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Comparative Analysis of Cross-Border and Cross-Sector Approaches for Flexibility in the Nordic Countries

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Abstract **– The Nordic electricity sector is on track to become fully decarbonized thanks to the large uptakes of electricity from renewable energy sources. However, future carbon-free energy systems create new challenges for the flexibility of supply. This study assesses four scenarios, building either on electricity market coupling or sector coupling between heat and electricity, that enable flexibility in the Nordic countries. We show that the critical role played by these countries in the European transition affects both investment choices and flexible operation of the resources available in the electricity and heat sectors. While the sector-coupling approach results in substantial economic gains from a system perspective, other redistributions of benefits enabled by the cross-border approach need to be considered too in designing appropriate energy policies and road maps.**

Keywords **– Flexibility; sector coupling; interconnection; carbon neutrality; variable renewable energy**

1. INTRODUCTION

The European power system is undergoing some profound transformations. The electricity mix is evolving from a centralized and dispatchable supply-side relying on thermal and hydropower plants to a low-carbon electricity mix with a large share of variable renewable energy (VRE), such as wind and solar (COM(2011) 885). In the “Clean Energy for all Europeans” strategy, the European Union has created a common energy and climate policy framework for its member states that is aimed at cutting down CO_2 emissions by 40 %, reaching a 32 % share of renewable energy sources and a 32.5 % energy-efficiency target by 2030 [2]. RES, including hydropower, currently account for one third of European electricity production [3].

More recently, the Nordic countries have committed themselves to entirely decarbonizing their energy systems in the electricity, heat and transport sectors by signing a declaration for achieving carbon neutrality [4]. In this effort, electricity will play a determining role as a vector of green energy in the other energy sectors through electrification.

According to IRENA simulations, the resulting higher demand for electricity due to electrification will further stimulate investments in variable renewable energies (VRE) in the electricity sector [3] and, along with it, increasing the need for flexibility [5]. A VRE-heavy electricity supply requires a diversified portfolio of flexibility solutions being available to balance the system. Given current shares of VRE, the need for flexibility principally concerns the ramping up of dispatchable power plants to cope with the sudden drops in wind or solar production. In future decarbonized systems, flexibility will also take the form of increased

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consumption or storage in order to absorb the peaks in VRE generation and make the best use of cheap, CO_2-free electricity, while limiting curtailments and energy waste.

In this study, we investigate two complementary policy approaches to enabling flexibility in a 100% carbon-neutral Nordic energy system, looking especially at Denmark, Finland, Norway and Sweden. Flexibility is enabled on the one hand through electricity-market coupling and interconnections and on the other hand by coupling the electricity to the district heating sector via Power-To-Heat (P2H) technologies. Past studies demonstrate the technical potential of district heating to mitigate CO2 emissions from the heat sector [6]–[8].

We show that the sector-coupling approach seems to offer the least-cost option in the long run if the Nordic countries' deep decarbonization target is to be met. Increasing cross-border capacity results in greater economic surpluses for electricity producers and environmental benefits for the rest of Europe, but it also slows down the transition road map in the Nordics, negatively affecting the cost of electricity for the final users.

The study is organized as follows. Section 2 describes the state of the art and provides background information on flexibility in energy systems. Section 3 defines the methodology. Section 4 presents our main findings, while Section 5 discusses the results and provides a conclusion.

2. BACKGROUND INFORMATION

2.1. Zoom on the Nordics

The European policy for energy decarbonization is rooted in the Third Energy Package and the Winter Package. These texts set the framework for the energy transition for all EU member states. Past studies have investigated various strategies to mitigating our carbon emissions at the country level such as in [9]–[11]. Large differences exist in the transition road maps and targets of the different European countries because of different factors such as their respective energy mixes and resources, energy markets and coupling, policies and the attitudes of their policy-makers to the fight against climate change, including in supporting more flexible systems [12], [13].

The Nordic countries have already reached their energy targets and stand out when it comes to integrating VRE as compared to the average European Union performance. The share of RES in the Nordic region already exceeds 35% of the total final energy demand [14] (against 13.9 % on average in the EU). In the electricity sector this gap is wider and is marked by the substantial presence of VRE within the RES mix, especially in Denmark, where 49 % of the demand for electricity was supplied by wind, and marginally by solar energy, in 2017. Half of Swedish and Finnish demand and the whole of Norwegian electricity consumption is based on RES (Fig. 1).

