system or market conditions. This results in an increase in the marginal cost of using electricity as an input for heat generation as well as mask of the price signal from the market.

Figure 29 exemplifies the issue with volumetric tariffs in a district heating system using an electric boiler, a heat-only boiler powered with natural gas and a CHP plant in Denmark as case.

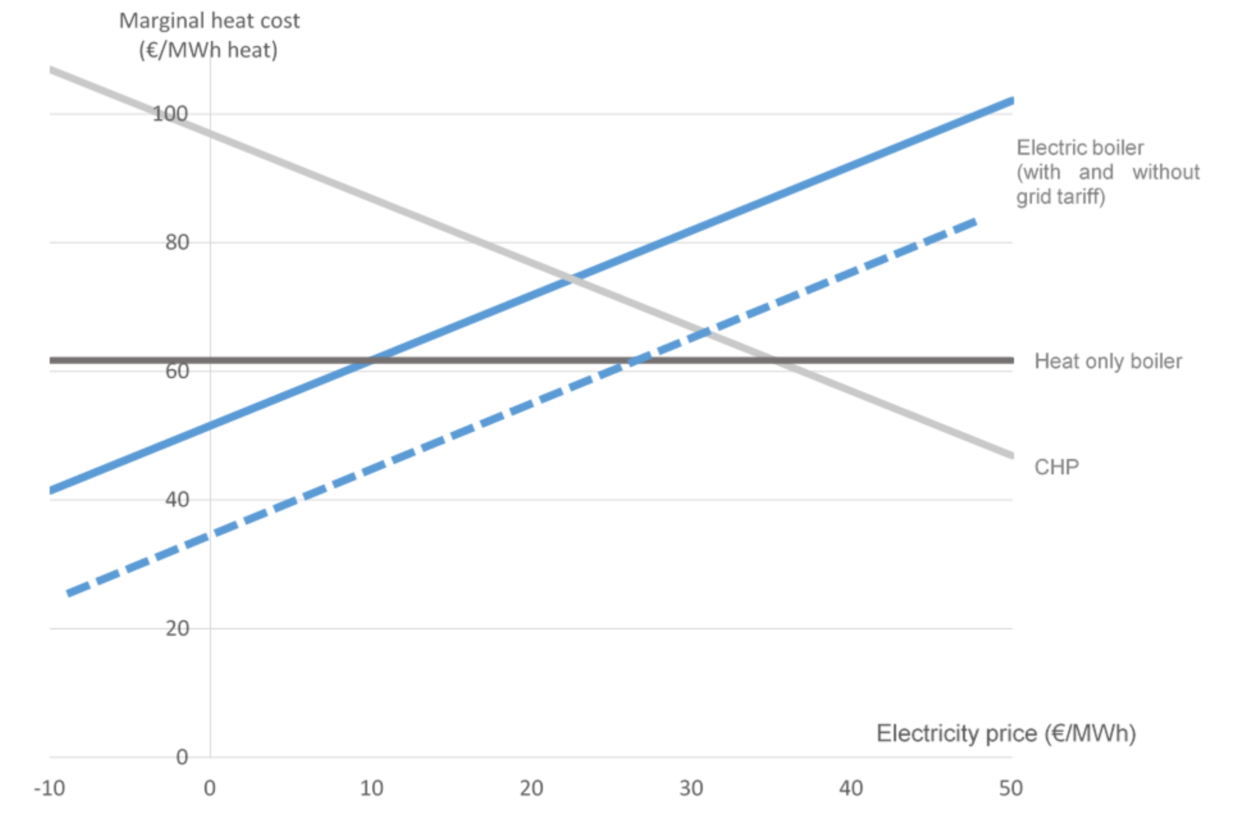

Figure 29: Optimal technology dispatch to produce heat in district heating in Denmark. Exemplified case study (Skytte et al. 2017).

The dashed line shows the marginal cost of electric boilers generating heat excluding the electricity grid tariff, whereas the bold line shows the grid-tariff-inclusive marginal cost. In the current situation, electric boilers are competitive during periods when spot prices are below 10 €/MWh. Assuming a complete removal of the tariff, this technology could compete with spot prices of up to 28 €/MWh - i.e. with operation in many more hours of the year, enabling increased use of (renewable) electricity.

B2: Uneven frameworks for different renewable energy resources

Technology or fuel specific fiscal policies such as tax exemptions, subsidies, and levies often give a comparative advantage to the specific energy resources or technologies, resulting in an unlevel playing field and market distortions.

An example of this is, if biomass-based generation receives a tax exemption, this would likely increase the comparative advantage of the heat generation units using bioenergy over the use of electricity in P2H. Likewise, if electricity used by P2H is charged an electricity tax and potentially a levy for each kWh of electricity consumed that do not apply to the other energy sources used for heat generation.

The growing competitiveness of RES, however, relaxes the future need of applying levies, which are often used to finance subsidies to renewables. Instead, revisions to current tax systems could be made in a way that actively supports flexibility and the fight against climate change.

Flexibility-friendly frameworks in the scenarios

New grid tariff designs can play a critical role in encouraging flexibility in the electricity consumption (P2H) and storage use during the hours when electricity is cheapest (hours with large wind resources). This should further improve the business case for operating and investing in P2H, provided that market price variations are not confounded by competing signals.

In the Flex4RES model analyses, we introduce new flexibility-friendly tax and electricity grid tariff schemes in the Policy and Combi scenarios. They have the purpose of letting market forces drive both investment and flexible operation decisions by allowing price signals from the wholesale market to reach end-users. In both cases, the grid tariff and the electricity tax are charged based on the installed capacity of the P2H equipment while being revenue-neutral for the State and the grid operators.

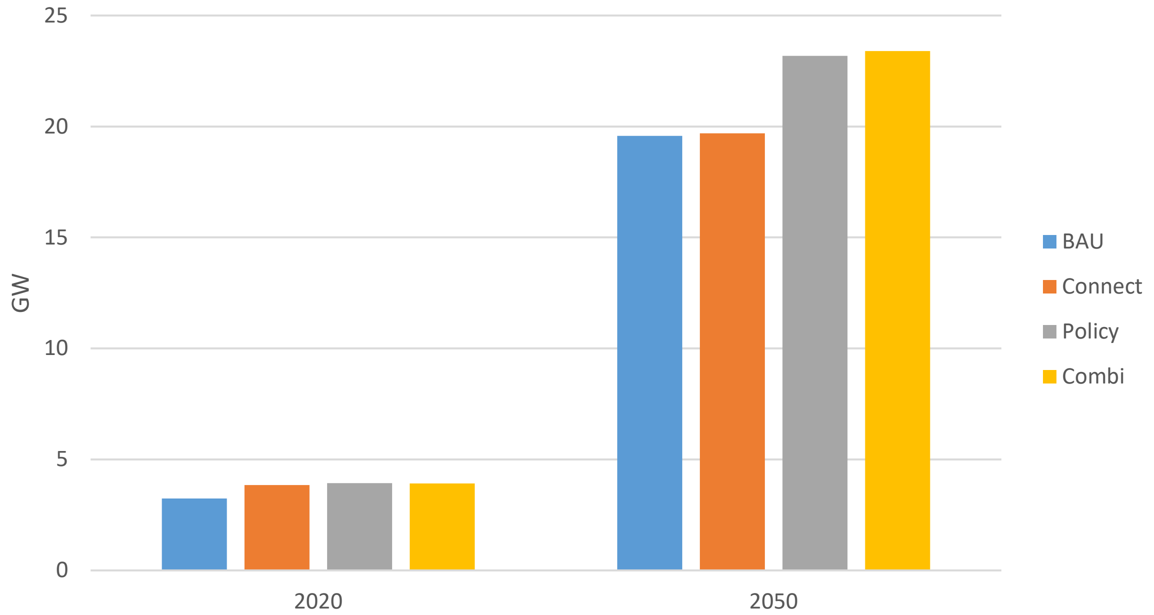

Figure 30: P2H deployment. Installed capacity of P2H in district heating

In all scenarios, both the installed capacity and the production of heat by P2H technologies increase significantly between 2020 and 2050 and are highest in the Policy and Combi scenarios. The most rapid increase of P2H occurs during the 2030s and is correlated with a higher utilisation rate of storage, which indicates that district heating actively contributes to the provision of flexibility. On average (all scenarios considered), the total installed capacity of P2H is multiplied by 9 between 2020 and 2050 and the participation of P2H in the production of heat is multiplied by 17 (Figure 30 and Figure 31).

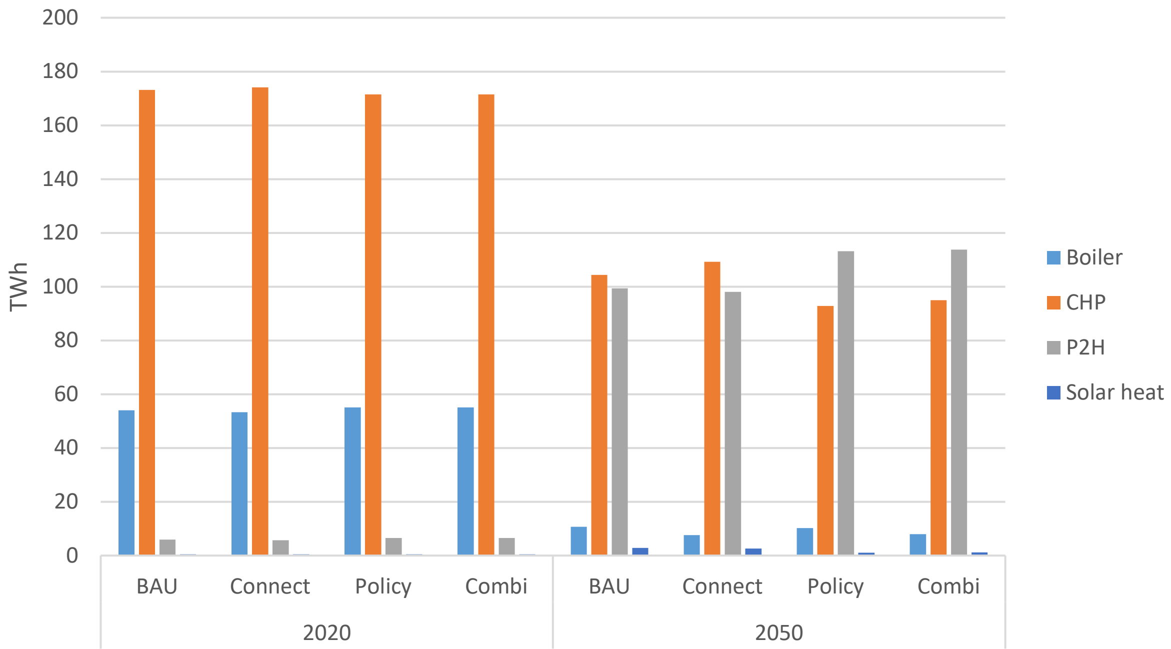

Figure 31: Heat production from different generation technologies

The sharp increase of P2H in all scenarios is largely influenced by steeply increasing CO_2 prices, which affect CHP plants and heat-only boilers powered by fossil fuels. The specific impact of introducing the new grid tariff and tax schemes is captured in Figure 32, which displays, for the three intervention scenarios, the differences in the composition of heat generation capacity with respect to BAU.

It shows that the specific impact of the new grid tariffs and taxes corresponds to an increase of 19% of the total P2H capacity in district heating. This confirms that the removal of regulatory barriers supports the further electrification of the heat sector.

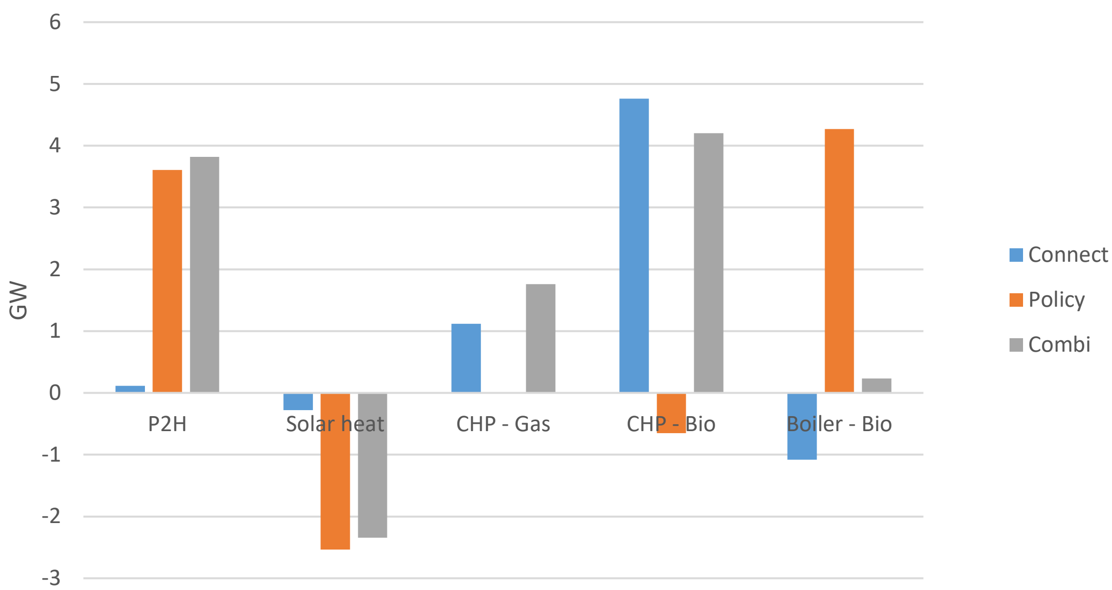

Figure 32: Growth and decrease of the generation capacities in district heating as compared to BAU in 2050

The new regulatory frameworks also affect the technology choice of the DH system (Figure 33). In the Policy and Combi scenarios, the production from P2H is 14% higher than in BAU in 2050.

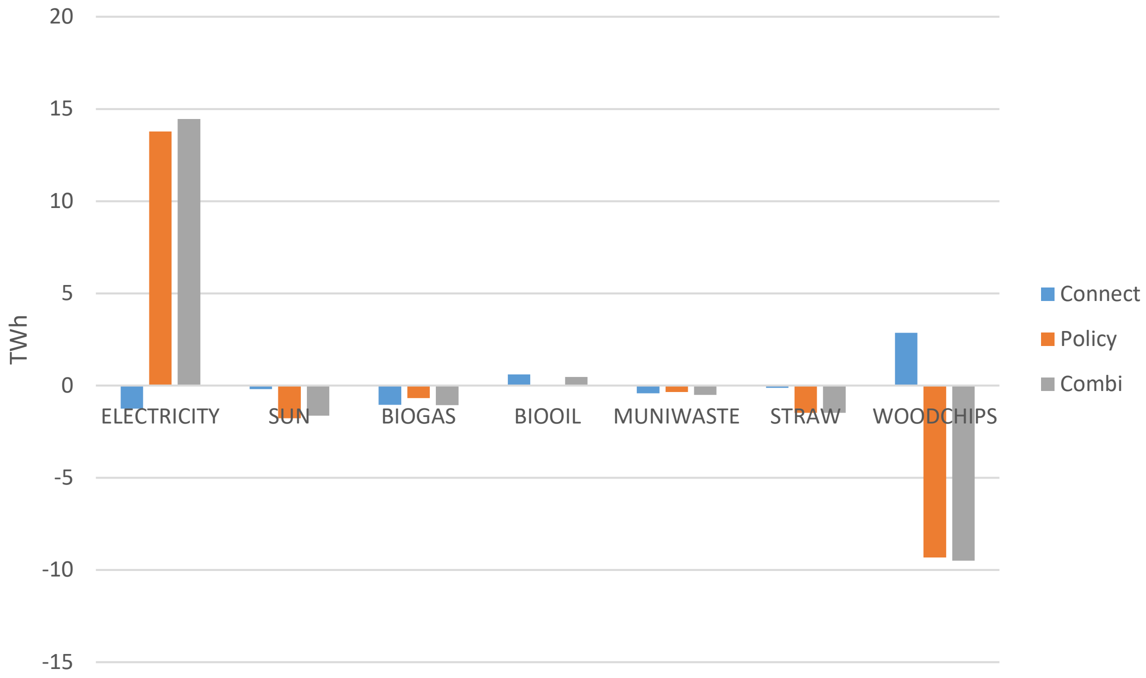

Figure 33: Production of each technology compared to the BAU scenario in year 2050.

While adjustments in the tax and the grid tariff schemes affect the flexible use of P2H in a relatively stable manner throughout the decades, the gap observed between the level of P2H production in the Policy and Connect scenarios is significant. During the decades 2030 and 2040, when the main transmission investments are made, P2H will have its potential significantly limited if increased transmission is not accompanied by the policy changes proposed here. This is shown by the comparison of scenarios Connect and Combi. When transmission is increased but the regulatory framework is not adjusted (Connect), the use of electricity for heat generation actually decreases. Contrarily, if the expansion in transmission happens alongside policy reform (scenario Combi), the use of electricity in the heat sector experiences a sharp increase (see Figure 33).This implies that the main variable affecting the business case for P2H is the regulatory framework rather than the amount of transmission capacity, as evidenced by similar results for both Policy and Combi (see Figure 31 and Figure 32).

