Wind power and the Swedish electricity market

An analysis of the impact of wind power production on wholesale electricity prices in bidding area SE3

Tapiwa Kachinda-Hofisi

Södertörn University | School of Social Sciences

Master's dissertation 30 credits

Economics | Fall semester 2020

SÖDERTÖRN UNIVERSITY | STOCKHOLM
sh.se

Abstract

Wind power has been growing rapidly in Sweden over the past decade as the country focuses on 100% renewable energy by 2040. The thesis seeks to investigate if increased wind power has had a dampening effect on the hourly day-ahead spot prices in Sweden's bidding area SE3. An empirical approach is undertaken to estimate the impact that wind power has had on prices. Hourly spot prices for bidding area SE3 for the years 2016-2019 are analysed using a multivariate regression method. Other important variables like hydropower and nuclear production which are very significant in the Swedish electricity market are controlled for in the study. The results confirm that in the period 2016-2019, bidding SE3 experienced a merit order effect on price caused by increased wind power. The study shows that a 1% increase in wind power production is estimated to have decreased SE3 hourly spot prices by between 0.0268% and 0.059% between 2016 and 2019.

Keywords: Bidding area, merit order effect, hourly spot price, wind production

Acknowledgements

I would like to thank my family and friends who have encouraged me through this journey and given me the courage and hope to keep going. Special thanks to all Professors and staff in the department of Economics for all their support and guidance.

Table of Contents

1. Introduction 5

1.1 Scope and delimitation of the study 6

2. Background and Theory 8

2.1 The Electricity market 8

2.2 Sources of electricity generation 8

2.3 Significance of non-intermittent sources 10

2.4 Electricity trade 11

2.4 .1 Day-ahead market 11

2.4.2 Intraday market 12

2.4.3 Balancing market 12

2.4.4 Futures market 12

3. Theory of the Merit order effect 13

3.1 Bidding areas 13

3.2 Bidding area SE3 16

3.3 The Merit order curve 17

3.4 Demand 18

3.5 The Merit order effect 19

4. Previous Studies 21

5. Method and Data 24

5.1 Regression model 24

5.2 Model specification 27

5.3 Descriptive statistics 28

5.4 Empirical Results 33

5.5 Results and analysis 34

6. Conclusion 38

References 40

Appendix 44

1. Introduction

The world has increasingly become aware of the problematic effects of fossil energy on the climate as well as on human life with calls for the reduction in Green House Gas (GHG) emissions and use of cleaner and more sustainable sources of energy. As governments aim to meet clean energy goals and meet GHG emissions targets, there has been massive support in the form of subsidies and other support programmes for the expansion of cleaner energy sources like wind and solar, more so in electricity generation. In Sweden, an Electricity Certificate System has been adopted, which encourages the production of electricity from cleaner sources. Since 2012 this system has greatly contributed to the expansion of cleaner energy like wind and solar power and allowed Sweden to meet its renewable energy development target a decade ahead of the set deadline (Swedish Wind Energy Association,2020).

While hydropower and nuclear power account for a combined total of more than 75 percent of the total electricity produced in Sweden annually, variable renewable energy (VRE) sources like wind and solar have proven to be not only cleaner alternatives but also more sustainable in electricity generation. In the past decade alone, the share of VRE in electricity generation in Sweden has more than doubled. Wind power accounted for more 10 percent of the total electricity generated in 2015 for example, compared to just 5 percent in 2012 and 2.4 percent in 2010 (Swedish Energy Agency,2020)

This increase in the share of wind power in electricity production has led to a number of problems in electricity markets. Wind power production is intermittent as electricity can only be produced when the wind is blowing, and because of the complexities associated with storing electricity, wind power-generated electricity must be consumed at the time of production. When wind speeds are high, consequently, large amounts of wind power are introduced into the grid, displacing other generation sources on the market and depressing electricity prices on the wholesale spot market. This phenomenon is referred to as the *merit-order effect*, Ketterer (2012). According to Hirth (2016), the biggest driver of price reduction in the German and Swedish electricity markets has been the investment in variable renewable energy. Clo, Cataldi, and Zoppoli,2015 also purport that the high levels of wind and solar penetration have contributed significantly to changes in wholesale electricity prices and also led to changes in the electricity mix. In the presence of large amounts of wind power, other generation sources like gas turbines are forced to operate inefficiently and unprofitably due to low spot prices that are often below their marginal operational costs (Hildmann, Ulbig and Andersson,2013).

One of the characteristics of the electricity market is that it has to be in equilibrium at all times and due to the variability of wind power, reliance on wind power provides uncertainties in the market. It is therefore important that in instances of increased demand which cannot be met by wind power other generation sources be available to close the supply-demand gap. On the Swedish market, hydropower and nuclear power offer the greatest flexibility in response to such cases. Other generation sources like gas turbines have less flexibility and hence are pushed further out of the merit order and forced to sell expensively produced electricity at low spot prices set by VRE sources. The increase in the share of wind energy on the grid and its variability means there are undeniable repercussions on wholesale electricity prices as well as how other generation sources operate.

1.1 Scope and delimitation of the study

Several scholars have investigated the effect that increased wind production has had on the electricity market. However, the Swedish market has received very few analyses hence there exists a gap in knowledge given the transformation that Sweden has undergone in increasing renewable energy and specifically wind power on its electricity market. The purpose of this thesis is to investigate the impact that the increased share of wind power has had on hourly wholesale spot prices (the merit order effect) in bidding area SE3 during the period 2016 to 2019. The study, therefore, seeks to answer the question: "*has the increased wind power production caused a decrease in hourly wholesale electricity spot prices in bidding area SE3 of the Swedish electricity market between 2016 and 2019?*

In order to manage grid congestion, market splitting measures were taken in 2011and the Swedish market was divided into four bidding areas: SE 1(Lulea), SE2 (Sundsvall), SE3(Stockholm), and SE4(Malmo). The study is delimited to the bidding area SE3 which encompasses cities like Stockholm and Gothenburg. Although bidding area SE3 does not produce the highest total wind power in Sweden, the bidding area also has the highest level of electricity consumption compared to other bidding areas and is the only bidding area in Sweden that produces electricity from all generation sources available in Sweden. The mix of generation sources in bidding area SE3 makes it an interesting study as this paper will seek to empirically test whether this will impact the results as compared to previous studies. The high levels of consumption in bidding area SE3 vis a vis the levels of production also provide for the aspect of electricity trade with other bidding areas, which is also an important aspect that this paper will take into consideration when investigating the price-electricity production relationship.

Hourly spot price data for SE3 from 2016 to 2019 are chosen as they are not only readily available but because they are more recent and relevant given the low level of study on the merit order effect subject in Sweden. Hourly pot prices from the day-ahead Nord pool market are analysed over the period 2016-2019. According to Klevnäs, Hansen and Danielson (2016), average hourly spot prices in Sweden fell by 40 percent since 2013. The largest price drop occurred in 2016 occurred in comparison to the previous year hence 2016 is chosen as the starting year for the study. Figure 1 shows the average daily spot prices for Sweden between 2013 and 2019. A general decrease is noted in the average prices in 2013 and the average prices in 2019. Spikes in the price are noted toward the end of 2016 as well as early 2018 with average prices going as high as approximately 820 SEK/MWh and 950 SEK/MWh.

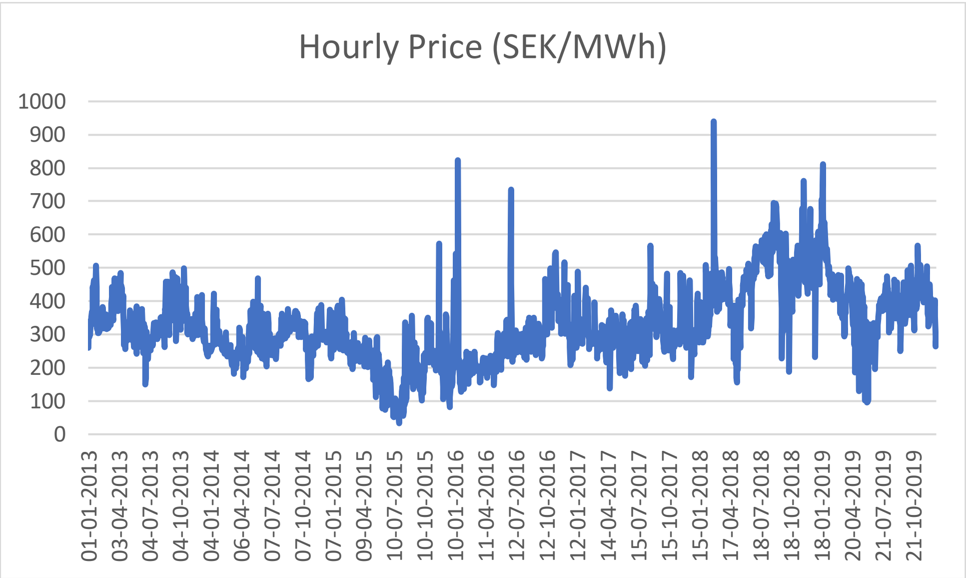


Figure 1*:* Daily spot prices 2013-2019

Source: Own depiction (Data from Nord Pool)

This study will take an estimated multivariate regression approach to investigate the merit order effect. Wind power will be the major explanatory variable with the hourly spot price being the dependant variable. The results show evidence of a merit order effect on hourly wholesale day-ahead spot prices between 2016 and 2019.

The paper is thus organized as follows: chapter 2 will introduce and give a detailed background of the theory upon which the thesis is based. In chapter 3, the merit order curve and merit order effect are detailed while chapter 4 discusses previous relevant studies and the major findings of the studies. Chapter 5 introduces the empirical model and details the model specification while a detailed description and outline of the data is also provided. Results and an analysis of the findings are presented in chapter 5 while chapter 6 concludes the paper with a summary and recommendations.

2. Background

2.1 The Electricity Market

The Swedish electricity market has undergone some transformation over the years including the deregulation of the market to encourage competition in generation and distribution of electricity, as well as the move towards renewable energy production. According to Bergman (2002), regulatory reforms within the Nordic region allowed for competition within electricity generation and retailing, and this saw the development of an integrated Nordic market (Nord Pool) of which Sweden became a part of in 1996. Nord pool is an important integrated electricity market in Europe and accounts for a high level of transmission to cater for high levels of consumption in countries like Sweden and Norway. In 2019, a total of 381.5 TWh was traded on the Nordic and Baltic day-ahead market. While the Nord pool handles the bulk of electricity trading, a small portion is also traded directly between electricity generators and electricity suppliers (Svenska kraftnät ,2020).

2.2 Sources of electricity generation

In the 1970s and going into the early 1980s, Sweden's electricity generation was reliant on biomass, coal, nuclear hydropower, and more heavily on crude oil and petroleum products. In 1981, nuclear energy production increased by close to 100 percent from the previous year and started on a steady rise on the share of the total energy produced soon overtaking crude oil and petroleum fuel as the major energy producer on the market.

