Energy System Transition in the Nordic Market: Challenges for Transmission Regulation and Governance

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The energy system in the Nordic countries faces changes driven by increasing integration with the rest of Europe and changes to the generation mix. These developments pose challenges with respect to future network development and operation. We focus on three major aspects: market integration; generation and network adequacy; the need for more flexibility and frequency control. We describe factors behind these problems and present possible solutions within the Nordic context. One conclusion is that supranational cooperation should be further improved.

Keywords: transmission regulation, energy policy, market integration

I. Introduction

Energy sector decarbonisation, electricity market integration and increased security of supply are the major factors that define policy and strategic decisions in the electricity sector in Europe (EC, 2010; EC, 2011). The long-term objective is to create an energy system based on renewable energy in an internal European market for energy.

The transmission network is the backbone of the electricity market and fundamental in achieving efficient performance, integration of renewable energy sources and security of supply. Hence, transmission networks have attracted the attention from policy makers and researchers because of their importance both when it comes to achieving the renewable targets and to achieving the desired market integration. Investments in network development have increased, as evidenced by the increasing number of cross-border projects (Nordic Grid, 2014; ENTSO-E, 2016A). Changes in the electricity production and consumption and the energy system structure challenge current approaches to the network operation, planning and economic valuation. In order to tackle these challenges and achieve the market development aligned with the European goals, one needs to revisit the ways we regulate transmission networks and to analyse new market tools.

Achieving the long term goals of the energy sector requires improved cooperation across the EU member states. The Nordic countries may serve as examples of the efforts to achieve such regional cooperation in energy market design and development. Some perceive the Nordic

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electricity market as one of the most successfully functioning regional markets in Europe (Amundsen and Bergman, 2006; Bredersen, 2016). Also, the energy mix is dominated by renewables, which gives a hint about the future European system. In this regard, we consider it useful to analyse the challenges facing the Nordic system concerning transmission network development and regulation.

The electricity markets in the Nordic countries (except Iceland) have historically been well-connected by cross-border transmission lines. Complementarities in the generation mix across the different countries and the close political and economic ties between them have contributed to the development of cross-country transmission capacity. A strong transmission network is required to connect big load centres around capital cities and big industrial sites, in particular with the Norwegian and Swedish hydro power located far away from demand. Historically, Swedish and Finnish nuclear power was able to offset variations in renewable production because the network was dimensioned to handle such variation. The generation mix is now changing, which puts increased pressure on owners to develop the network and on system operators to manage it efficiently. Further market integration with other neighbouring countries also contributes to the challenges of network development.

The purpose of this paper is to analyse the Nordic power system and the regulatory challenges this system is facing with respect to transmission network development. We summarise major issues in the current debate, discuss possible solutions that have been proposed and relate the Nordic perspective to the discussion in Europe.

The paper is organised as follows: Section 2 provides an overview of the European energy system trends. Section 3 presents a background of the Nordic electricity system and describes the electricity market organisation in the region. Section 4 analyses the regulatory challenges and briefly discusses possible solutions and barriers. Section 5 concludes our analysis and summarise the major findings.

II. The European context

The major objectives of the European energy system development are outlined in a number of strategic and regulatory documents. The 2030 Framework for Climate and Energy establishes five interrelated dimensions: security of supply at the Union level, a fully integrated internal energy market, energy efficiency, decarbonisation of the economy, and priority of research and innovations (EC, 2013A).

The goal of promoting clean energy includes an ambitious reduction in CO_2 emissions by at least 40% by 2030, and at least 50% renewable energy in the generation mix (EC, 2016). A long-term perspective, as established by the Energy Roadmap 2050, foresees an almost complete decarbonisation of the power sector (95-100% renewables). This is a major change comparing to the current situation. Achieving these ambitious climate goals will require a significant shift in energy production that in turn will emphasise network development. Renewable energy sources are often intermittent and geographically unevenly distributed. Hence, integration of renewable energy resources is one of the major factors governing transmission network development in the coming years (ENTSO-E, 2016a).

A fully-integrated internal electricity market is another ambitious goal of the European Energy Union. The single European market for electricity was set to be functioning by 2014 (EC, 2012). Arguably, the goal is still not fully achieved yet, though progress has been made. Most of the national markets in Europe have been connected through a market coupling mechanism (ACER, 2016). However, there are still remaining regulatory and structural limitations. It appears necessary to invest in cross-border transmission capacity (Meeus and Belmans, 2009), which then is an important driver for decisions at national and supra-national levels.

In 2016 the European Commission proposed new energy regulations, known as the "Winter package", with updated rules aimed at further increasing market integration and decarbonising the energy sector. The significant change in the regulation of transmission includes the strengthening of regional cooperation. The package introduces regional operational centres (ROCs) expected to complement national TSOs by undertaking the functions of regional relevance, including capacity calculations or enabling the regional procurement of balancing services (EC, 2015). However, ENTSO-E has expressed concerns with regards to the binding nature of the ROCs' decisions on cross-border capacity calculations and regional reserve capacities requirement. It is believed that such decisions can be in a conflict with the Members' national legal framework and they can threaten the national security of supply interests (ENTSO-E, 2017). Therefore, the question of the future role and powers of the ROCs in Europe remains open.

Overall, European coordination efforts with relation to the transmission network operation and planning are shaped through a set of administrative and financial measures. ENTSO-E provides planning guidance through ten year network development plans (TYNDP). These are non-binding plans for network expansion based on a Union-wide system analysis. They include a list of infrastructure projects deemed beneficial for the overall economic welfare as per a cost benefit analysis. Projects on the list can apply for the status of the Project of Common Interest (PCI), and if approved, receive financial and administrative support (EC, 2013B).

