Long-term trends of Nordic power market: A review

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Abstract
The Nordic power system will play an important role in a future carbon-neutral European power market. In this study, 43 scenarios in 15 Nordic power market outlooks published between 2016 and 2019 are reviewed. Most scenarios see high future power prices with substantial correlation with assumed gas and emission quota prices. The underlying uncertainties in gas and emission quota prices are passed on to future power prices. The power prices are well above the cost of wind power, indicating that the wind deployment is either underestimated or might be largely dependent on non-market factors. The models used for the outlooks have limited sector coverage and trade-offs are made between computational resources and complexity. A set of recommendations for future outlook publications are proposed based on this review experience. Moving towards a low-carbon future, more attention should be put to the demand side, especially with increasing importance of sector coupling and electrification. Also, to assess the profound uncertainties in the energy transition period, techniques besides scenario analysis can be applied. Explicit assessments on impacts of emerging topics, such as social oppositions to particular technologies and increased awareness of sustainability indicators besides clean energy, will add values for long-term decision making in the power markets. Last but not the least, best efforts of clarity and transparency should always be ensured.

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KEYWORDS
energy scenarios, fuel prices, market outlooks, Nordic power market, power prices

1 INTRODUCTION

Both public and private organizations in the energy sector issue publications with regard to long-term power markets. These publications with various objectives come in different names such as “prospects,” “outlooks,” “projections,” and
authorized to align 1.5°C (European Commission, 2020). A drastic transition from conventional thermal power plants to a large share of variable renewable energy (VRE) unfolds and will continue in the coming decades. The abundant renewable energy resources in the Nordic countries can benefit from a future fossil-free Europe through integrated power markets. Large amounts of Nordic wind power generation and exports are expected in studies of the European energy market that includes high renewable penetrations. For example, the optimal transmission scenario for 2050 in Schlachtberger et al. (2017) shows the scale of wind generation in Denmark reaching as much as 4.5 times its domestic demand, in Norway reaching 2 times its demand, and in Sweden reaching 1.5 times its demand. Child et al. (2019) find the ratio of net electricity export to demand in Denmark to be 52%, and 40% in Norway in a 100% renewable energy system in Europe by 2050. In addition to the abundant VRE resources, Norway, Sweden, and Finland combined had 217 TWh hydropower production in 2019, which contributed more than half of the Nordic power production (Gogia et al., 2019). Hydropower expansion potentials are limited by environmental regulations; however, its ability to provide flexibility may become more valuable (Tveten et al., 2016). Through physical transmission power lines and market integration, the Nordic energy market plays an essential role in the European energy transition (ENTSO-E, 2018).

To grasp the complexity of modern energy systems, a common practice in long-term energy market studies is to use an energy system model (or an electricity market model) with a set of input parameters to analyze several scenarios. A modern energy system analysis often combines traditional economics-oriented top-down and technology-oriented bottom-up approaches (Tol, 2000). References from well-recognized institutes or own assumptions are applied for parameters involving conditions outside of the modeling scope, such as international fuel prices. Finally, scenario analysis is a popular practice for exploring plausible futures. Each plausible future is formed under its storyline and can differ in, for example, fuel price levels, nuclear power development, or climate targets. In a modeling context, the diverting energy scenarios may originate from two main reasons: (a) differences in the models applied, due to, for example, different optimization objectives, geographical scope or time resolution, and (b) differences in input assumptions to the model. The scenarios along with their assumptions represent the interests and perspectives of the publishers. While there are several review publications on different methodologies or modeling tools (Fattahi et al., 2020; Gils et al., 2019; Prina et al., 2020; Ringkjøb et al., 2018), the parametric variations seem to have received less attention from the research community.

Power market outlook studies provide substantial value to medium-term and long-term decision-making in the energy sector. Meanwhile, publishers of outlook studies have significant influence, as the information that they provide can shape the future depending on how decision makers and power companies use this information. The Nordic region has a long history of deregulated power trading, and the markets have already been integrated through the Nord Pool power exchange since 2000. Market data are transparent and available on their website, offering great opportunities for liberalized power market research. Nordic power market outlooks can be seen as examples of information that is currently shared by major stakeholders in an integrated and low-carbon market. A comprehensive review of these outlooks summarizes the lessons-learned and reveals their strengths and weaknesses. A set of recommendations is subsequently listed based on the review experience and the recent discussions on a low-carbon future. We hope to increase the value of the information presented by future outlook publications in the time of energy transition.

Against this background, this study aims to summarize the insights of the power markets and lessons-learned stemming from various recent Nordic power market outlooks for the period toward 2050. This review has a parametric emphasis on the main market drivers, coupled with an assessment of differences in their scopes and methodologies. The Nordic focus adds values to European energy transition, as the well-functioning Nordic power markets with vast renewable penetration are likely to serve as a pioneer in deep decarbonization of the energy sector. Several stakeholders in the Nordic power market publish outlook reports, and many of them release updates regularly. The analysis aims to inspire regional and European energy system planners and investors, but also to make readers of outlook reports aware of differences in focus in such reports, and that results can be quite different with different methodologies and input data. This study also hopes to contribute as feedback to outlook and energy model developers for future outlook publications to provide insightful discussions towards a low-carbon future.
There is a large literature on cross-scenario analyses related to the energy sector. In this section we give a brief overview, indicating what they have been focusing on. Trutnevye et al. (2016) reviewed 12 scenario exercises released from 1978 to 2002 on the UK energy future and focused on scenario formations. They note a methodological shift from predictive to explorative or normative and argue that recent scenarios are more able to capture a wider scope of uncertainties. Laugs and Moll (2017) reviewed 30 scenarios with a global perspective and focused solely on the energy mix. The scenarios are clustered into two, and they find limited energy mix bandwidth within each cluster; however, other variables than the energy mix (e.g., prices) are not addressed in the study. Another study by Söderholm et al. (2011) studied 20 low-carbon energy scenarios covering global or regional aspects. They focused on low carbon policy measures, and CO₂ price in 2050 was the only parameter discussed explicitly across scenarios. An older, but thorough, review from Martinot et al. (2007) commented on different input parameters from a large selection of literature. They focused on future possible amounts of renewable energy with various geographic coverage, while reviewing several socioeconomic and technological parameters. They note large ranges of renewable shares and parameters across scenarios but lack further elaboration of the linkages among them. The aforementioned literature does not emphasize power prices in their reviews. A meta-analysis by Cochran et al. (2014) concentrated on high renewable penetration in a review of 12 scenarios. They compare data inputs including demand and costs as well as scenario outputs on generation mix and projected electricity costs. Nevertheless, most scenarios cover quite different geographic scopes, and it is difficult to discuss the comparison beyond that. Uncertainties across scenarios can be analyzed using computational techniques. For example, Guivarch et al. (2016) identified important uncertain factors of shared outcomes across 432 scenarios using a scenario discovery technique. Nevertheless, computational techniques are less suitable for regional power market outlooks due to insufficient sample size; thus, they are not applied in this review. To the best of our knowledge, no previous study has quantitatively examined perspectives on future power prices and other factors by reviewing scenarios in market outlooks. The method is simple, yet reflects the lessons-learned from key market stakeholders experience. As the aim of this study is to summarize the lessons-learned in the power market outlooks, not to compare the models, we would like to point to other technical reviews, such as the review of 75 modeling tools by Ringkjøb et al. (2018), for the readers interested in energy models.

