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Sweden's Energy Investment Challenge

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Abstract

Sweden faces a major challenge in the next decades because of a projected increase in electricity demand, aging supply infrastructure and the transition to an energy system with a substantial share of weather-dependent production. This paper discusses the incentives to invest in production capacity in the Swedish electricity market, the energy policies that drive the development and proposes changes in market design to cope with this energy investment challenge.

JEL codes: D25, D47, Q40, Q48

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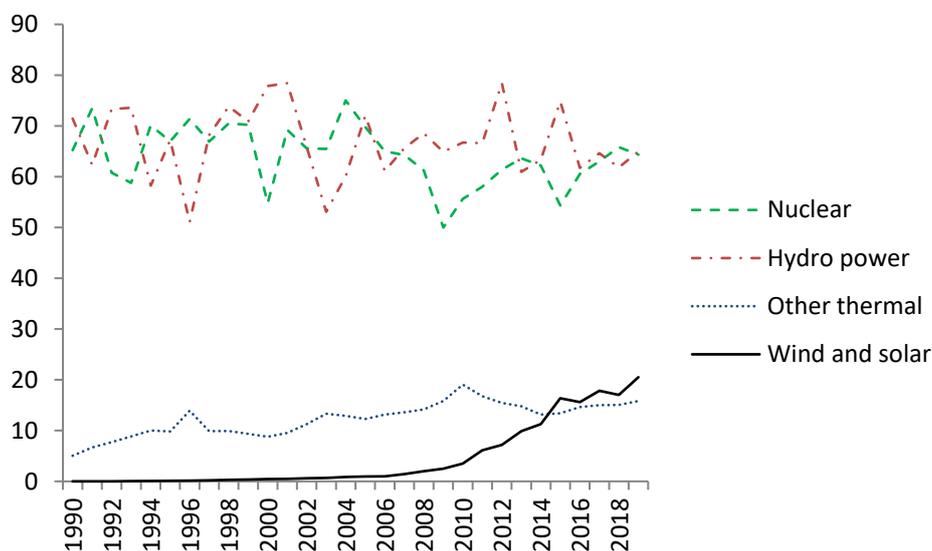
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1 Introduction

Electricity supply in Sweden faces major challenges in the next decades. Population growth and electrification of transport and industrial processes are projected to cause a large increase in demand. Server halls and other energy-intensive industries contribute to the development. Some estimate that annual demand for electricity will increase to 200 terawatt hours (TWh) by 2045 (Svenskt Näringsliv, 2020). In comparison, electricity production in Sweden was 175 TWh in 2019. At the same time, a large part of the generation capacity is approaching its technical life span and will have to be replaced. Large network investments are also needed to increase integration with other countries, replace aging infrastructure and adapt the grid to new consumption and production patterns.

Figure 1: Annual electricity production (TWh) in Sweden 1990-2019



Source: Statistics Sweden (statistikdatabasen.scb.se)

Electricity supply in Sweden has historically relied on nuclear, hydro and fossil-fueled power. Common to all these energy sources is that they deliver dispatchable and reliable electricity generation. Output from such facilities has remained quite constant over the last decades. As Figure 1 shows, hydro and nuclear power have decreased somewhat between 1990 and 2019. Other thermal generation has gone up due to an increase in production from combined heat and power (CHP) plants. Most of the investment in new capacity has been in wind power. The transition from dispatchable and reliable generation to inflexible and unreliable, *intermittent*, renewable electricity production is likely to continue during the next years. For instance, four nuclear reactors have shut down in recent years, leaving only six of the original twelve large commercial reactors in Sweden operative.

Sweden's energy investment challenge is how to replace current capacity and meet increasing demand at competitive electricity prices, while incorporating large shares of intermittent renewable electricity production and maintaining system reliability. Does the market provide

sufficient incentives to invest in generation capacity? If not, how can the market be reformed to improve efficiency? How does energy policy at the national and EU level affect investment incentives? Are capacity mechanisms necessary to generate investment and ensure system reliability? These are some of the questions we address in this article, where we analyze the incentives to invest in new electricity production in Sweden.