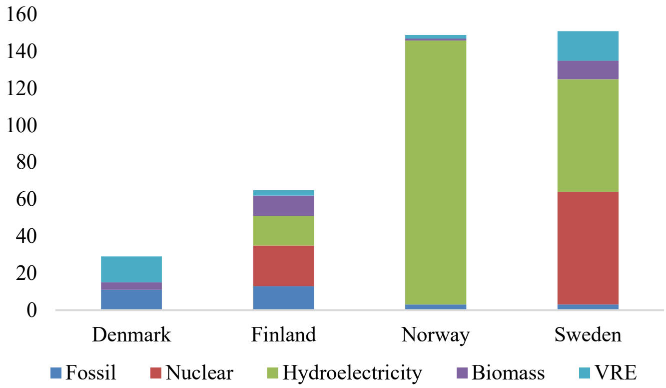

Fig. 1. Electricity mix in the Nordic-Baltic region in 2016 (TWh) [13], [15].

The large hydroelectricity and biomass resources available in the region give a clear edge when it comes to supplying decarbonized energy. In their declaration in favour of carbon neutrality in 2019, the Nordic countries reaffirmed their determination to fulfil the Paris Agreement and fully decarbonize their electricity, heat and transport sectors. Norway and Denmark should be fully carbon-neutral by 2050, while Sweden and Finland have announced that they will reach this target before that, in 2045 and 2035 respectively.

This far-going decarbonization strategy requires carbon emissions to match the capacity of carbon sinks and will rely greatly on the rapid replacement of current polluting sources of energy generation by renewables, including intermittent wind and solar energy.

Since the development potential of hydroelectricity and to a lesser degree of bioenergy is limited [16], [17], wind and solar energy should attract the main investments in the coming decades to replace aging thermal plants and meet demand, thereby intensifying the intermittent nature of the offer and stressing the need for flexibility.

In countries using district heating to supply heat, the development of Power-to-Heat (P2H) equipment such as electric boilers and heat pumps, connected to the storage capacities of district heating, will bring new flexibility solutions to the energy system while letting the heat sector benefit from cheap, low-carbon electricity [18]–[21]. With about half of the heat demand supplied through district heating (excluding Norway) (Fig. 2), the flexible operation of P2H equipment can become a strong asset in the Nordic countries' transitions.

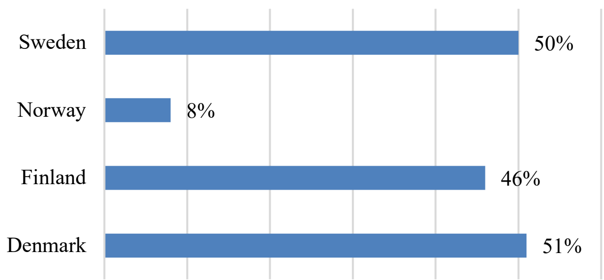

Fig. 2. Share of heat provided by district heating (based on [22]).

2.2. Shedding Light on Flexibility

The degree of flexibility in energy systems with large shares of VRE depends on the residual flexibility on both the supply and demand sides. An energy resource is considered flexible when it is possible to regulate it (increase and decrease it) either locally or on a larger scale through its interconnections, thus maintaining a balance between the supply of and demand for electricity.

The challenges and impacts linked to flexibility in an RES-based energy system have been widely investigated in terms of their potential and requirements [15], [23], [24], activation costs [25], [26], market price impacts [27], [28] and activation drivers and barriers [13], [21], [29]. These studies stress that geographical integration through interconnections and market coupling provides access to diversified energy mixes, with beneficial impacts on market prices, reliability and social welfare. In this context, the interconnections and a robust transmission network are central to the efficient integration of VRE. However, some studies also warn against the ripple effect between growing VRE-generated energy and the risk of increasing congestion at times when the load cannot be entirely met because of insufficient transmission capacities [30]. Other studies underline the challenge of building more lines as a response to acceptance issues [31].

Transmission grids combine the functions of transporting electricity from production to consumption centres with enabling exchanges of energy based on the diversity and availability of resources to which they give access in time and space [32]–[35]. For example, an excess of wind energy in Denmark can be exported to Germany, replacing higher German production and other energy supply from cheap and flexible foreign power plants such as Norwegian hydropower. In this way, both the flexible supply (hydropower in Norway) and the VRE (wind in Denmark) benefit by avoiding the production of excess supply at low or negative electricity prices, resulting in the community benefiting from a cheap and reliable green energy supply.