3 | OUTLOOKS AND SCENARIOS REVIEWED IN THIS STUDY

3.1 | Report selection criteria

The primary focus is reports that are widely applied or referred by local stakeholders. In addition, the following factors serve as study selection criteria: geographic focus, publication year, time horizon, and public availability. We target four Nordic countries excluding Iceland, which has an independent energy system. Considering the rapid development in energy policies and technologies, we have focused on publications released since 2016. As uncertainty increases over a longer time horizon, we are interested in studies covering at least the year 2030, but no later than the year 2050 for reasonable confidence. We assign public availability as one of the criteria because it enhances a report’s visibility to any general reader and thus, possible influence. In addition, readers of this article, who are interested in certain reviewed studies, can easily refer to the original report. Finally, only scenarios with power prices revealed together with fuel and quota prices are discussed. Up to the beginning of 2020, these criteria include 43 scenarios from 15 studies published by 8 organizations. Table 1 summarizes the outlooks reviewed in this study. The original titles are listed to match the references. Subsequently, we refer to each outlook by its abbreviation consisting of the publisher and the publication year. Appendix contains short descriptions of the reviewed outlooks from each publisher to provide a quick guide to the reviewed material. All outlooks are available online at the time of the study.

3.2 | Scenario classification and framing

Outlook studies analyze power markets under various scenarios. A classic classification developed by Börjeson et al. (2006) categorizes scenarios by their objectives into three types: predictive, explorative, and normative. Predictive scenarios answer “What will happen?” and they are often used in short-term forecasts. Explorative scenarios answer
What can happen? and typically focus on the medium or longer run. Normative scenarios answer “How can a certain target be reached?” by optimizing modeling or back-casting. Nevertheless, we find that most reviewed studies are explorative or have a combination of objectives; thus, it is difficult to classify them according to these definitions. Scenario formation varies significantly from one report to the other and even evolves over time; however, several factors or similar definitions are used repeatedly in different outlooks. We cluster scenarios using their main definitions as the following:

- **Reference** — A scenario that is presented as a reference case, base case, or business-as-usual.
- **High price** — A scenario that applies higher fuel prices than the others, in most cases, also higher CO₂ prices.
- **Low price** — A scenario that applies lower fuel prices than the others, in most cases, also higher CO₂ prices.
- **Green** — A scenario that has lower emissions, supports renewables, represents ambitious climate actions, or has an emission target in line with the Paris Agreement.
- **High emission** — A scenario that has higher emissions or limited renewables.
- **Others**
  - Nuclear — A scenario with more nuclear power capacities than the other scenarios in the same study.
  - No nuclear — A scenario with less nuclear power capacities than the other scenarios in the same study.
  - Electrification — A scenario with high electrification in other energy sectors.
  - Warm — A scenario that assumes a warmer climate.

Clustering is helpful to analyze scenarios in different outlooks under comparable settings and it is also helpful to present readable figures in the latter sections. It is noteworthy that the clustering is based on the qualitative scenario definitions in each outlook, and no quantitative condition is applied by this study. In general, the reference cluster corresponds to the predictive scenarios, the green cluster corresponds to normative or explorative scenarios, and the rest of the clusters contain mainly the explorative scenarios. The scenarios in the “others” cluster are various case studies and should be interpreted with caution. To maintain the link between each data point and the source scenario, Table 2 lists the scenario clusters in this study and the scenarios within each cluster in their original names.
3.3  **Focused parameters and data preparation**

A primary interest in our review is future power prices, as this is the main deliverable of most outlook studies and is an important information for today’s investment decisions. A common practice for power market outlooks is to apply a quantitative model with a set of assumptions to optimize energy supply and demand balance at a minimum cost, and the power prices are the marginal costs of electricity generation. Therefore, we summarize trends and differences in key power market drivers that affect the modeled prices in the reviewed outlook studies. Among all the relevant factors, the focused parameters in this study are nevertheless largely based on the preliminary observation of how the outlooks design their scenarios and reporting. Only the data that are disclosed in most outlooks can be compared.

The outlooks present data in various formats for various timelines, and we exclusively rely on data presented in the outlooks and their attached data files if available. Data are extracted directly from apparent texts, tables, and figures of every decade from 2020 to 2050, and there is no interpolation or extrapolation applied in this study to reflect specific parameters reported in a specific year. Price units are converted and expressed in USD/Mbtu for gas, USD/tonne for coal, EUR/tonne for CO₂ emission, and EUR/MWh for power. The choice of currencies reflects that gas and coal prices are dependent on the global market and are usually expressed in terms of USD, while CO₂ and power are traded within Europe and usually expressed in terms of EUR. Installed capacities are expressed in GW, and energy demands in TWh. Energy units are converted based on unit conversions from the IEA (2019). Prices are expressed in real values with the base year 2018. Price values found in the reviewed studies are converted to desired currencies first by exchange rates of the same year according to the European Central Bank (2019) and OFX (2020), followed by adjustments to 2018 prices using the consumer price index (CPI) in OECD (2019). For instance, if a power price from a report is given in NOK-2010/MWh, the price will first be converted to EUR using the exchange rate from 2010, and then CPI will be applied to convert the price from EUR-2010 to EUR-2018.

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**TABLE 2** Reviewed scenarios in each outlook. Scenarios in their original names are categorized according to their main definition.

| Report   | References | High price      | Low price      | Green       | High emission | Others                        |
|----------|------------|-----------------|----------------|-------------|---------------|-------------------------------|
| DK-E (2016) | WEO        | Forwards        | Klima          |             |               | Overflod (Nuclear)            |
| DK-E (2017) | WEO        | Forwards        | Klima          |             |               |                               |
| DK-E (2018) | WEO        | Forwards        |                |             |               |                               |
| DK-E (2019) | Blå        |                 | Grøn           | Sort        |               |                               |
| E.DK (2016) | REF         | Högabränslepriser | Låga          |             |               | Utfasning av kärnkraft (No nuclear) |
| E.DK (2017) | REF         | Högabränslepriser | Lågt elpris + 18 TWh | Hög BNP       |                               |
| EM (2017)   | Referens EU | Höga fossilpriser | Lågt elpris    |             |               |                               |
| EM (2019)   | Referens EU | Lågre BNP       | Lågre energipriser | Högerelektrifiering- (Electrification) | Varmare klimat- (Warm) |
| SK (2019)   | Ref        | Hög             | Låg            |             |               |                               |
| NVE (2017)  | Basis      | Høy             | Lav            |             |               |                               |
| NVE (2019)  | Basis      | Høy             | Lav            |             |               |                               |
| SN (2016)   | Basis      | Høy             | Lav            |             |               |                               |
| SN (2018)   | Basis      | Høy             | Lav            |             |               |                               |
| N-IEA (2016)| CNS-B      | Baseline        |                | CNS-B Nuclear fast phase-out (No Nuclear) |

*There is no scenario in Energinet, (2017); Energinet.dk, (2016), so they are seen as reference cases.*
LESSONS-LEARNED FROM THE MARKET OUTLOOKS

The main findings from reviewing the Nordic power market outlooks are reported in the following sections. We first concentrate on methodological issues, thereafter on data assumptions made in the analysis and observations regarding the outlook results, and finally on some aspects missing from current outlook studies.