In practice, the coordination efforts seem to be undermined by structural differences in the national electricity systems and the design of the support mechanisms themselves. Some express concerns over the issues regarding insufficient wholesale market integration and the question whether the pace of developments in system operations can keep up with the pace of change in the system. The concern is based on the fact (EC, 2015, p.3) "that TSOs operate their systems based on mostly national approaches, resulting from the historic development of national power systems and their operations". The PCI support mechanisms are sometimes argued to be too complicated and imply too many conditions and requirements to be practical (EU Task Force, 2014).

III. Nordic energy system overview

The Nordic electricity system consists of Denmark, Finland, Norway and Sweden. In the current analysis, we exclude Iceland because it represents an isolated system that is disconnected from the rest of Europe. The rest of the Nordic countries are well connected by transmission links (Fig. 1).

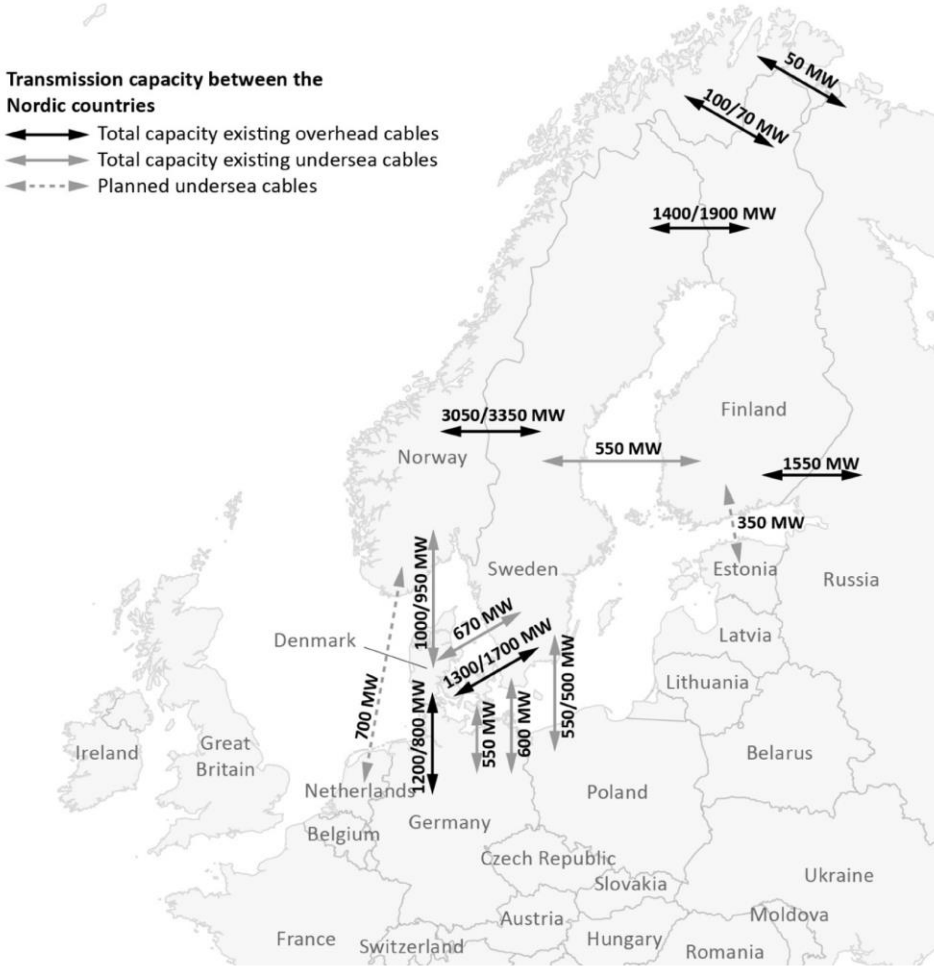

Fig. 1. Nordic system interconnections, 2016. *Source: Statnett*.

The Nordic transmission business model satisfies EU unbundling requirements. Each country has one transmission system operator (TSO), which is a state-owned company. The Nordic TSOs are Statnett (Norway), Svenska Kraftnät (Sweden), Fingrid (Finland) and Energinet.dk (Denmark). These TSOs are regulated as natural monopolies with revenue cap regulation, with the exception of the TSO in Denmark, where cost-plus regulation is applied (NordReg, 2012). Transmission tariffs in the Nordics are relatively low compared to other European countries (ENTSO-E, 2016b). In some countries certain non-network costs passed through the TSO (such as renewable support in Denmark), but the network cost part of the tariff is low compared to the average European level. In the Nordic market, consumers and producers are subject to transmission tariffs to a varying degree depending on their location in the network.

Each TSO is responsible for the operation and development of the national systems. Regional transmission planning is realised based on the Nordic Grid Development Plan, which is a planning document created under the cooperation of the Nordic TSOs (Nordic Grid, 2014). Since 2009, ENTSO-E has also played a prominent role in Nordic network planning through the network development plans.

The Nordic countries have a common wholesale electricity market. Most of the electricity is traded on the common power exchange, Nord Pool (Nord Pool, 2017a). Starting as a cooperation initiative between Norway and Sweden, at present, Nord Pool integrates the Nordic and Baltic countries (Nord Pool, 2017a). It is also linked through market coupling to Continental Europe. The market is divided into bidding areas where each area has a single price (zonal pricing). Local TSOs can decide on the number of bidding areas within their region, subject to the possibility of intervention at the European level. Notably, Sweden was divided into 4 bidding areas in 2012 after an emerging suspicion that SvK was moving internal congestion to the borders (Thema Consulting, 2013). Nord Pool operates the day-ahead market (Elspot) and the intraday market (Elbas). Currently, with the cooperation of the TSOs, a number of power exchanges, including Nord Pool, have taken the initiative to create a joint integrated intraday cross-border market. This market is expected to enable continuous cross-border trading across Europe (Nord Pool, 2017a).

Overall, the Nordic electricity market is a mature market with a design that has remained fundamentally the same since the start. There are some differences between the organisation of the market in the Nordics and in Continental Europe, including the division into the bidding zones.