In terms of energy resources, the Policy and Combi scenarios present a very similar technology mix for heat generation (Figure 32) with one main exception. Investments in CHP plants are predominantly affected by the policies supporting market coupling and cross-border interconnections since the better market conditions creates new business opportunities for CHP operators (scenarios Connect and Combi are therefore more similar). However, their actual production is mostly affected by the new regulatory framework where the CHP plants powered by bioenergy (mainly straw and woodchips) show a lower participation under the Policy and Combi scenarios (Figure 33).

Finally it seems that solar heat (Sun in Figure 33) is the main loser in terms of share in the energy mix from the flexibility-friendly measures. This can probably be explained by the fact that lower electricity prices occur mostly during the winter, when wind speeds are higher, while solar heat produces more during the summer and therefore requires more seasonal heat storage. When a level playing field lifts barriers to the use of P2H, it quickly becomes the more economical option, displacing solar heat.

Policy recommendations with respect to DH sector coupling

Sector coupling has the capability to play an active role in the deep decarbonisation strategy of the Nordic region, enabling system to use a CO_2-neutral bioenergy-electricity mix combined with flexibility and storage. The key to unlocking more flexibility through electrification is an adequate regulatory framework with flexibility-friendly grid tariff and taxes.

An important upcoming challenge faced by policy makers is the design of these flexibility-friendly framework conditions. In Flex4RES, we implement a capacity-based tariff and tax scheme so that their impact on the different stakeholders concentrates on promoting the flexibility signals while being neutral for the incomes of both the utility and the State. But policy makers may also pursue more than two objectives when setting up these charges. Regardless of the potential underlying policy targets, we urge policy makers to avoid interfering with market signals and to take advantage of the important synergies existing at the interface between electricity and heat. To do so, policy makers should abandon the current sector-specific, in-silo regulation to promote the decarbonisation of the energy system and reap the benefits of sector coupling.

In Flex4RES, we estimate that such policy change could unlock business opportunities for heat electrification and trigger flexible local solutions in district heating. Overall, this results in a 20% increase in flexible P2H in the Nordic DH mix. However, a more integrated policy set-up combining more market (interconnections) and sector coupling (new regulatory framework) clearly promotes the smart integration of electricity and heat while only marginally impacting the electricity sector. This means that the introduction of an adequate regulatory framework is a low-risk solution in terms of loss of surplus for the electricity producers and brings about large surplus gains for the district heating operators, all the while supporting local flexibility solutions.

Related Flex4RES publications

Flex4RES reports:

F. Karimi, P. D. Lund, K. Skytte, and C. Bergaentzlé, ***Better Policies Accelerate Clean Energy Transition. Policy brief - Focus on energy system flexibility***. 2018. Available: https://www.nordicenergy.org/article/better-policies-accelerate-clean-energy-transition/ ISBN: 978-87-93458-56-7.

D. Møller Sneum, E. Sandberg, E. R. Soysal, K. Skytte, and O. J. Olsen, ***Framework conditions for flexibility in the district heating-electricity interface***. 2016. ISBN: 978-87-93458-42-0

Published journal articles and books:

V. Arabzadeh, S. Pilpola, and P. D. Lund, ***Coupling Variable Renewable Electricity Production to the Heating Sector through Curtailment and Power-to-heat Strategies for Accelerated Emission Reduction***, Futur. Cities Environ., vol. 5, no. 1, Jan. 2019. DOI:10.5334/fce.58

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A. Khabdullin, Z. Khabdullina, G. Khabdullina, D. Lauka, and D. Blumberga, ***Demand response analysis methodology in district heating system***, in Energy Procedia, 2017, vol. 128, pp. 539–543. DOI:10.1016/j.egypro.2017.09.004

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D. Møller Sneum, E. Sandberg, H. Koduvere, O. J. Olsen, and D. Blumberga, ***Policy incentives for flexible district heating in the Baltic countries***, Util. Policy, vol. 51, pp. 61–72, Apr. 2018. DOI:10.1016/j.jup.2018.02.001

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F. Wiese et al., ***Balmorel open source energy system model***, Energy Strateg. Rev., vol. 20, pp. 26–34, Apr. 2018. DOI:10.1016/j.esr.2018.01.003

Forthcoming articles:

G. Bazbauers, ***Power sector flexibility through power-to-heat and power-to-gas application***, Submitted for publication.

C. Bergaentzlé, K. Skytte, and P. A. Gunkel, ***Comparative analysis of cross-border and cross-sector approaches for flexibility in the Nordic countries***, Submitted for publication.

I. Graested Jensen, F. Wiese, R. Bramstoft, and M. Münster, ***Potential role of renewable gas in the transition of electricity and district heating systems***, Submitted for publication.

P. D. Lund, V. Arabzadeh, J. Mikkola, and J. Jasiunas, ***Deep decarbonization of urban energy systems through renewable energy and sector-coupling flexibility strategies***, Submitted for publication.

P. D. Lund et al., ***Pathway analysis of a zero-emission transition in the Nordic-Baltic region***, Submitted for publication.

K. Skytte, C. Bergaentzlé, and O. J. Olsen, ***Grid tariffs that facilitate flexible use of power-to-heat***, Submitted for publication.

P. Sorknæs, H. Lund, I.R. Skov, S. Djørup, K. Skytte, P.E. Morthorst, ***Smart Energy Markets - future electricity, gas and heating markets***. Submitted for publication.

Published conference articles:

C. Bergaentzlé, K. Skytte, E. R. Soysal, L. R. Boscán Flores, and O. J. Olsen, ***Regulatory barriers for activating flexibility in the Nordic-Baltic electricity market***, in 2017 14th International Conference on the European Energy Market (EEM), 2017, pp. 1–6. DOI:10.1109/EEM.2017.7981948 ISBN: 978-1-5090-5499-2

C. Bergaentzlé, K. Skytte, J-G. Kirkerud, and O-J. Olsen, ***Electrification and Interconnections for Flexibility: A Comparative Analysis***, in 2019 16th International Conference on the European Energy Market (EEM). IEEE Xplore

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K. Skytte, C. Bergaentzlé, E. R. Soysal, and O. J. Olsen, ***Design of grid tariffs in electricity systems with variable renewable energy and power to heat***, in 2017 14th International Conference on the European Energy Market (EEM), 2017, pp. 1–7. DOI:10.1109/EEM.2017.7981940 ISBN: 978-1-5090-5499-2

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4.5 The role of transmission – the Nordics as drivers of EU decarbonisation

Transmission grids relax the spatial dependency of power generation and service demand. They have traditionally been a part of standard energy infrastructure and played an important auxiliary role in energy system development since the 19th century. The current transmission grid is a major reason for the success of Nordic energy cooperation. Both thermal and renewable-based power generation technologies have benefited from the transmission grids. For example, thermal plants in Denmark have exported electricity to Norway in dry years (low precipitation) and vice versa Norway has exported electricity in wet years. With an increasing share of VRE the additional benefit for short-term exchange of flexibility enlarges the value of transmission lines. Transmission grids are the only option which enables ***spatial flexibility*** and helps utilise clean power beyond borders.

Besides efficient use of existing lines, a prerequisite of a harmonised power market is having sufficient cross-border transmission capacities. For example, it is the European Commission's goal to reach a minimum of 10% electricity interconnections by 2020 with an extension to 15% by 2030 (see also Figure 15 in chapter 4.1). The motivation for developing a more interconnected power market is to utilise energy more efficiently across borders - exploring the specific regional advantages of technologies. Especially in light of the pursuit of carbon neutrality, primary energy sources will largely comprise VRE, which is not evenly distributed either temporally or spatially.. Furthermore, countries like Norway and Sweden possess abundant hydropower resources (Table 3 in chapter 4.1). Hydropower's ability to provide flexibility is valuable to a renewable-rich energy system. Transmission lines allow other countries to benefit from Nordic hydropower flexibility as well as from the vast wind resources in the region, accelerating the energy transition. It reduces the need for backup energy, accelerates decarbonisation and reduces the cost of renewable energy systems.

However, there are also downsides to transmission expansion. Excessively large energy infrastructures are commonly not welcomed. In addition, although overall social welfare improves, interconnection causes welfare redistribution. For example, in power exporting regions, power prices will increase when exports of cheap energy increase. Overcoming these challenges requires international cooperation and perhaps institutional reform. In this chapter, we more thoroughly analyse the benefits and costs of increasing cross-border transmission capacities in the context of the energy transition in Northern Europe. We see cross-border transmissions as one (although not the only) viable option towards a future carbon-neutral system.

Main model assumptions

The European Networks of Transmission System Operators for electricity (ENTSO-E) have published Europe's network development plan (TYNDP). Several transmission projects are already initiated and more are expected to follow. In Flex4RES, we use the transmission capacity in TYNDP by 2030 as the BAU case (see also the scenario definition in chapter 3) and assume no additional capacities will be built after 2030.

Thus, in addition to the existing capacities, 21 GW of lines are added to cross-border transmission capacities in the next 10 years.

Figure 34 presents a visualisation of the main interconnection capacities for the BAU scenario in 2050 for the Nordic-Baltic region. Belgium and France, although included in the model, are not shown in the figure as they have no direct connections to the Nordics and Baltics.

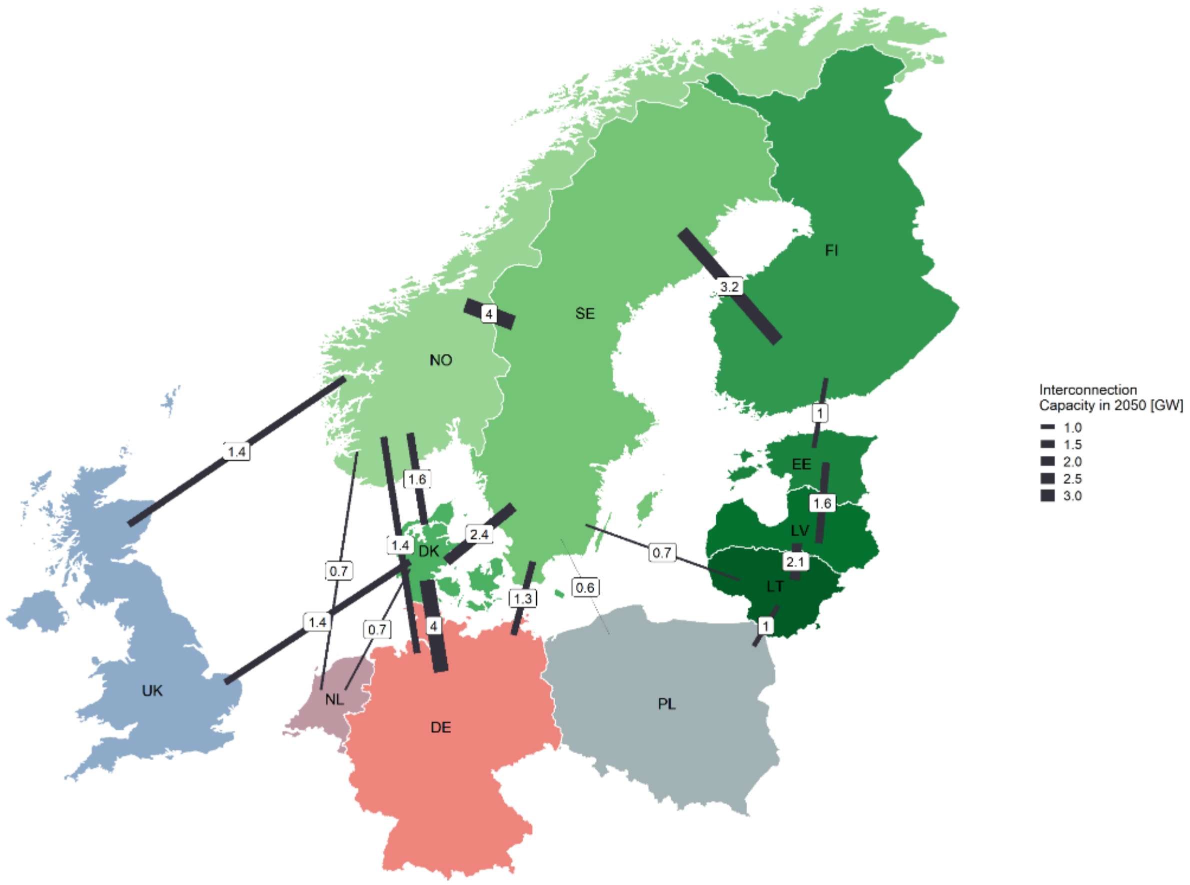

Figure 34: Transmission system of the BAU scenario in 2050 according to the ENTSO-E expansion plan until 2030

Important planned interconnections are those from Norway to the UK, Denmark, and the Netherlands, which are connected to Norway with a sea cable of 0.7 GW. The Nordic and Baltic transmission system is in general strong and several lines are constructed to connect them to central Europe. While Sweden will have connections to Poland and North-East Germany, Denmark will play a central role in the stronger interconnection between the Nordics and continental Europe. At the same time, BAU is considered to be a conservative scenario as no further lines will be constructed after 2030. The same is true for the Policy scenario.

The scenarios representing stronger market coupling (scenarios Connect and Combi) allow for additional investments in transmission capacities from 2030. Final transmission capacities are determined endogenously by the model based on the minimisation of the overall energy system cost, including the operation and investments in the electricity network, the electricity power plants and the district heating systems. Consequently, the model will simultaneously optimise the total transmission investments, generation capacities, and operation of the energy system.

Main model outcomes and projections

When additional transmission capacities are allowed for (Connect and Combi scenarios), the Nordics actively contribute to decarbonising the energy systems of neighbouring countries and ensuring their reliability. The level of imports to the Nordics grow moderate by approximately 480 GWh between 2030 and 2050, while the exports rise by approximately 1495 GWh. The Nordic countries consequently increase their exports by factor 3 compared to the imports. Danish wind power producers and the Norwegian hydropower industry are the two main beneficiaries of network expansion, while consumers in the UK and Germany are the actors who benefit the most from the wind surpluses and the flexible electricity supply from Norway.

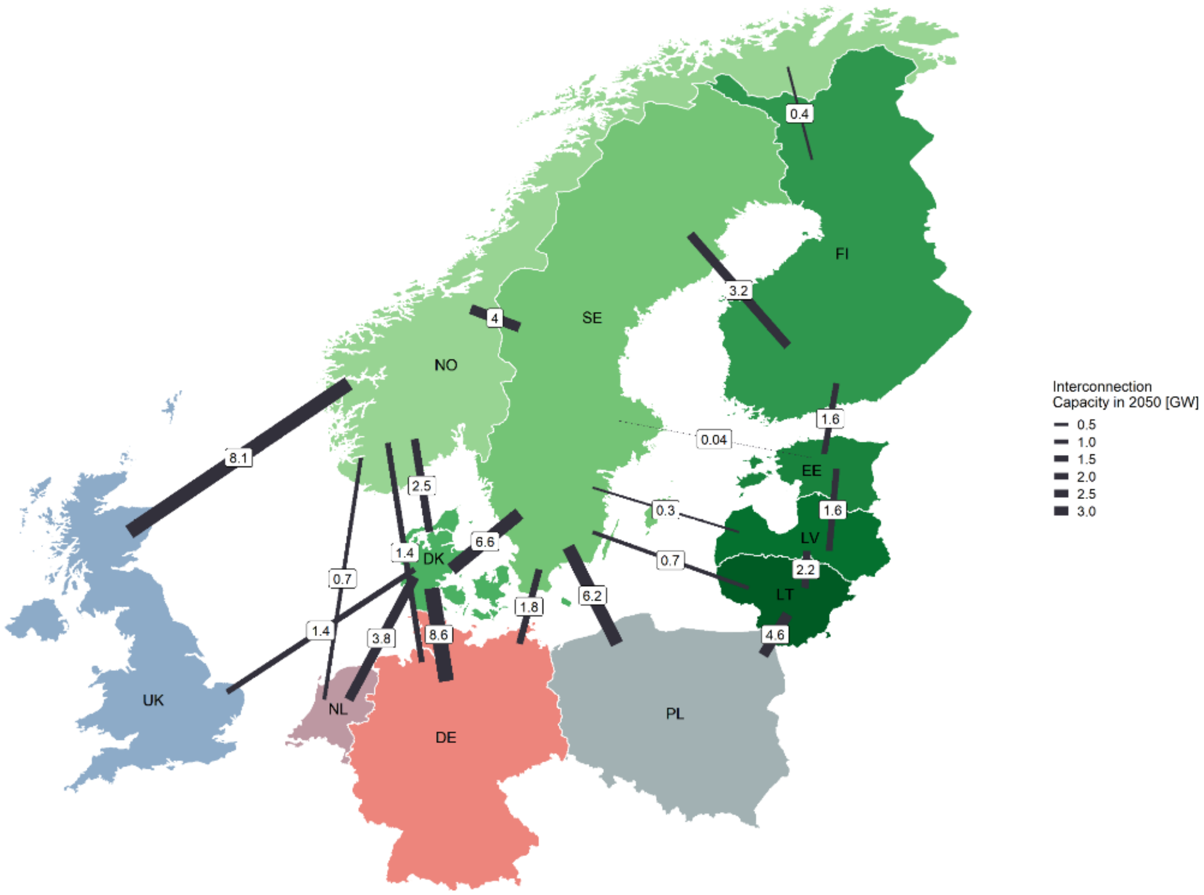

Figure 35: Transmission system of the Connect scenario in 2050

Figure 35 summarises the interconnections in the Connect scenario. In general, additional transmission expansion is identified compared to the BAU scenario (Figure 34), in particular from North to South. In this scenario, the Baltics increase their connections to Poland by around 3.6 GW and build two additional lines to Sweden. Their connection to Finland is further increased whereas within the Baltics only a small expansion of 0.1 GW between Latvia and Lithuania is required. The largest expansion of market coupling identified is between Norway and the UK. The difference between the BAU (ENTSO-E plan until 2030) and Connect scenarios is around 6.7 GW, meaning a line capacity of 8.1 GW in the latter. With additional sea cables, Norway can contribute significantly to the decarbonisation of the UK and help to balance the fluctuations of VRE with their hydropower.