4.1 The models used for power market analyses have often limited capability to analyze final energy use beyond electricity

Table 3 summarizes the methodological features of the outlooks by publisher. More than half of the publishers use models that covers only electricity as the final energy product. These models consider electricity supply-demand balance and other details, such as grid restrictions (i.e., the Samnett model), and start-up and shut-down costs (i.e., the Sifre model and the BID model). The scenarios are usually predictive or explorative and have assumptions of how the future systems look like. The other publishers cover heat besides electricity in their models, where the interaction between heat and electricity is captured. With more flexibilities in terms of how future systems can operate and develop, these models are suitable for normative and explorative scenarios. All the reviewed outlooks using the models covering heat and electricity are also investment models, which allow endogenous capacity expansion of certain technologies, whereas the others covering solely electricity do not allow endogenous capacity expansion, but exogenously given assumptions for future capacities. Some of the former models are perfect foresight investment models, which optimize the system for all years at once, while others are myopic investment models that optimize the system year by year.

One common methodology limitation shared by these outlooks is that they are not able to model the entire energy sector (only electricity, or electricity plus district heat), or at least not able to include different sources of electricity consumption at an equivalent level of detail. Depending on the sectors covered in the analysis, the coverage of the source of electricity consumption varies. To an electricity-only model, the electricity consumption is a simple assumption or an assumption after advanced pre-analysis, whereas to an energy system model that covers not only the power sector, the electricity consumption is determined by an assumption combined with the results of electrification from other included sectors. For example, among the reviewed studies, the ones from Dansk Energi, Energimyndigheten, and the Nordic Energy Technology Perspectives (NETP) cover district heat in addition to the electricity sector; thus, their electricity consumption includes the need for district heat electrification. The transport sector is also covered indirectly in some of the reviewed scenarios. For example, Energimyndigheten uses dedicated transportation models to calculate the future energy use in the transport sector. The resulting electricity consumption in the transport sector is then applied as part of the final electricity demand in the TIMES-Nordic model. Another example is the Norwegian regulator NVE, which applies the TIMES model to analyze total final Norwegian electricity demand as inputs to Samnett and The-MA models for further power market analysis.

Electricity consumption is vital to the scale of a country's power system. In addition to GDP per capita and population growth, the electrification aiming at emission reduction plays a key role in shaping future electricity consumption. The effect goes beyond efficiency improvements. Especially in the Nordic countries with significant resources of non-fossil-based energy supply, electricity can provide clean fuel to other sectors and thus increase demand in the power sector. The review shows that the development of electricity consumption has not been as focused as the production in the reviewed outlooks, and that the interactions between the power sector and the other sectors through sector coupling are often over simplified, if not omitted.

Figure 1 summaries the power consumption applied in the reviewed scenarios. Overall, there are relatively small differences in the assumed consumption levels across outlook studies. All scenarios assume constant or slightly increased consumption, except for IEA (2016), which assumes Nordic carbon neutrality with aggressive building efficiency improvement implementation and an important biofuel role. Many of the green scenarios also assume less consumption than the reference scenarios. In contrast, the electrification scenario in EM (2019) sees the largest consumption growth of 38% from 2020 to 2050 as a result of high electrification in the heating, transport, and industry sectors. The contribution from electrification appears to have larger influence than the effect from efficiency or energy savings. Overall, we find that the majority of the reviewed scenarios might have underestimated the uncertainties in future electricity consumption.
4.2 Tradeoffs are often made between temporal granularity, weather uncertainties, and the computational complexity

With increasing penetration rate of VRE, the supply–demand balancing challenge requires finer temporal granularity to be reflected in the model analysis. The decision on temporal granularity in power market outlook studies is often a trade-off between required temporal accuracy to represent a realistic model and the computation resources. The finest temporal granularity of the reviewed studies is at an hourly level. All the electricity-only models used in the reviewed studies include full hours in a year, and NVE, Statnett, and Svenska Kraftnät also consider multiple weather years for hydropower modeling. The other models cover electricity and district heating sectors and enable the potential of

| Report        | Model used for the electricity price outlooks | Covered final energy product* (electricity/heat) | Investment foresight | Temporal resolution | Multiple weather years | Notes                                                                 |
|---------------|----------------------------------------------|-------------------------------------------------|----------------------|---------------------|------------------------|----------------------------------------------------------------------|
| DK-E (2016, 2017, 2018, 2019) | Balmorel V/V | Myopic foresight | 2184/year (13 representative weeks with 168 h in each week) | –                   | –                      | The Sifre model includes Danish power and heat markets.             |
| E.DK (2016, 2017) | Sifre (Danish market) and BID (other markets) V/– | – | 8760/year | –                   | –                      | –                                                                      |
| EI (2016) | Apollo V/– | – | 8760/year | –                   | –                      | –                                                                      |
| EM (2017, 2019) | TIMES-Nordic V/V | Perfect foresight | 12/year (4 seasons with 3 timeslots in each season) | –                   | –                      | Investment with perfect foresight is allowed in complementary scenarios, which are not included in this study due to insufficient data. |
| SK (2019) | BID3 and EMPS V/– | – | 8760/year | V                   | V                      | The final Norwegian electricity demand is a TIMES model output, which covers all energy carriers. |
| NVE (2017, 2019) | Samnett (Nordic market) and The-MA (other markets) V/– | – | 8760/year | V                   | V                      | –                                                                      |
| SN (2016, 2018) | Samnett (Nordic market) and The-MA (other markets) V/– | – | 8760/year | V                   | –                      | –                                                                      |
| IEA (2016) | Balmorel V/V | Myopic foresight | 72/year | –                   | –                      | There are scenarios analyzed by the ETP-TIMES model, which covers the entire energy sector, but excluded in this study due to insufficient data. |

*Some of the reports use extra models to cover other energy sectors, such as transport, and the resulting electricity demand is then used as input assumptions to the main models. See Appendix for details.
power-to-heat technologies, but these models include fewer timesteps to represent a full year to mitigate the computational need. Note that this observation is based on the reviewed outlooks—there are other investment models not reviewed here with fine time resolution, or multiple weather years (for a cost of computational resources).