However, in 1980, the nuclear referendum initiated the debate surrounding the controversy of nuclear energy and safety concerns with an agreement to halt any further nuclear power reactor licensing and that existing reactors would not operate beyond the expected lifetime of the latest (at the time) reactor set at 2010 (Nordhaus,1995). Concerns for the environment within this period also led to the consideration of energy policies. With the deregulation of the electricity market and encouragement of competition in the 1990s and the focus on the environment and climate in the early 2000s, Sweden took a step in closing two nuclear power plants. The EU initiatives for reduced carbon emissions also received cooperation from member states like Sweden in the late 2000s into the new decade (Diczfalusy,2020) With the increased drive for cleaner energy and eradication of carbon-emitting energy sources, the Swedish electricity sector has gone through a massive and impressive transformation with the share of wind power in the national grid more than doubling in the past decade. In 2003, the government introduced a policy instrument to encourage electricity production from renewable energy called the Green Certificate System. In the Government Bill 2005/06:154, the Government outlines that the Green certificate system's main aim is to promote the development and growth of renewable energy production, more so the most cost-effective production of renewable energy. This has led to increased investment in renewable energy including wind power and in 2019, wind power accounted for up to 12 percent of electricity produced in Sweden (Energiföretagen Sverige,2020).

According to The Swedish Energy Agency (2020), the 2017 share of renewable energy sources in electricity production was 58 percent and included hydropower, wind, solar, and biofuels. Installed solar capacity also significantly grew by almost 70 percent to an installed capacity of 411MW between 2017 and 2018(The Swedish Energy Agency,2020). Energiföretagen Sverige (2020) reports that the current installed capacity of hydropower is 16 200 MW with a production capacity of 65TWh in a normal year. The development of wind power generation has been incremental over the past decade. Figure 1 below shows that the installed capacity of wind has more than doubled between 2009 and 2017. The installed capacity went up to close to 7 000MW in 2000 with 18 TWh produced in 2017, a 12 percent share of total production (The Swedish Energy Agency,2020). While nuclear is not a renewable source of energy, its role in the electricity market is still significant as it caters for the country's base load. In 2017, 39 percent of total production was from nuclear energy from an installed capacity of about 9 000MW. Thermal power in Sweden which includes CHP, Industrial CHP, condensing power, and gas turbines had a total installed capacity of 8 187MW in 2017 and accounted for 15TWh of total production also in the same year.

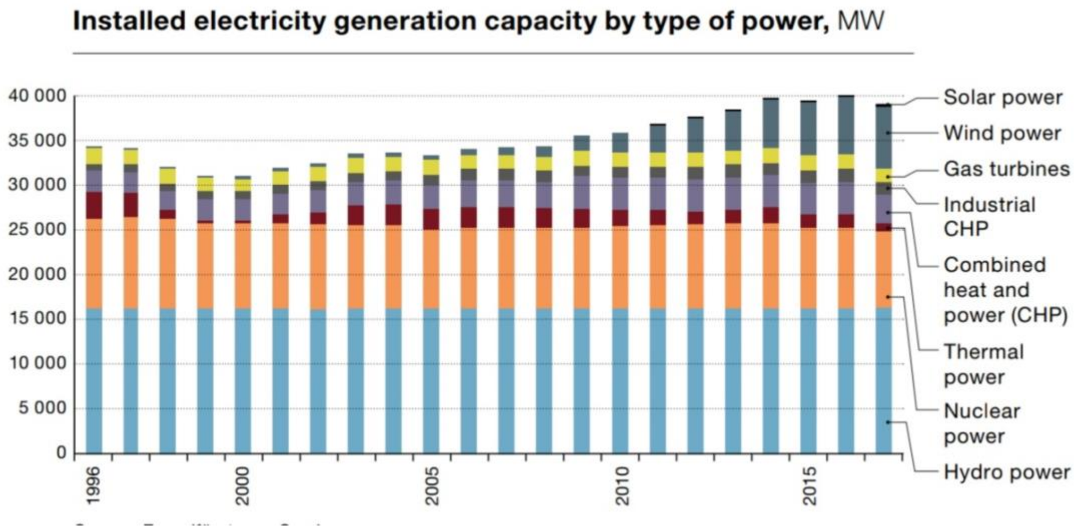


Figure2: Installed electricity generation capacity in Sweden by power source,1996-2017
Source: Energiföretagen Sverige

2.3 Significance of non-intermittent sources

Wind is intermittent and supply driven. This makes it an inconsistent source of electricity generation, one of the reasons why its rapid integration into the market has been a subject of debate. The electricity market as already mentioned, must always be in equilibrium and because wind cannot be scheduled in advance to meet anticipated or unanticipated peaks in demand, other generation sources must be immediately available to meet the residual demand (the excess demand that cannot be fulfilled by wind), setting the market to equilibrium, and ensuring power cuts or blackouts are avoided. This process of starting generation sources on command as and when needed is called ramping and has become increasingly crucial in the electricity market to mitigate the problems associated with wind power intermittency. Fast ramping requires that conventional generation sources be flexible in order to provide the needed stability on the market. However, ramping up and down is complex in most cases very costly.

In the Swedish market, hydro power is the most crucial source for flexibility due to the abundance of hydro power stations. Hydro power can also be stored as potential energy in reservoirs unlike other sources. Nuclear plants on the other hand, are so complex to run that it is equally complex and very expensive to shut them down (hence inflexible). As a result, nuclear plants run throughout regardless of whether or not their electricity is needed in the system and are used to cover base load needs. Natural gas and coal powered plants are also important in meeting residual demand as they are highly flexible. Natural gas turbines have the most flexible ramp up times and most suited to provide fast response to residual demand (Vos,2012). However, because gas turbines generate more expensive electricity, they are most often only brought online to meet residual demand which often means that they operate inefficiently.

2.4 Electricity trade

The role of the market is to establish an equilibrium between supply and demand and in the electricity market, this is crucial given the complexity of storing electricity and the costs associated with supply failure (Nord Pool). The Swedish market largely is made up of the day-ahead, intra-day, balancing market, and futures market where electricity is traded amongst actors and prices are set.

2.4.1 Day-Ahead Market

The day-ahead wholesale market will be studied in this thesis and a detailed description of how prices on this market are set is discussed and illustrated in section 3. The day-ahead market determines prices based on demand and supply and is operated by Nord Pool. On this market, market actors can submit their buy and sell bids and commitment to buy or sell 24 hours before the operating day (Nord Pool,2020). Nord Pool receives bids and offers from suppliers (electricity generating companies) and buyers (electricity distribution companies) respectively and after a market coupling system, an hourly price for each bidding area for the coming day is set and published (Nord Pool,2020). The market is based on periodic pricing and a single price is set where the "sell" and "purchase" bids intersect every hour. The day-ahead market comes up with a single, hourly market price if no congestions occur between the bidding areas otherwise each bidding area will have its own price.

2.4.2 Intraday Market

The intraday market unlike the day-ahead market works as a continuous auction settlement market (Gliniewicz,2016). On the intraday market, market actors have the opportunity to trade after the close of the day-ahead market, so as to balance their portfolios if production forecasts or loads are inaccurate (Jaraite, Kazukauskas, Brannlund, Kiran and Kristrom, 2019). When for example, wind forecasts fall short or demand changes, the intraday market would be the trading place to correct such imbalances. The intraday market is therefore a corrective market and operates on a pay-as-you bid-basis which is the major differentiating factor from the day-ahead market. The price in the intraday market is based on each completed transaction from the continuous auction. (Gliniewicz,2016, Next,2020, Nord Pool,2020) based on bilateral contracts that are negotiated off-market. This market is a short-term market in contrast to the futures market.

2.4.3 Balancing Market

Also referred to as the real-time market, this market is operated by the transmission system operator (TSO) and in the case of Sweden, Svenska kraftnät. Svenska kraftnät has the responsibility of real-time balancing of production and consumption (Jaraite et al,2019). When there is an imbalance caused by either excess or inadequate supply of power, the proponents of these imbalances are expected to pay the TSO price that is higher than the set or prevailing electricity price to make up for the excess or insufficient supply (Klevnäs et al,2016). The balancing market is especially important as it provides the grid balance which ensures that supply and demand are always at equilibrium and ensuring that there are no disturbances in transmission.

2.4.4 Futures Market

The futures market is the long-term electricity market. Trading is on the Stockholm Stock Exchange Nasdaq OMX and offers the opportunity for players in the electricity market to hedge electricity prices in the long term (Svenska kraftnät,2020). This is an especially important market because it allows players to mitigate the risk that is associated with fluctuating electricity prices over time and in the different geographical areas. According to a 2020 report by The Swedish Energy Agency, the increased penetration of wind power has led to increased decentralization of the electricity system and a need for better flexibility in ensuring that production and consumption remain in balance all the time. Since prices may differ in different bidding areas, market actors find the need to mitigate this risk and protect themselves (Energimarknadsinspektionen [Ei]2016) from low and volatile prices. Trading on the futures market provides this “protection” from profit erosion caused by mostly low and most recently negative prices on the wholesale electricity market.

3. Theory of the merit order effect

3.1 Bidding Areas

The Nord Pool market is divided into different predefined price areas commonly referred to as bidding areas which are set by the TSOs as a way of handling congestions within the grid (Nord Pool, 2020). The four bidding areas of the Swedish market are: SE 1(Lulea), SE2 (Sundsvall), SE3(Stockholm), and SE4(Malmo) and were implemented in 2011. The implementation of the bidding areas was to manage electricity transmission between regions and also to encourage the creation of generation and transmission capacity in areas that were facing electricity deficits (Hansson, Hackl, Taljegard, Brynolf and Grahn,2017). Bidding areas SE1 and SE2 characteristically produce more electricity than they consume given they have an abundance of hydropower. Bidding areas SE3 and SE4 on the other hand have higher levels of consumption than production with SE3 having 1.6 times more demand for electricity compared to SE1, SE2 and SE4 (Carvalho Figueiredo, Pereirada Silva and Cerqueira,2016). There is a significant amount of electricity flowing from bidding area SE2 to SE3 while SE3 also transmits to SE4 and Finland.