The electricity grid also supports geographical dispersal either within one and the same energy resource (based on the non-correlation of wind regimes in space) or between different variable resources (benefiting from different wind and sun regimes), thus reducing the probability of excessive production on a large scale. Transmission grids are therefore beneficial to the reciprocity of effort across areas that present different generation and load patterns. Transmission corridors will shape Europe's future decarbonized electricity systems, notably in regions with large expansions of offshore wind energy, such as in the Nordic and Baltic Seas.

The downside of relying on a "transmission only" strategy for purposes of system reliability comes from the limited capacities of the physical installation, which is itself challenged by VRE penetration. VRE development will happen in clusters: wind and solar farms will be geographically concentrated in areas with favourable weather conditions. Likewise, obtaining flexibility on the centralized supply side will come from those areas with available dispatchable capacities. In a carbon-free energy future, these areas are likely to be concentrated around large hydropower plants. The locations of both VRE supply and flexible resources will impact on power flows in the transmission and interconnection lines and are likely to generate bottlenecks, potentially leading to load or VRE curtailment. This suggests a better integration of both the supply and demand sides on both the centralized and local scales.

On the demand side, flexibility is a matter of the capacity to modify the load pattern in response to appropriate signals. The market price is the main driver that the providers of flexibility must adjust to over time. In hours with a large supply of VRE and low demand, prices in the wholesale market are low, which supports direct consumption, electricity conversion and storage. Conversely, during hours with a low supply of VRE and high demand, high-spot prices are achieved by dispatchable power plants, and the flexibility of demand is adjusted downwards.

Flexibility can originate from load-shedding or load-shifting [36]–[39]. In the Nordic countries, the potential for demand response during peak hours is substantial (15 % to 30 % for the residential segment and up to 7 % for industrials) [15]. However, the share of electricity in the final energy consumption is relatively low as compared to the need for heating, which makes the coupling between the two sectors even more relevant.

Sector coupling is based on the transformation of electricity into another type of energy, here heat, building on the large synergy effects, including access to flexibility at the interface between the two systems [22], [29], [40]. The appropriate seasonal match between electricity generated from wind and heat consumption supports this form of flexibility, as the heat sector can exploit the low-cost energy provided by the power sector [41]. P2H will convert peak electricity production into heat and provide access to large-scale thermal storage. In this case, electricity becomes a fuel that competes with other substitutes such as bioenergy or fossil fuels and that requires non-discriminatory conditions being guaranteed to all competing resources. For example, sector-oriented policy measures (e.g. taxes or subsidies) may distort the costs of running a given heat boiler in systems of district heating capable of using either electricity or gas as input, thus leading to sub-optimal choices for market actors [42].

Alternatively, flexibility can be provided by storing electricity surpluses in electric batteries and utilizing the energy at a later stage. However, this solution is sometimes considered expensive [43]. This builds the case for a better integration of all players along the electricity chain to create a diversified portfolio of flexibility solutions capable of responding to diverse flexibility needs.

In what follows, we model the future carbon-neutral Nordic energy system, assuming high shares of VREs, and estimate the costs and impacts of using the two approaches to enable flexibility – that is, using either more transmission networks or better sector coupling.

3. METHODOLOGY

3.1. The Optimization Tool

We use the Balmorel energy system model to perform the analysis [44] (http://www.balmorel.com/). This is written in the GAMS programming language and optimizes short-term operations and long-term investment in the heat and electricity sector using partial equilibriums.

The simulation period covers the decades from 2020 until 2050 and consists of a regime of 24 hours a day, three days a week, from seven representative weeks per year, thus reflecting the yearly pattern and combinations of variable renewable energy production and energy consumption to reduce computational time. The model is run with predictability limited to just two decades in order to optimize the current years with reference also to future developments. The transmission system is represented by a flow-based model using power transfer distribution factors, which provides a robust representation of the interlinkage between investment in transmission grid capacities, physical flows and commercial exchanges.

The spatial reference covers the Nordic countries, the Baltic States, the United Kingdom and Central European states (Fig. 3), but the results are only presented for the Nordics. We refer to the other countries modelled in this study as “the rest of Europe”, unless otherwise specified.