Weather impacts VRE and hydropower production, changes energy consumption volumes and patterns, and brings uncertainties. As noted by Cochran et al. (2014), all studies in their review assume particular weather year(s) in their scenario analyses. Most reviewed outlooks are not designed to address this issue, with few exceptions of stochastic hydropower production. In our sample of outlook reviews, 5 out of the 15 reports use more than one weather year in the analysis, while the remaining ones apply a single weather year. Depending on the scope of the analysis, assumptions of a single weather year may lead to results and conclusions that could be imprecise or even misleading. Moreover, climate change will affect temperatures, precipitation levels and wind speeds, all of which are affecting the energy markets. Uncertainties related to weather will increase with higher VRE shares on the supply side and more electricity used for heating on the demand side. Current and emerging research aim to cover weather uncertainties and climate impacts, but they are often not accounted for in extended power market outlooks (Füssel, 2019). Only one reviewed scenario from EM (2019) is designed to investigate the impact of a warmer climate.

As such, using a fine temporal granularity, multiple weather years, and accounting for climate change are of increasing importance with increasing time horizon of the outlook.

4.3 | Fuel and emission quota prices are key power price drivers in the coming two decades, with profound uncertainty

Fuel and emission quota prices are key power price drivers traditionally (Capion & Meibom, 2016), especially in power systems with significant shares of coal and gas power plants. Coal prices have declining influence on the Nordic power markets as there is no coal power generation in Sweden and Norway, and Finland and Denmark will ban coal in electricity production before 2029 and 2030. The indirect influence from the continent through the power exchange declines steadily with graduate coal phase-out. In this section, we focus on natural gas prices and the emission quota prices, both believed to have bigger influence in the following decades. The review shows that the gas and emission quota price assumptions are crucial to the reported power prices, and that there is a large degree of uncertainty within those assumptions.

The gas and emission quota prices are input assumptions for energy models to generate power prices in the outlook studies. Outlooks often use a low-price scenario and a high-price scenario to capture the range of uncertainties in power prices as a result of uncertain fuel and emission prices (Bøhnsdalen et al., 2018). Using forward prices is common for 2020 and 2030. Prognosis from well-recognized institutes such as the IEA and EC are also often applied. Fuel and
emission prices in the New Policy Scenarios (NPS) by the IEA or the EU Reference scenario (European Commission, 2016) are popular references, especially for the reference scenarios. Summarizing the gas and emission price assumptions across the outlook scenarios illustrates the uncertainty space of the price assumptions across the publishers.

Figures 2 and 3 stack all gas and carbon prices found, labeled by the scenario group. Price ranges are concentrated within the reference, high-price, and low-price groups. Both figures illustrate substantial uncertainties for the long-term price development of these major power price drivers, and the price range is particularly large for emission quotas.

All scenarios except IEA (2016) apply either fixed or increasing gas prices over time. Gas prices in IEA (2016) refer to the 2-degree scenario. It is stated in the report that fossil-fuel prices will increase considerably towards 2030 and decrease slightly from 2030 to 2050 owing to decreasing demand. Natural gas is used extensively also for other purposes than electricity generation, and thus the wide range of gas price assumptions represents mainly profound uncertainty about the future prospects of the European gas market.

All scenarios agree on continued quota price increase until 2050, which suggests a shared opinion of a substantial incentive to switch from coal to gas, and from fossil fuels to renewables. The quota prices in the carbon market in Europe (EU ETS) are established by policy makers. The market supply side (allocation of emission allowances) is determined politically by the EU, and the policymakers are free to adjust the supply through ETS regulatory changes, which they have recently done. This is very different from most other markets, where supply to a large degree is linked to costs of investments and operations. The majority of the scenarios have underestimated the 2020 quota price, especially the ones published before 2018 as the price increased considerably that year after regulatory changes in early 2018. There is also a common trait that updates tend to modify and increase the price from the old ones, possibly due to the actual price development. The highest carbon prices always appear in the green group, especially in IEA (2016), which assumes carbon neutrality. The ranges between the lowest and highest quota prices applied in 2040 and 2050 are approximately 90 EUR.
Assumed gas prices and quota prices are correlated to each other, as shown in Figure 4(a). The extent of the correlation depends on the scenario definitions. The reference, high-price, and low-price scenarios show strong gas and quota price correlations, which are expected considering fuel and quota prices are used to define the latter two groups of scenarios. The other two groups, green and high emission distinguish themselves primarily in quota prices, and less in gas prices. This implies that quota prices are more associated with emission level or renewable development than natural gas prices when designing outlook scenarios. Figure 4(b)–(e) illustrates the relationships between the power prices and gas prices, and between the power prices and the emission quota prices in Sweden and Denmark. Positive correlations to various degrees are observed. Overall, fuel and quota prices play important roles in setting the power prices in the next 10–20 years, but the influence will decline with increasing number of countries entering to the zero-emission era.

4.4 Renewable deployment will increase, but large variation is found across outlooks

An important driving force of the future power market is power generation capacity evolution. In the long term, power generation capacities are influenced by market signals as well as by policies. A general trend in Northwest Europe is to gradually phase out coal and limit nuclear power due to environmental and safety concerns, while VRE, especially wind and solar power, will steadily increase their electricity mix shares towards 2050.

Unlike the fuel and emission quota prices that are purely assumptions in the outlooks, wind capacities are model assumptions in some outlooks, while a mixture of assumptions and results in the others (from Dansk Energi, Energimyndigheten, and the NETP). The installed capacities in most of the outlooks are exogenous assumptions reflecting the expectation of wind deployment in each scenario. In the outlooks highlighted in green in Figure 5, wind capacities are optimization outputs based on minimizing system costs, with deterministic technology and fuel costs, which are quite uncertain in reality. One challenge encountered during the review process is that it is not always clear how the assumptions beyond the national targets are made, except a general statement such as “references from external reports” in Statnett’s outlooks (Bohnsdalen et al., 2016;
Bohnsdalen et al., 2018). The other challenge is that not all outlooks present power generation in the same way. In this case, some of the outlooks present the installed capacity and some show the annual generation. Both capacity and annual generation are important information and should both be presented. As a compromise, Figure 5(a) displays the installed wind capacities listed in the reviewed scenarios, and Figure 5(b) displays the wind generation in outlooks showing the generation only.

Overall, the installed wind capacity is expected to increase, and it appears that the more recent the outlook is, the higher the future installed wind capacity it expects, regardless of the scenario group. The EU reference scenario published in 2016 appears to have underestimated the wind deployment in comparison to the reviewed Nordic outlooks. Norway, in addition to abundant hydropower supply, can increase as much as five times the wind capacity until 2050 according to the Nordic carbon neutral scenario in IEA (2016). The deployment, nonetheless, is subject to the availability of international transmissions as well as acceptance from the public.