2 The deregulated wholesale electricity market

2.1 The day-ahead market

Sweden is part of the integrated Nordic electricity market that covers Denmark, Finland, Norway and Sweden plus Estonia, Latvia and Lithuania. The market is interconnected with the Netherlands, Poland, Russia and Germany. Most of the electricity produced in the Nordic region is sold on the *Nord Pool* power exchange.¹ The cornerstone of Nord Pool is the *Elspot* day-ahead market where retailers and large industrial consumers buy electricity wholesale from producers for delivery the subsequent day.² Elspot is fundamental also for other markets. For instance, retail prices are calculated as markups over Elspot prices, and they constitute reference prices for the financial contracts used for hedging production and consumption. Elspot prices therefore provide the strongest market signals about the profitability of investing in new generation capacity in the Nordic countries.

Every day before noon generation owners state how much electricity they are willing to offer, and retailers and large industrial consumers how much electricity they are willing to purchase, at different prices for every hour the following day. Nord Pool then creates 24 supply curves for the following day by adding all price-dependent offers for each hour, and also derives 24 corresponding demand curves by aggregating all price-dependent bids for each hour. The hourly *system price* is found where the supply curve intersects the demand curve for that hour.

A large part of Sweden's electricity supply is produced by hydro power in the north and much of the electricity is consumed in the metropolitan areas in southern Sweden. Regional differences between supply and demand generate bottlenecks in the system whenever the transmission network has insufficient capacity to handle all trade flows implied by the system price. To handle such capacity constraints, Elspot is divided into fifteen different price zones. Each zone has individual market clearing depending on the capacity constraints to and from the zone. Import-constrained zones have a higher clearing price than export-constrained zones. Sweden was divided into four price zones from north to south in 2011. Previously, Sweden constituted a single price zone.

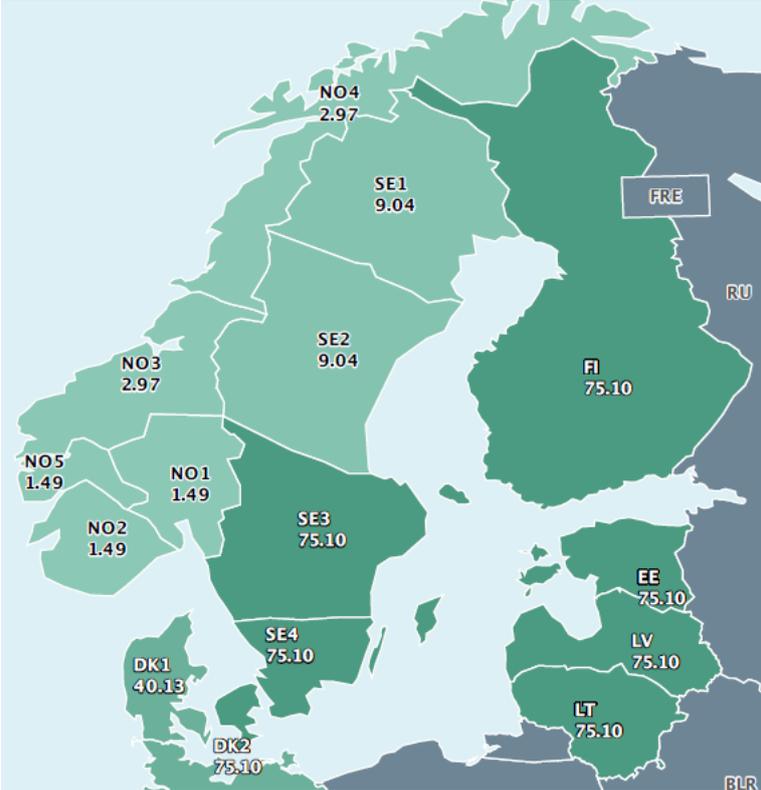
Figure 2 shows the prices in Euros per megawatt hour (EUR/MWh) in Elspot's different price zones (in green) for the delivery hour 08-09 on June 26, 2020. The system price was 5.60 EUR/MWh that hour. Zonal prices provide signals about where in the system there is a shortage or surplus of generation resources. In particular, the partitioning into price zones has increased

¹ Since June 2020, market participants in the Nordic region can also trade on the *EPEX Spot* power exchange.

² Nord Pool and the other power exchanges in the EU electricity market are coupled and cleared simultaneously.

prices in southern relative to northern Sweden and thus made it more profitable to invest in new generation capacity in the south and to locate electricity-intensive consumption units in the north. Zonal price differences also provide signals about the value of incremental transmission capacity. Hence, price zones are fundamental to an efficient electricity market in the short and long term.