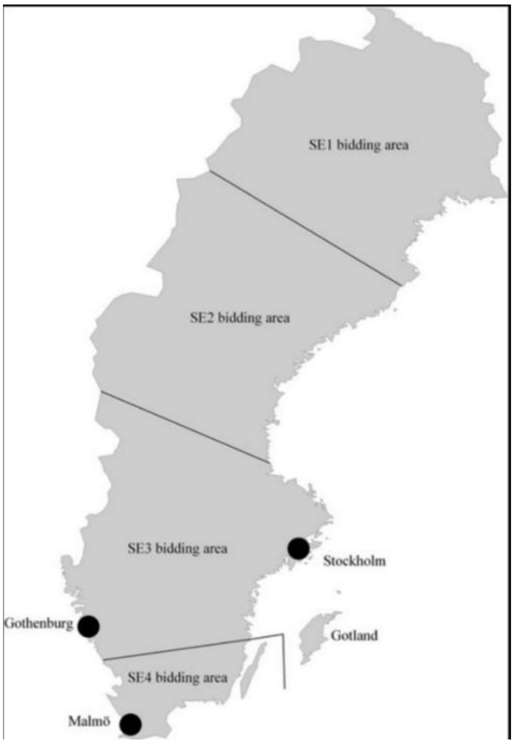


Figure 3: Sweden bidding areas

Source: Parks and Wallsten (2019)

Prices for each market are set where the supply and demand curve intersect at every hour and the clearing of the prices considers transmission capacity between the different bidding areas. Different prices can arise in bidding areas if congestion occurs and transmission capacity fails to converge prices in all the areas but if capacity limits (set by the TSOs) are met and no physical constraints exist, then prices are the same across the bidding areas (Nord Pool). When there are bottlenecks in the system, the bidding areas will have different prices. The separation of the bidding areas allows for the identification of transmission capacity constraints, this allows power to be transferred from the bidding area with the low price to the bidding area which has a higher price and more demand for power (Nord Pool Spot,2015) as illustrated in figures 3,4 and 5. Figure 3 shows the disparity in prices and demand in bidding areas A and B. The lower demand in bidding area A means suppliers have to sell at a lower price P_{A0} whereas the higher demand in bidding area B means the price is higher at P_{B0}. Suppliers in in price Area A acting rationally would want to sell their electricity in price Area B given the higher price while a rational customer in area B would want to purchase electricity in price area A because of the lower price. When a transmission capacity of 50MWis introduced and no constraints exist between the two bidding areas, this allows buyers and sellers to trade between the two bidding areas. This can be illustrated in Figure 4 as a shift of 50MW in the demand from bidding curves in both bidding areas. In bidding are A, the demand curve shifts outward to the right and in area B downwards to the left with price in area A moving up from P_{A0} to P_{A50} and down from P_{B0} to P_{B50} in area B. When full capacity transmission is allowed (and there are no constraints) between the bidding areas as illustrated in Figure 5 (at level 100MW), this allows prices to equate in both bidding areas.

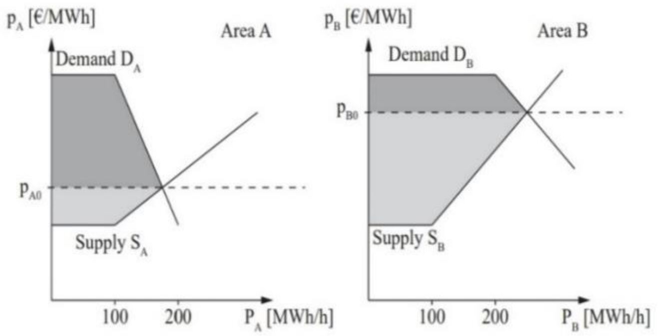


Figure 4: Bidding area price setting

Source: Gliniewicz,2016

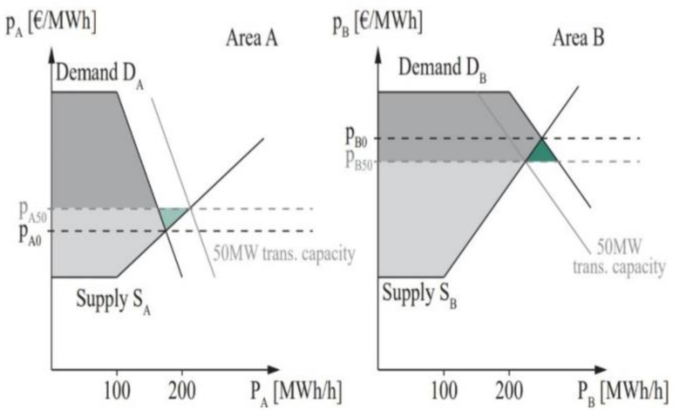


Figure 5: Bidding area price setting with partial transmission capacity

Source: Gliniewicz,2016

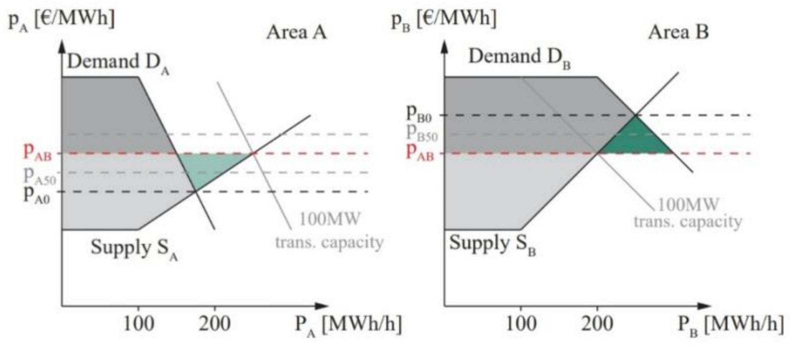


Figure 6: Bidding area price setting with full transmission capacity

Source: Gliniewicz,2016

3.2 Bidding area SE3

Bidding area SE3 is one of the price areas of the Swedish electricity market that includes the Stockholm Metropolitan region as well as the city of Gothenburg. Figure 7 shows the generation mix for each bidding area of Sweden. Bidding area SE3's total generation is largely comprised of nuclear power. This is because all of Sweden's nuclear capacity is exclusively produced in bidding area SE3. The bidding area's generation mix also comprises of hydropower, thermal and wind power. Bidding area SE3 has a high consumption level compared to both northern bidding areas SE1 and SE2 as well as SE4. Since the consumption levels in bidding are SE3 are higher than the production levels, there is a lot of transmission from surplus bidding areas into the SE3 area while transmission also flows out of SE3 to SE4 and Finland although import transmission numbers are much less than export transmission.

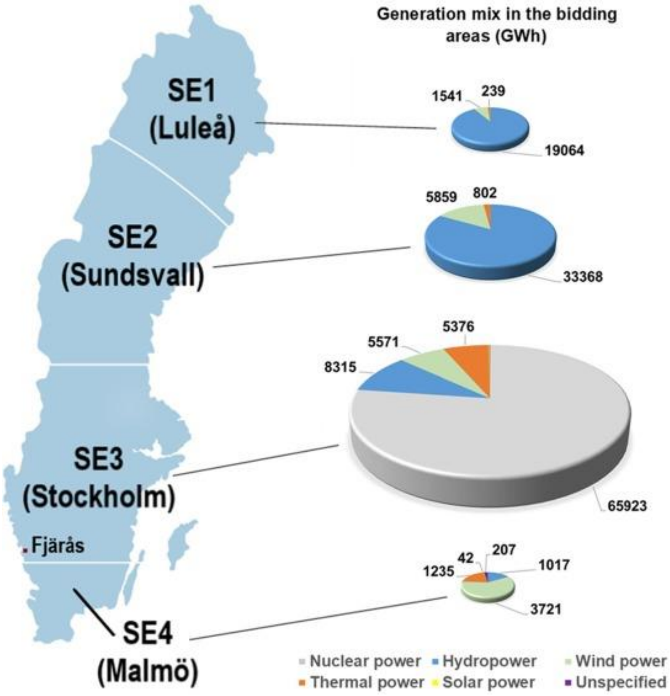


Figure 7: Electricity generation mix by bidding area.

Source: Papageorgiou, Ashok, Farzad and Sundberg (2020)

3.3 The merit order curve

As with the supply curves of most commodities, the supply curve for electricity is upward sloping. It is referred to as the merit order curve and is characterised by a “stacked” curve as illustrated in Figure 6. The merit order in electricity markets refers to the order or sequence in which available generation sources are brought online to meet electricity demand. The goal of merit ordering is to optimize electricity supply and the ordering may be based on (in ascending order) marginal costs or variable costs of production, levels of pollution and or the amount of electricity that will be generated. For the purposes of this thesis, the merit order will refer to ordering based on marginal or variable costs of production. The allocation or merit order sequence entails that generating sources that produce electricity at the lowest marginal cost are brought online first and those with higher marginal costs are subsequently added until demand is met (Next Kraftwerke,n.d) and this is done so as to minimize the costs of generating electricity. Higher marginal cost generation sources are brought online during periods of high demand and in such instances, this usually occurs out of merit order. In figure 6, wind and nuclear (as well as hydro power in the case of Sweden) are dispatched first while CHP, condensing plants and gas turbines follow, respectively. The generation sources at the lower end of the merit order are dispatched to meet the base load or continuous demand while those further up the curve are usually dispatched in high demand periods to meet the residual demand. Another important factor to note is the role of imports and exports in the total supply of electricity. Any excess generated electricity on the national grid where transmission capacity allows is exported to neighbouring countries and Sweden most often has more exports than imports annually.

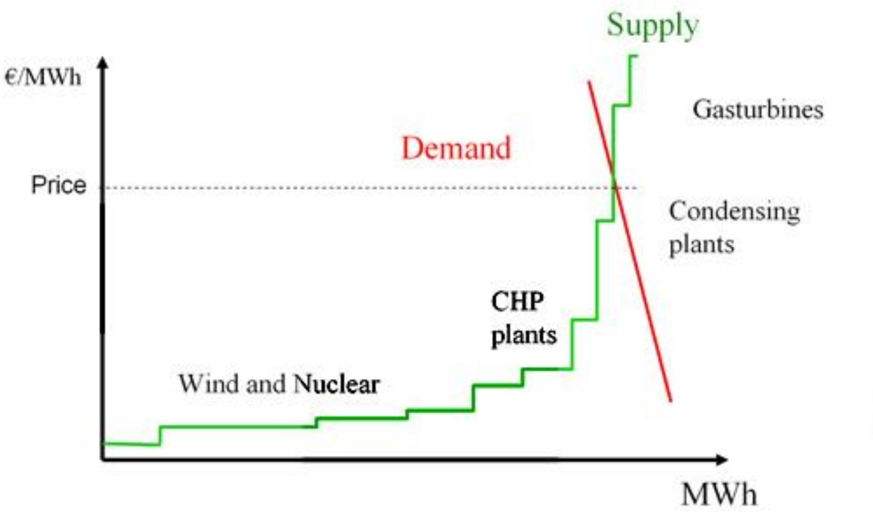


Figure 7: The merit order curve

Source: Risø DTU

Suppliers of power from wind turbines and photovoltaic installations do not need to use any fuel and have very little to need for labour and therefore they have almost zero operating costs. However, they trade their electricity in the day-ahead market together with suppliers of other generation technologies (Jaraite et al, 2019). Introducing renewable sources like wind and solar into the merit order means that conventional generation sources moved further up the merit order curve. In periods of very high wind speeds, the merit order curve shifts to the right further displacing conventional sources out of the merit order.

3.4 Demand

The electricity demand curve is also referred to as the load (summing up the total demand in the market at any given time). The demand for electricity is generally described as price-inelastic in the short run. This is largely because electricity does not have any close substitutes. The demand curve for electricity is characteristically download sloping with a very steep gradient due to the price insensitivity.

The base load largely consists of autonomous demand for electricity and this is highly inflexible and requires that electricity must be running at all times to meet this demand (Nicolosi,2010). Shifts in the electricity demand curve are largely driven by factors such as time of the day, day of the week as well as season. In Sweden for example, the demand for electricity significantly increases in the winter as the need for heating increases. Demand for electricity also tends to be higher during the day going into the evenings and much lower at night. These fluctuations in demand tend to shift the demand curve. Since the price is set where the demand and supply curves intersect, the continuously shifting demand curve causes fluctuations in price throughout the day. On the Nord Pool market these prices are set every hour. Figure 7 below shows fluctuations in the hourly load and price for bidding area SE3 between 1st January 2016 and 7th January 2016. The fluctuations of hourly and load and hourly price depicted in the graph show a positive relationship. Hours with high load coincide with high spot prices, for example, the highest load recorded between 7th January and 9th January also coincides with the highest spot prices recorded.