Solar power is less important in the Nordics than wind power. Energimyndigheten (2017) suggests that solar PV investments are highly sensitive to power prices, and with high power prices, solar power production in Sweden (mainly from private houses) can increase 3–5 TWh after 2030, equivalent to 3–5 GW of installation, and remain at the same level towards 2050. Nuclear development reflects contemporary acceptance, not just economic competitiveness, but the analysis from Energimyndigheten reveals that nuclear power is unprofitable even when it is allowed as an investment option. The nuclear capacity in Finland is rather stable and newer outlook scenarios reflect the announced plans. Most studies do not specifically discuss gas power capacity. Growing wind power stimulates the need for regulated power, which may be one reason for the increasing gas power capacities indicated by EC (2016). It is expected that the gas power between 2030 and 2050 grows from 3.3 to 4.7 GW in Sweden, from 3.2 to 4.1 GW in Finland, and 1 to 4.3 GW in Denmark. The Nordic countries have all announced ambitious carbon neutrality strategies, but capacity adequacy is important to ensure energy security. The gas power plants have the potential to offset their emissions through other sectors or by using carbon capture technologies, or by switching to renewable gases.

4.5 The growth of the onshore wind power in the Nordics appears to be restricted by factors beyond the economic potentials

There is no explicit wind energy target in the Nordics, and the amount of wind power in the reviewed studies is mainly an assessment of the modelers on what is feasible and realistic. Whether a wind project attracts investors is subject to

FIGURE 4 Summary of (a) emission quota price in EUR/tonne CO2 versus gas price in USD/Mbtu, (b) Swedish power price in EUR/MWh versus gas price and (c) emission quota price in EUR/tonne, (d) Danish power price in EUR/MWh versus gas price and (e) emission quota price in EUR/tonne. All data are from the reviewed outlook scenarios, colored by scenario group defined in Section 3.2.
the outlook of the electricity market, technology costs, policies, and many other factors. Power prices are important investment signals for power producers. The projected power price levels after 2030 are in most scenarios well above the Nordic levelized cost of electricity (LCOE) of wind and solar PV. The LCOE of onshore wind reaches as low as 30–35 EUR/MWh in Norway (Bøhnsdal et al., 2018) and around 37–56 EUR/MWh in Sweden (Energimyndigheten, 2019). Eventually, power generation investors will likely adapt to high prices by expanding their production capacities. These long-term effects are not consistently handled by models with exogenous capacity change assumptions.

However, average power prices exceeding LCOE for wind and solar will not automatically lead to new technology investments. First, wind and solar power generation are variable and produce when the wind is blowing, and the sun is shining. It is shown by, for example, Tveten et al. (2013) and Hirth (2013) that the merit order effect, causing lower prices with renewable generation, may be substantial in areas with large renewable shares and limited energy system flexibility. Deviation between power prices and LCOE of wind and solar power may hence be expected, also from a long-run perspective. Second, although the cost of wind turbines may be similar across countries and regions, the locational cost will typically differ due to different land prices, construction costs, and other factors. Finally, regulatory obstacles can also hamper new investments. This is especially relevant for wind power, as resistance towards new wind turbines from public protests or ecological concerns may prevent otherwise profitable investments. Social barriers are very case-specific, from environmental, political to cultural context. Over the last decade, with the number of installed wind turbines soaring, oppositions against wind power have also grown (Bolwig et al., 2020; Borch, 2018; Borch et al., 2020).

Overall, we observe that the onshore wind capacities in many reviewed scenarios appear low from today’s perspectives, which may reflect recent rapid reductions in wind power costs as well as other changes in the energy sector, such

Figure 5  Wind capacity (a) and generation (b) in 2030, 2040, and 2050 found in each scenario in Nordic countries and the 2018 levels. The full scenario names are given in Table 2. The columns colored in green are the scenarios enabling wind capacity expansion investments in their models. Source of 2018 levels: Wind Europe (2019)
as stricter climate targets. Future power prices in the outlooks are often found well above the LCOE of onshore wind. We do not have sufficient information to assess why the model results seemingly are limited by other factors than economic ones, but the merit order effect, uncertainties regarding the social acceptability of large amounts of onshore wind, or other non-economic factors are likely among the reasons.

4.6 High average power prices and larger power price variation are expected by the outlooks

Power prices reported in the reviewed outlooks in each scenario are listed in Figure 6, divided into Figure 6(a) with models covering power and heat, and Figure 6(b) with models covering only electricity. The green columns in Figure 6(a) are the ones with perfect foresight investments, and the blue ones are with myopic foresight. None of the outlook reports in Figure 6(b) include endogenous investments in their models, and hence future generation capacities are

![Figure 6](image_url)

FIGURE 6 Modeled power prices in 2020, 2030, 2040, and 2050 found in reviewed outlook scenarios, using endogenous modeling of power-to-heat (a) or an electricity only model (b). N, Norway; S, Sweden; D, Denmark; F, Finland; Nd, Nordics. The columns colored in green are the scenarios enabling generation expansion investments with perfect foresight, the ones in blue are with myopic foresight for investment, and the ones in white are with exogenous capacity assumptions. The columns surrounded by yellow dot lines are the scenarios considering multiple weather years, while the others assume one normal weather year. The full scenario names are given in Table 2.
input assumptions. The columns surrounded by yellow dot lines indicate the application of multiple weather years, which does not apply to any scenario in Figure 6(a).

Continuously growing power prices are reported in many studies. Most of the scenarios, except for the low-price scenarios, expect power prices after 2030 above 40 EUR/MWh, and the reported 2050 prices are at the 50–60 EUR/MWh levels. The modeled future prices fall roughly in the range of the prices in the past decade, between the lowest at 25 EUR/MWh in 2015 and the highest at 61 EUR/MWh in 2010. Denmark, which is closely connected to the continental market, generally has higher prices than the other Nordic countries. Nonetheless, the modeled future power prices show large uncertainties regardless of the scenario types. For example, differences in 2040 power prices found in two different studies within the reference group were as much as 35 EUR/MWh. It is worth mentioning that the modeled future prices should not be interpreted solely from the scenario definition, especially the additional scenarios that are not in the main clusters. The modeled prices are results of mixed factors.

In our sample, outlooks using a stochastic approach of multiple weather years show smaller price differences between the years than outlooks using a deterministic approach. One explanation is that the stochastic approaches implicitly assume close to normal weather conditions since they use multiple weather years and normally report the mean values of the simulated years. Apart from this, no obvious distinct pattern from differences in modeling methodology is observed, indicating that the choice of input data assumptions has more profound impact on power prices than the choice of model. Nevertheless, the choice of model may be of larger importance when focusing on price volatility, but this is beyond the scope of this review due to insufficient data.