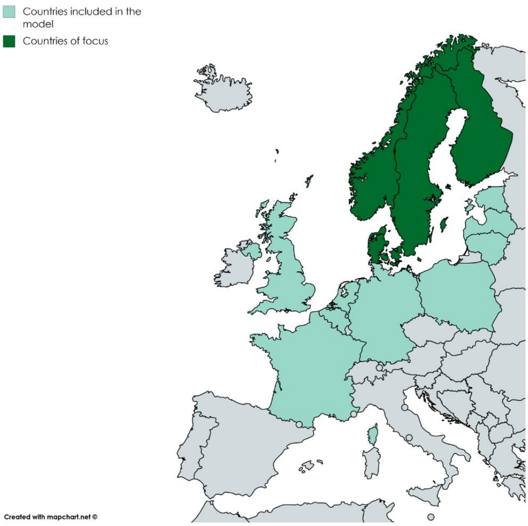

Fig. 3. Countries represented in the modelling.

3.2. Main Assumptions

The costs and technical data are based on [36], while energy resources and technology cost developments are based on [37]. We assume a steadily increasing CO_2 cost, from 65 €/tCO_2 today to 130 €/tCO_2 in 2050), following the estimates of [47] [48], and we calibrate the model so that a fully carbon-neutral electricity and heat sector is achieved by 2050, in compliance with the Nordic countries' target.

The EU population is projected to increase over the coming decades following the calculations in [45]. It is assumed that the legally binding targets for the share of RES in energy consumption are met by 2020. Nuclear and coal power plants under construction are included, but it is assumed that the technology is not renewed after phase-out. Future investments in bioenergy power plants result from market conditions and CO_2 prices, and are limited by the availability of biomass resources. We assume that hydropower is already fully deployed and remains constant.

The costs associated with the final use of energy are in the form of taxes and, in the case of electricity, also include the grid tariff. The available flexibility potential on the demand side is assumed to be optimally activated in accordance with market conditions.

3.3. The Scenarios

The four scenarios developed in this study apply to all the countries within it and are as follows:

- **Scenario (SC) 1** is the business-as-usual (BAU) scenario. It resembles the current situation in the Nordic countries in terms of system size and energy policy. The transmission system is expanded according to the current ENTSO-E Ten Years Network Development Plan, after which further investments are blocked. Energy policies affecting grid tariffs are modelled mainly as energy-based costs representing today's existing tariff schemes. The same goes for energy taxes;
- **SC 2, "*Connect*",** is based on BAU, but removes all technical barriers to network expansion and reinforcement. The TSOs are assumed to be benevolent, and investment in incremental capacity is driven by market forces;
- **SC 3, "*Policy*",** adjusts current energy policies and lifts the regulatory barriers on the demand side, including district heating and building flexibility as in [42], while

re-establishing the technical restrictions on network investment used in the BAU case. The regulatory barriers that hamper power-sector flexibility and sector coupling are eliminated, and technological neutrality in investments is assured. In this scenario, we use a revenue-neutral capacity-based electricity grid tariff and an electricity tax system that is designed to ensure a level playing field for all competing energies across all sectors;

– **SC 4, "*Combi*",** combines the *Connect* and *Policy* scenarios (2 and 3) and thus envisages the removal of all technical and regulatory barriers. The model chooses optimally which flexibility option between interconnection and flexible sector coupling should be operated and invested in.

4. RESULTS

SCs2 and 4 show similar trends regarding technology investments and generation and are used interchangeably in this section.

All scenarios show that the increase in electricity demand, which is mostly driven by EV and heat pumps in the residential segment and to a lesser extent by P2H in district heating, is met by wind energy. At the country level, the share of wind capacity approximates to 90 % of the total installed capacity in Denmark, regardless of the scenario. This share reaches 50 % in Sweden and Finland and between 15 % and 31 % in Norway.

More is invested in generation, regardless of the energy source, under SCs 2 and 4, where transmission capacities are added. Coal capacities are entirely phased out by 2050, leaving in the Nordic mix the thermal capacities associated with the Finnish nuclear power plants that are still operating, the waste incineration plants and the peat-based plants, which together represent 2 % of the Nordic mix in 2050. The steep reduction in thermal power plants is mainly replaced by the increase in wind and solar capacity. Investments in dispatchable RES power plants such as biomass CHPs also make progress in the 2040s along with the penetration of electric cars, mainly covering peak hours with low VRE production (Fig. 4).