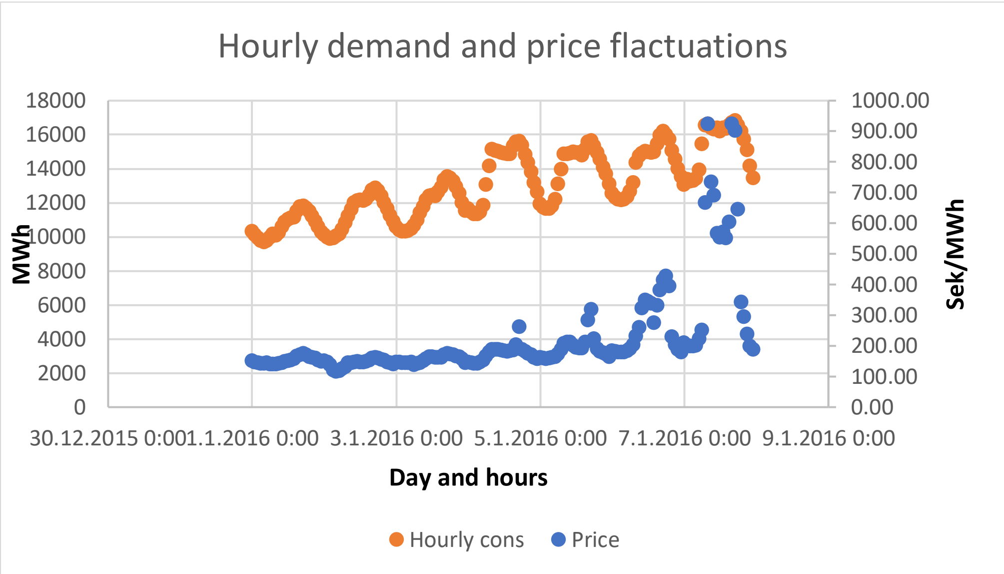


Figure 8: Hourly spot price and consumption fluctuations (Week 1 2016)

Source: Own illustration (data from Nord Pool)

3.5 The merit order effect

During high wind periods, more wind power is injected into the grid and as shown in Figure 8, the merit order curve is shifted to the right. Prices are depressed downwards from Price A to Price B and other generation technologies are pushed toward the end of the merit order curve which is referred to as the merit order effect. When periods of high VRE coincide with peak load periods (common with solar), conventional generation technologies are left to meet even lower residual demand, not covered by VRE, and because high levels of VRE reduce spot prices, conventional electricity generators have to endure profit cuts or simply lose money by selling expensively produced electricity at very low prices.

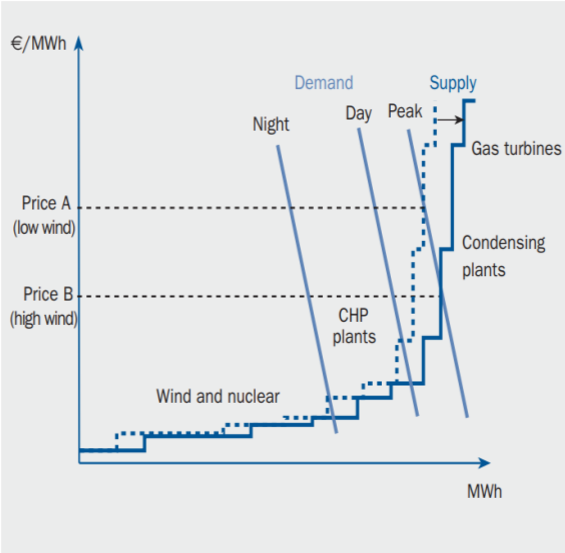


Figure 9: Merit order effect on the price at low and high wind levels

Source: Morthorst and Awerbuch (2009)

Periods of high wind do not often coincide with peak load periods and in such instances, the generation sources that are up in the merit order curve are brought online to meet the higher demand and this pushes up the price. The merit order effect poses problems for the market in many ways. The intermittency of wind power means that other generation technologies have to increase the flexibility of their ramping capacity to meet demand during no wind periods. Operating costs for these other generation technologies are relatively high and increasing flexibility may add to those already high costs which may consequently be passed down to end consumers in the form of higher electricity retail prices. The increased injection of VRE has meant that, in hours with high wind, the grid experiences asymmetrical bouts of electricity which must be disposed of quickly and this leads to negative prices. Negative prices have been recorded in Germany in hours of high combined wind and solar power share in the instantaneous electricity mix. In April 2020, the European market recorded six straight weeks of negative prices, with Germany reaching a low of -€44.25/MWh (Montel News, 2020). In Denmark, the bidding area DK1 experienced negative prices for the first time in

December 2012. The price fell to -€7.40/MWh and this was caused by low demand, strong wind generation and co-generation on a particularly cold day. Sweden and Finland both recorded negative prices for four consecutive hours in February 2020 on the back of strong winds. When the system experiences negative prices, this implies that convention power producers (e,g gas turbines and coal) experience loss in profits or money as they have to keep their generating units running due to complexities and costs associated with ramping off.

4. Previous Studies

Several simulation-based and econometric model-based studies have been undertaken in recent years, to investigate the impact that VRE production has had and continues to have on electricity markets and prices. The findings have been varied from study to study and market to market. Table 1 summarises some notable empirical and simulation studies on the merit order effect in various markets. The studies and findings will be discussed in more detail within this section.

Table 1: Previous studies and findings

Author(s)	Study Objectives	Years of study and country	Methodology	Findings
Clò et al,2015	The merit order effect on the Italian wholesale electricity market	2005-2013, Italy	Multivariate regression	An increase of 1GWh of average hourly wind and solar production decreases prices by €4.2/MWh and €2.3/MWh respectively
Gelabert et al,2011	The effect of renewable energy on wholesale electricity prices	2005-2009, Spain	Multivariate regression	1GWh increase in renewable energy production leads to a decrease in wholesale prices of about €1.9/MWh
Wurzburg et al,2013	The price effect of renewable energy production	2010-2012, Austria and Germany	Multivariate regression	A price decrease of €1/MWh for every 1GWh of increased wind production
Hu et al,2010	The relationship between wind production and wholesale electricity price	2004-2008, Denmark	Statistical methods	Increased wind penetration reduces the spot price as well as the regulation up and down prices

Ketterer,2012	The relationship between intermittent wind power and electricity prices	2006-2012, Germany	GARCH model	Increased wind power production reduces electricity prices over time but also increase price volatility
Brancucci Martinez-Anido et al ,2016	The impact of wind power on electricity prices	2010, New England, USA	ISO production cost model	Electricity prices decrease with increased wind power penetration
Nieuwenhout and Brand (2011)	The influence of wind power on day ahead prices	2006, The Netherlands	Empirical forecasting	Price reduced by 5% With price depression continuing but at a slower rate in the future
Sensfuß et al. 2008	The merit order effect of renewable energy production on spot prices	2001, 2004-2006, Germany	Simulation (PowerAce Model)	Price decrease of between €1.70 and €7.83 in the years 2001,2004-2006
Woo et al,2011	The impact of increasing wind power on prices,	Texas (USA) 2007-2010	Multivariate regression	1% increase in wind reduces price by 0.2% - 0.9% in different bidding areas

Using a multivariate regression, Gelabert et al (2011) study the Spanish wholesale electricity market to estimate and how hourly spot prices have been affected by subsidized renewable energy and cogeneration. They use daily average hourly spot data from hourly prices so as to reduce unwanted noise, and using OLS, they estimate the regression models. They model average daily prices using daily total demand, daily renewable energy production, daily hydro production as well as daily production from nuclear, combined cycle, fuel and natural gas plants and they include: daily, monthly, and yearly dummies to account for seasonality. Their results show that a 1GWh marginal increase in wind power production led to a decrease of about €4.2/MWh for the period 2005 to 2010.

Texas is an especially interesting market to study given that it is a deregulated market that has seen an increase in the penetration of renewables and the high levels of consumption and according to Whiting (2020), is the world's fifth-largest wind-energy producer. Woo, Horowitz, Moore, and Pacheco (2011) studied the four bidding areas of Texas' wholesale electricity market Electric Reliability Council of Texas (ERCOT). They use partialadjustment linear regression to estimate the electricity spot prices in ERCOT's four bidding areas. They use historical 15- minute spot price data from all four price areas of ERCOT (for the period 2007 to 2010) as the explanatory variable in their regression model. The model also includes hourly, daily, and monthly dummies to control for seasonality. Their model 's explanatory variables are 15 -minute wind, load and nuclear production. The fourth explanatory variable is the natural gas price, and they use daily price data. According to their findings, a 100 MWh increase in wind production led to a decrease of $0.39/MWh in the Houston bidding area, $0.61 /MWh in the North bidding area, $0.32/MWh in the South bidding area, and $1.53/MWh in the West bidding area.

Nieuwenhout and Brand (2011) found that, although wind power only constitutes 4 percent of power in The Netherlands, it depresses the average day-ahead electricity price by about 5%. They use a meteorological model and time series of hourly day-ahead wind forecasts and compare this to APX-ENDEX spot market prices for the years 2006 to 2009 to assess how increasing levels of wind power affected spot prices in The Netherlands. APX-ENDEX operates the electricity spot markets for The Netherlands, Belgium, and the United Kingdom (at the time of the study). They use hourly wind prognosis in the day-ahead market as this is known when the day-ahead market closes. They find that the increase in wind power indeed depressed electricity prices and that the impact of future additional wind power would reduce in every future year. An increase in wind power production level from 2 200MW to 6 000MW reduced the spot price by 3 Euro/MWh equivalent to 6 percent of electricity prices. They also found that a 30 percent increase in wind capacity (which translates to 3541 MW), decreased prices (in 2016) by 1.73 Euro/MWh or 3 % and that when only wind capacity increased and other conventional sources remained unchanged, a decrease of 2.73 Euro/MWh (5%) would be expected.

Traeber & Kemfert (2011) study the merit order effect that increasing wind power has on wholesale market prices and CO_2 emissions using a simulation model (ESYMMETRY). Their results for the period 2007-2008 showed that, an increase in wind power production by 1GWh led to a decrease in price of 0.3 Euro cents/MWh and also that a third of conventional power units' production was crowded out or pushed out of the merit order for every unit of wind power. They also reported that, increasing the total wind power production double-fold only reduced prices by one-third of a cent, a relatively small impact with the biggest impact of increased wind power production found in the reduction of carbon dioxide. They further report that increased wind power generation actually reduces the extent of the merit order effect over time.