Due to a large share of hydro and nuclear in the mix, the Nordic electricity system has historically been characterised by low levels of carbon emissions. According to the International Energy Agency, the CO_2 emissions per unit of electricity generated are already at the level that the rest of the world must reach by 2045 to limit global warming to less than 2°C above pre-industrial levels (Nordic Research, 2016). In addition to hydro and nuclear generation, the increasing share of wind power as well as the high fuel taxation and subsidies for electric cars in the transport sector (though transport is still a major producer of CO_2 in the Nordics) have major effects on low levels of CO_2 emissions. Strategic documents manifest the political determination to continue the decarbonisation of the Nordic countries (Nordic Research, 2016).

In summary, the Nordic electricity system presents a relevant case of applied regional cooperation: it is a relatively well interconnected market with a high level of renewable generation and established institutional connections. The advanced state of these economies and the high initial penetration of renewable energy sources have contributed to the favourable environmental performance of the power sector. However, the Nordic countries have not pursued the challenge of further renewable transformation as a unified whole. In particular, the different countries have adapted fairly different support systems; for instance, Norway has an extensive support scheme for the promotion of electric cars, whereas Sweden has a particular support system for roof-top solar power.

Furthermore, the system is expected to face more challenges with the coming changes. First, each Nordic country is expected to be increasingly integrated into the common European electricity market. Such integration will be achieved by the expanded transmission interconnectors and harmonisation of the market design. Increasing transmission interconnection will require high volumes of investment and new approaches to the allocation of costs and benefits (as in Tohidi and Hesamzadeh, 2014). Second, the generation mix is expected to change. Future changes in the generation mix within and between countries are likely to affect the degree to which TSOs will have to cooperate to maintain system stability. In particular, Sweden is expected to decommission a substantial part of its nuclear power over the next five to ten years, partly replacing it with hydro and wind power and new nuclear facilities in Finland. This substitution will challenge the flexibility of the Nordic system. Coupled with increasing investments in Danish off-shore wind generation (Windspeed, 2015), these changes will have a substantial impact on electricity flows in the system, which, in turn, will increase the interdependencies of the countries and challenge network operations.

IV. Challenges to the Nordic electricity system

Here, we present what we believe are important challenges that Nordic regulators and the TSOs face or we expect them to encounter, over the course of the energy system transition. This does not represent a full list of problems but, rather, an overview of acute topics directly or indirectly related to transmission network planning and operation.

We analyse the factors underlying the challenges and provide an insight into possible solutions. Solution options generally include infrastructure measures, market design measures or operational changes. Finally, we analyse the potential barriers in the way of introducing new measures and discuss possible ways to overcome them.

Challenge 1. Further market integration

The ultimate goal of a single integrated European electricity market is to increase economic efficiency, improve competition and provide consumers with a reliable supply of electricity at a low cost (EC, 2012). Essentially, market integration assumes the free trade of electricity between parties in different locations within Europe, restricted only by network capacity. The regional prices are formed based on the congestion between bidding areas. At present, the

European market remains fragmented, with the Nordic market being one part of the entire structure.

At a general level, Glachant and Ruester (2014) characterise the general challenge for a single European electricity market as a decentralisation dynamic. First, renewable support schemes result in a decentralised electricity consumption-production cycle. Uncoordinated national renewable support mechanisms and capacity policies then distort the common market. Finally, there is a risk of disruptive innovations to which markets are not flexible enough to adapt. This dynamic aspect of the electricity system poses a number of regulatory challenges, as summarized by Perez-Arriaga et al. (2017). These include possible mismatch between industry structure and planning requirements, and an inadequacy of the current electricity pricing to facilitate integration of new technologies. The decentralisation dynamic and regulatory challenge corresponds well with those faced by the Nordic countries, with some region-specific peculiarities.

Market integration currently is quite high in the Nordic market. The price area differences serve as an indication of the level of market integration. Fig. 2 displays the average monthly prices in the Nordic and Baltic countries for the period 2014-17. The average price area spread decreased significantly during that time span. Hourly price differences can still be substantial, especially between the Nordic and Baltic prices. Figs. 3 and 4 show the hourly Nord Pool day-ahead prices during two specific days in 2017. Prices in Latvia and Lithuania were substantially higher than in the rest of the market during a number of hours. These price differences are associated with congestion in cross-border transmission lines.

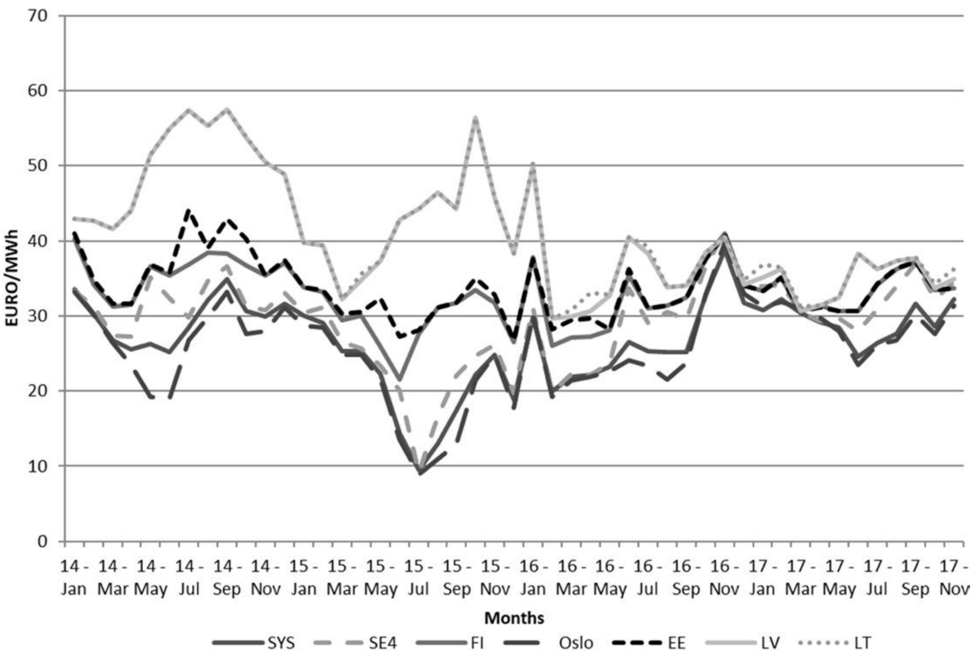

Fig. 2. Monthly average day-ahead prices 2014-2017. *Source: Nord Pool*.