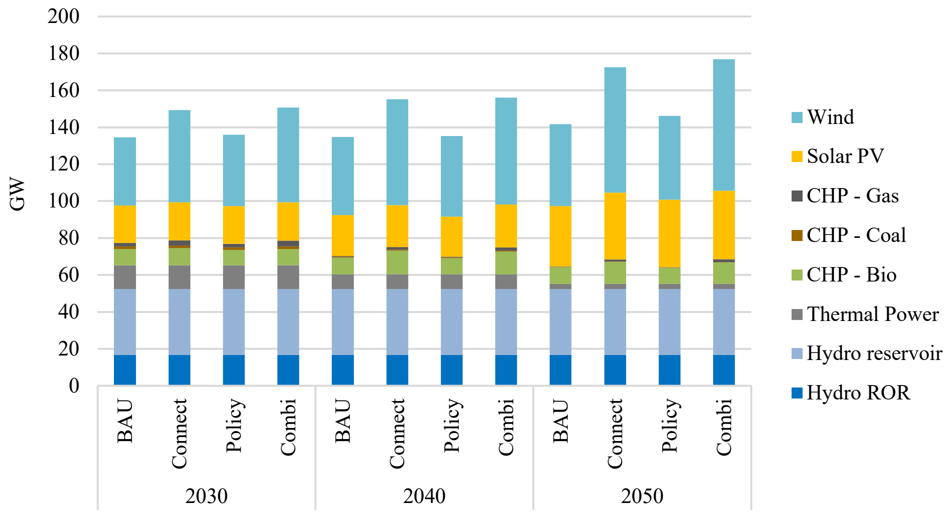

Fig. 4. Evolution of installed capacities in the electricity sector of the Nordic countries (GW).

In terms of power generation, SC3 alone shows a slight increase in the total electricity demand as compared to the reference case, due to the increased flexibility provided by DSM and sector coupling. Accumulated throughout the overall period, the electricity produced in the Nordic countries increases by less than 0.5 %. In comparison, SCs 2 and 4 show higher generation outputs of 8.5 % and 7.6 % respectively, encouraged by the trading opportunities that result from more interconnections.

Wind generators benefit the most in all four scenarios, as their production represents an average of 90 % of the total production increase by 2050. Fig. 5 shows the impacts of each scenario on the electricity output of the three main technologies: wind, thermal power plants (aggregated biomass, nuclear, gas and coal), and CHPs. It also highlights the inverted trends between wind and thermal energy and the stabilization of CHP production from 2030 onwards. All scenarios reduce the participation of thermal plants in similar proportions. The contribution of hydroelectricity remains constant throughout all years and in all scenarios.

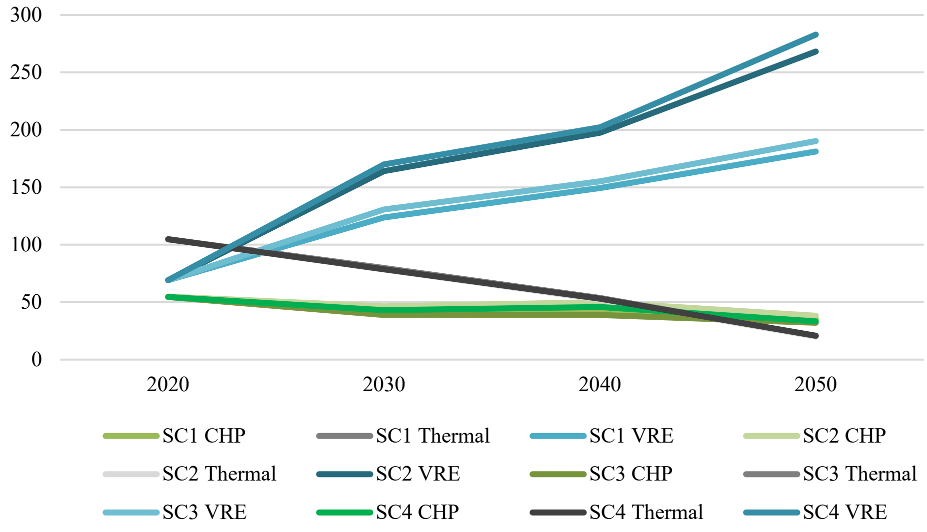

Fig. 5. Impact of the scenarios on the production of electricity from wind, CHPs and thermal power plants (TWh).