The studies on merit order effect discussed in this section while reaching the general conclusion that renewables have caused the merit order effect in various markets also leave room for debate as other scholars have found evidence of price decreases caused by factors other than VRE. Variables such as demand and fossil prices for electricity for example were found to also have some bearing on the decrease in wholesale prices, as reported by Swinand and O'Mahoney (2015). Hirth (2016) finds that, between 2008 and 2015 the Swedish wholesale electricity market experienced three major shocks that led to the price decrease: increased renewable energy production, increased hydroelectricity due to a wet season in 2015 as well as the decline in end-user demand for electricity. According to Cutler, Boerema, MacGill and Outhred, (2011), although wind penetration has an inverse relationship with prices, electricity demand is the main driver of electricity prices in South Australia. Nilsson (2020) raises a question around the empirical studies. He is of the notion that the empirical studies discussed capture the factual aspect of the variables included in the studies by making use of actual market data, but they also miss variables like investment in VRE which is an important aspect when discussing the impact that VRE has on wholesale electricity markets. He also points to the issue of over capacity in electricity markets which he says may be the reason for decreasing electricity prices.

5. Method and Data

5.1 Regression Model

The study will take a reduced form approach and follows the model applied by Wurzburg et al (2013) They take a multivariate approach with the hourly spot price being the dependent and endogenous variable. Wurzburg et al (2013) use hourly day ahead price data from the wholesale electricity market for Austria and Germany for the period 1st July 2010 to 30th June 2013. However, they convert all hourly data for the study period to daily average data so as to reduce unwanted noise. In this study, I use hourly spot price data for bidding area SE3 (SEK/MW/h) collected from Nord pool as the dependent variable in my empirical model to give a more concise result that captures the activity on the market on an hourly basis, given that prices are set every hour on the wholesale market. The use of the day-ahead hourly spot price from Nord Pool also allows for the elimination of measurement error in the dependant variable as actual prices are used in the study (Mauritzen,2011).

The general form of a multivariate regression can be presented as:

$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_p X_{ip} + \varepsilon_i \text{ where i = 1,2……. n} \qquad (1)$$

The model assumption is that hourly spot prices are a function of demand and supply and to capture these aspects, hourly consumption prognosis (demand) is the demand side explanatory variable while hourly wind production, hourly hydro power production, hourly nuclear production, hourly thermal production and hourly net imports and exports are the supply side explanatory variables. Wurzburg et al (2013) similarly assume that hourly spot prices can be explained by hourly wind production, hourly load (consumption), price of gas and net import and exports of electricity. Unlike Wurzburg et al (2013) the paper does not include the price of gas as an explanatory variable due to the unavailability of the data and because gas turbines in Sweden are used for district heating and only used for electricity production in very rare situations of disruption in production.

As mentioned, this study uses hourly wholesale spot prices from Nord Pool as the independent variable. Hourly spot prices for bidding area SE3 are collected for the period 1st January 2016 to 31st December 2019 and are presented and measured in SEK/MWh. A total of 35 064 observations are made. The major explanatory variable for the study is wind power production between 1st January 2016 and 31st December 2019. Hourly wind production data for bidding area SE3 is collected from Svenska Krafnat and 35 064 total observations are made and presented in MWh.

Demand is an important component in the formation of prices given that prices are set where the demand and supply curves intersect. Demand levels are highly associated with weather conditions, time of day as well as day of the week. In lower temperatures, the demand for electricity is expected to go up as consumers use more heating. Industrial demand for electricity in bidding SE3 is also very high, hence it is particularly interesting to study to what extent these characteristics of electricity demand affect the hourly price. Consumption prognosis will be used as a proxy for demand and the data is collected hourly for the period 1st 2016 to 31st December 2019. A total of 35 064 observations are made for this period and data is collected from Svesnak Krafnat and presented in MWh.

Hydropower is an important production source on the Swedish electricity market and remains very crucial for ramping in hours of no wind production. Hydropower is also associated with low variable costs of generation and tends to also impact the merit order although not in an uncertain or highly variable way as wind does (Brancucci Martinez-Anido et al,2016) hence it is important to include this as an explanatory variable in the model. As such, the model also includes bidding area SE3 's hydropower production between 2016 and 2019 which is collected on an hourly basis with 35 064 observations made and presented in MWh. Hydropower is expected to have a negative relationship with price in this model. Hydro plants are normally brought online during hours of low wind to meet demand but still enter the merit order at a low cost and therefore would still displace higher order sources like gas turbines and CHP plants that would only be brought online to fulfil residual demand.
As earlier mentioned, the assumption made is that the hourly spot price for bidding area SE3 between 2016 and 2019 is also dependent on nuclear production, thermal production as well as imports and exports. Nuclear energy in Sweden continues to contribute a very notable amount of electricity on the Swedish electricity market. It is also important in meeting the base load due to the fact that nuclear stations operate for the majority of the year regardless of the wind production situation. Thermal on the other hand is also important as it is introduced to the grid in hours of high demand and low wind. Both nuclear and thermal production are, therefore, important to include in the model as they are expected to contribute the response of hourly spot prices. Consequently, hourly nuclear and thermal production for bidding are SE3 are collected form Svenska Krafnat and a total of 35 064 observations are made respectively for the period between 1st January 2016 and 31st December 2019. Both variables are presented in MWh. Bidding area SE3 experiences a lot of electricity trade given the good transmission capacity with other bidding areas in Sweden and the Nordic countries. Bidding area SE3 has very high levels of consumption and is also the only bidding area in Sweden producing electricity from nuclear energy which is a vital part of meeting the base load for the Swedish electricity market. As a result, imports to and exports out of bidding area SE3 are in this model assumed to have an effect on hourly spot prices. Hourly net import and export data for bidding area SE3 is collected from Svenska Krafnat with a total of 35 064 observations between 2016 and 2019 and is presented in MWh. Table 2 below summarises the expected result for each variable's relationship with hourly electricity spot price.

Table 2: Expected coefficient results

Variable	**Expected coefficient result**
Demand	Positive
Wind production	Negative
Hydro production	Negative
Thermal production	Positive
Nuclear production	Negative
Net import/export	Negative

5.2 Model specification

The multivariate model estimated in this paper is inspired by Wurzburg et al (2013) and will be separated into 4 models, one for each year of study.

The assumption of no perfect multicollinearity between the independent variables must hold so as to preserve the predictability of the model regression results. To assess the suitability of the chosen variables for the model, a correlation analysis is run. The correlation matrix for all variables in presented in Table 8 in the Appendix. As shown in Table 8, some correlation exists between some variables, these should not prove to be problematic for the model. According to Kutner, Nachtsheim, Neter, and Li (2004), although correlations may exist between variables, this will generally not affect inferences of mean responses or new predictions. A log-log model with the natural logarithm of the hourly spot prices and all explanatory variables will be used. The exception is made for the variable net import/export which has some negative values in the observed data. To address seasonality which is a very important factor in electricity price behaviour, daily and monthly dummy variables will be included in the model.

The regression model is therefore estimated:

$$\ln(P_t) = \beta_0 + \beta_1 ln(D_t) + \beta_2 ln(W_t) + \beta_3 \ln(H_t) + \beta_4 ln(T_t) + \beta_5 \ln(N_t) + \beta_6 IE_t + \sum_{i=1}^{6} \beta_{i+6} dd_{i,t} + \sum_{j=1}^{11} \beta_{j+12} dm_{j,t} + \varepsilon_t \quad (2)$$

Where:

$P_t = hourly\ electricity\ price$

D_t= Hourly consumption

W_t = hourly wind production

H_t= hourly hydro production

T_t= hourly thermal production

N_t= hourly nuclear production

IE_t= hourly net import/export

$d_{i,t}$= daily dummy

$m_{j,t}$= monthly dummy

ε_t= error term

t=1,2…..n = time dimension

Four separate regressions following equation 2 will be run, one for each year of study. Running four regressions will allow the model to capture the yearly variations in the spot prices and all variables of the model. The coefficients will be estimated using ordinary least squares and heteroskedasticity-robust standard errors are also used in all four regressions. Dummy variables are included in the model to control for the variations in weekdays and weekends as well as the different months.

5.3 Descriptive statistics

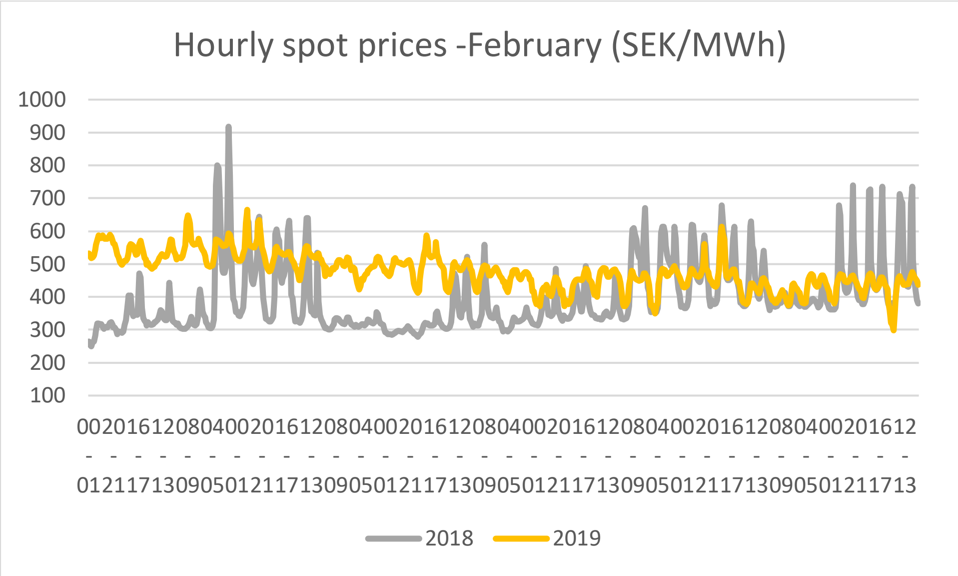
Table 3 below shows mean and standard deviation data for all hourly variables in bidding area SE3 for each year of study. From the data, one can note an increase in the mean of hourly spot price between 2016 and 2017 and an even more significant increase between 2017 and 2018. According to Klevnas et al (2016), average day ahead electricity prices in Sweden have fallen by about 40 percent since 2013 with the largest drop observed in 2016. From Table 3 below, 2016 shows relatively low average spot prices compared to all other year. Between 2017 and 2018, the average hourly spot price increased significantly and an increase in average hourly demand is also observed. 2018 was a relatively dry year and reservoir levels were lower than average. According to European Commission (2018), the lower hydro reservoirs contributed to the spike in hourly spot prices as while wind production was unable to make up for the decreased supply from reduced hydro reservoirs. Average spot prices show a decrease in 2019 and this can be due to decrease in demand during this year which was a year in which Sweden also experienced good levels of wind as well as increased capacity building within the electricity sector that saw the increase of wind turbines installed (European Commission,2019).

Table 3: Descriptive statistics (Standard Deviation and *Mean)

Hourly Variable	**2016**	**2017**	**2018**	**2019**
Spot price (SEK/MW)	119.23 (277.75)	76.36 (300.90)	126.84 (457.79)	107.00 (405.49)
Consumption prognosis (MWh)	2 303 (9 939)	2 137 (9 983)	2 342 (10 035)	2181 (9 850)
Hydro (MWh)	380 (1 054)	339 (984)	478 (949)	356 (1 173)
Wind (MWh)	461 (633)	464 (692)	491 (636)	552 (789)
Thermal (MWh)	337 (545)	323 (623)	365 (614)	378 (653)
Nuclear (MWh)	1 326 (6 908)	1 771 (7 202)	1 100 (7 525)	4 986 (7 361)
Net import/export (MWh)	1 476 (605)	1536 (161)	1570 (-48)	1541 (209)
Observations	8 784	8 760	8760	8 760

Mean in parentheses.