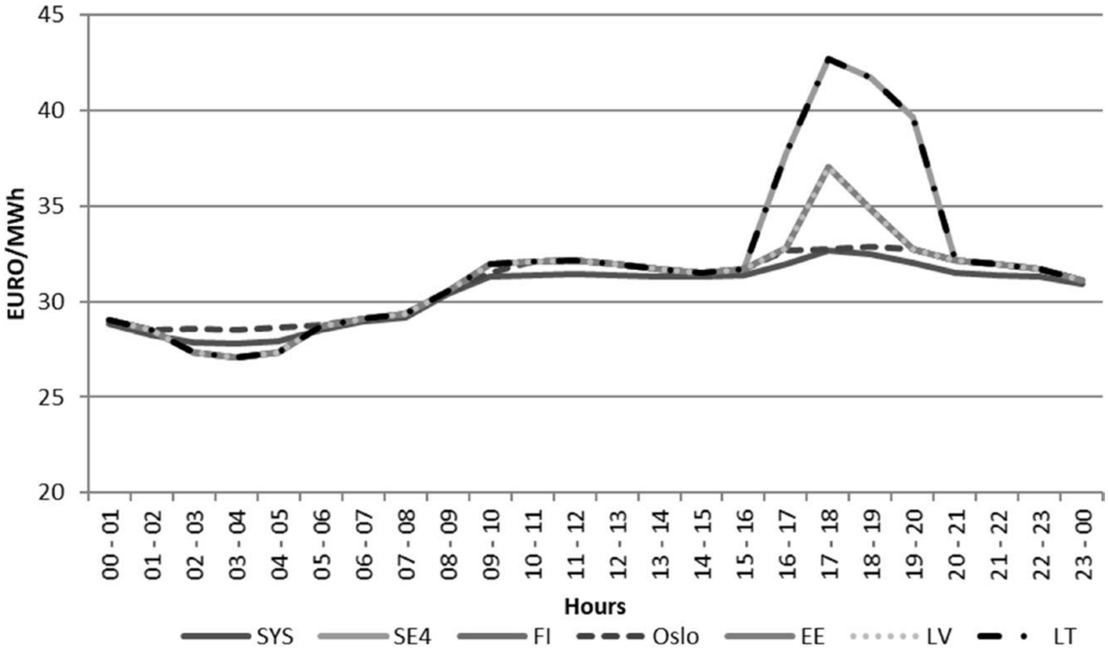

Fig. 3. Hourly day-ahead prices on 15 January 2017. *Source: Nord Pool*.

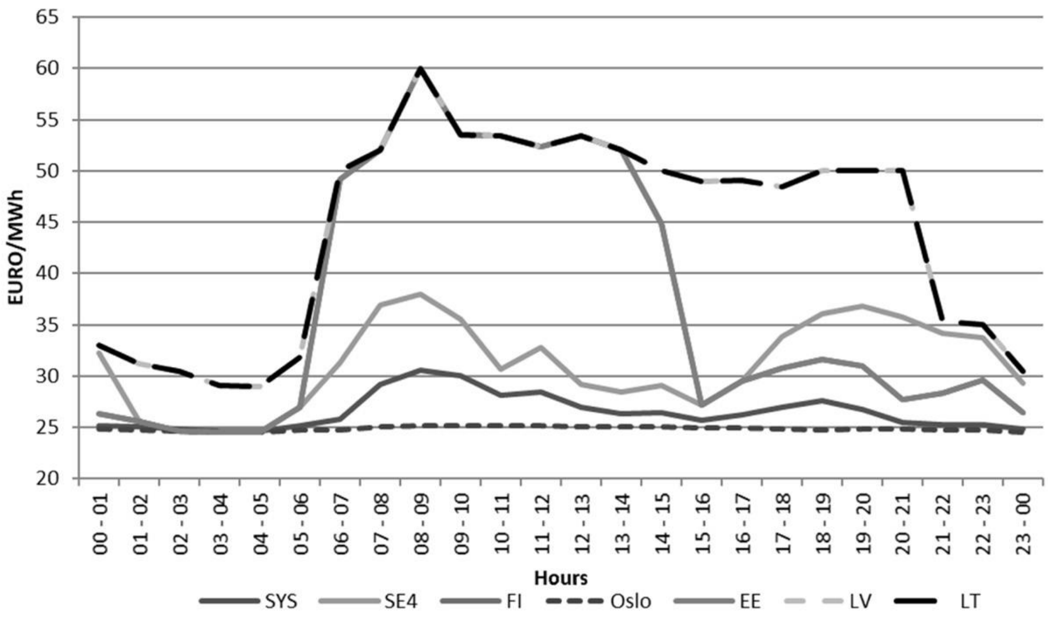

Fig. 4. Hourly day-ahead prices on 15 June 2017. *Source: Nord Pool*.

Newbery et al. (2016) estimate the potential benefits of market integration as very high on the European level. Nonetheless, integration incentives on the national (or regional) level exist only when the national economic benefits largely exceed the costs of integration. The national benefits often come with a trade-off in terms of national security of supply and possible economic losses for local producers and consumers (see Puka and Szulecki, 2014). Cost-benefit analysis is complicated by the increased uncertainty in the market and network performance due to the increased share of distributed renewable generation. Hence, the benefits and costs of the further integration of the Nordics are challenging to estimate.