A more detailed analysis shows that production of electricity from biomass CHP and solar PV is inversely affected by the sector coupling scenario (Fig. 6). Increased trading of electricity across borders significantly affects CHP producers. The shortfall between SC2 and SC3 equals on average a fifth of total CHP production in SC2 from 2030 onwards. This represents the volume of the cheaper Nordic production from cogeneration that is exported to the rest of Europe, where condensing coal plants are less efficient and competitive. The effect observed in SC3 is the result of the combination of a lower need for CHP due to a greater usage of P2H and hydroelectricity, and of the market constraints that result from the lower overall export potential. The disaggregation of CHP technology also clearly shows the progressive replacement of coal and gas by bioenergy, representing 100 % of CHP-based generation in 2050.

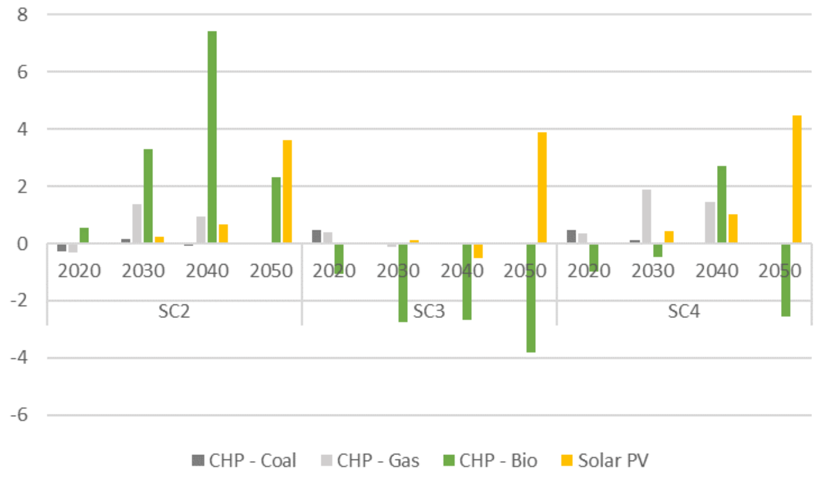

Fig. 6. Impact of each scenario on the production of Nordic electricity from CHP and solar PV as compared to SC1 business as usual (TWh).

Regarding the electricity trade balance, the results show more exchanges in both directions when the model is allowed to invest in cross-border lines and when there is a growing positive trade balance throughout the period. Fig. 7 shows the evolution of imports and exports from the Nordic region to the rest of Europe at the aggregated level. In this illustration we only compare the BAU scenario to SC2, as the difference in terms of exchanges between SCs1 and 3 on the one hand and between SCs2 and 4 on the other hand is marginal.

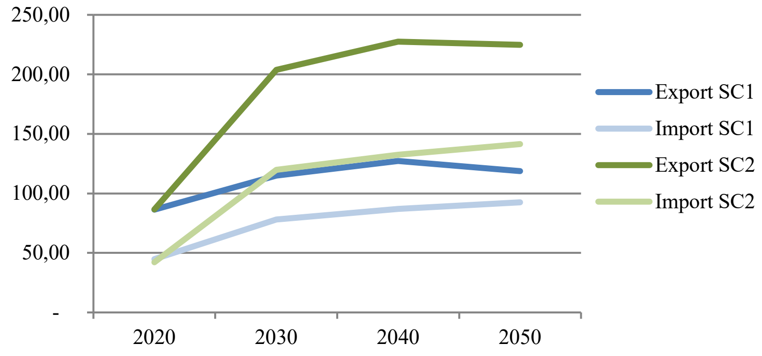

Fig. 7. Energy traded in SC1 and SC2 between the Nordic countries and the rest of Europe (TWh).

The Nordic region almost doubles its exports of electricity to the rest of Europe, while its imports increase by 50 %. A large share of the exported Nordic energy serves to cover the demand in Germany and the UK. Market prices in the Nordic region are consistently lower than those in the rest of Europe, a price difference that increases as we approach 2050. On average, Nordic electricity prices are 24 % lower than in the rest of Europe throughout the period and in all scenarios.