Hourly prices are highly variable as they are dependent on various factors like demand. One thing affecting the demand level for electricity is seasonal variations. In colder seasons, there tends to be a higher demand for electricity as more heating is used while warmer seasons tend to have lower demand for electricity. Figure 10 shows the variations in hourly spot prices in a week during the coldest month (February) and a week in the warmest month (July). Generally, higher spot prices are observed in the colder month compared to the warmer month in both 2018 and 2019. 2018 also shows higher levels of prices compare to 2019 both in the winter and summer.



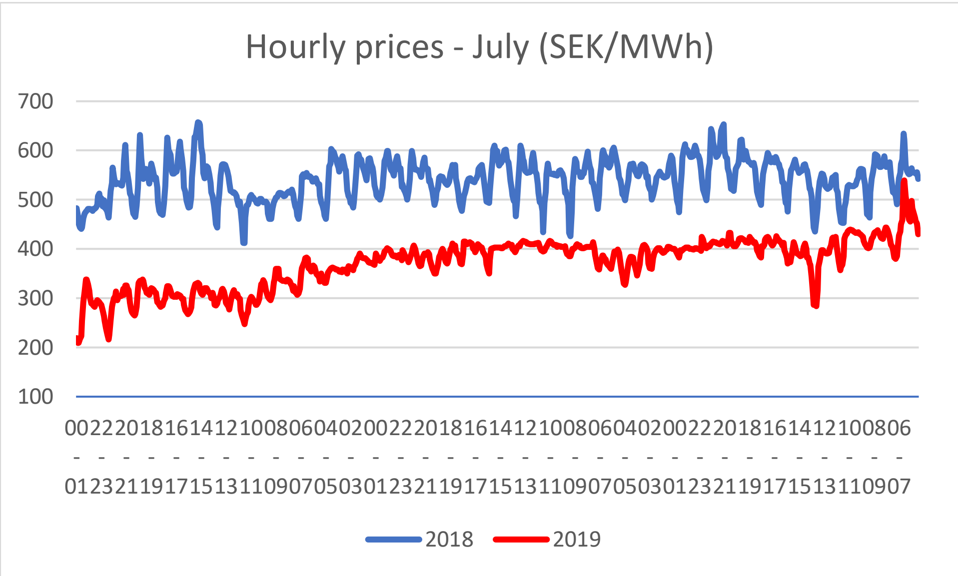
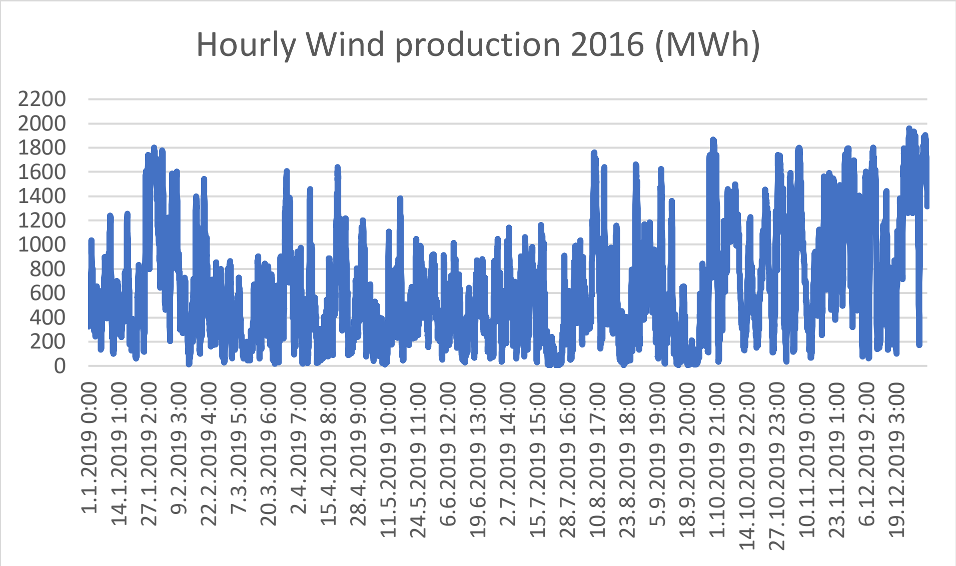
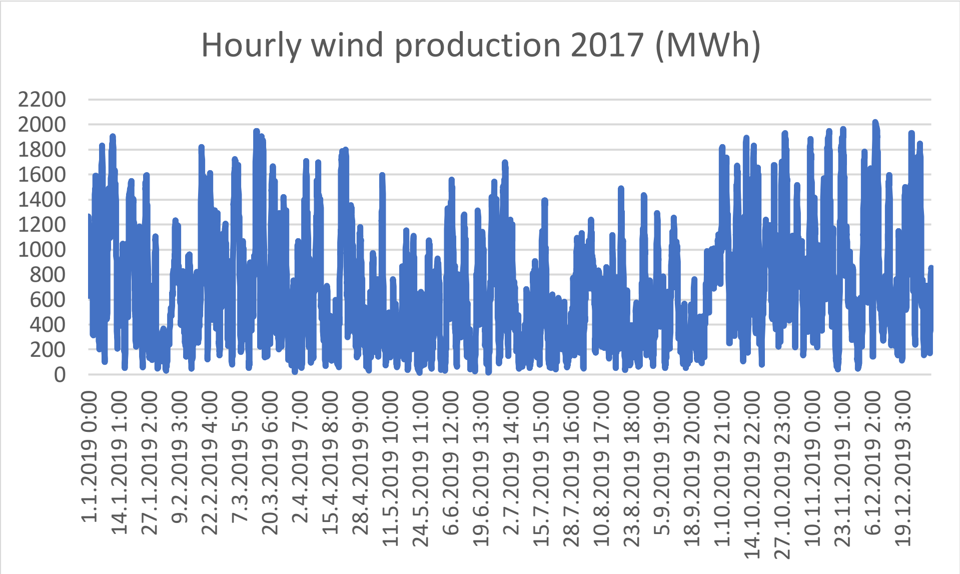


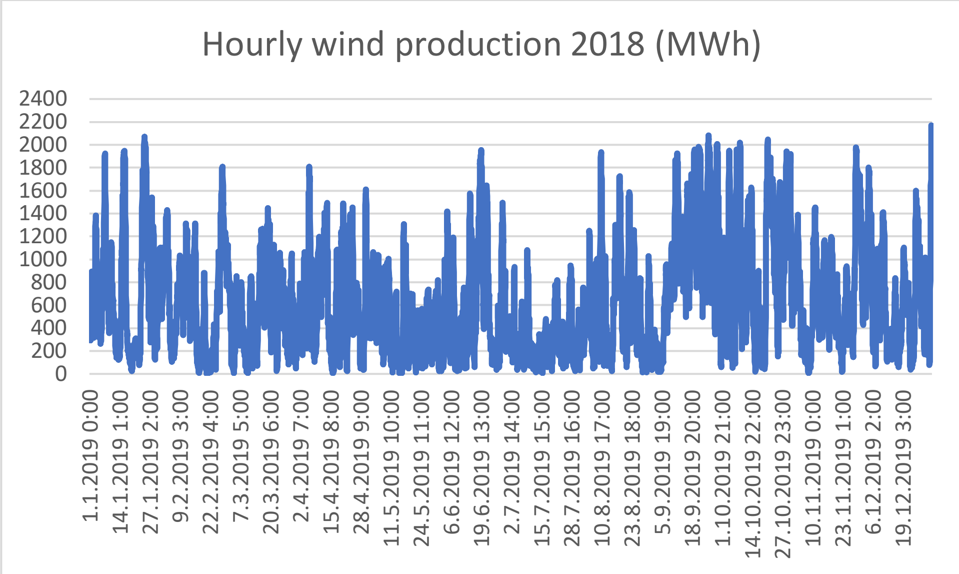
Figure 10: Hourly spot price comparison (February winter day vs July summer day)
Source: Own depiction (Data from Nord Pool)

Figure 11 shows the progression of hourly wind power in SE3 from 2016 to 2019. There is a clear increase in hourly wind production. In 2016, the highest production was just below 2000MWh while the highest in 2017 was approximately 2050MWh. In 2018, the highest wind production was about 2200MWh while that number grew distinctively in 2019 to about

2450MWh. Because wind is a naturally occurring phenomenon that cannot be controlled, there is a large disparity between the highest and lowest levels of wind production. On days that the wind does not blow, no wind generation occurs, and those hours record 0MWh wind production compared to very high generation levels (e.g 2450MWh) that may be recorded on very windy days.







-

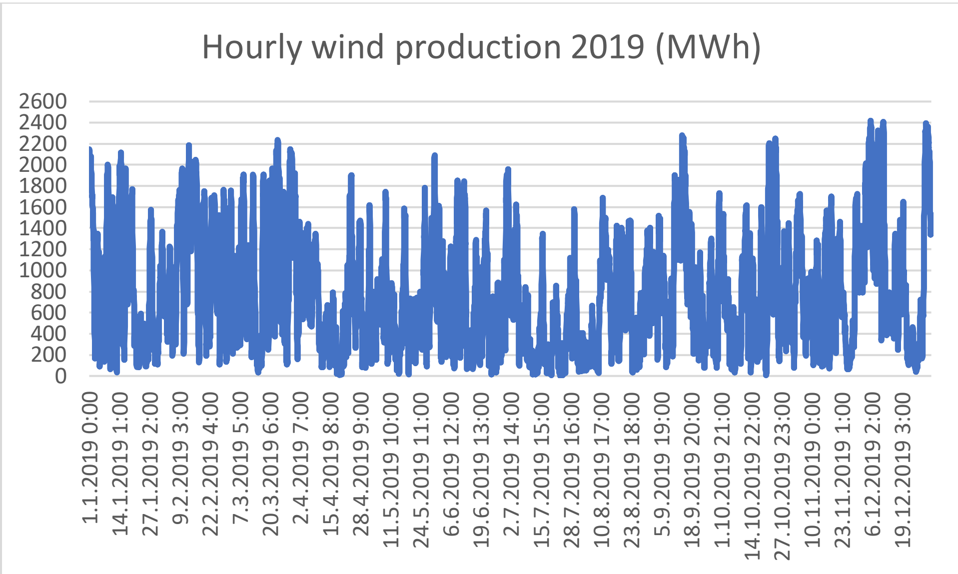


Figure 11: Hourly wind production in Bidding area SE3 2016-2019

Source: Own depiction (Data from Nord Pool)

5.4 Empirical Results

To address the issue of variance stabilization and heteroscedasticity as shown by the Breush-Pagan test results (Appendix: Table 4) in the estimated results, heteroskedasticity and autocorrelation consistent (HAC) standard errors are used as a remedy and as earlier alluded, a log-log model is estimated.