Given the integration incentives are present, the efficient functioning of a single (in this case, coupled) market requires the following conditions:

1) Sufficient cross-border transmission capacity to achieve the efficient dispatch of the generation plants;
2) Market rules that do not prevent foreign buyers and sellers from participating in the national markets; and
3) Harmonised, or at least aligned, national market and operation rules to avoid distorted incentives and to reduce the possibilities of market power abuse.

Concerning the role of TSOs in the integration of markets, they first are expected to facilitate market integration by ensuring sufficient cross-border capacity. Second, the existing interconnectors should be allocated in an efficient manner.

The Nordic region is reasonably well-connected in terms of cross-border transmission, and the grid is continuously expanded to increase integration (Statnett et al., 2016). Recall the small average price differences in Fig. 2. In Sweden alone, planned network investments amount to 5,5 billion Euros (SvK, 2015) over the next years. The overall capacity of the interconnectors is expected to increase by 50 per cent by 2025 (Statnett et al., 2016).

As an infrastructure measure, increasing interconnection capacity requires large investments. The Nordic TSOs perceivably do not have significant problems with financing network development. Additionally, a significant share of the infrastructure projects is PCIs, and therefore receives financial and administrative support by the EU. However, the investments can be hindered by a number of factors:

a) High uncertainties in future system developments make it difficult to estimate the costs and benefits of the cross-border projects and, therefore, the social value of the projects. Illustratively, a Nordic study of future system development (Statnett et al., 2016) accounts for several scenarios within which the directions and volumes of the system flows significantly vary. The uncertainty complicates the planning process and increases the risks for society and investors. This calls for improved robust planning methods, closer cooperation between TSOs and stakeholders, and better risk management.

b) Even if a new cross-border link would generally improve overall economic welfare, it can still worsen the position of producers or consumers in one of the interconnected markets or a third market affected by the electricity flow changes. Sometimes the "losing" party can block project implementation. A comprehensive review of the issues associated with the cost and benefits of the interconnectors can be found in Hogan (2017). While being economically rational and efficient, the proportional cost allocation between beneficiaries seems to be challenging in practice. ENTSO-E provides a compensation mechanism (CBCA) for members that would experience a decrease in economic welfare. In reality, this mechanism has been applied to only a limited number of projects (Meeus and Keyaerts, 2015). The Nordic TSOs take a sceptical view of this particular mechanism due to its complicated structure and project-to-project approach (Statnett et al., 2016). TSOs believe that the CBCA actually increases the risk of the project and that a holistic approach based on regional cooperation and commitment would be superior. However, there is currently no exact proposal for an alternative mechanism.

c) The long lead times and other problems associated with building new transmission lines in continental Europe is less of a problem in the Nordics. A simple explanation could be that cross-border transmission tends to be subsea cables mostly out of sight. Still, the process of gaining approval for a new transmission line can be difficult and lengthy, particularly if it has a significant on-land component. Even interconnections with a high expected social net benefit are sometimes delayed. The problem is partly rooted in national land regulations and conflicting European and national provisions. Makkonen et al. (2015) suggest that the national goals in transmission development contradict the Nordic capacity development targets. A potential solution requires more transparent and stricter administrative rules with clear responsibilities assigned to national regulators and the harmonisation of land regulation. The study by Tenggren et al. (2016) confirms the existence of the administrative and institutional barriers for network development, including the concession regime in Sweden. The authors propose further harmonisation of the planning and approval processes in the Nordics and the rest of Europe as a potential solution.

Once in operation, an interconnector should be available to the market at maximal capacity to ensure its optimal use. Instead, a study by the national regulatory authority in Sweden showed that interconnectors often are operated below capacity (Ei, 2012). There could be maintenance or other reasons for why capacity is withheld from the market. But sometimes TSO deliberately reduce capacity to affect market outcomes. Glachant and Pignon (2005) conduct a simulation study of the Nordic market to analyse the phenomenon of moving congestion to the border by which TSOs limit export capacity to reduce domestic excess demand. Imbalances are likely to decrease if the country introduces multiple price areas, as Sweden did in 2011. The price mechanism then causes markets to clear at the local level. Germany maintains one single price area and has huge domestic imbalances to cope with. The Nordic regulators conducted a study of the welfare effects associated with capacity withholding between Germany and the Nordics (Ei, 2016). The study proposed a number of possible remedies, for instance to allocate interconnector capacity at market-based terms and compensate TSOs for resulting redispatch costs, or to optimise a number and size of the price areas. Further, the EC “winter package” emphasises the measure prohibiting TSOs from using cross-border capacities to relieve internal congestion. However, due to the information asymmetry between the regulator and the network company, the measure is difficult to enforce. That is, only a TSO knows whether the reason for capacity withholding is a concern for the security of supply, or a technical problem or whether it is aimed at internal congestion relief. There is limited experience introducing operational standards and special economic incentives for capacity availability (similar to those used for NorNed cable between the Netherlands and Norway (e.g., see DTe, 2005)), which must be evaluated.

The capacity availability problem can be considered an aspect of the increasing role of the TSO in the integrated market. TSOs are typically responsible for cross-border trades and capacity management. Furthermore, TSOs manage the balancing of the system. Even so, TSOs are seldom considered market players, contrary to generator owners and load-serving entities. For further research purposes, we suggest it worthwhile to reconsider prevailing paradigms TSOs as benevolent social planners and to think about them as agents with separate objective functions.

Transmission expansion affects competition in the electricity market, although the direction of this effect is ambiguous (Küpper et al. (2009), Tanaka (2009)). Market participants can interact through numerous markets (e.g. day-ahead and balancing markets) and therefore have significant opportunities to exercise market power. Additionally, the level of concentration in the Nordic electricity market is high. The concentration rate of CR3[3] in Sweden in 2014 was 83 per cent, whereas in Denmark, East CR3 constituted 100 per cent (Böckers et al., 2013). For assessments of market performance in the Nordic electricity market; see for instance Fridolfsson and Tangerås (2009). In theory, increased market integration is likely to improve competition in the Nordic market due to a higher number of market participants. Even so, the market should be continuously monitored by regulators and researchers.