More high-price hours and more low-price hours are expected with increasing VRE shares. Price variation is expressed in various forms across the outlooks, for example in duration curves by Dansk Energi and Statnett, in chronological price curves over a certain period by Energimarknadsinspektionen and NVE, or in bar charts showing differences between the maximum and minimum prices over a certain period by Svenska Kraftnät. Outlooks from Energinet and Energinet danmark and Energimyndigheten do not disclose quantified information of price variation. Price variation is important to assess the profitability of VRE and flexibility solutions (Hirth, 2013). The review shows that there is no standard format to disclose such information, but an overall tendency of greater variation is agreed.

Great price variation reflects the need for flexibility. Although no particular flexibility option is relied on heavily in the reviewed scenarios, a common approach is to include supplementary scenarios to illustrate the impact of certain flexibility options. For example, the impact of consumption flexibility and storage is investigated by IEA (2016), NVE (Amunsden et al., 2017; Gogia et al., 2019), and Svenska Kraftnät (Brunge et al., 2019), and a common finding is that consumption flexibility and storage can increase low prices and lower peak prices.

5 | RECOMMENDATIONS FOR OUTLOOK PUBLICATIONS

Power market outlook studies provide substantial value to medium-term and long-term decision-making in the energy sector. Meanwhile, publishers of outlook studies have significant influence, as the information that they provide can shape the future by how decision makers and power companies use this information. Based on this review experience of the 15 recent Nordic power market outlooks, we propose the following recommendations for future publications to provide more value to their readers.

5.1 | Best efforts should be done to ensure the clarity and transparency

The credibility of an outlook study improves when the methodology is transparent, and quantitative and qualitative assumptions are readily available. The importance of transparency has been addressed with a growing number of available quantitative analyses (Morrison, 2018). During the review process, we still at times find incomplete public information, such as in methodology, parameter definitions and references. Many factors can cause model output disagreements, which can lead to misinterpretation or misuse if a report is not clearly understood or correctly communicated. It is understandable for outlooks to focus on the aspects that are important to them in order to convey clear messages. One solution is to provide supplementary files containing more complete methodological details, input assumptions and output results. It increases the credibility when the analysis can be validated or replicated and can spark more discussions. There are also projects such as Open Energy Outlook (2016) aiming to enhance the value of energy modeling and its application in informing future policy efforts by putting the entire model with data in open.
source, with detailed documentation. Another example is the Open Energy Modeling Initiative (Openmod, n.d.), which is a community of modelers to promote open models and open data through discussion forum, workshops, and other activities. Besides increasing the credibility, more openness in energy modeling and data assumptions would benefit the energy modeling community as a whole.

5.2 More attention to total electricity consumption is needed to capture the complex dynamics of energy efficiency, sector coupling, and new electricity-intensive industries

Compared to the production side, the reviewed outlooks take rather simplified approaches and write less about the electricity consumption side. The simplest approach is to assume a fixed consumption level, justified by assumptions about efficiency improvement and growing economy and population. Another common approach is to apply external references for determination of exogenously given consumption levels.

With more ambitious and broader emission reduction targets, assessments of electricity consumption development should be extended beyond changes in energy efficiency, demography, and the wider economy. Electrification and sector coupling are regarded as important aspects in the energy transition because they improve efficiency, flexibility, reliability, and adequacy of energy systems (Van Nuffel et al., 2018). With their increasing importance, future outlook publications should put more emphasis on these topics, and the models used to inform about the future energy system should to a larger degree reflect this expectation. Radical technological transformation must happen for net-zero transitions (IEA, 2020), and solutions such as electrification and hydrogen will have strong impact on final electricity demand. In addition, the emergence of new electricity-intensive industries such as data centers and battery factories in the Northern Europe will also stimulate electricity demand. Outlook publishers are advised to take these emerging driving forces of total electricity consumption into account in future publications.

5.3 Underlying uncertainties must be highlighted and uncertainty techniques besides scenarios analysis can be applied

The large variation in assumptions related to the main power market drivers identified in this review is noteworthy because it indicates a large underlying future market development uncertainty. It is not necessarily a weakness that there is little consensus in the input data assumptions for, for example, fuel and carbon prices; however, it suggests that outlook studies should explicitly address the major market driver uncertainties and their impacts on power prices. An example of a good practice is the outlook SK (2019), where the procedure to set fuel and carbon price assumptions is explained and comparison with other studies is shown. We also encourage publishers to broaden their techniques to address uncertainties. Besides multiple weather years for stochastic hydropower modeling, scenario analysis is the only technique used in the reviewed outlooks for uncertainty analysis. Other uncertainty techniques, such as Monte-Carlo analysis, models to generate alternatives, and other approaches as mentioned by Yue et al. (2018), are yet to be applied in such analysis.

5.4 Challenges related to sustainability and limitations of certain technologies arising from social oppositions should be explicitly addressed

The energy or the electricity sector is relevant for several of the Sustainable Development Goals proposed by the United Nation (SDSN, Columbia Center on Sustainable Investment, Business and Human Rights Resource Centre,, & Equitable Origin, 2019). The Nordic countries have performed well and are among the countries that scored the highest in the 2020 Europe Sustainable Development Report (SDSN & IEEP, 2020). Still, conflicts between renewable energy production and other sustainability goals, like preservation of eco-system functionality and biodiversity, will likely increase as the renewable shares increase. These conflicts are likely to affect the energy transition to an increasing extent. The energy mix may shift from the pure cost optimal solutions (i.e., from a narrow economic perspective) to more costly ones with less environmental footprints, which can also affect energy consumption in the long run. Based on the review studies, we conclude that the impacts of trade-offs between climate friendly energy production and other sustainability criteria should be discussed more explicitly in long-term outlook studies.
As discussed in the earlier sections, increasing social oppositions against certain technologies, such as onshore wind turbines and power transmission lines, are observed. Although the lack of social acceptance might have been embedded in the technology deployment assumptions, we recommend these challenges to be explicitly addressed. They are usually location-specific and culture-specific, and understanding specific difficulties is helpful for improving the presentation of such technologies in energy system models, especially when done transparently.

5.5 | Price volatility, technologies’ market values, and sensitive parameters to power prices can be included for better interpretation

Future outlooks should also include parameters receiving increasing attention, such as short-term price volatility or the market values of different power generation technologies (Hirth, 2015). In this review, we focus on the annual power prices, partly because of the limitation of extracting data from charts in reviewed outlooks and partly because not all reviewed outlooks provide price volatility, but only annual averages. We believe that disclosing such information will attract and benefit more readers.