Also notable is the role of Denmark in serving as a distribution hub between the Nordics and central Europe. Noticeable interconnection expansions are carried out from Denmark to Norway and Sweden to the north and Germany and the Netherlands to the south. In particular, the capacity of the Danish-German interconnection will slightly more than double and the connection to the Netherlands increase by almost 3.1 GW. In the end, a large line between Sweden and Poland rounds up the additional lines needed to quickly decarbonise the European system. All in all, the scenario indicates large potentials and synergies which should be pursued in order to build a cost-efficient European energy system. Moreover, expansions of lines of this magnitude emphasise the urgent need for stronger market coupling in order to optimally explore regional potentials.

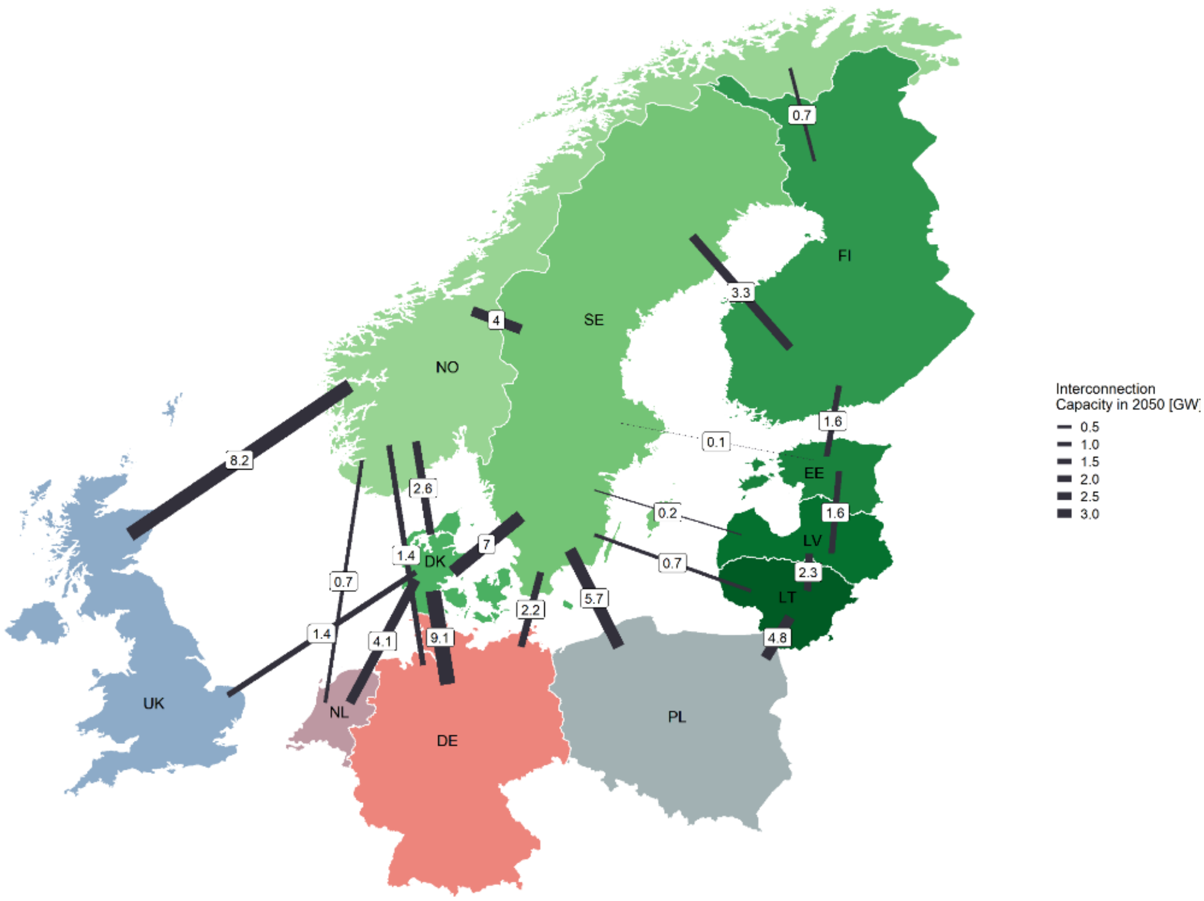

Figure 36: Transmission system of the Combi scenario in 2050

While the Connect scenario shows the optimal interconnections with the business-as-usual electricity tax and grid-tariff regime, the Combi scenario optimises transmission for the case of capacity-based taxes and grid tariffs, which promote flexibility through sector coupling. Figure 36 shows the expansion of the transmission system with the new policies.

The general overview of the composition of the transmission system leads to similar outcomes as in Connect. The expansion of lines occurs in the same locations as in Connect with only a very slight increase in magnitude. Transmission lines from Denmark to Germany and the Netherlands are particularly affected, with expansions 0.5 GW and 0.3 GW larger than in Connect, respectively. Lithuania also builds a stronger line to Poland, now yielding 4.8 GW instead of 4.6 GW in Connect. Sweden is focussing a little bit more on the German interconnection, now with 1.5 GW whereas the sea cable to Poland is reduced from 6.2 GW to 5.7 GW. The market coupling between Norway and the UK stays largely unaffected. Therefore, the additional flexibility brought about by policy change is used to further integrate the markets, although the impacts are not dramatic. Better operation helps to send even more energy from VRE towards central Europe, acting to decarbonise the system.

Additional transmission lines are indispensable in order to guarantee a least-cost European energy system. Allowing for the expansion of interconnection leads to a rapid increase in line capacities in the model. This indicates an urgent need for stronger market coupling. In particular, lines from the Nordic and Baltic system towards consumption centres like the UK, Poland, and Germany are built in the Connect and Combi scenarios. Additional cables to the Netherlands are also needed in order to diversify the export options. A policy change towards capacity taxes and tariffs mildly increases line capacities compared to energy-based schemes.

Distributional effects

The additional transmission capacity changes the technology mix in Europe. Mainly by reducing investments in PV and wind power capacity in Continental Europe, which is substituted by additional wind power in the Nordics.

Allowing more cross-border transmission capacity leads to 30 GW more wind power capacity in the Nordic region, replacing a similar amount of wind power capacity in Continental Europe (Figure 37). However, the biggest surprise is that it also implies 65 GW less PV capacity in continental Europe. One of the main reasons for this is a relative small capacity factor for PV and that Nordic wind power often has a higher capacity factor than continental European wind, meaning that more energy is generated with the same amount of turbines and will offset the Solar PV. Another factor is increased prices in the Nordics and lowered prices in Continental Europe. Finally, additional flexibility enabled by the transmission lines between the regions also reduce the total needed capacity.

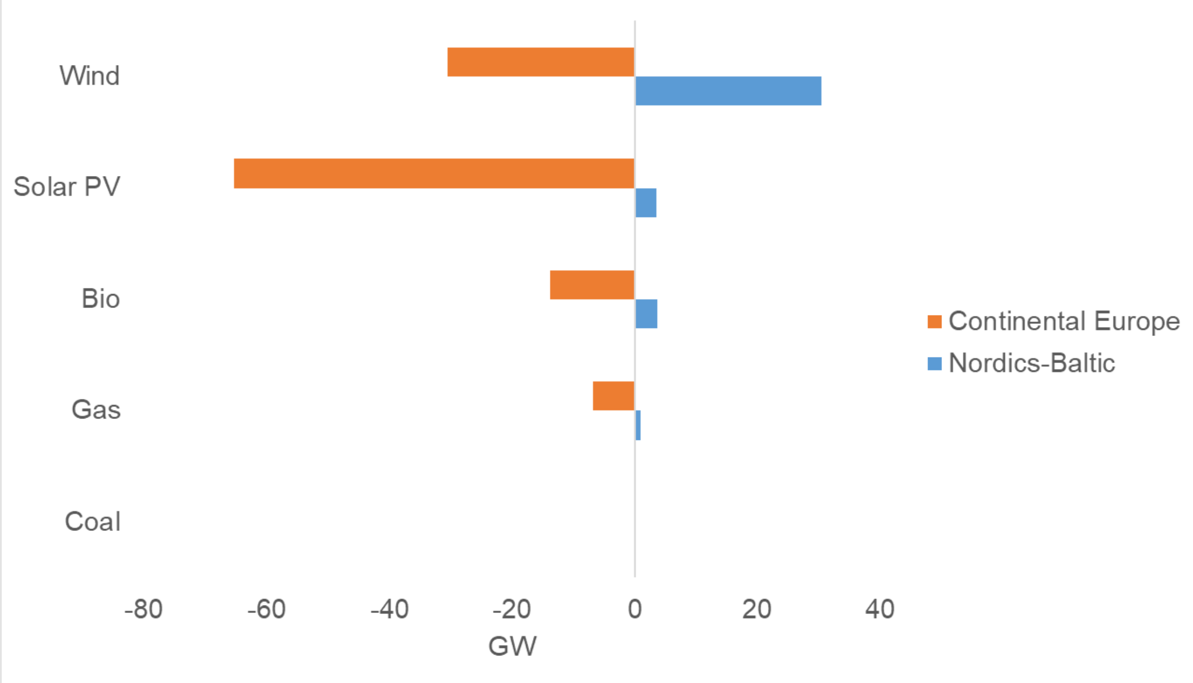

Figure 37: Difference between Connect and BAU in installed power generation capacity in 2050 by fuels.

The favourable wind resources in the north generates benefits beyond national borders and facilitates the transition to a cleaner energy system. Flexible hydropower also benefits from increased interconnection. Unlike wind power, which has great potential for expansion, hydropower is nearing the limits for capacity expansion given the available resources. Still, the revenues of Nordic hydropower increase up to 73% with expanded transmission lines (Figure 38). Swedish wind power producers have the largest increase in revenue (left map in Figure 38).

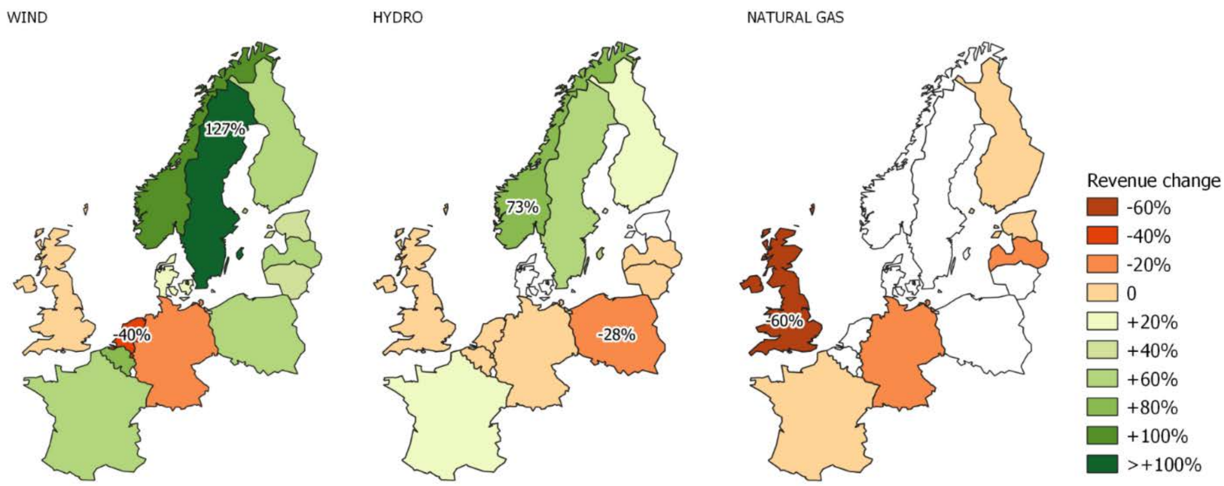

Figure 38. Change in producer revenues in 2050 with the cost-optimal transmission level for respectively wind power, hydropower and natural gas based generation. .

National power price levels tend to equalise when countries are more interconnected. That is, current low-price areas will experience price increases, while higher-price areas will enjoy lower prices. As Figure 39 demonstrates, power prices in the Nordic region will most likely increase with more cross-border transmission. Nevertheless, power prices in hydro-dominated regions like Norway and Sweden are also influenced by weather conditions. Assuming Norway experiences a dry and cold year, the interconnections can also help stabilise power prices using imports from other regions.

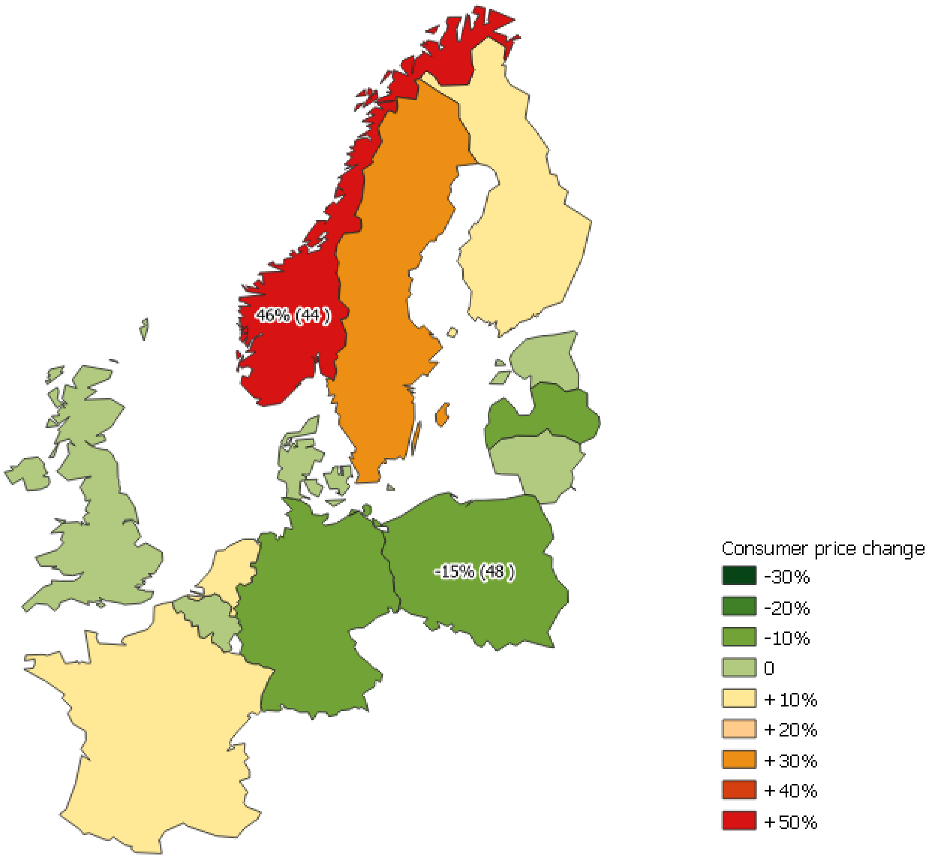

Figure 39. Change in consumer prices in 2050 with the cost-optimal transmission level.

Transmission versus EU carbon prices

Carbon-taxation/pricing is an important underlining policy instrument that accelerates the phasing-out of fossil fuel generation, i.e. the underlying assumption of high and increasing carbon prices drives the Nordics, Baltics, and Central and Western Europe towards carbon neutrality in 2050 in all scenarios (Figure 40).

In the main simulations, it is assumed in all scenarios that the carbon price increases during the 2020s to 65 €/tCO2 and double to 130 €/tCO2 by 2050, similarly to what is assumed in other international studies. If future carbon prices fail to reach these levels needed to reach the target of a carbon-neutral power system, transmission capacity expansion can play an even bigger part in emission and cost reduction.

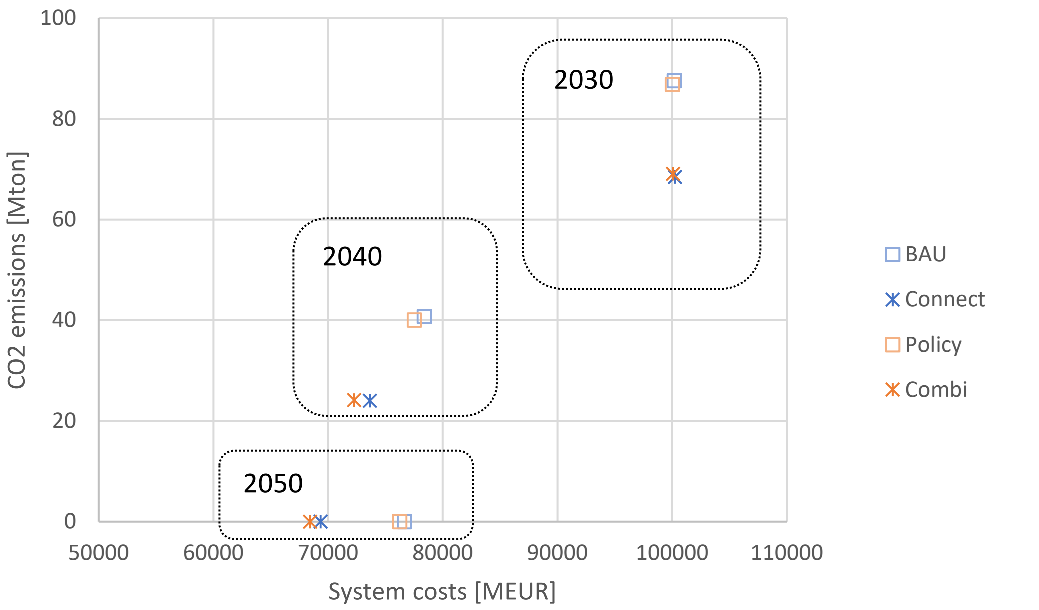

Figure 40: Total CO_2 emissions and system costs in all modelled countries (the Nordics, Baltics, and Central and Western Europe). With the carbon price increasing during the 2020s to 65 €/tCO2 and double to 130 €/tCO2 by 2050

Figure 41 shows emissions and cost reductions from increased interconnection under ***lower future carbon prices***. In this low carbon price illustration, the price increases mildly from 26 €/tCO2 in 2030 to 54 €/tCO2 in 2050. The "Planned" case refers to the BAU scenario where transmission capacity follows the TYNDP plan until 2030. Whereas, the "Optimal" case (Connect) lets the model endogenously optimise transmission grid capacity under the objective of system minimisation.