At the country level, Norway and Sweden benefit the most from increased cross-border exports of their flexible hydroelectricity. Denmark's exports of wind surpluses are multiplied by four between 2020 and 2040 to reach 80TWh before plateauing, and its imports slow down considerably. In Finland, the effect of interconnection shows a different picture, with a balance deficit in all scenarios from 2030 or 2040, which results from its proximity to the Baltic States, with their cheaper average electricity prices, and from the construction of the "highway (transmission) line".

In the heat sector, the contribution of district heating to supplying heat diminishes in absolute terms as a result of greater energy efficiency in buildings (Fig. 8). The decommissioned capacities, mainly CHPs and Heat-Only boilers (HO boilers in the figure) using gas and coal, are not renewed or serve as back-up. All new investments are made in flexible P2H, thermal solar and marginally in biomass-based CHPs.

The flexibility potential in district heating, which corresponds to the progression of P2H and CHP and to the utilization of storage, increases substantially and is maximized under SC4 at the regional level. Long-term (or seasonal) storage, characterized by the utilization of large storage capacities such as pit storage, that is the least used option in 2020 in the base case, but it increases significantly and becomes the first source of storage from 2030 onwards in terms of both capacity and utilization. This progression is particularly acute in SC3, with the exception of 2050, when long-term storage marginally loses ground. SCs 2 and 4, on the other hand, result in increasing short-term storage, thus allowing for more hourly flexibility.

The model shows an important decrease in heat-only boilers in all scenarios, being replaced by CHP plants and P2H, a trend accelerated by the decommissioning of coal- and gas-based boilers. In 2050, the remaining heat-only boilers are powered by biomass. P2H capacity reaches up to 34 % in the overall Nordic region in 2050 under SC3.

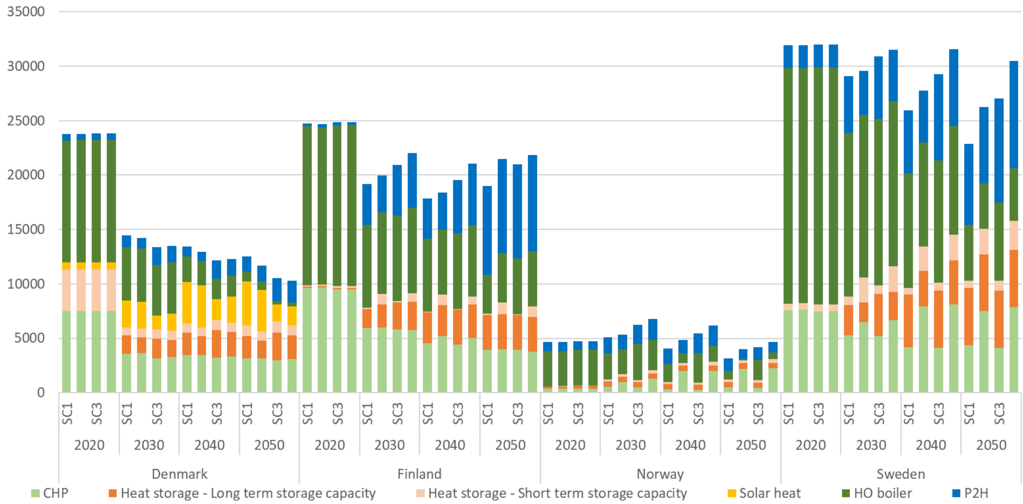

Fig. 8. Installed capacities in DH by technologies and country (MW).

A closer look at the production from each technology used in district heating highlights how district heating becomes highly flexible in the scenarios with sector coupling (SCs3 and 4). CHP and P2H replace the heat-only boilers and provide complementary flexibility services (up and down regulation) to the electricity sector. In spite of the larger installed capacity in CHP, the results show a slowing down of CHP's contribution to the generation of heat from 2040 and a growing participation by P2H. This trend suggests an accelerating uptake of flexibility from district heating following the RES investment boom in Europe.

Finally, the model shows that the temporality of system (electricity + heat) investment is non-linear (Fig. 9). The system costs are driven by the new investments made in electricity generation and the rapid take-off of wind power plants. Regardless of the scenario, important investments are expected in the 2030s and 2040s before coming back to current investment levels. In the scenarios with an altered policy regarding sector coupling, the total system cost in 2050 reaches a lower level than today, prior to the decarbonization effort. The additional expansion and reinforcement of the transmission grid naturally generates higher network costs and stimulates investments for new power plants in SCs 2 and 4.