The Nordic market design differs from most European markets in terms of the hedging of price risk. All financial contracts are supplied by market participants (see Marchoff and Wimschulte, 2008). In many other countries, system operators issue financial and physical transmission rights. Such contracts are believed to provide incentives to maximize the transmission capacity available to the market. Still, market participants have expressed concerns about introducing transmission rights on Nord Pool for the fear of reduced liquidity of the other financial contracts. Some also have doubts as to whether transmission rights really would incentivise network owner to provide the maximum capacity to the market (Elforsk, 2011). Transmission rights in the Nordic market and hedging instruments in the integrated market are a hot topic for regulators and market participants.

Overall, we consider the problem of harmonising market rules to be a classic case of balancing the efficiency gains of harmonisation with the distributional costs associated with loss of independence. The end result will eventually evolve as a result of political and economic discussions and convergence.

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[3] The concentration rate CRn is a measure of market concentration calculated as the sum of the market shares of the n largest companies.

Challenge 2. Ensuring generation and network adequacy (security of supply)

The generation mix in the Nordic market is expected to undergo substantial changes in the coming years. One major factor is planned shut-down of nuclear power in Sweden. To begin with, four reactors with a total capacity of 2,900 MW are to be decommissioned by 2020. Another factor is the rapidly growing wind and solar capacity. Denmark and Sweden have ambitious plans to replace all non-renewable generation with renewables by 2050. The change from base-load to intermittent production has raised concern whether production will be sufficient to match load at all times.

A first step to addressing the challenge of the security of supply is to develop a clear understanding of the scale of the problem by quantifying capacity requirements, for instance by establishing reliability standards. Although such standards are under debate, the Nordic countries have not yet formulated any. There are different methods for assessing capacity requirements, see e.g. ENTSO-E (2014), but in the end it relies upon national TSOs responsible for system reserves in the Nordic countries to develop and implement instruments for adequacy assessment.

There are several ways to accomplish the desired generation capacity. The first is to rely on spot prices and current support systems. For instance, new nuclear capacity (one unit of 1,600 MW) in Finland is expected to come online during 2018, and Finland plans for an additional unit of 1,200 MW for 2024. Sweden and Finland recently decided to change how the capacity reserve is bid into the market. Previously, the reserve was offered at the maximal actual bid in the day-ahead market. In the future, the TSOs will bid in the capacity reserve at the bid cap of 3.000 Euro. This change in market design will improve investment incentives at market based terms and reduce the need for a capacity reserve if policy makers are able to commit to this rule.

Simulations of capacity adequacy in the Nordics for the next decade do not predict substantial reliability issues, in part because of the new nuclear capacity expected to come online (Thema, 2015). The region is predicted to have enough renewable resources to decommission nuclear power production in Sweden, in addition to replacing Nordic fossil fuel-based production simulation (SEI, 2015). However, these simulations only considered whether there will be sufficient capacity in the market to cover maximum load. But problems can occur even if the system is not on the brink of collapse. Prices will below for long periods of time in a market where most of the capacity has very low marginal costs. But this means that prices necessarily must be very high in those instances where the system is supply constrained, for generators to be able to recover their fixed costs. As an indication of what is to come, Sweden has experienced periods of record high prices in peak demand periods with low nuclear availability. January 21, 2016, for instance, the demand-supply balance was very tight in the Swedish market (Statnett et al., 2016). With the recent market design changes, prices could triple in those situations compared to what we have seen before. Developed financial markets can relieve the problem of the tight capacity balance by ensuring sufficient price hedging (Tangerås, 2017). But price increases may still not be palatable to the general public and cause the state to intervene in the market.

The most direct solution to a resource adequacy problem is to procure capacity reserves outside the spot market to keep as backup in case the spot market alone has insufficient capacity to cover demand. Cramton et al. (2013) contains an extensive overview of capacity mechanisms. European Commission guidelines establish that capacity mechanisms should not adversely affect the operation of market coupling, including intra-day and balancing markets (ACER, 2013).

Given the close market integration between the Nordic countries, a supranational approach to reliability can significantly improve efficiency compared to planning from a narrow domestic perspective. According to the THEMA (2015) simulations, Sweden and Finland are expected to rely on the electricity import for a significant share of the time in the future. With a system dominated by wind power, Denmark will also need significant inflows in periods of low wind output. Regional capacity planning would be an attractive tool for achieving economically efficient capacity solutions. TSOs play the key role here because of their being responsible for the strategic capacity reserve and their ownership of the transmission network. Mastropietro et al. (2015) similarly argue in favour of a transparent capacity mechanism open for national and foreign market participants.

However, the Nordic countries so far seem to have taken a non-coordinated stance of reliability. Sweden and Finland currently maintain strategic reserves, whereas Denmark and Norway so far rely on the spot market for incentives. These countries have no capacity reserve.

Tangerås (2017) illustrates the problem of achieving in a multinational electricity market. He shows how decentralised policy making generally distorts capacity reserves and network investment, thus pointing to the value of coordination and cooperation. In particular, defining security of supply at a multinational instead of national level would improve efficiency by ensuring an efficient deployment of capacity reserves.

However, there are other ways than maintaining production capacity in reserve to secure reliability. One can view transmission networks as a substitute for generation capacity because network capacity reduces the need for building local generation capacity. Hence, with sufficient network capacity, capacity reserves can be placed at the locations where the cost of building production is the smallest, not necessarily where the local supply shortage arises. In a multinational electricity market, this means that some capacity reserves optimally could be placed abroad. Simultaneously, efficiency dictates that the current network be efficiently deployed. To benefit from access to neighbouring markets, cross-border interconnectors should be available at the moment of contingency.