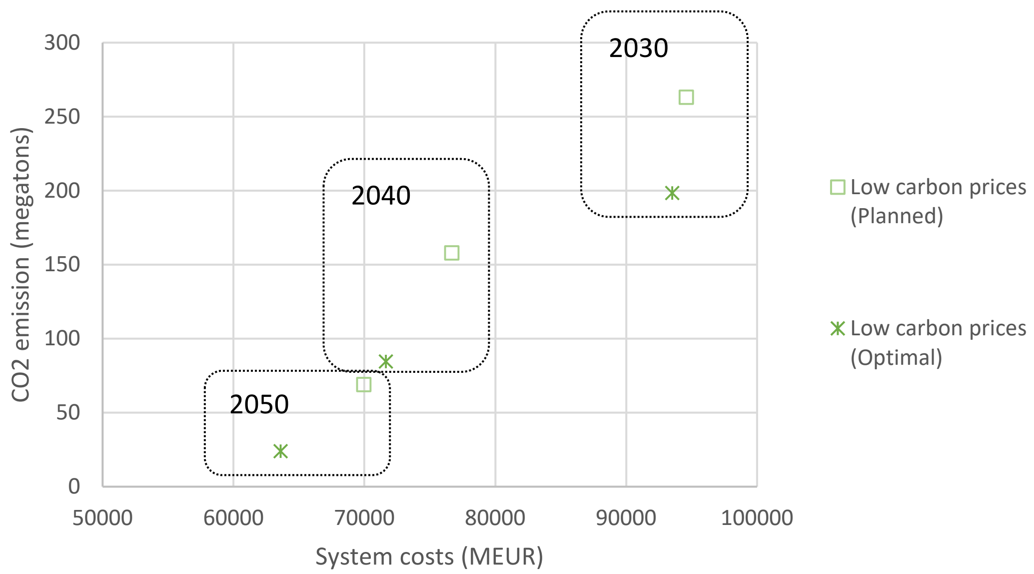

*Figure 41: Total CO_2 emissions and system costs in all modelled countries (the Nordics, Baltics, and Central and Western Europe) in the case study with **lower** carbon price assumptions. The carbon price increases mildly from 26 €/tCO2 in 2030 to 54 €/tCO2 in 2050.*

Total system costs are lower in the case of lower carbon prices than in the main model runs (Figure 41 versus Figure 40). Total CO_2 emission is also higher and it can be observed that with a lower carbon price than expected, transmission capacity expansion can play an even bigger part in emission and cost reduction. The additional transmission lines reduce emissions in 2050 by more than half in addition to cost reductions of a similar scale. Mainly by reduced coal and natural gas power generation in continental Europe, which is substituted by additional wind power in the Nordics.

Still, better interconnections lead to additional deployment of renewables - substituting fossil-fuel-based power generation (Figure 42) with a further reduction of 15 – 20 Mton of CO_2 emissions as well as up to 10% of system cost reductions in total for all the modelled countries.

Allowing more cross-border transmission grids in the low carbon price case leads to additional 13 GW of wind capacity in continental Europe and 26 GW in the Nordic region (Figure 42), replacing 30 GW of fossil-fuel-based power generation. Compared to Figure 37 (high CO_2 prices) wind power benefit in both the Nordic region as well as in Continental Europe (West) by additional transmission capacity.

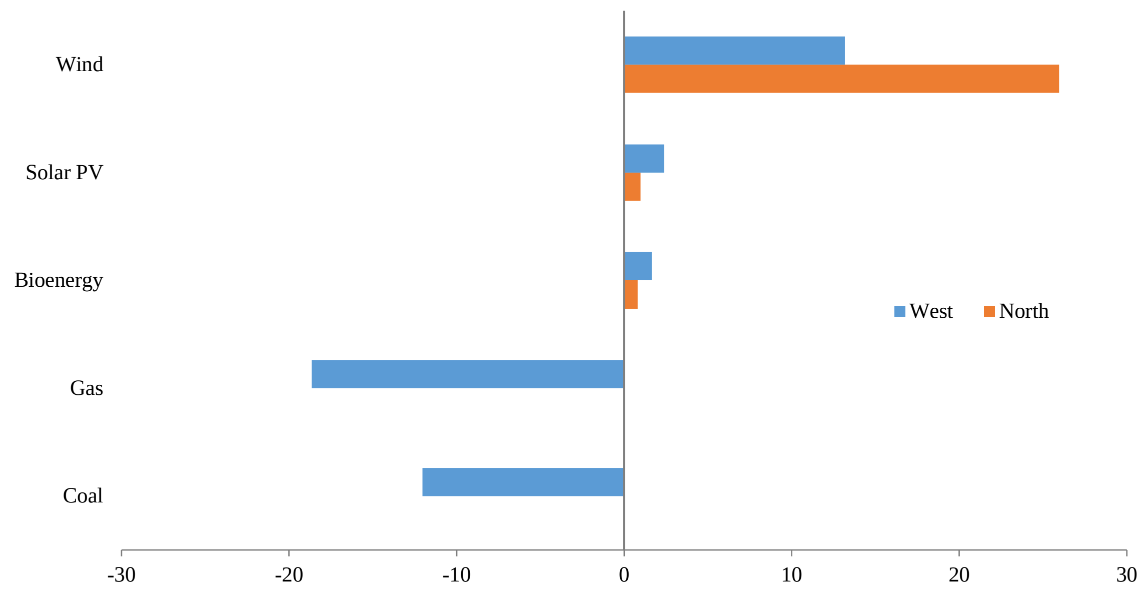

Figure 42: Difference between Connect and BAU in installed power generation capacity in 2050 by fuels under lower carbon price assumptions. North includes Nordic and Baltic countries and West includes the surrounding countries.

Conclusions

The analysis in this chapter has shown that stronger geographical market coupling through increased transmission capacity helps us reach carbon neutrality faster and more cost-efficiently. It can be seen as a fallback option in case a policy-driven carbon market does not deliver the desired results.

The advantage of international cooperation is clear. Although there are potential barriers, particularly an asymmetric welfare distribution, total welfare increases. If cooperation is effective, these hurdles can be overcome to the benefit of the whole continent - with the Nordic renewables as one of the drivers of the EU decarbonisation.

Related Flex4RES publications

Published journal articles and books:

A. Gravelsins *et al.*, ***Modelling energy production flexibility: System dynamics approach***, in *Energy Procedia*, 2018, vol. 147, pp. 503–509. DOI:10.1016/j.egypro.2018.07.060

F. Wiese *et al.*, ***Balmorel open source energy system model***, *Energy Strateg. Rev.*, vol. 20, pp. 26–34, Apr. 2018. DOI:10.1016/j.esr.2018.01.003

Forthcoming articles:

C. Bergaentzlé, K. Skytte, and P. A. Gunkel, ***Comparative analysis of cross-border and cross-sector approaches for flexibility in the Nordic countries***, *Submitted for publication*.

Y.-K. Chen, H. Koduvere, P.A. Gunkel, J.G. Kirkerud, K. Skytte, H. Ravn, T.F. Bolkesjø, ***The role of cross-border power transmission in a renewable-rich power system – a model analysis for Northwestern Europe***, *Submitted for publication*.

Y.-K. Chen, A. Hexeberg, K.E. Rosendahl, T.F. Bolkesjø, ***Review on long-term trends of North-West European power market***. *Submitted for publication*.

P. A. Gunkel, H. Ravn, S. Petrovic, F. Fausto, H. Koduvere, and J. G. Kirkerud, ***Modelling transmission systems in energy system analysis: a comparative study***, *Submitted for publication*.

Published conference articles:

C. Bergaentzlé, K. Skytte, J-G. Kirkerud, and O-J. Olsen, ***Electrification and Interconnections for Flexibility: A Comparative Analysis***, in 2019 16th International Conference on the European Energy Market (EEM). IEEE Xplore

J. Gea-Bermúdez, L. Pade, A. Papakonstantinou, M Koivisto, ***North Sea Offshore grid - effects of integration towards 2050***, in 2018 15th International Conference on the European Energy Market (EEM), 10.1109/EEM.2018.8469945

M. Koivisto, P. Sørensen, and J. Gea-Bermúdez, ***North Sea Offshore Grid Development: Combined Optimization of Grid and Generation Investments Towards 2050***, 17th Int. Wind Integr. Work., no. October, 2018.

T. Traber, H. Koduvere, and M. Koivisto, ***Impacts of offshore grid developments in the North Sea region on market values by 2050: How will offshore wind farms and transmission lines pay?***, in 2017 14th International Conference on the European Energy Market (EEM), 2017, pp. 1–6. DOI:10.1109/EEM.2017.7981945 ISBN: 978-1-5090-5499-2

4.6 Smart charging of electric vehicles

The carbon neutrality and emission targets mentioned in chapter 4.1 (Table 1) apply not only to the electricity and heat sectors, but also to transport. Therefore, in the coming years, transportation must undergo a rapid shift in technology and fuels. While petrol and diesel currently dominate the market for transport fuels, the aforementioned emissions targets will force these energy carriers out of the market. As a consequence, electric vehicles (EV) and green fuels are under development to provide cost-effective options for zero-emission vehicles. With a large fleet of EV, their charging behaviour has substantial effects on the energy system. These effects are investigated in Flex4RES for the Nordic system, with a particular focus on the increased coupling between the electricity and transport sectors.

Vehicle stocks and demand

Two main possibilities for EVs are widely available: battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). BEV rely solely on the installed battery for power, whereas a PHEV has a smaller battery coupled with a supporting engine. The powertrain of electric vehicles with batteries currently has an energy efficiency of around 70%.

In our calculations, EV stocks are mostly taken from national projections, but also estimated based on expected demographic and economic development (Gunkel et al. 2019). Figure 43 and Figure 44 present the projected stocks of EV in the Nordics and Baltics.

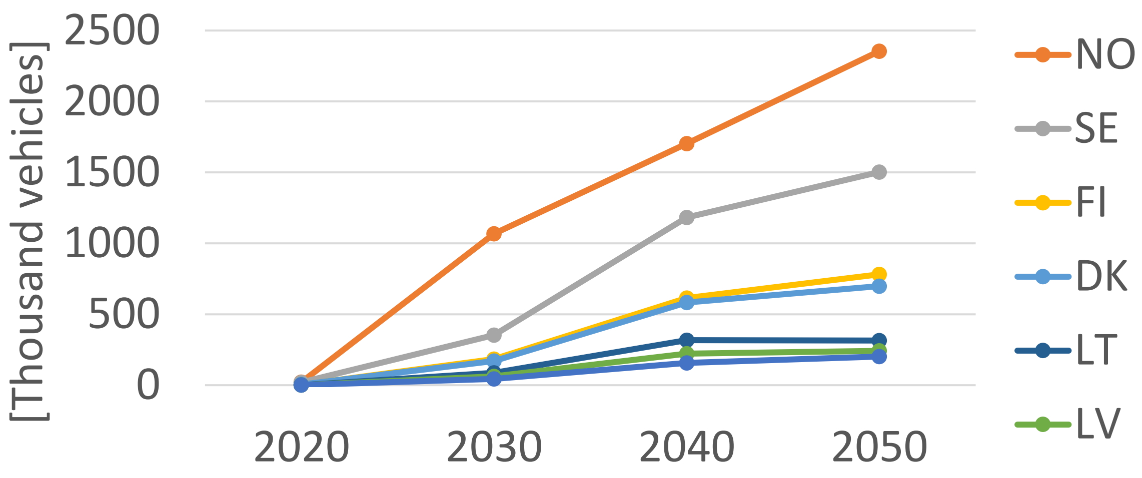

Figure 43: Projected development of BEV in the Nordics and Baltics

The stock of BEV is assumed to grow steadily in all countries until 2050. PHEV fleets also grow, but hit a peak in 2040, from which point they are replaced by BEV. The effects of a diminishing stock of vehicles in general, smart transportation solutions, and increased use of public transport have not been taken into account.

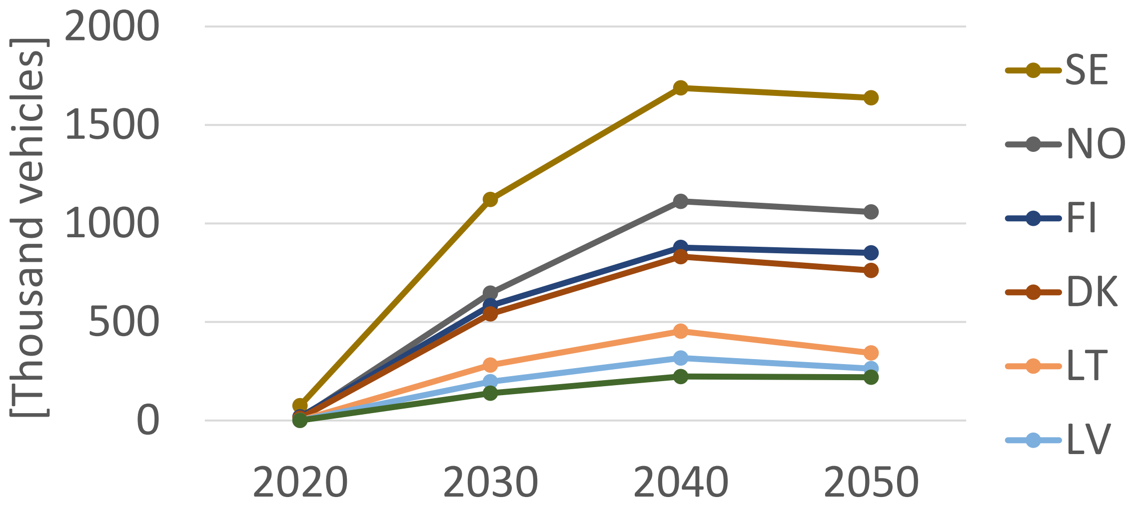

Figure 44: Projected development of PHEV in the Nordics and Baltics

Charger capacities at home are assumed to develop from 10kW to 20kW from 2030 to 2050, while the efficiency of the EV slowly increases and results in less energy used per kilometre driven. Average battery capacity for BEV rises from 30kWh in 2020 to 50 kWh in 2050. The state-of-charge is required to be 100% one hour before each trip, even though the full battery charge is not necessarily used. PHEV are assumed to always have a battery capacity of 10kWh and are fully charged before every trip. Finally, the battery is assumed to be charged at home.

Figure 45 presents the electricity demand for the EV calculated for the Nordics and Baltics.

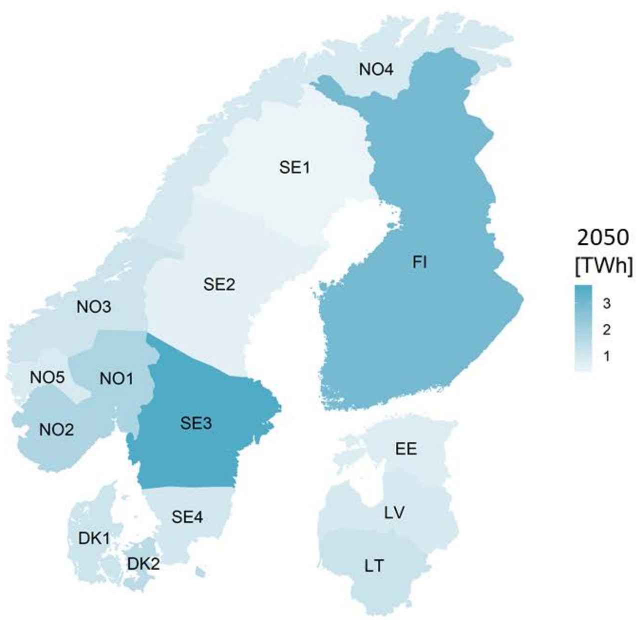

Figure 45: Exemplary Nordic electricity demand of BEV and PHEV in the Nordics and Baltics

The largest demands are observed in SE3 and Finland, followed by NO1, NO2, and DK2. It largely follows current consumption and population patterns. It has to be noted that, due to the spatial setup of the Nord Pool Spot market areas, Finland appears to have particularly high demand. However, it represents the entire country while in e.g. Sweden and Norway the energy demand is divided amongst several Nord Pool price-zones.