Figure 2: Zonal electricity prices (EUR/MWh) on Nord Pool Elspot, June 26, 2020, 08-09



Source: Nord Pool (nordpoolgroup.com/maps/#/nordic)

Because of the energy transition, electricity prices can sometimes be very low. In February 2020, the Nord Pool power exchange for the first time reported *negative* prices in Sweden. Mild and windy weather, combined with a large hydro-reservoir inflow drove down demand and increased supply. Electricity was sold at negative prices since wind power has negative variable costs because of the support system (see below), and hydro power is not permitted to waste water. The transition has also created large electricity price *differences* across zones because of increased regional imbalances in supply and demand. During several hours in the summer of 2020, the price of electricity fell below 10 EUR/MWh in northern Sweden, while electricity was sold for over 75 EUR/MWh in southern Sweden, see Figure 2. Important reasons for these price differences were hot weather with little wind, reduced nuclear production in southern Sweden, and severe transmission network constraints. Swedish consumers and producers are not accustomed to such huge price differences.

Structural changes on both the producer and consumer side imply that network bottlenecks can change over time. Economic and demographic change in Sweden is now creating resource constraints in metropolitan areas that are not reflected in the current zonal structure. Prices

therefore fail to identify areas of excess demand where additional generation investment would be profitable, and they also yield distorted incentives to shut down critical generation units that are unprofitable because zonal prices do not reflect the system value of those units.

Internal congestion within price zones can lead to arbitrage trading when market participants exploit these constraints. Such behavior distorts prices and may exacerbate existing resource constraints (Holmberg and Lazarczyk, 2015; Hirth et al., 2019). Internal congestion can also create problems in an integrated market if the system operators responsible for maintaining the balance between consumption and production, see discussion below, reduce trade in order to alleviate domestic congestion problems.

Conclusion *A division of Sweden into additional price zones would increase security of supply and efficiency by visualizing network bottlenecks, thereby increasing the profitability of existing critical production and stimulating new investments in critical areas.*

Some have raised concern that small metropolitan price zones with excessive demand will make it difficult for consumers to hedge prices. One solution to this problem could be zonal pricing only on the supply side (Tangerås and Wolak, 2017), as in Italy. Another could be a regulatory mandate which forces the system operator to sell financial contracts. A second concern with a small price zone is that some local producer could achieve a dominant position. Such market power could be mitigated by forcing the producer to sell financial contracts.³

Resource shortages sometimes occur in the day-ahead market when supply is insufficient to cover demand even after all available import capacity had been utilized. In Sweden, this happened during several peak hours in the winter of 2009-10, due to unusually cold weather, reduced nuclear capacity and reduced network capacity. In such situations, the transmission system operator (TSO), *Svenska Kraftnät* (SvK), activates its strategic reserve to cover the difference. The price during a resource constrained hour was previously set equal to the maximal offer price at Elspot that hour. This market design gave weak incentives to invest in such peak capacity that is particularly useful during resource shortages because those units would only ever recover their variable costs in a competitive market. Since 2018, the price is instead set equal to the Elspot price cap of 3 000 EUR/MWh during resource shortages. This change should stimulate investment particularly in peak-load capacity.

2.2 Balancing markets

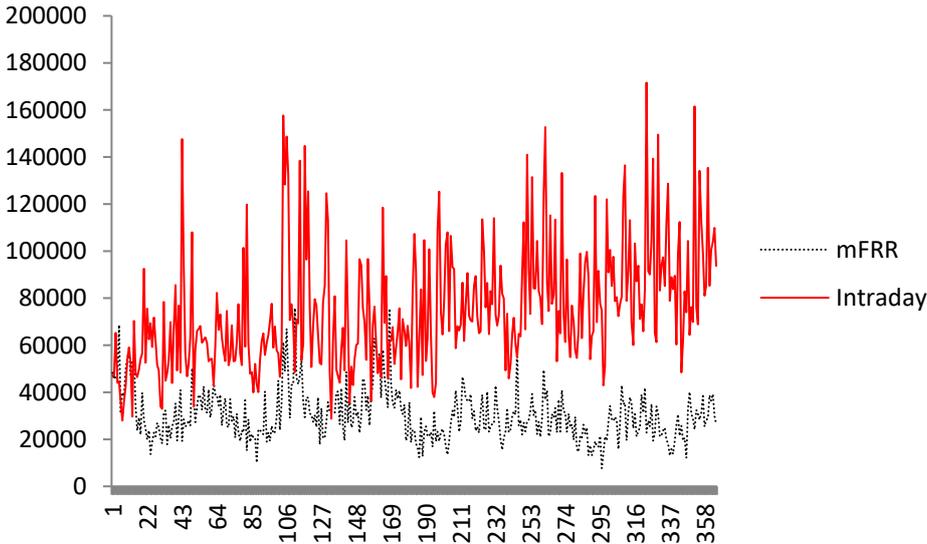
A fundamental task of system operation is to maintain a continuous balance between the amount of electricity injected into the grid and the amount withdrawn from it. Costly system disruptions and power outages may otherwise result. The equilibrium positions at Elspot can be determined as much as 36 hours ahead of the delivery hour. Updated weather forecasts, plant failures and unscheduled reductions in network capacity render it necessary to rebalance the system relative to Elspot market allocations. The transition to an energy system based on larger amounts of