Table 7: OLS estimation of hourly price changes in bidding area SE3

Variables	**Model 1 (2016)**	**Model 2 (2017)**	**Model 3 (2018)**	**Model 4 (2019)**
Ln (Demand)	0.7561***	0.8216***	0.8119***	0.8267***
	(0.0264)	(0.0092)	(0.0631)	(0.0018)
Ln (Wind)	-0.0551***	-0.0537***	-0.0268***	-0.0598***
	(0.0333)	(0.0185)	(0.0523)	(0.0971)
Ln (Hydro)	-0.0137***	-0.0256***	-0.0110***	-0.03731***
	(0.0090)	(0.0022)	(0.0061)	(0.0012)
Ln (Thermal)	0.0108**	0.0076**	0.0114**	0.044***
	(0.0081)	(0.0387)	(0.0866)	(0.004)
Ln (Nuclear)	-0.2133***	-0.2260***	-0.1956***	-0.1869***
	(0.0190)	(0.0244)	(0.0594)	(0.0514)
Net Import/export	-0.0036***	-0.0022**	-0.00199***	-0.0024***
	(2.68e-01)	(2.397e-03)	(2.465e-03)	(1.683e-01)
Daily dummy	Yes	Yes	Yes	Yes
Monthly dummy	Yes	Yes	Yes	Yes
Constant	25.055***	12.633***	18.065***	24.997***
	(0.0208)	(0.1527)	(0.0339)	(0.0614)
Adjusted R-squared	0.533	0.426	0.381	0.577
Observations	8784	8760	8760	8760

*****p<0.001, **p,0.01, *p,0.05**

parentheses show robust standard errors.

5.5 Results and Analysis

Table 7 presents the results for OLS estimates for Models 1,2,3 and 4. Demand was expected to have a positive relationship with spot price. As expected, the coefficient is positive in all four models. The results from all models show the expected relationship between electricity price and wind production. Wind and spot price were expected to have a negative relationship and models 1,2,3,4 all confirm this expected result with negative coefficients for β_2 .These results confirm evidence of the merit order effect of wind in bidding area SE3 in 2016, 2017, 2018 and 2019. The expectation was that increasing hydropower would lead to a price decrease in spot prices while increasing thermal power production marginally would have a positive effect on spot prices. The results for the coefficients of both hydropower and thermal production align with the expectations of the assumption in all four models confirming the expected negative relationship between hydropower and spot price as well as the positive relationship between thermal power and spot price. The expectation for the coefficient of nuclear from the model was negative and this is the same result in all four models. The final variable that is controlled for in all models is net imports and exports. The regression results in all models align with the expectation of a negative coefficient for net imports and exports. All four models show statistically significant results that align with the expectations on the relationship between spot price and all explanatory variables in the regression model presented.

An increase of 1 % in demand according to the regression results is associated with an estimated 0.76 %change in hourly spot prices in 2016 while in 2017 the same increase is associated with approximately 0.82% increase in prices. In 2018 and 2019, the estimated increase in hourly spot prices given a 1% increase in hourly demand is about 0.81% and approximately 0.83% respectively. The findings of a positive relationship between hourly spot prices and hourly demand align with Jaraite et al (2019). They find an increase of 1.31% from a 1% increase in hourly demand in bidding area SE3 in the period 2015-2018. The result for the associated price increase from an increase in hourly consumption in bidding area SE3 in the years of study is consistent with general findings of studies such as Gelabert et al (2011) who find a positive relationship between demand and price when they control for renewable energy production and demand. Similarly, a positive relationship between demand and price is found by Clo et al (2015). Gelabert et al (2011) find an associated increase of between €1.294 and €1.467 increase in demand from 1GWh increase in demand which translates to about 5% of the average price. This is a higher effect compared to the findings in this study. A possible explanation could be that this study is based on a single bidding are of the Swedish electricity market whereas studies like Gelabert et al (2011) and Clo et al (2015) study entire markets, Spain, and Italy, respectively.

The major explanatory variable in the thesis wind production has the expected association with spot prices in all four yearly models. As expected, the hourly spot prices decreases with an increase in hourly wind power production confirming that indeed there is evidence of the merit order effect in bidding area SE3 in all four years of study. This aligns with previous studies on the merit order effect of wind in other market. From the results, in 2016, a 1% increase in hourly wind production is associated with approximately 0.055% decrease in hourly spot prices. In 2017 and 2019 the associated price decrease from an additional 1% increase in hourly wind are 0.053% and 0.059%. The three results are around the same value range, however, the associated price decrease in 2018 is significantly lower at 0.0268% decrease in hourly price from 1% increase in hourly wind production. The general results showing a negative association between hourly wind and hourly spot prices align with previous studies that confirm the decrease in price from a marginal increase in wind production. Jaraite et al (2019) also find evidence of the merit order effect in bidding area SE3. They find that an increase in wind power production by 1% in bidding are SE3 lead to a 0.083% decrease in prices. This is a much higher result compared to this thesis' results. Jaraite et al (2019) employ a different methodology, they use an autoregressive conditional heteroskedasticity (GARCH) model as in Ketterer (2012) and perhaps this may be a reason for the different results. In their model, they control for wind, demand, Nordic hydro reservoirs, nuclear, demand and price of biofuels. Ketterer (2012) finds that a 1 % increase in wind power reduced prices by 0.1% in the German electricity market between the years 2006 and January 2012, However, Ketterer (2012) specifies that this price reduction happens over time and with progression of time this effect continues to lessen, a conclusion that is also reached by Sensfuss (2011). Swinand & O'Mahoney (2015) reported a price reduction of 0.06% for a 1% increase in wind on the Irish electricity market. Other studies with findings that support evidence of a merit order effect include Clo et al (2015) who find statistically significant results on the effect of wind power production on day-ahead spot prices when controlling for variables like demand and the spot price of natural gas. Gelabert et al (2011), results show that a marginal increase in wind power accounted for a 4 percent decrease in prices over the period 2005 to 2009 a result that is also in line with the expectations and results of this paper. Würzburg et al (2013) also find a merit order effect of 20 percent on the German electricity market. Although Holttinen (2004) uses a simulation model and reports evidence of the merit order effect of wind in the Nordic market where each 10TWh of added wind power lowered Nord pool spot prices by €2/MWh. The results of the estimated effect that wind production has on prices in bidding area SE3 found in this thesis although confirming the merit order effect, show a relatively lower effect compared to previous studies on the same subject. The result for 2018 is even lower and this may be because Swedish average electricity prices rose in 2018 due to a drier year that saw reservoir levels in Sweden reducing and average hydropower production also falling compared to the previous year. Consumption levels in 2018 were also relatively higher and this may also account for the general increase in electricity prices in the same year. According to European Commission (2018), the generally lower reservoir levels coupled with lower hydro production (compared to the preceding five years) and a relatively higher level of consumption generally supported the price increase and wind production could only partially compensate for the reduced hydro production. This may explain the lower coefficient values in 2018 for both wind and hydropower compared to other studied years in this thesis. According to Wurzburg et al (2013), in general, one would expect that given the high number of flexible hydro power plants in the Nordic region as a whole, the price reducing effect of wind (in the Nordics) would not be high as other markets. Whether this may be an explanatory reason for low coefficients in this study and for bidding area SE3 is an interesting avenue that might provide grounds and avenues for future study.

Hydropower and nuclear in Sweden provide not just the most flexible ramping capabilities and baseload fulfilment respectively but also produce the highest amount of electricity combined. The expected result for hydro power was a negative relationship between increasing hydro power production and spot prices and the results show statistically significant negative coefficients for all four models. Nuclear was also expected to show a negative coefficient. The regression results show that in 2016, a 1 % increase in hourly hydro power production led to an estimated 0.014 % decrease in spot prices, approximately 0.026 % in 2017 and 0.011% in 2018. The effect was much smaller in 2019 where a 1 % increase in hydro only led to an estimated price decrease of 0.037%. The negative coefficients for both hydro power and nuclear are in line with Jaraite et al (2019) and Cludius, Hermann and Matthes (2014) who also find that marginal increases in hydro production and nuclear production were estimated to cause a price decrease. Jaraite et al (2019) find a 0.191%

decrease in spot prices in bidding are SE3, although they control for hydro reservoirs and not hourly hydro production. They assume that an increase in hydro reservoirs would translate into more hydro power production. Their result for nuclear was 0.213% decrease in spot price in bidding are SE3 given a 1% increase in nuclear production. The results from this thesis show a decrease in spot prices of 0.213%, 0.226%, 0.1956% and 0.1869% from 1 % increase in nuclear in 2016, 2017, 2018 and 2019, respectively. These results align with Jaraite et al (2019) and even the lower coefficients are close enough to their findings. Cludius et al (2014) also find a negative relationship between nuclear and spot prices in their study of the German market. Their results are in absolute terms and they find that a 1GWh increase in wind power decreased prices by 0.27€/MWh and 0.28€/MWh between 2008 and January 2012.

Since thermal power generally has higher variable costs than hydropower and wind, for example, the higher costs mean that thermal power enters the market and merit order at high marginal costs which can shift the supply curve to the left and hence increase spot prices. As a result, the expectation was a positive coefficient. As expected, the coefficient in all four models for thermal power is positive. A marginal increase of thermal power according to the results is associated with approximately 0.01% increase in 2016 prices while in 2017, the associated price increase was about 0.076%. In 2018, the price decrease from 1% increase in thermal production was estimated at 0.011% and in 2019, 0.044%. Studies such as Gelabert et al, (2011) find a statistically significant result on the positive relationship between coal price and spot price. Although my model and the referenced study do not use the same variable for thermal production, coal is a major input in thermal plants in markets like Spain and Germany but not so much in Sweden.

The last variable that is controlled for in the model is net import and export. The expectation for net imports and exports was negative and the results for all four yearly models are negative and significant although the coefficient values are quite small. In 2016, the associated decrease in spot price from a 1% increase in net imports/exports is approximately 0.0036%, 0.0022% in 2017, 0.00199% in 2018 and 0.0024% in 2019. Wurzburg et al (2013) also find a negative relationship on the German and Austrian electricity market. They find an unexpected negative but insignificant result on net import and export which they attribute to the import/export imbalance cause by the exit of nuclear in Germany. However, they do find the expected and significant negative result in one yearly regression model and they also attribute to the recovery of import/exports in Germany toward the end of 2011.

6. Conclusion

With the growing concerns around climate change and the harmful effects of GHG, the use of carbon free and renewable sources of energy has become particularly front and centre in the world. Sweden has committed to increasing the use of renewable sources and the use of variable renewable energy sources like wind and solar have been on the increase over the past 5 years. With the expansion of wind farms and increasing wind power production, a lot of changes have happened on the Swedish electricity market.

This paper sought to find evidence of the merit order effect of increased wind power production on wholesale spot prices in bidding area SE3 between the years 2006 and 2019. The investigation was carried out by empirically testing the relationship between hourly wind power production and hourly wholesale spot prices in bidding area SE3. To investigate and understand the impact that wind production has had on spot prices, yearly regressions were run including all production sources in bidding area SE3 as well as demand. The results confirm the theory that increasing wind power production indeed reduced hourly spot prices in bidding area SE3 between 2016 and 2019 as expected. Estimated price decreases of between 0.0068% and 0.0198% were reported for a 1% increase in hourly wind production in bidding are SE3 between 2016 and 2019. The findings of this study were in line with previous studies like Jaraite et al (2019) who also confirm a merit order effect in bidding area SE3. The results also detail the relationship that other production sources had on hourly spot prices and these findings also echo the findings of studies by Gelabert et al (2011), Clo et al (2015) and Wurzburg et al who also study the effect of increased wind power in Spain, Italy, and Germany, respectively.