Flexible charging schemes of electric vehicles

EV can provide flexibility to the energy system in different ways depending on how they interact with the grid, i.e. their charging scheme. Additionally, services for the distribution system like reactive power control and congestion management can be offered. The participation in different electricity markets such as day-ahead, balancing, and frequency markets is another important determinant, which influences not only how EV can contribute to the system, but also how they are remunerated for their contribution.

In Flex4RES, we focus on hourly energy generation. Therefore, the analysis described below only considers the charging schemes with respect to hourly contributions within the Balmorel model for the Nordics and Baltics.

Three main charging schemes modelled:

- passive charging (PC),
- grid-to-vehicle (G2V), and
- vehicle-to-grid (V2G).

The most prevalent scheme today is PC, which is characterised by charging at full capacity as soon as the vehicle is plugged into a charger and stopping only when the battery is full. Private drivers of EV often return between early and late afternoon and thus start their energy withdrawal when pressure on the grid is largest and electricity prices highest. Consequently, this charging scheme does not serve flexibility and is seen more as a threat to the stability of the system than a promise.

G2V, on the other hand, can solve this issue by charging EV more flexibly. This is done by scheduling the charging based on the charging costs of the EV. This includes the cost of electricity and the degradation cost of the battery cells, which is minimised to prolong the lifetime of the battery. Due to the scheduling according to electricity prices, the vehicles are charged when the energy is cheapest, which coincides with the flexibility needs of the energy system (as discussed in chapter 4.2). G2V is beneficial both to the energy system, as charging follows market signals to minimise the pressure placed upon the system, and to the EV users, as it reduces the cost of charging and extends battery lifetime.

V2G is the most flexible charging scheme - allowing both flexible charging and discharging of the EV. It follows the same general approach as G2V by schedules the energy purchase based on the charging costs of the EV, but it also extends the options by adding the capability of actively discharging the battery into the grid. By using a bidirectional charger, energy can be bought (e.g. during the night when prices are low) and sold (e.g. in the afternoon when prices are high) to contribute to the balance between supply and demand. As a consequence, price variability can be reduced and consumers face fewer high-price hours. Installing the bidirectional charger, however, imposes additional cost and, thus, a balance must be stricken between the costs and benefits of adopting V2G. It is important to note that, since the costs are mostly private and some of the benefits are socialised, there could be a role to be played by policy in incentivising the installation of bi-directional chargers.

Changing the charging scheme from PC to G2V and V2G will result in economic benefits which are illustrated by our model runs in Figure 46 in relative terms highlighting relative savings for fixed and variable cost.

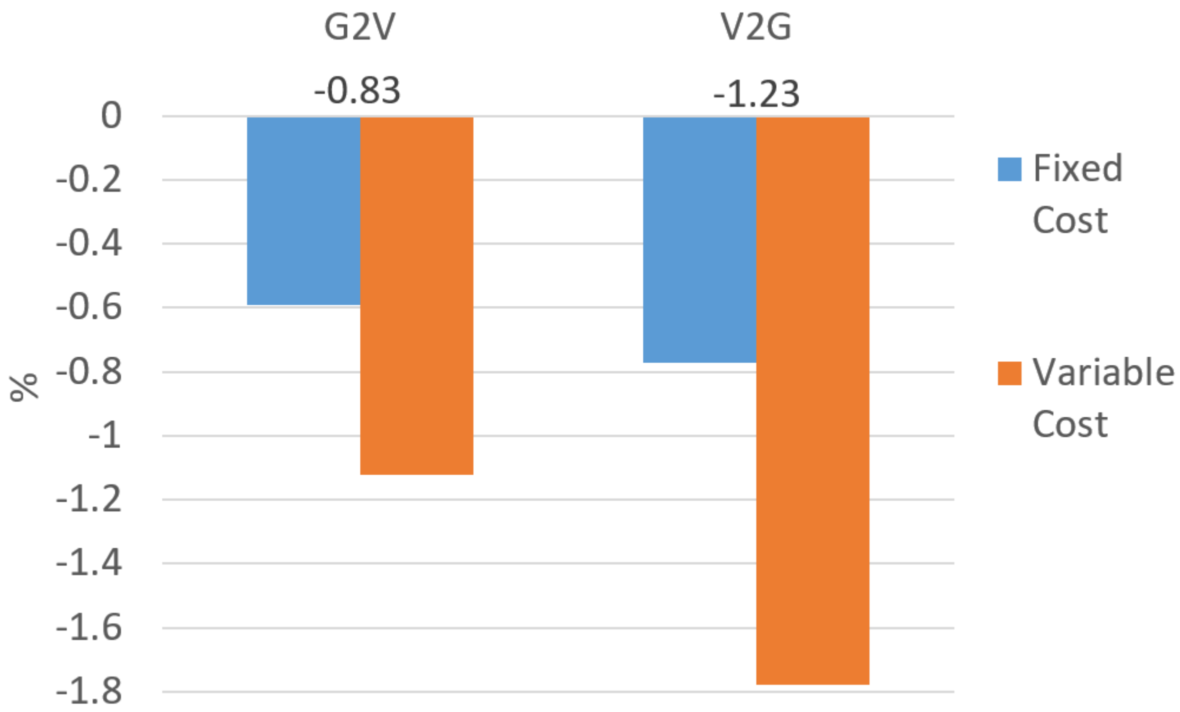

Figure 46: Relative reduction of total energy system costs by introducing flexibility of EV to the Nordic energy system compared to passive charging (PC).

When introducing G2V and V2G, system cost can be reduced by 0.83% and 1.23% respectively. In the case of V2G this corresponds to over half a billion Euro only in the Nordics alone. In particular, variable costs, which include fuel expenses, can be reduced when EV can actively discharge energy during peak hours when thermal plants usually operate. Furthermore, price variability is reduced significantly despite the average electricity price increasing by approximately 1.5% and 3% with G2V and V2G respectively. Consequently, sector coupling with EV can be managed well when integrated with flexible charging schemes which result in lower system cost.

The largest changes can be seen in the investment decisions regarding generation technologies in the electricity sector. Figure 47 summarises the relative changes in the Nordics compared with PC in 2050 for the BAU scenario.

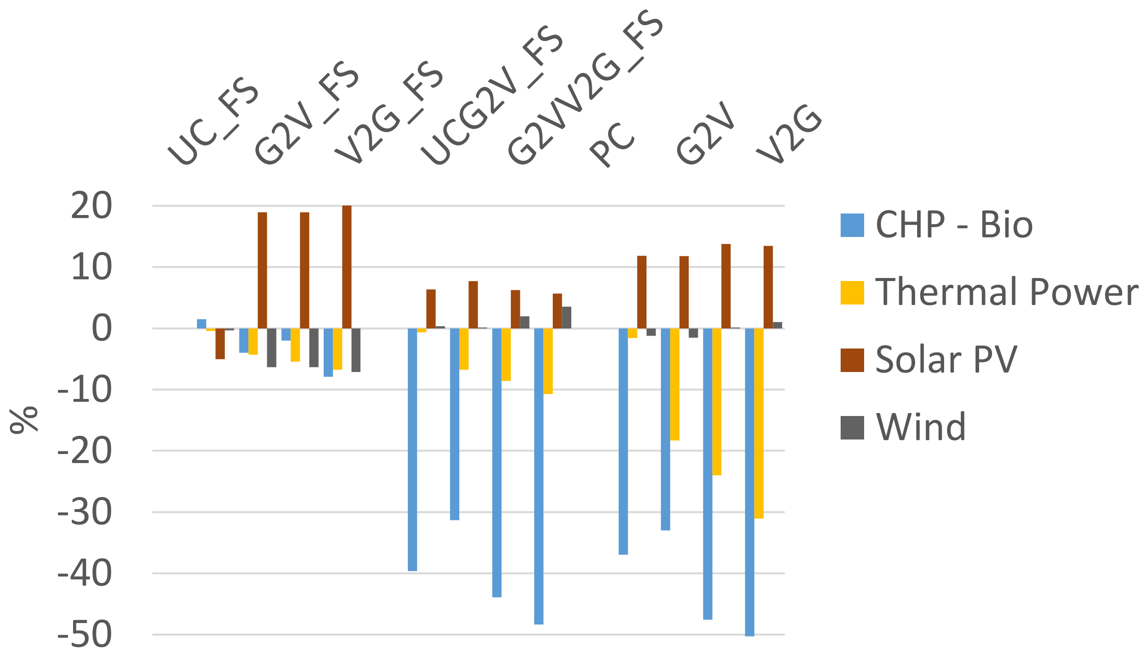

Figure 47: Relative changes of installed electricity generation capacity in the Nordics in 2050.

The additional flexibility in charging the vehicles affects central power plants, especially the ones using biomass as a fuel. With PC, these units are used to cover peak demand, whereas this is also covered by G2V and V2G that react to prices and shift their charging accordingly. In particular, V2G could reduce the required CHP capacity by up to 50% if the impacts on the heat supply are not considered. Wind power is not affected by the adoption of smarter charging schemes.

On the contrary, substantial synergy effects are observed between both G2V and V2G and the expansion of solar heat that is respectively 12% and 13.5% higher than under passive charging (PC). Furthermore, it has to be noted that the model outcome for PC requires additional stationary batteries to cover peak charging demand, whereas V2G can avoid these investments until 2050. Thus, PC will require a significant amount of flexibility from the production side and additional storage systems. With G2V and V2G, these investments can be delayed and reduced, not to mention the synergy of these schemes with variable renewable energies.

Discussion of challenges with respect to EV

Overall, EV can reduce system cost when integrated with flexibility from charging and discharging. Price variability can be reduced with G2V and actively smoothen with V2G. With these two flexible demand schemes, there is a reduced need for power plants offering flexibility (flexible supply). The same is true of stationary batteries, which under PC are needed to cover peak capacity. Consequently, EV flexibility can contribute significantly to the system and its users by adopting smart charging schemes.

Even though integrating EV with G2V and V2G brings large benefits at the system level, there are still barriers which can hinder this development. Cost benefits have to pass through to the end-user in order to encourage participation. Likewise, despite the charging of vehicles being optimised to fulfil all driving requirements, feelings of range anxiety can arise if the battery is not fully charged most of the time. Therefore, to ensure the rapid deployment of EV, it is important to inform the public about the benefits of such vehicles and create business models which generate sufficient financial compensation for EV users.

The effects of an expanding EV fleet on the distribution system are also significant and depend crucially on the prevalent charging schemes. A passive integration can lead to high investment costs in reinforcement. Contrarily, a smart integration which includes charging schemes like G2V and V2G can not only solve physical issues at the distribution level, but also improve grid resilience through voltage control and congestion management. The avoided costs can be used to compensate EV users for their contribution to the system, reducing their share of grid costs. This is particularly relevant given the projected rising cost of grid tariffs at the distribution level.

Related Flex4RES publications

Published journal articles and books:

R. Bramstoft and K. Skytte, ***Decarbonizing Sweden's energy and transportation system by 2050***, International Journal of Sustainable Energy Planning and Management, vol. 14, p. 3-20, 2017. DOI:10.5278/ijsepm.2017.14.2

K. Skytte and R. Bramstoft, ***Decarbonising the finnish transport sector by 2050—Electricity or biofuels?*** in Green Energy and Technology, no. 9783319636115, Springer Verlag, 2018, pp. 3–22. DOI:10.1007/978-3-319-63612-2_1

K. Skytte, A. Pizarro, and K. B. Karlsson, ***Use of electric vehicles or hydrogen in the Danish transport sector in 2050?***, Wiley Interdisciplinary Reviews: Energy and Environment, vol. 6, no. 1. John Wiley and Sons Ltd, 01-Jan-2017. DOI:10.1002/wene.233

F. Wiese et al., ***Balmorel open source energy system model***, Energy Strateg. Rev., vol. 20, pp. 26–34, Apr. 2018. DOI:10.1016/j.esr.2018.01.003

Forthcoming articles:

P. D. Lund et al., ***Pathway analysis of a zero-emission transition in the Nordic-Baltic region***, Submitted for publication.

Published conference articles:

P.A. Gunkel, F.J. Fausto, K. Skytte, C. Bergaentzlé, ***The Impact of EV Charging Schemes on the Nordic Energy System***, in the 2019 16th International Conference on the European Energy Market (EEM). IEEE Xplore.

L. Herre, J. Dalton, L. Söder, ***Optimal Day-Ahead Energy and Reserve Bidding Strategy of a Risk-Averse Electric Vehicle Aggregator in the Nordic Market***, 2019 IEEE Milano PowerTech, Year: 2019

4.7 Demand response - Industrial and residential demand-side flexibility

Active demand response might prove to be a cost-efficient way of providing flexibility. An opportunity to increase system flexibility is to better utilise the potential flexible demands from the industrial and residential sectors. Electricity demand from these sectors is traditionally considered inflexible and unresponsive to short-term volatility in power prices. There are exceptions: industrial consumers are already active, having placed demand-curtailment bids of roughly 5 GW in 2016 in the Nord Pool market. Historically, however, households and other small consumers have not had any incentive for this because metering has been manual and infrequent. These consumer segments are likely to become more active as digitalisation and the rollout of smart metering equipment open up the possibility for economic incentives to reach flexible consumers. Smart meters can provide hourly metering information to consumers allowing them to adapt energy consumption efficiently based on price signals. The current state of the smart meter roll-out differs among the analyzed countries but is moving swiftly towards connecting most end-users. EU targets to replace at least 80% of electric meters with smart meters by 2020 propel this development forward.

In this chapter, demand response (DR) refers to flexibility at the demand side from all electricity loads except the ones treated as sector coupling (chapter 4.4) and electric mobility (chapter 4.6).

Demand response potential

The potential for demand response in a Nordic context has been assessed before, but the numbers are uncertain as the market is still in its infancy and many assumptions must be made to produce a sensible estimate. By reviewing literature with estimations of potentials in Norway, the potential for downshifting in the Nordic and Baltic is estimated to lie between 15.3% and 29.5% of peak load (Söder et al. 2018).

Table 5: Summary of DR flexibility potentials in the Nordics and Baltics (Söder et al. 2018)

Country	Sweden	Denmark	Norway	Finland	Estonia	Latvia	Lithuania	Total:
Utilization time [h]	5037	5053	5250	5462	5161	5482	5273	5204
Peak [MW]	27,000	6100	24,000	15,105	1550	1368	2200	77,323
Industry energy %	36.8%	33.1%	43.7%	47.0%	32.0%	28.0%	40.0%	40.6%
Industry flexibility, share of peak	7.0–8.5%	0.3–3.5%	1.1–6.3%	9.0%	4.2%	0.5–1.0%	0.2–0.8%	4.7–7.1%
Household heating energy %	22.1%	6.1%	36.1%	15.8%	10.0%	2.0%	2.8%	22.8%
Household heating share of peak	7.4–20.4%	1.4–2.8%	4.2–11.4%	7.6–9.6%	3.6–14.7%	0.0%	0.0%	5.6–13.1%
Other Flexibility share of peak	0.7–0.8%	9.9–23.1%	3.2–7.2%	12.5%	7.2%	4.6–5.1%	3.3–3.7%	5.1–9.4%
Total: Share of peak	15.2–29.7%	11.5–29.4%	8.5–24.9%	29.1–31.1%	15.0–26.1%	5.1–6.1%	3.5–4.6%	15.3–29.5%

Figure 48 displays the electricity loads of applications able of exhibiting flexibility for the year 2016. In the household and tertiary sectors, electric space heating is only considered in the Nordic countries due to data availability.

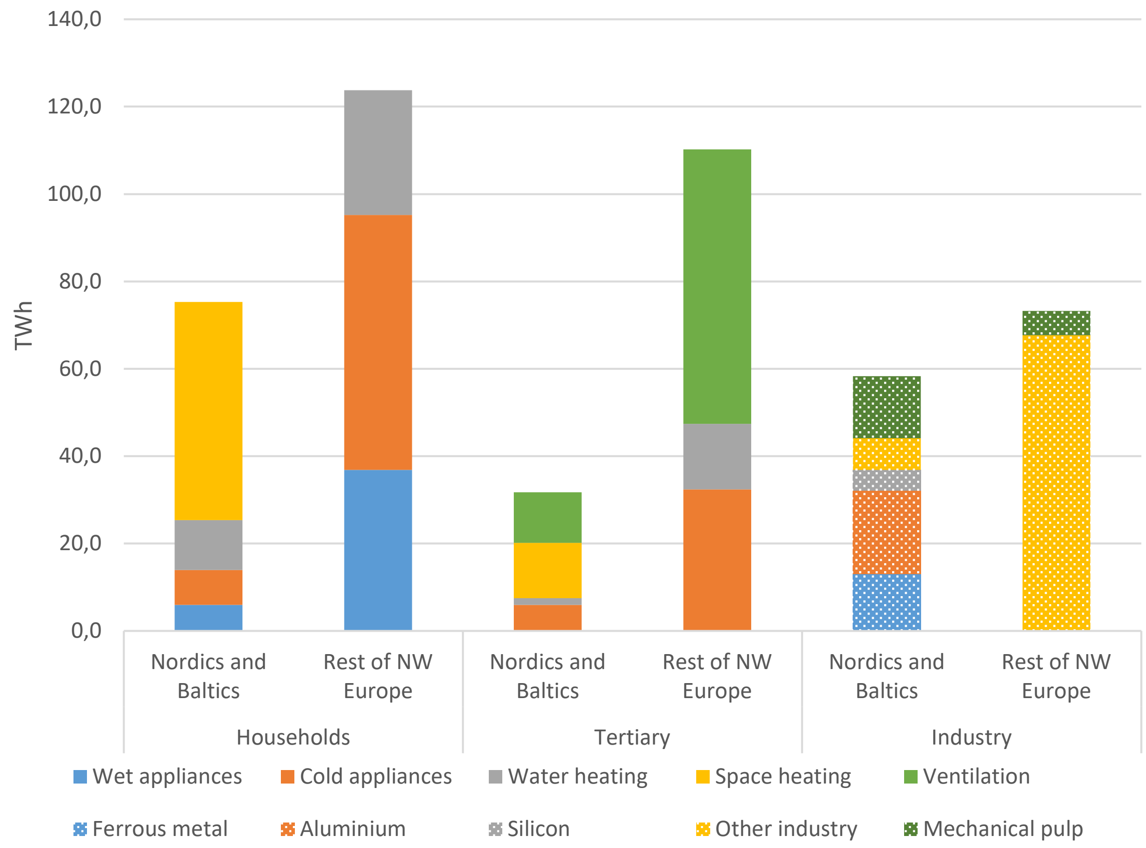

Figure 48: Electricity loads (2016)

Demand response can mean either load shifting or load shedding. *Load shifting* is a reduction of the demand in one period that is recovered by an increase in load at an earlier or later point in time. *Load shedding* is simply a reduction in consumption without recovery.