³ A similar mechanism that has occasionally been implemented in Europe is the virtual power plant (VPP) auction. In this auction, dominant producers are forced to sell a fixed share of their capacity to competing firms or to consumers (Ausubel and Cramton, 2010).

solar and wind power has increased the demand for such rebalancing since it has become more difficult to plan electricity supply far in advance.

The electricity market offers two main opportunities for rescheduling consumption and production. The first is Nord Pool’s *intraday* market. This market opens two hours after gate closure of the day-ahead market and closes 60 minutes before the delivery hour. The intraday market functions similar to a stock market in the sense that buyers and sellers continuously place bids to buy or sell electricity. Continuous trading means that the price can change over the course of the trading period, even for electricity with the same delivery hour. The second opportunity is to participate in one of the various markets for reserve power run by SvK. The most important is the market for *manual frequency restoration reserves (mFRR)*.⁴ This market is structurally similar to Elspot in that market participants submit price-dependent bids to increase or decrease their production or consumption compared to the day-ahead positions. SvK then clears the market given the transmission constraints in the system. The mFRR market closes 45 minutes before the delivery hour. The balancing markets have the same zonal partitioning as the day-ahead market.

Figure 3 Balance volumes (MWh) in Sweden per week 2013-2019



Source: Nord Pool (nordpoolgroup.com/historical-market-data)

Figure 3 depicts the balancing volumes across the four price zones in Sweden during 2013-19, measured in MWh. The solid line shows the total accepted purchase and sell bids in the Nord Pool intraday market week by week during the sample period. The volume almost doubled from 58 GWh in 2013 to 93 GWh in 2019, but displays substantial weekly variation. The dotted line shows the sum of up- and down regulating volumes in the mFRR market week by week over the same period. Even here there is a lot of variation, but no visual increase over the period. The average volume remained steady around 30 GWh annually. On the basis of these

⁴ SvK runs three additional markets for reserve power. All these markets differ in terms of the requirements they place on the participating units regarding the maximal time lag between SvK’s call for activation and actual activation. mFRR has a 15-minute requirement, aFRR has 2 minutes, FCR-Normal has 1-3 minutes, and FCR-Disturbance must be activated within 5-30 seconds of SvK’s call.

observations, it seems as if rescheduling primarily occurs in the intraday rather than the regulating market. A reason is probably the penalties that SvK charges for imbalances during the delivery hour.

There are welfare economic benefits of rebalancing electricity in the intraday compared to the SvK markets for reserve power. Competition is likely to be better in the intraday market because of the entry barriers associated with the technical requirements in the reserve power markets. Moreover, demand and supply are entirely market-based in the intraday market, whereas demand in the reserve power markets relies on estimates by the TSO.

Nord Pool and other European intraday markets plan on introducing an auction-based setup in which the market is cleared at regular and predetermined intervals, in parallel to continuous trading. This reform will probably increase liquidity compared to the current design (Neuhoff and Boyd, 2011). An auction-based market increases efficiency by a more appropriate handling of network constraints and by reducing entry barriers (Neuhoff et al., 2016; Ehrenmann et al., 2019). These types of markets also reduce automated trading which is difficult to handle, and may destabilize the market (Budish et al., 2015; Ahlqvist et al., 2018). A disadvantage is a delayed response to relevant information.