The study provides a contribution to the academic field in regard to adding to the literature around the merit order effect in Sweden as studies on the impact of the growing wind power capacity and production on the Swedish electricity market remain few and far in-between.

The general consensus provided in previous studies and as shown in this study is that indeed, increasing wind power production reduces wholesale spot prices. However, various studies have differing findings on the long-term extent of this effect. Ketterer (2012) find that the price reducing effect of increasing wind power dwindles with each preceding year while Nilsson (2020) points the price decreases instead, to overcapacity. Future research in the area remains significant as Sweden aims to attain 100% renewable energy by 2040. The developments as the country moves toward this goal and the further planned closure of nuclear power plants provide even more grounds for study given that nuclear power accounts for about 40 percent of the total electricity produced in Sweden annually and the effect this will have on the electricity market would be prudent to study. The intra-day market accounts for a significant amount of the total electricity traded in the Nordic region at large and it would be a prudent and interesting direction for future study to understand how increased wind power has affected prices on this market as well as the impact this will have on future wind power investment decisions.

References

Amelang.S and Appun. K, (2018) https://www.cleanenergywire.org/factsheets/why-power-prices-turn-negative

Bergman, L. (2002), "The Nordic electricity market – continued
Brancucci Martinez-Anido.C. B, Brinkman. G, & Hodge. B. (2016) The impact of wind power on electricity prices, In Renewable Energy (Vol 94 pp 474-487) Elsevier

Byman. K. (2016). Electricity production in Sweden IVA's Electricity Crossroads project. In Royal Swedish Academy of Engineering Sciences

Carvalho Figueiredo. N, Pereirada Silva. P and Cerqueira. P. (2016) Market splitting and the Swedish electricity market at The 201613th International Conference on European Energy Markets (EEM), Porto Portugal

Clò. S, Cataldi. A, Zoppoli. P, (2015). The merit order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. In Energy Policy, (Vol 77 pp 79–88), Elsevier

Cludius. J, Hermann. H, Matthes. F.C, Graichen.V. (2014). The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016 In Energy Economics (Vol 44 pp 302–313) Elsevier

Cutler. N. J, Boerema.N. D, MacGill. I. F, Outhred. H.R., (2011). High penetration wind generation impacts on spot prices in the Australian national electricity market. In Energy
Diczfalusy.B (2020), Sveriges energipolitik under 50ar-en aterblick, North European Energy Perspectives Project

Energiföretagen Sverige, (2021)
https://www.energiforetagen.se/energifakta/elsystemet/produktion/

Energimarknadsinspektionen (2016). Area price hedging and the Nordic market Model in Energimarknadsinspektionen R2016:11

European Commission (2018), Quarterly Report on European Electricity Markets. (Vol 11 issue 4)

European Commission (2019), Quarterly Report European Electricity Markets. (Vol 12 issue 2)

European Wind Energy Association, n.d. https://www.wind-energy-the-facts.org/power-markets-7.html

Gelabert. L, Labandeira. X, Linares. P, (2011). An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. In Energy Economics (Vol 33 pp 59–65)

Gliniewicz. V (2016), Economic impact assessment of using congestion management methods to enable increased wind power integration on Gotland, Vattenfall R&D

Held. A, Ragwitz. M & Haas. R. (2006) On the success of policy strategies for the promotion of electricity from renewable energy sources in the EU. In Energy & Environment (Vol. 17, No. 6)

Hirth.L, (2016) What caused the drop in European electricity prices? In USAEE Working Paper No. 16-282
Holttinen. H, (2004). The impact of large-scale wind power production on the Nordic electricity system, Doctoral Thesis, Helsinki University

https://ec.europa.eu/energy/taxonomy/energy-strategy_en#:~:text=The%202020%20energy%20strategy%20(2010,energy%20in%20their%20transport%20sector.

https://web.archive.org/web/20151225045741/http://www.nordpoolspot.com/How-does-it-work/Bidding-areas/

https://www.energiforetagen.se/energifakta/elsystemet/produktion/

https://www.government.se/49b73b/contentassets/41902ab952bd49d887367ea10c0eefce/renewable-electricity-with-green-certificates

https://www.next-kraftwerke.com/knowledge/intraday-trading

https://www.nordpoolgroup.com/trading/Day-ahead-trading/Price-calculation/

https://www.weforum.org/agenda/2020/01/texas-us-wind-power-renewable-energy/

https://swedishwindenergy.com/press-releases/swedish-government-propose-effectless-stop-mechanism-in-the-electricity-certificate-system

Hugo. AG, Gomez-Quiles. C, Riquelme. J (2012). Large-scale wind power integration and wholesale electricity trading benefits: Estimation via an ex-post approach. In Energy Policy (Vol 41, pp 849–859). Elsevier.

Jaraite. J, Kazauskas. A, Brannlund. R, Kiran. CN, Kristrom. B, (2019). Intermittency and Pricing Flexibility in Electricity Markets. In Energiforsk Report (2019:588)

Ketterer. J.C, (2012) The Impact of Wind Power Generation on the Electricity Price in Germany. In IFO Working Paper No. 143

Klevnas. P, Bo Hansen. M, and von Utfall Danielson. C, (2016). Electricity market design for a reliable Swedish power system, Copenhagen

Kutner. M.H, Nachtsheim. J.N and Li. W (2014). Applied linear statistical models,5th Edition, McGraw-Hill, New York

Mauritzen. J (2011) What happens when it is Windy in Denmark? An Empirical Analysis of Wind Power on Price Volatility in the Nordic Electricity Market. In NHH Dept. of Finance & Management Science Discussion Paper (No. 2010/18)

Montel News (2020), https://www.montelnews.com/en/story/eu-day-ahead-markets-see-6th-week-of-negative-hourly-prices/1107284

Murphy. B (2019). https://www.forbes.com/sites/brianmurray1/2019/06/17/the-paradox-of-declining-renewable-costs-and-rising-electricity-prices/?sh=3f37845e61d5

Neubarth. J., Woll, O., Weber, C., Gerecht, M., (2006) Beeinflussung der spotmarktpreise durch windstromerzeugung. Energiewirtsch. Tagesfr. (Vol 56 pp 42–45)

Nieuwenhout. F & Brand. A., (2011) The Impact of Wind Power on Day-ahead Electricity Prices in the Netherlands. 2011 8th International Conference on the European Energy Market (EEM) 25-27 May 2011, Zagreb, Croatia

Nicolosi. M, (2010) Wind power integration and power system flexibility–An empirical analysis of extreme events in Germany under the new negative price regime. In Energy Policy (Vol 7257-7268)

Nilsson. M, (2020) A meta-analysis of merit order effects – How subsidies to renewable power production kills the electricity market (Unpublished)

Nordhaus. W (1995), The Swedish Dilemma-Nuclear Energy v. The environment. In Energy Infrastructure (Vol 27)

Ostergaard, P., Morthorst, P.E., Moesgaard, R., Enevoldsen, S., (2006). Vindkraftensbetydning for elprisen i Danmark. IBTWind, Herning, Denmark.

Papageorgiou,A , Ashok, A. , Farzard,T.H.,and Sundberg,C. (2020). Climate change impact of integrating a solar microgrid system into the Swedish electricity grid in Applied Energy (Vol 268)

Roldan-Fernandez. J, Burgos-Payana. M, Riquelme-Santosa. J and Trigo-Garcia. A, 2016, The Merit-Order Effect of Energy Efficiency in Energy Procedia 106 (2016) 175 – 184. Science Direct

Saenz de Miera. G, del Rı´o Gonzalez. P, and Vizcaı.I, (2008). Analyzing the impact of renewable electricity support schemes on power prices: The case of wind electricity in Spain. In Energy Policy (Vol 36 pp 3345–3359)

Sensfuß.F, Ragwitz. M, Genoese. M, (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. In Energy Policy (Vol 36 pp 3086–3094)

Skytte. K & Grohnheit. P. E, (2018) Market Prices in a Power Market with More Than 50%Wind Power, Springer International Publishing AG

Stewart. J (2009), Independent Commodity Intelligence Services, https://www.icis.com/explore/resources/news/2009/12/22/9321337/danish-spot-hits-negative-value-for-first-time/

Studies in Systems, Decision and Control 144, https://doi.org/10.1007/978-3-319-74263-2_4

success or emerging problems?". Regulatory Reform – Remaining Challenges for Policy

Swedish Energy Agency. (2020), Energy in Sweden 2019: An Overview. Swedish Energy Agency

Swinand. G.P & O'Mahoney. A, (2015). Estimating the impact of wind generation and wind forecast errors on energy prices and costs in Ireland. In Renewable Energy (Vol. 75 pp 468-473), Elsevier

The Swedish Energy Agency, (2020). The Swedish-Norwegian Electricity Certificate Market

Traber T.; Kemfert, C; Diekmann, J (2011). German electricity prices: Only modest increase due to renewable energy expected. In Deutsches Institut für Wirtschaftsforschung (DIW), Berlin Weekly Report (Vol. 7, Issue. 6, pp. 37-46).

Weihao Hu, Zhe Chen, Birgitte Bak-Jensen (2010). The Relationship Between Electricity Price and Wind Power Generation in Danish Electricity Markets, Danish Public Service Obligation (PSO) research funding program, project 2006-1-6316, “Operation and Control of Modern Distribution Systems”, the Danish Academy of Wind Energy (DAWE) and Aalborg University.

Woo. C.K, Horowitz. I, Moore. J & Pacheco.A. (2011). The impact of wind generation on the electricity spot-market price level and variance: The Texas experience. In Energy and Environmental Economics (Vol 39 pp 3939–3944) Elsevier

Würzburg. K, Xavier Labandeira. X & Linares. P, (2013) Renewable generation, and electricity prices: Taking stock and new evidence for Germany and Austria. In Energy Economics (Vol 40 159–171) Elsevier

Appendix

Table 4: Correlation matrix for all variables

	PRICE	DEMAND	HYDRO	WIND	THERMAL	NUCLEAR	NET IMP/EXP
PRICE	1						
DEMAND	0.246	1					
HYDRO	0.004	0.554	1				
WIND	-0.130	0.129	-0.098	1			
THERMAL	0.200	0.418	0.370	0.185	1		
NUCLEAR	-0.003	0.567	0.216	0.155	0.657	1	
NET IMP/EXP	-0.323	-0.542	-0.285	0.250	-0.225	0.289	1

Breusch-Pagan Test Results

Studentized Breush-Pagan test

data: model1

BP = 41.713, df = 4 , p-value = < 1.208e-06

Studentized Breush-Pagan test

data: model2

BP = 48.284, df = 4, p-value = < 1.328e-05

Studentized Breush-Pagan test

data: model3

BP = 38.406, df = 4 , p-value = < 1.099e-06

Studentized Breush-Pagan test

data: model4

BP = 28.562, df = 4, p-value = < 1.2e-16