Table 6: Cost for load shedding in energy-intensive industries

Load	Cost for down regulation, €/MWh
Ferrous metal	2000
Aluminum	1000
Silicon	200
Other	2000
Mechanical pulp	200

In the household sector, an equipment cost of 10 € per appliance is assumed for wet, cold, and water heating appliances. For space heating, a cost of 100 € per household is assumed. The rollout of smart meters is already well underway and, for that reason, there is no extra cost for this.

For load shedding, the main limiting factor for acting flexible is the cost of shifting down the consumption (Table 6), while for load shifting it is the *shifting time.* In other words, the maximum time before the energy needs to be recovered (Table 7). For space heating, the shifting time is not defined. Instead, the assumed effective heat capacity in buildings with electric heating per installed capacity of heating equipment is used.

Table 7: Maximum shifting times for demand response

Sector	Load	Shifting time, h
Households	Wet appliances	4
	Cold appliances	1
	Water heating	6
Tertiary	Ventilation	1
	Cold appliances	1
	Water heating	6
Industry	Mechanical pulp	2

A third limiting factor is the penetration rate of flexible appliances.-The penetration rates and total potential used in our analysis is described in Table 8.

Table 8: Adoption rate input parameters

	Penetration rate		Total potential	
	Residential sector	Tertiary sector	Residential sector	Tertiary sector
Cold appliances	38.9 %/yr	24.2 %/yr	100%	100%
Wet appliances	38.9 %/yr	24.2 %/yr	50%	100%
Water heating	24.2 %/yr	24.2 %/yr	100%	100%
Space heating	15.4 %/yr	24.2 %/yr	100%	100%
Ventilation	-	24.2 %/yr	-	100%

The industry sector has largely already adopted measures to provide flexibility. In “Mechanical pulp”, the potential is already fully utilised, and the other industry categories follow a linear growth path from around 60% adoption in 2019 to 100% adoption in 2050. Figure 49 displays the adoption curves for the different categories in each sector.

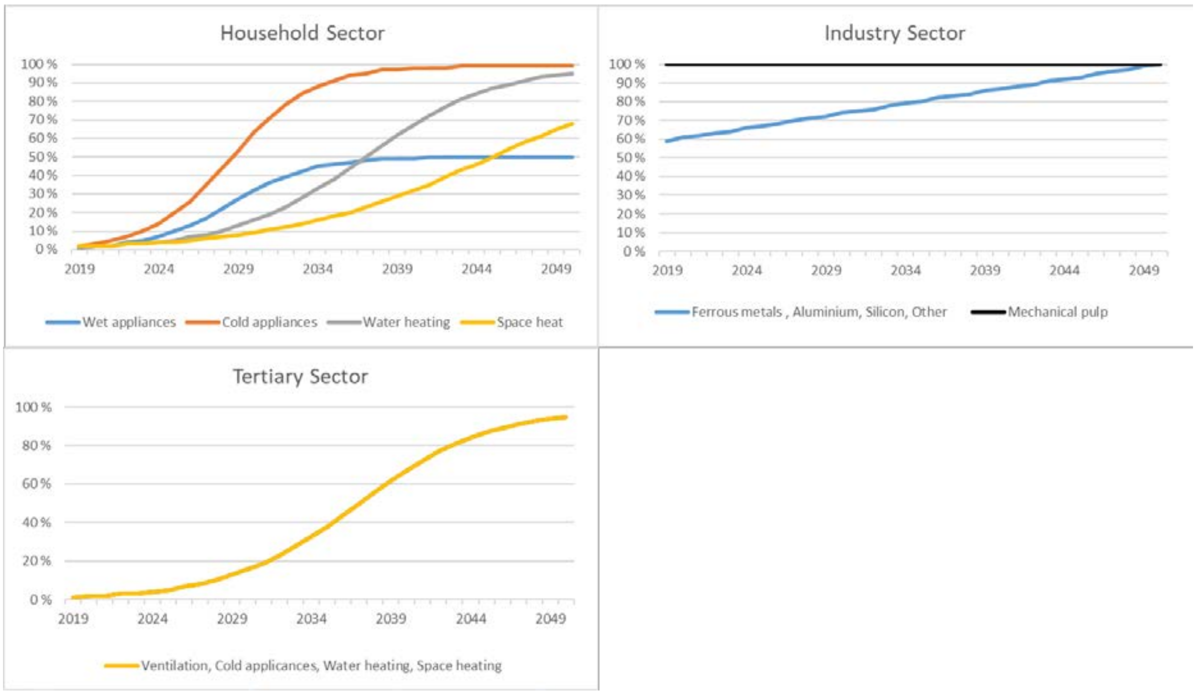

Figure 49: Assumed adoption rates of different DR-categories

Results from model runs

The model runs show a potential for demand response to downshift 17.5%, or 11.6 GW, of power in peak hours in the Nordic and Baltic region by 2050. The results indicate a promising potential in water and space heating. These loads have high assumed shifting times and annual consumption, located mainly in Norway, Sweden, and Finland. Demand response in the industrial sector is rarely activated due to high activation costs.

Table 9: Overview of impact of DR categories in Nordic and Baltic countries in 2030 and 2050

			Total downshifts (GWh)		**Net downshift in peak hour (relative to peak load)**	
Sector	**DR Category**	**DR Type**	**2030**	**2050**	**2030**	**2050**
Industry	Aluminium	Shed	4	–	0.2 %	0.0 %
	Silicon	Shed	2	2	0.2 %	0.0 %
	Pulp and paper	Shed	4	4	0.6 %	0.5 %
	Pulp and paper	Shift	127	96	1.2 %	0.7 %
	Other	Shed	0.3	–	0.0 %	0.0 %
Households	Wet appliances	Shift	864	1 050	0.4 %	0.8 %
	Cold appliances	Shift	312	136	0.1 %	0.0 %
	Water heating	Shift	1 151	4 254	0.3 %	4.2 %
	Space heating	Shift	1 327	5 706	1.2 %	6.6 %
Tertiary	Ventilation	Shift	203	1 047	0.2 %	0.7 %
	Cold appliances	Shift	100	588	0.1 %	0.1 %
	Water heating	Shift	132	716	0.0 %	0.2 %
	Space heating	Shift	910	3 925	0.3 %	3.7 %
			5 136	**17 524**	**5.0 %**	**17.5 %**

Table 9 gives an overview over the impact of the different demand response categories in terms of total downshifts and net downshifts in the highest peak hour. The results are given for 2030 and 2050 and show that overall shifts increase in magnitude towards 2050 and provide higher downshifts in the peak hour, thus contributing more to lowering peak demand. Space and water heating in the residential and tertiary sectors shift particularly large shares of the energy.

Modelling results for investments in new generation capacity show that flexible demands coincide with less of a need for power plants serving as peak-load units in the system (Table 10). Technologies such as battery storage, gas turbines, and internal combustion engines are significantly less invested in. Additionally, more energy is being generated in typical baseload plants, due to increased consumption in the night-time. The combination of these two effects results in efficiency improvements and, consequently, lower total system costs.

Table 10: Investments in generation capacity (MW) in the Nordic and Baltic countries between 2030 and 2050

Technology	DR	No DR
Battery storage	0	212
Gas turbine	0	367
ICE	4 429	5 575
Steam turbine	6 757	6 920
Offshore wind (far)	2 340	2 340
Offshore wind (near)	1 140	1 140
Onshore wind	48 348	47 289

In what concerns variable renewable energy (VRE) like wind power, it is not evident that demand response will benefit generation from these resources. The duration of peaks and valleys of wind power output are often too long compared to the assumed maximal shifting time for flexible loads. A better application of DR is to shift energy consumption from peak hours to the night-time and mid-day valleys, which mainly benefits baseload generators and reduces the need for peak-capacity generators.

Discussion and recommendations

The large flexibility for P2H in district heating can be supplemented by demand responds from end-users of electricity. This demand response analysis shows that particularly electric water and electric space heating have high potentials due to relatively long shifting times and high electricity consumption in these applications. This results in Norway, Sweden, and Finland being well prepared to harness high demand response potentials while Denmark, Estonia, Latvia, and Lithuania currently have lower potentials.

Encouraging investments in flexibility-ready electric water and space heating technologies for active participation of end-users in demand response is thus beneficial to the development of demand response potentials. Likewise, harnessing the full potential of demand response from end-users requires an efficient incentive structure with tradeoff between a form of variable pricing exposing the customer to real time rates, while also acknowledging that many households have a preference for stability and predictability thus preferring simplified pricing schemes.

Related Flex4RES publications

Reports:

D. Møller Sneum, D. Blumberga, J. Katz, and O. J. Olsen, ***Framework conditions for flexibility in the individual heating-electricity interface***. 2017. Available: http://www.nordicenergy.org/publications/framework-conditions-forflexibility-in-the-individual-heating-electricity-interface/ ISBN: 9788793458499

Published journal articles and books:

A. Khabdullin, Z. Khabdullina, A. Khabdullin, G. Khabdullina, D. Lauka, and D. Blumberga, ***Analysis of Industrial Electricity Consumption Flexibility. Assessment of Saving Potential in Latvia and Kazakhstan***, in Energy Procedia, 2017, vol. 113, pp. 450–453. DOI:10.1016/j.egypro.2017.04.037

A. Roos and T. F. Bolkesjø, ***Value of demand flexibility on spot and reserve electricity markets in future power system with increased shares of variable renewable energy***, Energy, vol. 144, pp. 207–217, Feb. 2018. DOI:10.1016/j.energy.2017.11.146

L. Söder et al., ***A review of demand side flexibility potential in Northern Europe***, Renewable and Sustainable Energy Reviews, vol. 91. Elsevier Ltd, pp. 654–664, 01-Aug-2018. DOI:10.1016/j.rser.2018.03.104

Å. G. Tveten, T. F. Bolkesjø, and I. Ilieva, ***Increased demand-side flexibility: market effects and impacts on variable renewable energy integration***, Int. J. Sustain. Energy Plan. Manag., vol. 11, pp. 33–50, Oct. 2016. Available: https://journals.aau.dk/index.php/sepm/article/view/1419 DOI:10.5278/ijsepm.2016.11.4

F. Wiese et al., ***Balmorel open source energy system model***, Energy Strateg. Rev., vol. 20, pp. 26–34, Apr. 2018. DOI:10.1016/j.esr.2018.01.003

Forthcoming articles:

J. G. Kirkerud, N. O. Nagel, and T. F. Bolkesjø, ***The role of demand response in the future renewable Northern European energy system***, Submitted for publication.

Published conference articles:

A. Crosara, E. Tómasson and L. Söder, ***Generation Adequacy in the Nordic and Baltic Area: The Potential of Flexible Residential Electric Heating***, 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)

L. Herre and L. Soder, ***Enhancing market access of demand response through generation forecast updates***, in 2017 IEEE Manchester PowerTech, 2017, pp. 1–6. DOI:10.1109/PTC.2017.7981023 ISBN: 978-1-5090-4237-1

4.8 Social acceptance in the energy transition

The magnitude of the changes needed to meet the targets of the Paris Climate Accord represents a major transition from the present fossil-fuel based energy economy to a carbon neutral one (see Table 1 in chapter 4.1). The changes ahead are not only about technology changes, but also include major societal changes, turning the changes into a major social-technical transition.

A literature review performed under Flex4RES (Bolwig et al. 2019) seeks to better understand and model the transition from the present energy system to a sustainable one in line with the ambitious climate goals. The literature reveals that technical-economic analyses alone often miss considering the social factors that interfere with energy developments and decarbonisation roadmaps. The proposition is that an enriched modelling approach should not focus just on technology development and deployment, but also on societal characteristics. In Flex4RES, we restrict the technical potentials of technologies in the quantitative modelling of energy scenarios according to the critical socio-technical factors. We link our analysis in particular to the factors affecting both the future development of VRE generation such as wind and solar power and the future expansion of electricity networks.

Social acceptance of renewable energy technologies

The concept of social acceptance of renewable energy technologies first emerged as a form of instrumental knowledge in the early 1980s, especially in relation to wind power. Since then, wind power has been the focus of studies of social acceptance of renewables. Yet the issue is also relevant for other key technologies needed for the transition to a zero-carbon energy system.

In spite of the public’s general positive attitude towards renewable energy, wind power projects receive a growing opposition from the local communities, which feel directly affected by their perceived disamenities. Low acceptance seems increasingly to affect the construction of new wind and solar parks, to cause delays in project approval, to affect the overall development costs and to block ongoing projects in some cases.

One can identify several common factors influencing acceptance across diverse contexts. Most important seem to be the visual impact, noise pollution and other environmental impacts such as the impact on birds and other wildlife, and the economic impact resulting from the loss of property value. Wind power also 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'. Altogether, the low acceptance for nearby energy projects and the limited amount of space to construct new wind and solar plants negatively affect the techno-economic potential for wind energy growth.

Acceptance of transmission lines

The massive integration of renewable energy may also require the reinforcement and expansion of the electricity transmission lines (see section 4.5). However, the construction of new high voltage lines is also increasingly unpopular and faces a number of reluctances from the local communities. The high pylons, the overhead lines and the tree-less corridors in forested areas are the three main recurring arguments against transmission lines projects and consist of the main factors for the lack of acceptance due to visual impact. Other factors related to local economies may also influence the development of transmission grids such as the deterioration of tourism activities caused by the landscape modification after the construction of the lines, or simply the loss of property value. A relatively recent trends also affecting electricity grid projects is the reluctance of some citizens to be exposed to the electromagnetic fields generated by the overhead lines. Finally, the lack of acceptance of transmission grids may also result from competitive and distributional concerns, particularly when it comes to interconnecting two countries with large electricity market price differences. For example, the increased transmission capacity for export of renewable electricity from Norway and Denmark to the United Kingdom has met some opposition in Norway on both economic and environmental grounds. Such a development may threaten the competitiveness of the domestic power-intensive industry and P2X by raising wholesale electricity prices as well as increased electricity prices for household consumers. It will further require domestic grid reinforcements, affecting the hitherto untouched landscapes. All these factors put together result in constraints that should not be ignored when modelling the future European electricity system.

Effects of social acceptance on the Nordic-Baltic energy system

In order to assess the influence of less social acceptance of wind energy and transmission lines on key technical and economic attributes of the energy system, we ran four scenarios in the Balmorel model. The scenarios are defined by the assumptions on investment potentials of onshore and nearshore wind power and high-voltage electricity transmission lines (in short: transmission) between countries, in the Nordic-Baltic region, as follows:

1. **LowLow**: The total capacity of onshore or nearshore wind power cannot exceed the current (2019) level in the Nordic-Baltic countries, except for the already planned projects. Transmission follows the BAU scenario (Chapter 3) with no additional capacity after 2030.
2. **BAU** (LowTransmission): New investments in wind power in all regions are possible but transmission is restricted.
3. **Low Wind**: Same as in the "LowLow" scenario, but new investments in power transmission lines become possible from 2030 onwards (like the Connect scenario, but with restriction on the wind power potentials).
4. **Connect** (HighHigh): New investments in both on/nearshore wind power and power transmission are possible.

In order to study the effect of acceptance of wind power one can compare LowLow with BAU or Low Wind with Connect respectively under the different assumptions on transmission capacity expansions. In all scenarios, the energy system in the Nordic-Baltic region is carbon neutral at the latest in 2050.

Generation capacity investments

Figure 50 displays the modelled investments from 2030-2050 in the Nordic countries for the four scenarios. In the two scenarios having restrictions on onshore wind power (LowLow and Low Wind), we observe more investments in solar power, offshore wind as well as biomass-based CHP (bio-CHP).