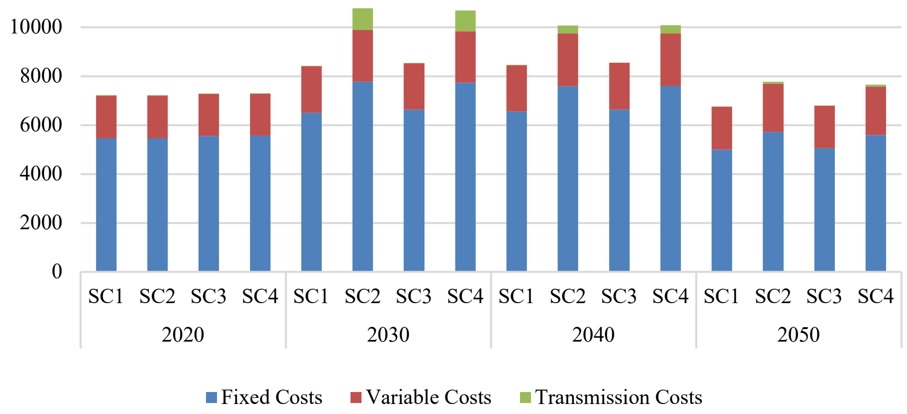

Fig. 9. Total System Costs in the Nordic Countries for electricity and heat (M€).

Overall SC3, which promotes more sector coupling, results in lower system costs due to the lower levels of investment in new grid capacities, but also because the operation of and investment in non-VRE power plants permitted in SCs2 and 4 is limited in this scenario. Ultimately investments in new capacities in district heating only marginally increase, while the heat fuel cost benefits from cheaper resources.

5. DISCUSSION AND CONCLUSION

In 2050, RES will supply up to 97 % of the total demand for heat and electricity in the Nordic countries, or almost 1.5 times more than today. The penetration of wind energy is on average 6 % higher in SCs 2 and 4 than in SC3, demonstrating the complementarity of transmission grids and VRE integration. SCs 2 and 4 show similar trends regarding investments in technology and generation in 2050, suggesting that investments in additional transmission capacities are prioritized over sector coupling as the least-cost flexibility option.

The interconnection and the sector-coupling policy approaches to achieving flexibility also affect the different stakeholders as a result of their respective redistribution effects. In spite of the relatively weak level of investment in new generating capacity outside of wind and solar energy, the participation of thermal power plants to the electricity market is higher until 2040 in the scenarios with increased network capacity, encouraged by higher average prices in the rest of Europe and the greater profit opportunities of the thermal plants. More market coupling with interconnections especially benefits the VRE generators and the baseload electricity producers in the Nordic region, who also benefit from higher infra-marginal rents in the wholesale market.

However, the increased participation of shoulder and peak thermal plants also negatively affects the average price paid by Nordic consumers and slows down the reduction of Nordic greenhouse gas emissions. In the rest of Europe the result is the opposite, since the main share of the energy imported from the Nordic region is CO2-free and cheaper.

This distribution of benefits is changed with less interconnection. Nordic consumers actually benefit from lower average electricity prices, and the surplus shared by the generators diminishes. In return, accumulated CO2 emissions in the Nordics are lower, but the rest of Europe faces a slower and more costly transition.

The rapid increase in the P2H contribution in 2030, which is correlated with an increase in the utilisation of storage, indicates that district heating fully contributes to the overall flexibility effort together with the electricity supply side, especially when a level playing field exists between different energy resources. The different trend observed in P2H and storage in district heating also stresses the complementarity and substitution effect with CHPs and DSM respectively.

The model also reveals an important aspect of the transition timeline. Important investments in generating capacity are expected during the studied period before coming back to current investment levels in 2050, when the energy system is 100 % fossil-free. In this study the investments are preconditioned by the policy strategy to opening up markets more or to turning to smart sector coupling. In other words, the sooner the policy line is defined, the sooner the transition. In this optimal arrangement, the investment efforts peak in the 2030s and 2040s, meaning that policy-makers and society must act fast to facilitate and introduce a supportive framework for the investment boom that lies ahead [49]. Delays in the implementation of consistent regulatory frameworks are likely to result in higher transition costs for society in the Nordic countries reaching a CO_2-free energy system in thirty years' time.

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