Arguably, the benefits of current interconnectors are not fully realised in the Nordic market, partly due to TSOs withholding network capacity to alleviate domestic supply imbalances. There are no specific rules establishing requirements to provide interconnector capacity for foreign supply security purposes, although the issue of cross-border capacity reserves is topic of an ongoing debate in the Nordic countries (Elforsk, 2014). Gebrekiros and Doorman (2014) find it optimal to reserve up to 30% of capacity of the Norway-Netherlands interconnector. Baldursson et al. (2017) consider three models for cross-border reserve cooperation: autarky, exchange and sharing. Exchange and sharing common reserves are found to be superior to the autarky in both high and low demand scenarios.

Vertical coordination, which is the coordinated planning of the transmission and generation expansion, helps avoid economic inefficiencies in both network and generation investments (see Tohidi et al., 2017). The issue is particularly relevant to offshore wind investments. Farahmand et al. (2014) modelled the extensive development of wind power in the North and Baltic seas and its effects on the grid. The results highlight the importance of long-term coordinated planning of network and generation investments. There are different approaches to organising offshore generation and interconnectors, similar to the German regulation of HVDC offshore cables or the UK OFTO approach (for details, see Regaraiz et al., 2017); the choice of the most appropriate way for the Nordic countries is a matter for discussion.

Alternative ways to balance production and consumption include demand side participation, electricity storage, and electric vehicles. Electricity markets in the coming years will witness an increasing importance of such resources where the regulators are expected to provide an appropriate framework. We discuss issues associated with the coordination of the transmission planning and alternative resources below.

Challenge 3. Increased need for flexibility

Flexibility is closely connected with generation and network adequacy, but focuses on the ability of the system to react quickly to unplanned fluctuations in demand or supply. The system operator uses balancing services to keep system injections and outflows in balance. These services differ in response times and can be activated automatically or operated manually in case of a disturbance (ACER, 2012).

The Nordic system has historically benefited from the availability of abundant hydro resources. Hydro plants in Norway and Sweden have been able to provide a sufficient and relatively inexpensive way to cover most of the flexibility needs in the region (Statnett et al., 2016). Inflexibility therefore is not a major issue in the Nordic systems for the moment. But the anticipated replacement of nuclear base load capacity by wind and other intermittent energy sources increases the need for additional system flexibility. Additionally, a significant drop in nuclear generation in the Nordics reduces the availability of hydropower to accommodate more intermittent sources. These factors are expected to increase system fluctuations and the likelihood of imbalances, as acknowledged by the Nordic TSOs (Denholm and Hand, 2011; Lund et al., 2015; Flex4RES, 2016; Statnett et al., 2016).

Frequent power imbalances disturb system operation. In this situation, system operators can benefit from better prediction tools and instruments to manage such imbalances. Lange and Focken (2015) show that improved forecasting techniques for wind are important for minimising errors that result in imbalances. The Nordic TSOs also believe that a finer resolution for day-ahead and intra-day markets could be beneficial for operating the balancing services (Statnett et al., 2015). The Nordic intraday market, Elbas, is in line with the European target model (ENTSO-E, 2016c) and could be developed further to improve the efficiency of short-term redispatching.

As the integration between the Nordic and the continental system (Germany in particular) increases, the demand for the Nordic flexible resources will increase together with the need of efficient transmission allocation. The Nordic TSOs expect that new transmission capacity will lead to an increase in the overall value of hydro production, at the cost of increased short-term price volatility and higher balancing costs in the Nordic market. The reserve requirements of system operation may increase due to greater changes in the power flow and larger imbalances (Statnett et al., 2016), although the impact of cross-border links on national system imbalances is a subject for additional analysis..

Efficient use of the cross-border capacity is a prerequisite to addressing flexibility needs in an efficient way (Passey et al., 2011). While Nordic TSOs have a developed toolbox to manage flexibility, further harmonisation with the neighbouring countries might be required. For instance, auctioning of the cross-border capacity can potentially increase efficiency (Flex4RES, 2016).

The need for more flexibility places pressure primarily on the TSOs. For instance given that the EU Network Code states that “the role of procuring balancing services is on TSOs; also TSOs organise the [balancing] market”. Observers have suggested that system operation and ownership be collected in one single Nordic TSO to increase coordination. While facilitating cross-border cooperation, it is far from obvious that such a solution would uniformly increase efficiency because the merger of TSOs increases the market power of that entity. Tangerås (2012) examines the welfare implications of different cross-border regulation and TSO ownership arrangements in multinational electricity markets and identifies the conditions under which the welfare of some structures dominates that of others.

The sources of system flexibility in the system include not only network and generation expansion, but also demand side response, storage technologies and electric vehicles. In the Nordics, one of the important sources of the flexibility is district heating (Flex4RES, 2016). However, the roles in the sector are distributed in such a way that mainly TSOs are responsible for the system flexibility and their investment options are often limited to improving the network. Some argue that current regulations feature insufficient incentives to invest in the alternative sources of flexibility (Flex4RES, 2016). Future research should address the relationship between incentives for increasing flexibility and the institutional structure of the electricity sector.

Mountain (2017) outlines the problem in the context of investing in a grid-scale battery in South Australia. He argues in favour of separating transmission planning and transmission asset ownership to prevent network developers from crowding out batteries or other market-based substitutes. This is aligned with the work of Perez-Arriaga et al. (2017) who point out that the evolution of the electricity sector should lead to a reassessment of the roles and responsibilities of the players in the sector.

Zakeri and Syri (2014) analyse the cost efficiency of battery storage technologies in the Nordics and find none of them be profitable under current market conditions. Still, the technology is advancing at a significant pace, so large-scale electricity storage might be economically justified in the future (Lin and Wu, 2017). Verzijbergh et al. (2014) suggest that electric vehicles (EVs) can be a substitute or a complement for the network expansion as a source of flexibility depending on RES penetration. Notwithstanding these developments, the ample supply of hydro power suggests that an efficient solution to securing flexibility in the Nordic market might not necessarily involve introducing new and flexible resources, but rather to release more flexible hydro power by investing in base-load power to replace nuclear.