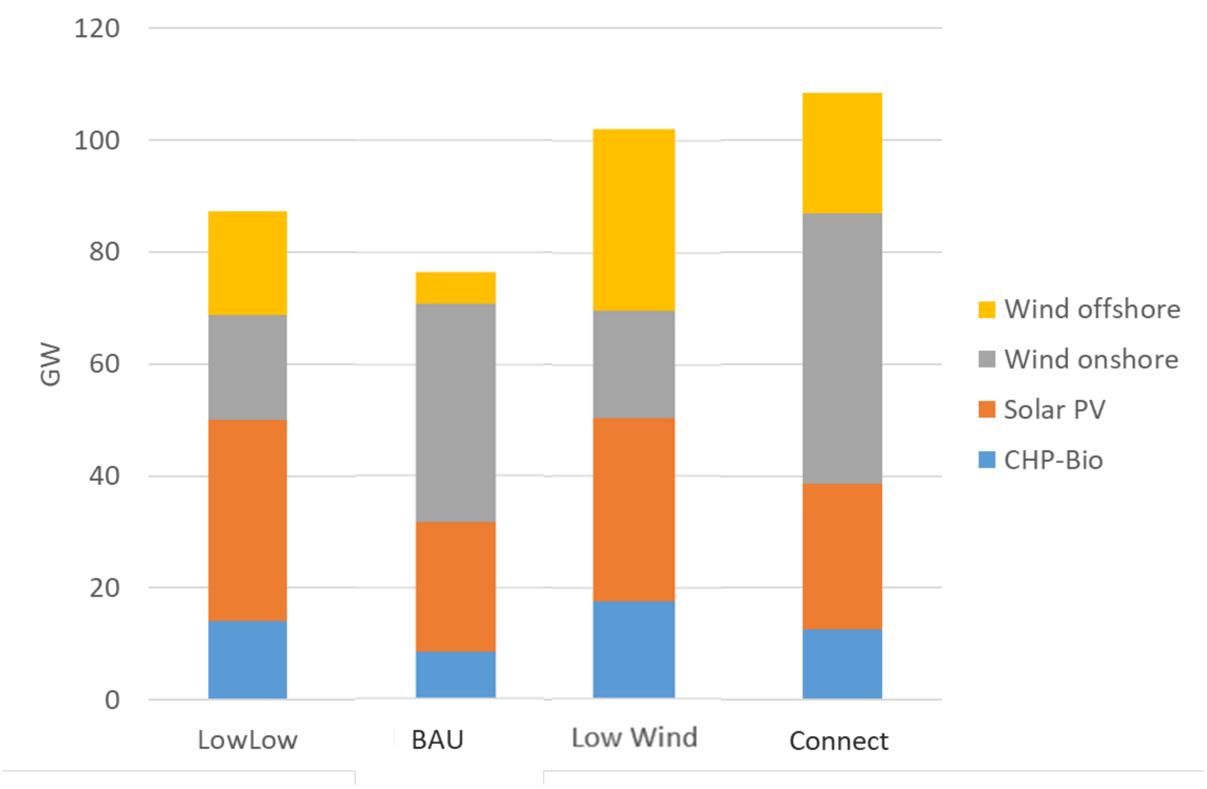

Figure 50: Generation capacity investments 2030-2050, Nordic countries

Due to the pathway toward carbon neutrality with a relatively high CO_2 price, there is hardly any investment in fossil-based capacity in the Nordic countries, even in the LowLow scenario. The modelled solar PV investments (small scale, behind the meter) are relatively high in all scenarios. The "behind the meter" assumption in the analysis in this chapter only, implies no grid tariffs for this technology and therefore a considerable higher deployment than in the model runs presented in the rest of this report. However, as discussed in chapter 3.1 due to a lower capacity factor, solar PV does not contribute nearly as much in electricity production as wind power does.

We find similar results for the Baltic countries (Figure 51), but the magnitude of investments in alternative technologies to onshore wind is lower. In the Baltics, it is more evident that increased transmission capacity is required for, and incentivized by, large-scale utilization of onshore wind resources, i.e., we find much larger investments in onshore wind in scenario Connect (opening for investment in transmission) compared to BAU.

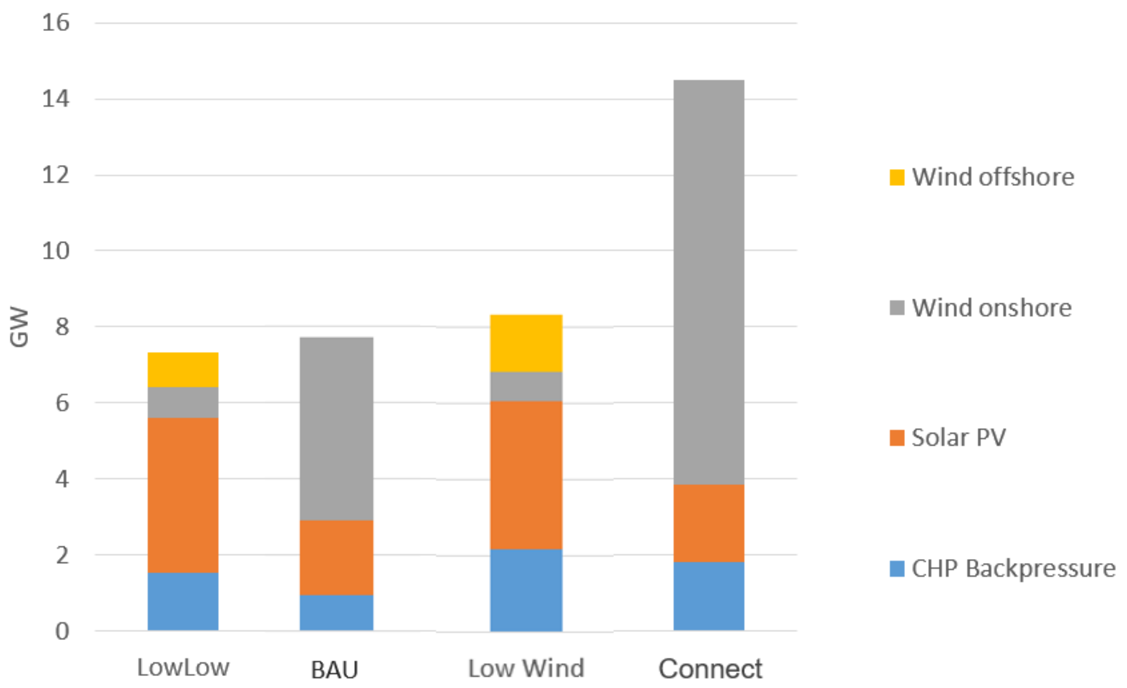

Figure 51: Baltic generation capacity investments 2030-2050.

In general, the scenarios illustrate a centralized versus a decentralized development in the Nordic-Baltic region: the less the cross-border capacities, the more decentralized onshore wind and PV capacities are installed.

Power price impacts

The relative power price changes from the LowLow scenario to the other scenarios are substantial for some countries (Figure 52). Restrictions on onshore wind (LowWind) increase prices in the Nordics (except Denmark) and Baltics and lower them in Denmark and Germany and in the other south-western countries.

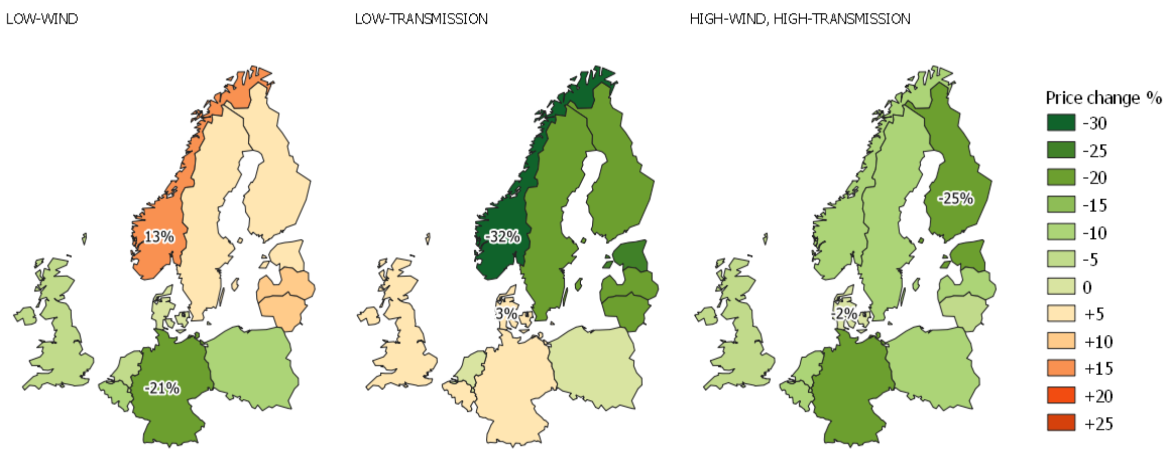

Figure 52: Changes in the modelled power prices in 2050 compared to the LowLow scenario (annual averages) (%)

Restrictions on transmission capacity (BAU/LowTransmission), conversely, lower prices significantly in the Nordics and Baltics (except in Denmark) while the south-western countries experience zero or a slight increase in prices.

It is also interesting to note that when investments are opened for both wind and transmission (Connect / HighHigh), power prices fall in the entire region, with as much as 25% in Finland, compared to the restricted scenario (LowLow). As Germany is the largest power market in the region, the price reduction of 22% means a large reduction in the absolute value of electricity in the region as a whole.

Discussion of the model results

The Balmorel model results confirm that the Nordic and Baltic countries have onshore wind resources that may contribute significantly to a cost-efficient decarbonisation of the North-West European energy system. In the cost-optimal model scenario (Connect / HighHigh), with no restriction in investments, roughly 40 GW (Nordics) and 20 GW (Baltics) of new onshore wind power would enter the market in the period 2030-2050. Such investments would, however, not only affect land use and the environment but also have economic and distributional impacts on consumers and producers of electricity (as also discussed in Chapter 4.5).

A key concern here is the distribution of costs and benefits associated with new energy technologies and infrastructures among different groups in society. An unfair distribution of costs and benefits could cause resistance to the energy transition and change its form, speed and cost. Resistance can manifest itself as low social acceptance at the local level where new energy technologies are sited, or as opposition to wider systemic changes at the national political level, for example in relation to changes in electricity prices. Indeed, processes at the two levels can reinforce each other, e.g. national political debates reported in the media can fuel local resistance, and vice versa, and there can also be interactions with supra-national debates - at the Nordic, EU and global levels.

As an illustration of economic benefits, the assumption of distributed PV "behind the meter" (exemption of grid taxes) in the model runs in this chapter, reveal a much higher deployment of this technology. Such private economic incentives could improve the acceptance of PV and other renewable technologies, but it may also imply an additional costs to other parts of the system due to lost grid tariffs that have to be covered by others.

If public resistance or landscape concerns restrict onshore wind power investments, solar PV and offshore wind power would replace much of the onshore wind investments, under the assumption of high carbon prices. The model results also illustrate 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 storage technologies, on the other hand.

Altogether, a zero-emission transition in the Nordic-Baltic region may depend critically on the ability to manage and overcome socio-technical barriers at local to national scale during the 2020-2040 period, particularly regarding the distributional and governance aspects of renewable energy technologies and infrastructures.

Related Flex4RES publications

Reports:

K. Skytte, L. Söder, N. Mohammad, ***Methodology of Determine Flexibility Costs and Potentials and major flexibility potentials in the Nordic and Baltic countries***. DTU/KTH, 2018.S.

Published journal articles and books:

S. Bolwig et al., ***Review of modelling energy transitions pathways with application to energy system flexibility***, Renewable and Sustainable Energy Reviews. Elsevier Ltd, pp. 440–452, 01-Mar-2019. DOI:10.1016/j.rser.2018.11.019

F. Wiese et al., ***Balmorel open source energy system model***, Energy Strateg. Rev., vol. 20, pp. 26–34, Apr. 2018. DOI:10.1016/j.esr.2018.01.003

Forthcoming articles:

S. Bolwig et al., ***Transition pathways to a flexible and carbon-neutral energy system in the Nordic-Baltic region: Coupling techno-economic modelling and socio-technical analyses***, Submitted for publication.

P. D. Lund et al., ***Pathway analysis of a zero-emission transition in the Nordic-Baltic region***, Submitted for publication.

4.9 Nordic carbon negativity by 2040

As mentioned in the Introduction (Chapter 1), the UN IPPC report from 2018 urges nations to cut their greenhouse gas emissions to limit the global temperature rise to 1.5°C - regarded as the upper limit for ecosystem sustainability. As mentioned in Chapter 4.1, the Nordic countries have set ambitious carbon neutrality targets (Table 1 on page 29) for the years 2030 and 2050.

Two of the main questions in the climate debate are:

- Is it enough to become carbon neutral or is it necessary to go ***carbon negative*** in order to fulfil the commitment made in the Paris Climate Accord to staying below a 1.5°C temperature rise?
- What are the benefits of going carbon negative and what is the pathway to carbon negativity?

In order to illustrate the temperature rise caused by the increasing CO_2 content in our atmosphere, one can think of the atmosphere as a bathtub filling up with CO_2 (Figure 53). The higher the level of CO_2, here represented by the "bathwater", the higher the temperature rise. To become carbon neutral, one must balance the sources (the CO_2 tap) and the CO_2 sinks (CO_2 drain). If the 1.5°C level is exceeded, drainage must surpass input – i.e. go net carbon negative – in other periods in order to re-establish the CO_2 balance.

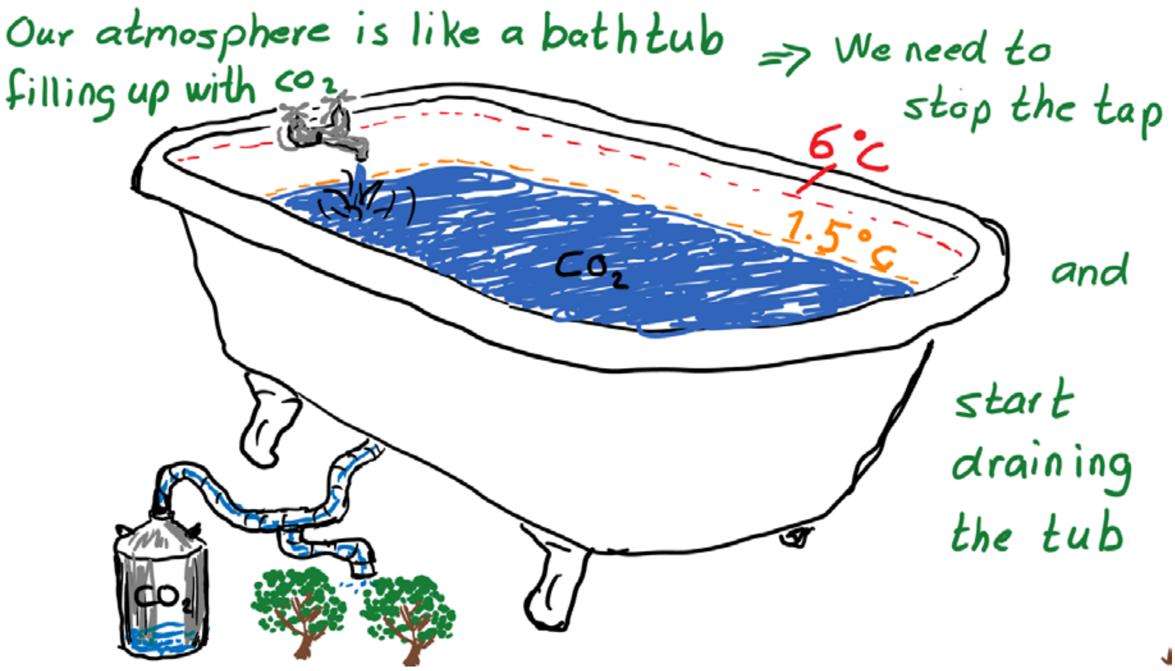

Figure 53: Our CO_2 balance illustrated as a bathtub.

Another way of illustrating it is by thinking of the 1.5°C level as a carbon budget that we have to stay within. Figure 54 illustrates the relative magnitude of the Nordic carbon budgets (level of the "bathwater" in the Nordic "bathtub") from 2018-2050 according to different temperature increases and the associated levels of CO_2. The grey area indicates the present yearly amount of emissions. This implies that we can only emit 2-10 years of what we do today before we have used our entire CO_2 budget (<1.5°C).

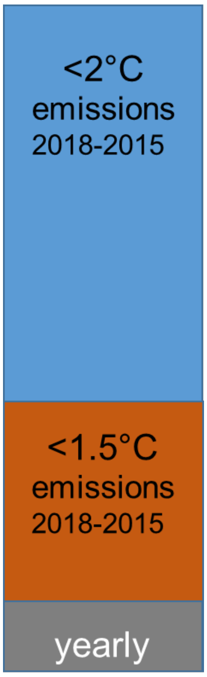

Figure 54: Nordic budget projections for the total net CO_2 in 2018-2050 under different budget restrictions (temperature increases), as well as the present level of yearly CO_2.

As we have argued in other chapters of this report, we can act fast in the Nordic electricity and heat sectors, but some of the other sectors may take more time to decarbonise, e.g. aviation and shipping. By going net carbon negative by 2040 in the energy sector, we can "buy time" to decarbonise these sectors - allowing us to exceed our carbon budget in the transition years and "pay back" the carbon debt afterwards (Figure 55).

The blue line in Figure 55 illustrates a pathway towards carbon neutrality in 2050 - staying within the carbon budget by a swift decarbonisation. The orange line illustrates a pathway with a less nimble decarbonisation in the 2020s - exceeding the carbon budget but going net carbon negative after 2040 in order to re-establish the carbon balance.