Increased trade in the balancing market particularly increases the profitability of investing in hydro power, batteries and other energy storage technologies. We illustrate this effect in a simple example. Let the day-ahead price be 400 EUR/MWh. Assume that the balancing price is 600 EUR/MWh if there is excess demand in the balancing market (up-regulation) and 200 EUR/MWh if there is excess supply (down-regulation). Consider a battery with 2 MW storage capacity and assume that this battery is fully charged. The owner sells 1 MW in the day-ahead market and saves 1 MW for the balancing market. In case of down-regulation, the owner keeps the battery fully charged and instead buys the 1 MW in the balancing market, thereby earning $200=400-200$ EUR. In case of up-regulation, the owner sells the remaining 1 MW capacity in the balancing market at 600 EUR and earns 500 EUR/MWh on average. The battery is fully discharged the next period, so the owner buys 1 MW in the day-ahead market at 400 EUR. In case of up-regulation, the owner sells this capacity in the balancing market and earns $200=600-400$ EUR. In case of down-regulation, the owner buys 1 additional MW in the balancing market, and recharges its battery at a cost of 300 EUR/MWh on average.

This simple example provides a number of insights. First, the profitability of the battery depends on participation in the balancing market. The day-ahead price in the above example was constant and equal to 400/EUR in both periods. Second, an appropriate choice of strategy makes it possible to profit from all types of imbalances. Third, the profitability of the battery does not depend on the price level in the day-ahead market. The owner makes a profit from selling electricity at an average price above and buying electricity at an average price below the day-ahead price whatever that price may be.

Increased trade in the balancing market increases the profitability also of other types of flexible and dispatchable generation capacity, but has no effect on investment in non-flexible capacity that cannot participate in the balancing market.

Conclusion *Introducing an auction-based intraday market will increase liquidity, efficiency and transparency in the intraday market. Increased trade in the balancing markets will particularly benefit investment in storage technologies.*

The delivery period in the electricity market is currently 60 minutes. This means that all electricity produced within the same delivery hour receives the same price. With an increased share of variable electricity production, more high-frequency price changes will be necessary to account for short-term changes in availability. To adapt the market to these needs, the EU will shorten delivery periods to 15 minutes. These changes will impose a larger share of the system costs of variable electricity production on the generation units that cause fluctuations and thereby favor investments in dispatchable and reliable electricity production.

2.3 Financial markets

The profitability of investing in new capacity is determined by prices in the electricity market, capacity utilization, costs of constructing and operating the facility, tax levels and energy policy. The revenue of intermittent generation is particularly volatile because of the random fluctuations in output. Investors reduce uncertainty by entering into *Power Purchase Agreements* (PPA). These are long-term forward contracts that protect investors from risk by setting a predetermined price for a predetermined amount of electricity over the contract period. Buyers are large electricity consumers who want to contribute to sustainable investment and simultaneously hedge their electricity consumption. Purely financial investors also buy PPAs to diversify risks in an asset portfolio.

Trade in PPAs appears to be extensive, but the market is non-transparent. Organized trade in standardized PPA contracts would increase competition and liquidity of this market, thereby facilitating for investors to reduce investment risk. If trading in long-term contracts still is insufficient, consideration may be given to regulating those volumes. In some Latin American countries, retailers are required to purchase up to 90% of their expected electricity consumption through long-term financial contracts.

3 Energy Policy in Sweden and the EU

A key idea behind deregulation of the wholesale electricity market was to expose firms to market prices and thereby stimulate investment on market-based terms. In reality, energy policy has always been a key driver of investment, in particular for nuclear power and renewable electricity.