Helistö et al. (2017) use an analytical approach with the Balmorel model to explore the sensitivity of Northern European electricity prices. They compare how the average price and duration curves change under various given wind and solar shares, and their conclusions emphasize the importance of the whole supply and demand structure, such as the capacity mix and capacity margin. The initial goal of this review was to summarize drivers and uncertainties in the Nordic future power prices through reviewing the available market outlooks, but the scope was limited by the material. Each publisher uses different details of reporting and focus, which can also change by year. As a result, a literature review is less flexible about the choice of price drivers to review across the outlook studies. Factors that are neither disclosed nor focused by most of the studies are difficult to analyze. For example, while Swedish wind capacity can be found in five outlooks, the Swedish total generation capacity is revealed in only two outlooks. Maximum load assumptions are disclosed in only two reports from Energinet (the Danish TSO) out of 15 outlooks. It is beneficial to the interpretation of the power prices, if more sensitive drivers, such as capacity mix and capacity margin, are explicitly reported.

5.6 | In the phase of energy transition, the ability of a market outlook to provide the newest insights is highly appreciated

Outlook publications with frequent and regular updates are valuable during the time of energy transition, when studies can be outdated rather quickly. Taking the WEOs from the IEA, which are popular references in the energy sector, as an example, annual updates are released. Two update directions are observed: the design of the scenarios, and the future prices calibrated by the recent price development (Figure 7). We find a similar behavior in the reviewed outlooks.
that newer publications have higher gas and emission quota prices, greater wind capacities, and more attention to electrification in general, following the price development and renewable deployment since 2016.

It is important to distinguish between the temporal drivers and the long-term impact of technology developments, policy priorities, and climate change, that are far more relevant in long-term analysis. For example, the influence of major policy announcements, such as EU Green Deal, is likely to sustain for decades. The impact of a single extreme weather event might not last, but new climate norms will have to be considered in long-term analyses. In early 2020, the world was hit strongly by the Covid-19 pandemic. Economic activities were interrupted globally, leading to minimum energy demand. For the first time in history, the US oil benchmark price turned negative in April 2020. Since February 2020, the Nord Pool spot market price has been around 60%–80% lower compared to the same period in the past 2 years (see Figure 8), as a result of reduced demand, low fuel prices, and mild weather. At the study completion, it remains unclear whether Covid-19 will create a new benchmark in the energy sector. Ad-hoc analysis in response to the impact of unexpected events will be helpful for timely decision-making. Long-term market studies should stay critical in the assessments of whether the influence of an event is only temporal or likely to last for decades.

The review includes outlooks from eight different publishers. Two (Dansk Energi and Energinet) out of eight update their reports annually, and three (Energimyndigheten, NVE, and Statnett) have biannual updates. They adjust the assumptions and, sometimes, the scenario setup or report scopes to bring out the latest insights regarding technological development as well as policy means and targets. In light of the energy transition, outlooks should ideally have frequent updates to reflect the latest economic trends, policies, and long-term effects of major events to provide prompt information.

6 | CONCLUSIONS

This study reviews 43 scenarios in 15 recent Nordic power market outlooks with a particular emphasis on assumptions for major market drivers and their impacts on the modeled power prices. The review reveals expectations of growing trends of future power prices towards 2050, which are highly correlated with the gas and emission quota input assumptions. The assumptions for gas and carbon prices towards 2050 show profound uncertainty. The reported future power prices are found well above the LCOE of onshore wind power, which suggests that the assumed onshore wind deployment is restricted by factors beyond the economic potentials.

The demand side development is found less focused in our review, and most scenarios assume constant or slight increases in electricity consumption towards 2050. As a result of limited modeling scope, dynamics between electricity and other sectors are often simplified. Some of the outlooks expand the scope to include the heating sector, with computational tradeoffs, such as temporal granularity.

A set of recommendations for future outlook publications are proposed. Clarity and transparency are among the most important criteria. With increasing importance of sector coupling and electrification, more attention should be paid to electricity consumption development. Underlying uncertainties in the long-term market development must be highlighted, and uncertainty techniques beyond scenario analysis can be applied to a larger extent than today. Assessments of emerging environmental and social challenges are also valuable. With higher VRE share, information such as price volatility becomes essential in addition to the average prices. Lastly, new data and new information are
formed constantly in this phase of transition, and the ability to include new data and information that affect the long-term development of the energy markets are highly appreciated. This review hopes to contribute to more credible and informative future power market outlook publications.

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CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS
Yi-kuang Chen: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; validation; visualization; writing-original draft; writing-review & editing. Anne Hexeberg: Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; visualization; writing-original draft; writing-review & editing. Knut Einar Rosendahl: Formal analysis; investigation; methodology; resources; supervision; validation; visualization; writing-original draft; writing-review & editing. Torjus Bolkesjø: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing-original draft; writing-review & editing.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTE
1 Iceland is excluded in the Nordic scope because it has an independent energy system.

RELATED WIREs ARTICLE
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Historical price developments, recent status, market scenarios for 2020. This review includes the publications from 2016 to 2019. They are composed of similar structures including market outlooks annually to show electricity wholesale prices in Denmark and Northwestern Europe in possible future scenarios. Dansk Energi is a non-commercial lobby organization for Danish energy companies. They publish midterm electricity material.

The following section includes short descriptions of the reviewed outlooks by publisher as a quick guide to the reviewed material.

**APPENDIX**

**DESCRIPTION OF THE REVIEWED OUTLOOKS**

The following section includes short descriptions of the reviewed outlooks by publisher as a quick guide to the reviewed material.

Dansk Energi

Dansk Energi is a non-commercial lobby organization for Danish energy companies. They publish midterm electricity market outlooks annually to show electricity wholesale prices in Denmark and Northwestern Europe in possible future scenarios. This review includes the publications from 2016 to 2019. They are composed of similar structures including historical price developments, recent status, market scenarios for 2020–2035, and earnings of various producers. The

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2016 and 2017 publications contain more details on methodologies, assumptions and results. The 2018 and 2019 publications contain much limited information and further data are only available to the members upon request. The scenario formations in outlooks until 2018 depend mainly on fuel and emission quota price assumptions, and the 2019 outlook formulates its main scenarios by the degree of the emission reduction commitment. Both the 2018 and 2019 outlooks develop several sensitivity scenarios from the main ones by varying technology investment costs or changing technology investment options, but they are excluded in this review because of the limited results that can be found in the public reports.

The analyses are based on the energy system model Balmorel with no-foresight investment. It assumes spot market only, and the modeling of the Nord Pool price ceiling (3000 EUR/MWh) is included. In the 2016–2018 outlooks, future transmission and most generation capacities are given exogenously in the reviewed scenarios, and the following technologies (gas turbines, gas cogenerations, coal cogenerations in Germany and Netherland, wood pellet cogenerations, offshore wind, large scale solar PV, and woodchips CHP, biomass boilers and heat pumps in Denmark) can be invested if economically attractive. The 2019 outlook includes onshore wind, transmission (Blå and Grøn scenarios), batteries (Blå and Grøn scenarios), and long-term storage (Grøn scenario) investment possibilities.