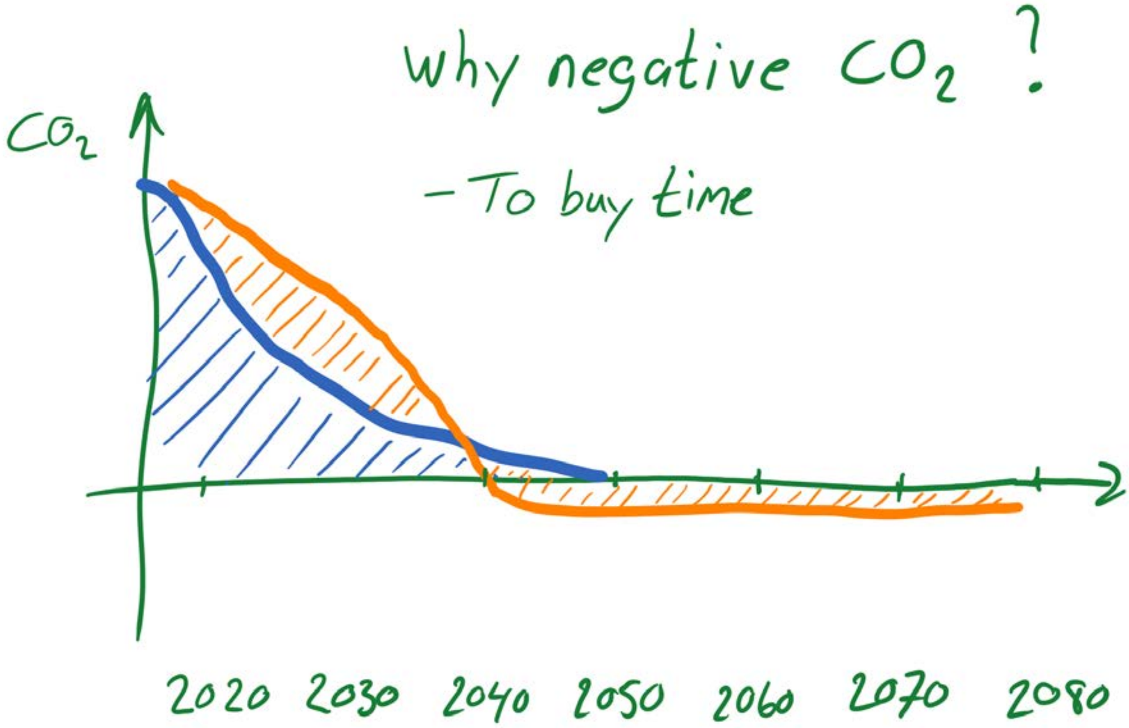

Figure 55: Carbon neutral by 2050 (blue line) versus carbon negative by 2040 (orange line).

As mentioned in Table 2 (on page 30), the Nordic countries' economies have different carbon footprints. As an example, Figure 56 illustrates a possible CO_2 pathway for Norway allowing for a "slow" decarbonisation with net negative CO_2 emissions in later years. The blue dashed areas indicate the uncertainty and possible outcomes.

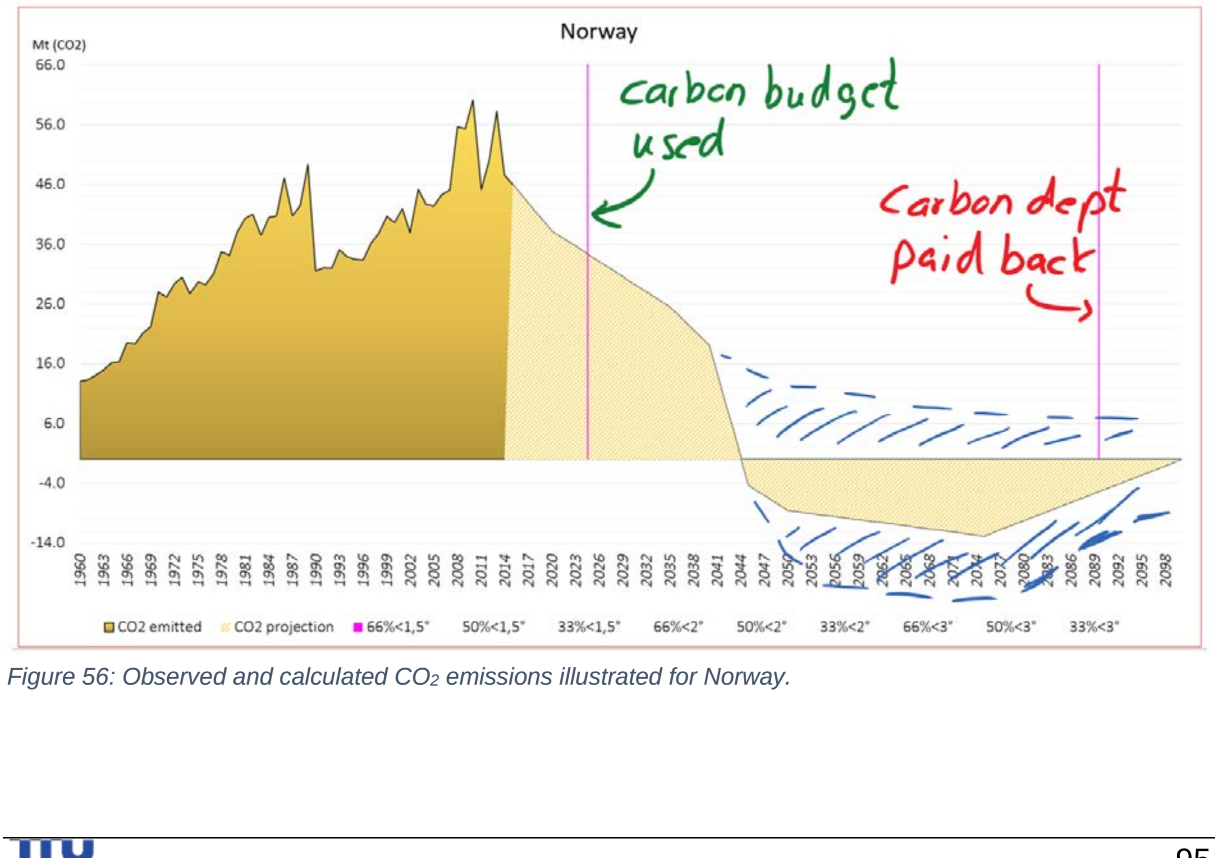

Figure 56: Observed and calculated CO_2 emissions illustrated for Norway.

Carbon capture is needed in order to go carbon negative ("draining the CO_2 bathtub") in both the industry and energy sectors. In the energy sector, this could require carbon capture in biomass-based energy generation as well as the integration of natural carbon sinks (sustainable forests/terrestrial sequestration), among others. Potentials for geological sequestration (carbon storage) as well as the biomass resources differ between the Nordic countries. Nordic collaboration is therefore needed in order to do it in a cost effective way.

The captured carbon can also be used in industrial processes and biofuels - at least in a transition period. However, keeping the carbon in the system does not "drain the CO_2 bathtub". With a soon maturity of conversion technologies for electro fuels, parts of the biofuels can be substituted, e.g. by hydrogen (H_2) or ammonia (NH_3), and the corresponding "saved" carbon can be taken out of the system and stored.

In order to analyse different CO_2 pathways, we used the three Scandinavian countries (Norway, Denmark and Sweden) as case studies and developed three different scenarios (Table 11). With the Nordic Energy Technology Perspective (Nordic NETP) 1.5°C scenario as a reference case, we extended the analysis with two additional scenarios: Nordic IPCC 2014 and Nordic IPCC 2014 Bio. The latter one, in addition to the 1.5°C carbon budgets, also restricts biomass imports in order to reflect the uncertainty surrounding the sustainable level of biomass consumption in the Nordics.

Table 11: Scenarios used for the carbon budget/negativity analysis in this chapter.

Scenarios	Demand projections	Fuel prices	CO2 tax	Carbon budget	No biomass or biofuel imports
Nordic ETP (NETP)	NETP	NETP	**X**	-	-
Nordic IPCC 2014	NETP	NETP	-	**X**	-
Nordic IPCC 2014 Bio	NETP	NETP	-	**X**	**X**

The scenarios also differ with respect to the way CO_2 is regulated. In the Nordic NETP scenario, a CO_2 tax (or price) accelerates the transition from fossil to renewable energy. Whereas the carbon budget restrictions are the driver behind this switch in the Nordic IPCC scenarios.

With the other analyses in Flex4RES focusing mainly on the electricity and heat sectors, we modelled the scenarios by soft linking our power and heat model Balmorel with the energy system model TIMES-Nordic (http://timesnordic.tokni.com/) in order to include several sectors of the Scandinavian economies.

The model runs show that the power sector becomes carbon neutral relatively fast in all scenarios (Figure 57) – with slightly higher CO_2 emissions in the 2010s in the IPCC scenarios (leftmost red circle in the figure). Carbon capture and storage (CCS) starts to enter the market around 2030, leading to net carbon neutrality in 2040 while still allowing part of industry, aviation, and heavy transport to emit CO_2 (rightmost red circle in the figure).

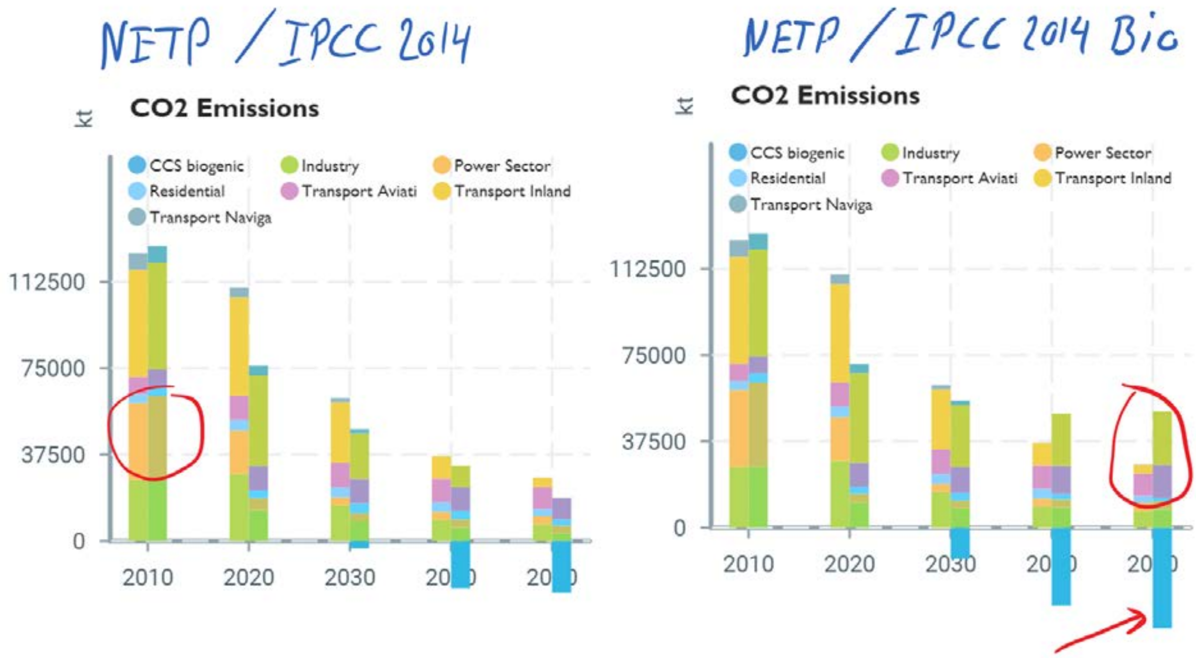

Figure 57: CO2 emissions from difference sectors.

Carbon capture is mainly done by carbon capture and storage (CCS) on biomass-fuelled CHP plants in the power sector as well as carbon capture in industry (Figure 58). Therefore, the carbon budget restrictions increase the deployment of biomass-based CHP coupled with CCS compared to the reference scenarios or to a case where we decarbonise the power sector separately without CCS to help other sectors.

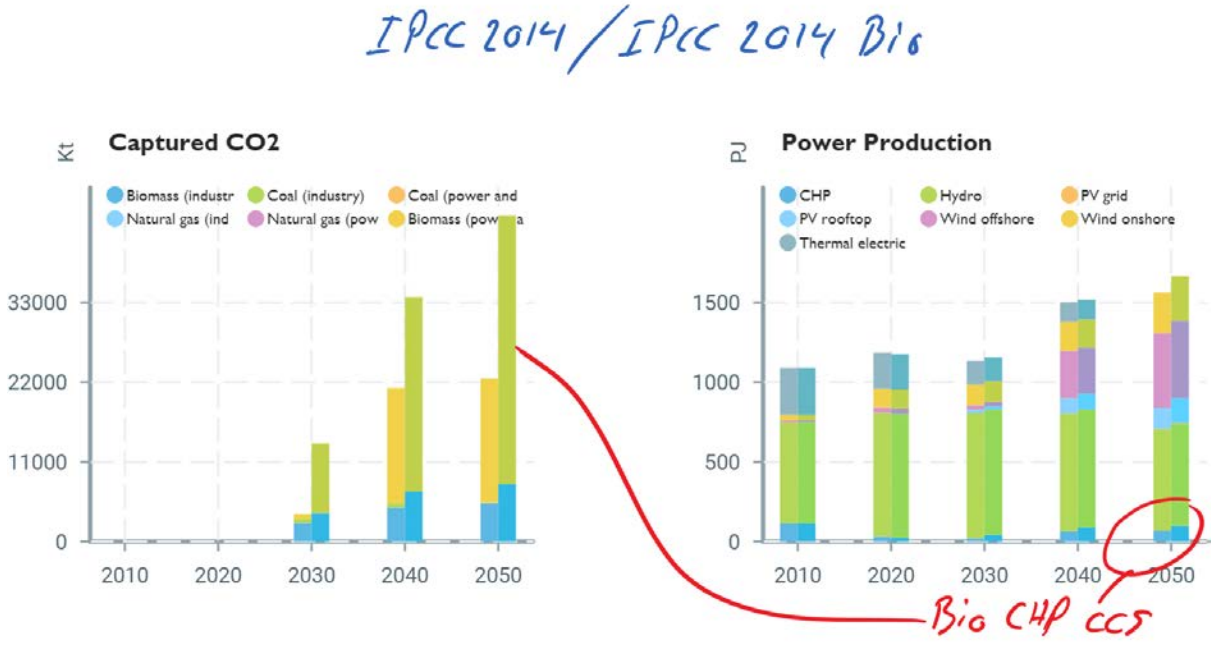

Figure 58: CCS and power production.

The restrictions on sustainable biomass use in the IPCC 2014 Bio scenario imply that industry seeks alternative fuels. Coal will still be used in the industrial sector, implying a larger need for CO_2 capture – both in industry and the power sector. This enforces the need for biomass-based CHP with CCS (red circle in Figure 58) as well as a higher degree of electrification. The energy sector has to become more carbon-negative and the need for flexibility increases.

With different storage possibilities, biomass resources and power technology mixes, as well as different levels of coupling of electricity and district heating, our analysis shows that:

- **The Nordics can become frontrunners** in solving climate challenge.
- **The Nordics can become net negative by 2040** with the power and heat sectors mainly leading the way.
- **A Nordic CO_2 negativity target needs to be translated into realisable policies** for each sector.
- **Without carbon capture, utilisation, and storage (CCUS) we cannot fulfil the target set in the Paris agreement** – to limit temperature rise to 1.5°C until the end of the century.
- **Without Nordic collaboration, it does not make sense** - reaching carbon negativity cost-efficiently is not achievable.

Critical points:

- **Enough sustainable biomass?** The green transition requires a lot of biomass in the power, heat, and industrial sectors as well as for greening the aviation and heavy transport sectors.
- **Sector coupling and smart integration need to be in place**. Act fast and smart, and ensure that the regulatory frameworks provide the right incentives for flexibility.
- **Greening transport**. Are we moving fast enough?
- Disruptive technology development:
    - **Carbon capture/carbon storage**. The technologies need to come from demonstration plants to full-scale operating plants with high reliability and low costs.
    - **Electro fuels** (P2X), e.g. hydrogen (H_2) and ammonia (NH_3), will play a larger role in the future. The development of electrolysers and conversion process needs to progress in order to ensure economic feasibility and reliability.
- **We need to push the technology development** - not only with R&D in the above mentioned disruptive technologies but also with policies that ensure a fast deployment of mature P2H and other P2X technologies as well as wind and solar power and thermal energy storage (in district heating).

Related Flex4RES publications

Published journal articles and books:

F. Wiese et al., ***Balmorel open source energy system model***, Energy Strateg. Rev., vol. 20, pp. 26–34, Apr. 2018. DOI:10.1016/j.esr.2018.01.003

Online information:

Model outcomes: http://timesnordic.tokni.com/

Biomass based CHP with CCS: ***Negative CO2-project***. Nordic Energy Research. https://www.nordicenergy.org/flagship/negative-co2/

Greening transport: ***SHIFT project***. Nordic Energy Research. https://www.nordicenergy.org/flagship/project-shift/

5 Flex4RES publications

Several publications have been made in the Flex4RES project - going into depth with the research questions summarised in this report as well as with related issues within the framework of Flex4RES. Some are available at the Nordic Energy Research webpage others are available on request to the authors if they are not online accessible from the journals.

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C. Bergaentzlé, L. R. Boscán Flores, K. Skytte, E. R. Soysal, and O. J. Olsen, ***Framework conditions for flexibility in the electricity sector in the Nordic and Baltic Countries***. 2016. ISBN: 978-87-93458-46-8

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