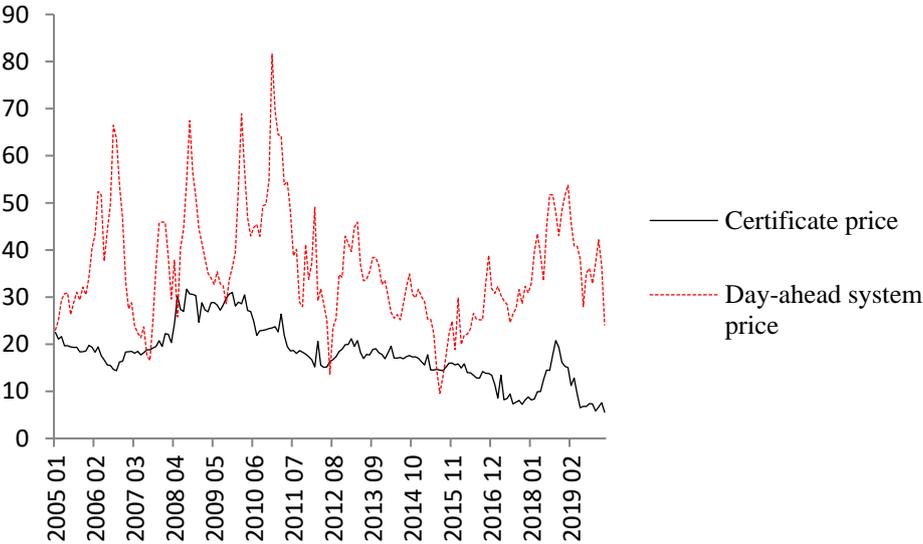
3.1 Tradable green certificates

In 2003, Sweden introduced a system of tradable green certificates to stimulate investment in electricity production from renewable energy sources, *RES-E*. Introducing this support scheme was part of implementing the EU Renewable Energy Directive that set binding targets for the share of RES-E in each member state. The original ambition was to increase RES-E by 17 TWh between 2002 and 2016. The goal has been expanded on several occasions and now amounts to

an increase of 48 TWh compared to 2002. In 2019, Swedish wind power alone produced nearly 20 TWh electricity.

Certified generation units receive one certificate for each MW electricity they produce. These certificates are sold to retailers that have an obligation to cover a fixed proportion of their end-users’ consumption by certified electricity production. Certificate revenues have constituted a substantial source of income in addition to what the owners have earned from selling their electricity on Nord Pool. The solid line in Figure 4 shows the average monthly price for certificates and the dotted line the Elspot system price between 2005 and January 2020. The price of a certificate has on average been half of the system price. In a competitive market, the certificate price equals the difference between the cost of building and operating marginal renewable generation and the market price of electricity. The cost of building wind power has fallen sharply in the last decade due to technological development and lower capital costs. Declining investment costs can explain the development in Figure 4.

Figure 4: Monthly certificate and day-ahead system prices in EUR/MWh 2005-2019



Source: Holmberg and Tangerås (2020).

The support scheme is the main explanation for the increase in installed wind power capacity in Figure 1. However, the certificate system not only increases the profitability of investing in RES-E, but also reduces the value of non-certified generation by reducing electricity prices. The certificate system therefore enables the energy transition both by favoring RES-E and by disfavoring other generation such as fossil-based gas power and even nuclear power. The accelerated shut-down of nuclear power has been attributed not least to lower prices.

Support is limited to at most 15 years in the certificate system whereas the technical life span of the facilities can be 25 years or more. Hence, there is a risk of crowding out by which fully functioning facilities are replaced in order to obtain certificates for the new units. Such effects have been documented in Danish wind power (Mauritzen, 2014). There is also a risk that CHP plants switch back to non-renewable fuels when they no longer receive certificates to

compensate the cost of the more expensive biofuels. Hence, a RES-E support system should cover the technical life of the facilities to be efficient.

A problem with production-based support schemes is that owners have incentives to run the facilities even at negative prices. One solution would be that owners only receive certificates in peak hours when the likelihood of negative prices would be zero, or that the support scheme subsidizes investment costs.

3.2 The Energy Agreement

In 2016, the parties in the Swedish parliament, except the Liberals, the Sweden Democrats and the Left Party, entered into the *Energy Agreement* in order to lay down the framework for a future Swedish electricity market. The agreement clearly states that there should be no legal end-date for Swedish nuclear power. However, a fundamental goal in the agreement is also to achieve 100% renewable electricity production by 2040. Due to the long lead times in planning and constructing facilities, this ambivalence creates political risk that affects investments in nuclear power and other types of electricity production.

Conclusion *The Swedish parliament should clarify whether domestic nuclear power has a role in Sweden's electricity supply after year 2040.*

The agreement further states that expansion of hydro power will primarily take place through capacity increases in the current facilities. What then remains to meet the expected growth in demand is large-scale expansion of onshore and offshore wind power, solar power, and bio-fueled CHP and gas turbines. In addition, reduced exports or increased imports from surrounding countries may contribute to domestic electricity supply.

A main motivation for the Energy Agreement was to reduce political risk in the electricity market by laying the foundation for an energy policy with broad-based parliamentary support. Foreign firms are also covered by international agreements. *The Energy Charter Treaty* (ECT) is a multilateral investment agreement that reduces risk by compensating foreign investors for regulatory expropriation by the host country. A relevant case in point is the litigation by the Swedish energy company Vattenfall against Germany for the decision to accelerate the phase-out of nuclear power after the Fukushima accident.⁵ The political risk of domestic investment would diminish if Swedish legislation would offer domestic firms the same legal protection as that offered to foreign firms under ECT.