Energinet

Energinet is an independent public enterprise owned by the Danish Ministry of Climate and Energy. They prepare annual documents and associated spreadsheets describing the assumptions used in internal analyses. This review takes the assumption reports released in 2016 and 2017. The newer versions do not include power prices and, thus, are excluded in this review scope. The reports are structured with chapters describing assumptions of economic growth, fuel, quota and energy prices, energy consumptions, generation facilities, international connections, gas sector development, and so on by 2040, and the reasonings behind. The 2017 report reveals that the assumptions of larger plant future capacities are set through dialogues with stakeholders and industry players, and that of small plants like PV, EV, and heat pumps apply general S-curve approach.

Two models are used to calculate electricity price projections on the basis of the analysis assumptions from 2020 to 2040. At first, the Energinet’s BID model calculates the expected prices by simulating the North European electricity system in hourly resolution, taking start-up and shut-down costs into account. The resulting prices of the neighboring countries around Denmark are sent to the inhouse model SIFRE, which simulates the Danish electricity and heating system in hourly resolution and calculates the Danish spot prices. Although both models simulate hours prices, only annual average prices are shown in the Energinet’s assumption reports.

Energimarknadsinspektionen

Energimarknadsinspektionen (Ei, the Swedish Energy Markets Inspectorate) is an authority which supervises the Swedish electricity, district heating and natural gas markets. The reviewed report was commissioned by the government to investigate the effects of increased variable electricity production share on prices. The report describes the historical and current Swedish electricity trading system, methodology, assumptions and scenarios, results of prices, profitability and investment incentives. The study horizon covers 2020 and 2030. The quantitative analysis is carried out by the electricity market model Apollo, which simulates the day-ahead market and covers European countries and the surrounding regions. Apollo simulates wholesale prices by minimizing the electricity production costs with given consumption, generation and transmission capacities, inflows, fuel and quota prices, and weather-dependent productions. The electricity demand is partly elastic that the consumption reduces if the price exceeds 200 EUR/MWh. The generation and transmission capacities follow nation’s development plans. Three scenarios are analyzed, two with various fuel prices and one with nuclear phase-out.

Energimyndigheten

Energimyndigheten (the Swedish Energy Agency) works on behalf of the government and develops long-term energy system scenarios as a part of the basis for biannually climate reporting to the European Commission. This review covers
the reports released in 2017 and 2019. It is stated that purpose of the reports is not to forecast but to show the uncertainties and how they affect outcomes. In accordance with the requirements of climate reporting, one reference scenario, one scenario with higher and one with lower CO₂ emissions are analyzed to estimate emission levels. In addition, the 2017 version includes two supply side scenarios and three transport sector scenarios, and the 2019 version includes three additional scenarios focusing on demand side. Note that only the scenarios showing electricity prices are reviewed in this study. The reports cover the whole Swedish energy sector, and the sectoral results are discussed by chapter.

TIMES-NORDIC is the model used by the Swedish Energy Agency for the analysis. It includes the Nordic and Baltic countries, Germany and Poland. The time horizon covers every 5 years until 2050 and a year is divided into 12 timesteps, consisting of four seasons and three times slots in each season. Besides existing capacities, the model can invest in new generation capacities, subject to potential constraints when applicable. For example, hydropower potential is very limited, and Swedish onshore wind has 100 TWh expansion potential. The transport sector is not modeled, but its electricity demand is an input to TIMES-NORDIC model. The reports show only the Swedish annual average electricity prices, defined by the marginal costs of electricity production, and the electricity prices are also used in sectorial analysis.

Svenska Kraftnät

Svenska Kraftnät is the authority responsible for Swedish transmission system. They publish their long-term market analysis every 2 years, but this review covers only the 2019 version, as the earlier ones are not available on their website. The analysis comes with an excel file containing the Swedish data including sectoral demand, generation and transmission capacities, fuel and emission quota prices.

The analysis is performed with two models, BID3 and EMPS. The simulation has hourly resolution and 31 weather years are taken into account. The reference scenario, representing the best estimate from 2020 to 2040, is based on the sustainable transition scenario in TYNDP 2018 and the generation capacities are given assumptions. Two complementary scenarios, high and low, are drawn in 2040 to mark the uncertainty space between business as usual and electricity being the primary energy carrier. In the complementary scenarios, the BID3 model seeks an optimal production mix, subject to maximum 20% capacity expansion of different types or power generation per country from the reference scenario. The report also analyzes the price volatilities, adequacy and stability of the Swedish power grids under various weather conditions or grid availability.

Norges Vassdrags-og Energidirektorat

Norges Vassdrags-og Energidirektorat (NVE, the Norwegian Water Resources and Energy Directorate) is an administrator managing Norway’s water and energy resources. They publish annual power market analysis describing the Nordic power market development, and this review includes the 2017 and 2019 versions. The 2017 report covers until 2030 and the 2019 report covers until 2040.

NVE uses three optimization models. Firstly, TIMES model projects the Norwegian consumption of all energy carriers and the electricity demand is used in the other models. Secondly, The-MA model calculates power markets in the 19 European countries and finally, Samnett model with a Nordic focus calculates the Nordic prices taking 30 weather years and grid restrictions into account. The generation capacities are given assumptions. In addition to a base scenario, one high scenario and one low scenario draw the uncertainty space in fuel and emission quota assumptions. Norwegian price variations are further discussed under various conditions such as weather, international transmissions, and flexible demands.

Statnett

Statnett is the Norwegian power system operator and they publish the long-term market analysis every 2 years that covers the main trends, uncertainties and the most likely development in the power system. This review includes the 2016 and 2018 versions and they both cover the time horizon until 2040.
There are two main tools used for the analyses with given generation capacity and demand assumptions. The power market model BID covers 19 European countries with hourly resolution and generates power prices in the neighboring countries to be used in the second model Samnett. Samnett covers Nordics and Baltics and has detailed modeling of hydropower and transmission system. It is stated in the 2016 version that up to 50 historical weather years are simulated, while the 2018 version uses 29 weather years. Similar to the NVE’s analyses, a base scenario plus one high and one low scenario marking the power price outcome space caused by uncertainties in input price assumptions.

**Nordic Energy Technology Perspective (NETP)**

Unlike the other reports included in this review that are published by one institute, the NETP is a collaborative work between the International Energy Agency and several Nordic research institutions. It provides a case study on how Nordics go beyond the 2°C target. The report consists of three chapters. The first chapter focuses on the whole energy sector in the Nordic countries and the decarbonization pathways. The second chapter focus solely on urban areas. This review focuses on chapter 3 where electricity system integration in the carbon neutral scenario is analyzed. Balmorel is the main tool for the analysis and it is coupled with the ETP-TIMES global model used in the first chapter. Same fuel and emission quota price assumptions used by ETP-TIMES and its electricity and district heat demand outputs are applied to Balmorel. Several iterations are done to harmonize both models. The time horizon covers until 2050 and a year is represented by 72 hours. Balmorel models generation capacity expansion and transmission investments after 2030 with myopic foresight.