An efficient approach to solving the problem would be to attract as many sources of flexibility as possible and evaluate them in terms of their cost-benefit ratio. For instance, Amelin (2015) shows that involving all available balancing sources and a shift from day-ahead to intraday trading can potentially relieve the problem of system flexibility when the share of wind power is increasing. One of the least costly methods of providing the system with flexibility is demand response (Li et al., 2011; D'hulst et al., 2015). There is a significant body of literature studying the benefits of demand-side management and how to organize the market to achieve it (see Borenstein et al., 2002). In practice, the potential of demand response has hardly been realised. Demand response requires a sound market model in which small and large consumers have an incentive to provide flexibility services to the system. A solution could be an aggregator model (Gkatzikis et al., 2013). Equally important is that market participants receive a correct price signal, which requires smart metering of the consumption of a substantial share of consumers. Such meters have been installed in most Swedish households.

Challenge 4. Frequency control and inertia

Frequency control is a part of the balancing services discussed in the previous section and necessary in order to maintain system frequency (at around 50 Hz in the Nordic system). We discuss the issue separately because it involves a specific problem associated with system inertia.

Inertia is valuable in a power system because it slows down changes in system frequency, giving balancing reserves appropriate time to react. Reduced inertia in the system makes it more difficult for network operators to restore the system after frequency disturbances. The quality of electricity supply drops because electricity spikes become more frequent. Although the problem is presently not acute in the current power systems, it is expected to play a significant role in system operation in the years to come. Researchers and industry experts largely expect a reduction of inertia in systems with a high penetration of solar and wind power (Chavez et al., 2016; Ulbig et al., 2014; Tielens and Van Hertem, 2016). Shutting down nuclear plants and increasing imports through interconnectors all contribute to reducing inertia in the Nordic system. In 2025, the inertia in the Nordic system, measured as kinetic energy, is estimated to be below the required volume (120-145 GWs) up to 19 per cent of the time, depending on the climate year (Statnett et al., 2015). In the current Nordic power system (2010-2015), the kinetic energy is estimated to be less than 140 GWs only 4 per cent of the time.

However, there is no consensus on how to address the inertia problem. One option is to consider inertia a pure technological issue, and treat any associated cost as a network reliability issue. O'Sullivan et al. (2017) conducted a technical study of an isolated island system (Ireland) to show that the frequency stability problem in a system with high RES penetration can be solved by altering ROCOF (rate-of-change-of-frequency) protection and enabling emulated inertia measures. Furthermore, one can increase short term inertia by running existing production units at lower capacity utilization. In the long term, infrastructure measures might be required, including the fortification of the power system and increasing the reaction speed of reserves for obtaining faster responses during disturbances. System reinforcement includes adding more frequency containment reserves and HVDC emergency power control, installing system protection schemes or using HVDC links (Statnett et al., 2016). Adding rotating mass, such as synchronous condensers, is beneficial for system inertia. Gonzalez-Longatt et al. (2013) propose adding synthetic inertia to the system as an alternative solution. Synthetic inertia can be described as the kinetic energy generated in the rotating blades of wind turbines or Nordic system can specifically benefit from the use of synthetic inertia due to the significant amount of wind generation.

An alternative approach to achieving inertia in the system is to apply market tools (Davari and Hesamzadeh, 2017). A major obstacle is that this product is not clearly defined. And there is no established method for calculating the economic value of inertia. The issue boils down to whether inertia should be managed within the existing frequency control mechanisms, or if additional tools are needed to manage inertia. How should the cooperation between neighbouring systems be organised for inertia service exchange? How should the inertia service be measured and priced? Tielens and Van Hertem (2016) review methods to address the inertia problem, without arriving at a conclusion as to which methods are the most efficient.

V. Conclusion

The anticipated changes to the Nordic power system pose significant challenges that TSOs and regulators need to address. Three major challenges are: improved market integration, ensuring generation and network adequacy, and an increased need for flexibility and frequency control due to reduced inertia in the system. These challenges can be approached with a combination of market, infrastructural and operational measures. We present an overview of available solutions and possible barriers in Table 1.

Table 1. Major challenges in the Nordic electricity system

Challenge	Possible solutions	Possible barriers
Further market integration	Increasing interconnection capacity; Efficient use of interconnectors.	High uncertainty; Cost-benefit allocation is not optimal; Administrative procedures are too long; Differences in the market rules Misaligned incentives in the markets (different types of markets as well as in the neighbouring markets).
Generation and network adequacy	New generation capacities; Improved assessment methodologies; Increasing interconnection capacity; Efficient use of interconnectors; Deployment of the "alternative sources" such as demand participation, storage, EVs; Vertical coordination.	Low financial incentives (low electricity prices); Differences in the reserve mechanisms; Lack of harmonisation.
System flexibility	Increasing interconnection capacity; Efficient use of interconnectors; Finer dimension of market trading (from 1 hour to 15 min or less); Demand-side participation; New sources of flexibility – storage, electric vehicle.	Interconnectors can increase the cost of balancing services; Mismatch between the industry structure and new roles; Lack of market incentives; No market mechanisms for new sources of flexibility.

Frequency control and inertia	Operational changes; Network reinforcement; Synthetic inertia; Market for inertia.	High cost; Difficulties in product pricing; Lack of market mechanisms.

Based on our analysis, we expect that addressing the challenges will require more coordination among TSOs and regulators. The following principles should be considered when implementing any measures:

- Focus on total economic efficiency while acknowledging local losses;
- Perform a comprehensive cost-benefit analysis, with the evaluation of the relevant alternatives;
- Improve coordination and mutual information sharing;
- Align economic efficiency incentives in different existing and new markets;
- Explore innovative approaches.

Our analysis contributes to the literature by summarising the current debate on issues related to transmission network in the Nordic market. We indicate possible ways forward to solve the identified problems and provide directions for further research of potential benefit to the research community and policy makers.

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