3.3 EU-ETS

In 2005, the EU introduced its Emissions Trading System, EU-ETS. All plants included in the EU-ETS must acquire emission rights corresponding to their greenhouse gas emissions. The total amount of emission rights is below the facilities' historical emissions. This creates a demand for emission rights and a price for emissions that drives the transition to a fossil-free energy system in Europe. EU-ETS has no direct effect on the cost of electricity production in

⁵ Readers interested in the economics of investment agreements might consult Horn and Tangerås (2021).

Sweden as this production mostly consisted of nuclear power and hydro power already before the introduction of the system. However, increased costs for fossil-based generation will drive up the electricity prices on the European continent. These price increases then spill over to the Nordic market because of market integration. The EU-ETS increases the profitability of new electricity production in the Nordic region, especially fossil-free base-load that is produced during the hours when the markets are integrated.

3.4 The EU internal electricity market

One of the most important ambitions of energy policy in the EU is to create an internal electricity market. Realizing the gains from trade of an integrated electricity market requires sufficient cross-border transmission capacity between the member countries. The Nordic countries have long invested in domestic and international transmission capacity.

A significant benefit of market integration in the Nordic region has been to take advantage of variation in electricity production across countries. For example, the large expansion in wind power in Denmark has been possible with maintained system reliability only because of the reliance on Norwegian and Swedish hydro power to offset the weather-dependent fluctuations in domestic electricity production. In general, market integration reduces the cost of maintaining system reliability.

Sweden is a net exporter of electricity most of the hours of the year. Market integration then increases the price of electricity in Sweden, and therefore the profitability of investing in new generation, especially base-load. Market integration also increases efficiency in the electricity market in the short and long term by reducing companies' market power. Increased integration of the electricity market therefore increases the reliability of electricity supply, reduces the need for peak-load generation and improves competition in the electricity market.⁶

4 Capacity mechanisms

The Nordic electricity market was originally based on the *energy-only* principle, which means that generation owners only are paid for the electricity they produce, and consumers only pay for the electricity they use. Under certain conditions, an energy-only market is sufficient to ensure a reliable and cost-efficient electricity supply in the short and the long run. However, efficiency requires that the price of electricity sometimes reaches very high levels, to the level at which customers would rather be disconnected instead of consuming electricity. This price level is the *Value of Lost Load* and is denoted p_{VOLL} . In an energy-only market, the price cap must be set at p_{VOLL} to generate sufficient returns so that it will be profitable to invest in peak-load capacity that is necessary to maintain security of supply during the hours of the year when intermittent capacity generates very little or no electricity.

⁶ Price changes that arise because of investments in new large-scale generation affect the value of investment in network capacity and vice versa. This economic relationship creates added value of coordinating investment. Development of the network is coordinated at the European level through grid plans developed by the European Network of Transmission System Operators, *ENTSO-E*. For those interested in reading more about network investments in an integrated electricity market, we refer to Persson and Tangerås (2020).

There are several reasons why markets may set a price cap below p_{VOLL} . It is a theoretical construct that is difficult to measure, and it may be more politically sustainable to set the price cap too low rather than too high. A low price cap reduces consumers' price risk and improves competition in the market. If so, there will be too little investment to maintain reliability. A related concern is that the energy transition risks reducing system reliability because of wind power and other intermittent electricity production that replaces reliable generation capacity. In order to minimize the risk of system failure, electricity markets often are supplemented by a *capacity mechanism* in which generation owners receive a capacity payment to guarantee a certain volume of capacity for a predetermined period. Such payments represent a form of income security additional to the revenue that owners receive for their actual production. Investment in peak-load capacity becomes profitable even if the price never reaches p_{VOLL} .

During the energy transition, authorities will probably make a number of political decisions to guide the electricity market in the desired direction. Moreover, investment cycles and technological development of solar power, wind power, batteries and demand flexibility can create temporary imbalances in electricity supply that lead to transitory risks of shortage. Hence, there may be reasons to supplement the market with an extra margin when capacity becomes temporarily low due to short-term lack of resources in the market and deviations from the long-term market equilibrium.

One can distinguish between two main types of capacity mechanisms. The most common in the US is a *capacity market*. This is a market-wide mechanism in the sense that all capacity receives a capacity payment. To avoid paying for capacity that may not be available when it is needed, generation owners receive capacity payments in relation to the *firm capacity* defined for each facility. A generation unit's firm capacity measures its reliable output during stressed system conditions. More common in the EU is a *(strategic) capacity reserve*. Authorities then only procure the extra capacity required to cover excess demand when there is insufficient capacity bid into the market. Sweden introduced a strategic reserve in the early 2000s to cope with shut-down of nuclear power in southern Sweden.

A difference between a strategic reserve and capacity market is that only a small part of total capacity receives capacity payments in the first mechanism. Unlike in a capacity market, a strategic reserve avoids the task of defining firm capacity for renewable electricity generation, hydro power and energy storage. Their relatively low variable costs imply that these units will operate under regular market conditions outside the reserve. The strategic reserve will usually consist of thermal peak power plants with high variable costs and low capacity factors, facilities for which defining firm capacity is relatively straightforward. Flexible demand can also be suitable for a strategic reserve, but here the problem arises how to measure reliable demand reduction. Another advantage of procuring a smaller volume as in a strategic reserve, is that the relatively large supply of suitable capacity should increase competition in the procurement auction. In addition, the size of the reserve has little impact on the spot market since the strategic reserve is bid in at the Elspot price cap whenever activated. The rest of the market essentially functions as an energy-only market.

SvK distributes its procurement costs for the strategic reserve across market participants in a rudimentary manner. The procured reserve can easily become too large if electricity-intensive industries with political influence view reserves as a cheap insurance against outages. Hence, decisions about the reserve should be preceded by a careful evaluation of the value of such reserves. This is in line with a new EU regulation which states that TSOs can introduce reserves only if they are justifiable based on analysis of the risk of electricity shortages.⁷

5 Discussion

Sweden has better conditions than most other countries to switch to a completely fossil-free electricity supply, even given a substantial increase in demand. The reason is the large amount of hydro power that offers necessary flexibility to offset the fluctuations that occur in a system with large shares of solar and wind power. The main resource adequacy problem is not insufficient investment incentives in gas turbines or other peak-load power. Instead, the fundamental challenge is that much of the Swedish base-load production might disappear as nuclear reactors are shut down. The Energy Agreement explicitly disallows new large-scale hydro power. If the vision of 100 % renewable electricity production is to be implemented, this leaves on- and offshore wind power, solar power, bio-fueled combined heat and power and import capacity as the main sources of electricity supply. To maintain domestic security of supply, it can be necessary to complement the system by bio-fueled gas plants as backup.

For the market to function efficiently in the short run and provide correct price signals for investment, prices must be sufficiently granular across space and time that they reflect the resource constraints in the system everywhere and at all times. This property is especially important in a market with a large share of intermittent electricity generation. Partitioning the market into additional price zones, shortening delivery periods, introducing an auction-based intraday market and bidding capacity reserves into the market at the price cap will improve the functioning of the market and stimulate investment in flexible generation capacity, flexible demand and energy storage. Improved market integration and more efficient pricing of greenhouse gas emissions will facilitate the energy transition.

Critical issues concern the future of nuclear power given its significance for Swedish energy supply. Capacity upgrades will mostly depend on whether expected electricity prices will be high enough to warrant investments within the framework of the remaining life-time of the remaining facilities. The profitability of new reactors on market terms is questionable. The latest generation of reactors is currently under construction at Hinkley Point in southern England. These investments are undertaken with a guaranteed price floor of 89.5 GBP/MWh. Average electricity prices in Europe are well below this level. New nuclear reactors would therefore require a targeted support system to be profitable under current market conditions. Despite the economic and political uncertainty surrounding nuclear power, this energy source may nevertheless form an important part of electricity supply even in the future if Sweden can import base-load nuclear power from surrounding countries. Exploiting differences in the

⁷ See Holmberg and Tangerås (2021) for a more detailed discussion of capacity mechanisms.

technology mix across countries has historically been an important source of gains from trade and a major driver of market integration.

Inflexible demand that does not respond to short-term price changes or resource scarcity is the fundamental problem that leads to inefficient prices and reliability problems. In a future electricity market with flexible demand, consumption will automatically be disconnected at prices chosen by consumers. The associated price sensitivity in demand increases the possibility of balancing consumption and production in the short term. Increased reliability of the electricity system reduces the risk of curtailment and the need for capacity mechanisms. Focus can then shift towards improving efficiency in the day-ahead and balancing markets to increase the short-term and long-term efficiency of electricity supply.

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