Drivers of the Day-Ahead Electricity Prices in the Nordic Market: A Panel Data Analysis of Denmark, Norway, and Sweden

Master's Thesis

Dorottya Bereczki

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Supervisor: Christian Montes Schütte

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Summary

The electricity markets are facing rising concerns when it comes to price volatility and the growing shift towards renewable energy, which makes understanding the electricity price dynamics exceptionally important for market stability. In this thesis it is studied how do renewable electricity generation, alongside consumption, trade flows, and weather conditions influence the day-ahead electricity market prices across Denmark, Norway, and Sweden, with using country-level hourly data between 2020 and 2024.

The theoretical framework is based on the merit-order effect, which lowers market-clearing prices by introducing the low marginal cost renewables, moreover it also introduces the concepts of market interconnectivity, market coupling, and cross-border spill-over effects, which puts light on the structural bases of electricity trading in the Europe and the Nord Pool area. Furthermore, there is also an emphasis on the relevance and the effect of European gas prices on electricity prices.

The thesis uses fixed effects panel data estimation with instrumental variables method by two-stage least squares (2SLS) estimation to account for endogeneity in the renewable electricity generation, and it also applies Driscroll-Kraay standard errors to correct for heterogeneity and serial correlation. The analysis is focusing on one main model, which tests the main explanatory variables' effects on the day-ahead prices across the Nordic region: consumption, renewable electricity generation, net imports, temperature, rainfall, with adding daily and monthly time controls, while wind speed and sunshine duration were used as instruments for the renewable electricity generation. Moreover, on top of the main model five significant robustness tests were done (out of which two are in the appendix), which deepened the understanding of the market by separating the effects by countries, and by adding Dutch TTF day-ahead gas prices, and by also separating the TTF model by countries (while the last two are focusing on the exceptionally high renewable period's effect on prices in the whole region and also separately by countries).

The key limitations of the thesis are lying in the use of only capital cities for weather-related data and the use of country-level renewable electricity generation, instead of source-and-country-specific generation. Moreover, while in most models the used IV methods are addressing the endogeneity problem in the renewable generation, the two robustness models in the appendix are still raising concerns when it comes to their high RES dummy coefficients.

The empirical findings showed throughout all model specifications that consumption is a increasing the prices, while renewable electricity generation, temperature, rain and weekend days are driving down the day-ahead electricity prices, moreover the models that included the TTF day-ahead gas prices also showed that the gas prices are positively impacting the electricity spot prices, however the different countries showed different sensitivities to both renewable output and gas prices.

Overall, the analysis confirmed the renewable electricity's role in shaping the electricity prices throughout the Nordic market, while the findings have practical implications for market participants, regulatory organizations and for policymakers as well, since they are important when it comes to managing volatility and price formation in a market where renewable penetration is already high and is still growing. Based on the findings, the electricity markets have to account for not only increased renewable capacity, but they also have to take into

consideration the complexity that comes from cross-country trade, weather changes and alternative fuel prices and their availability.

1. Introduction

In recent years electricity markets across Europe were affected more and more by the combination of structural challenges, supply shocks, and the growing penetration and impact of renewable energy. Norway in 2024 raised concerns because of the rising domestic electricity prices and they considered limiting their electricity exports to Europe to protect their own consumers (Euronews, 2024a), which was a significant moment for the Nordic region, where cross-border electricity trade is important for market stability and price convergence. At the same time Sweden reopened debates about expanding its interconnection with Germany, however they made it conditional on new reforms to make sure that the distribution of price pressures is more reasonable (Financial Times, 2024).

These events took place during reforms in the Nordic electricity market, as in 2024 the region introduced a new day-ahead market model to improve price formation and to integrate the increasing shares of renewable electricity better (Reuters, 2024b). The mentioned policy shift shows efforts to modernize how prices are set in systems where the shares of renewables are growing and to strengthen cross-border efficiency within the Nord Pool market (Ibid.).

Besides these policy related events, another important thing to take into account when it comes to the understanding of how prices are determined across Denmark, Norway, and Sweden is that even though these markets are interconnected and part of the same electricity market, their generation mixes and system flexibility differs a lot, as according to Euronews (2024b) Denmark heavily relies on renewables, which takes up 87,58% of their electricity generation, Norway shows even a higher renewable share with its 98,26%, while Sweden generates 69,06% of its electricity from renewables and 29,19% comes from Nuclear power, while the remaining electricity generation comes from fossil fuel in the mentioned countries. These structural differences imply that price responses to renewable generation and demand shocks might not be the same across the whole region (Euronews, 2024b).

While renewable energy sources such as wind, solar and hydro have near-zero marginal costs (Bahar and Sauvage, 2013; Wen et al., 2022) and they are expected to push down prices due to the merit-order effect (Würzburg et al., 2013; Bahar and Sauvage, 2013), they also introduce new risks. One of the most discussed topics in countries where renewable share is high is the phenomenon of Dunkelflaute, a period during which wind and solar production is very low or they are not producing at all due to high cloud cover and no wind. During these episodes the renewable output is minimal, which leads to price spikes and reliance on backup generation or electricity imports (Reuters, 2024a).

Despite these important dynamics there is still limited empirical research which would examine how the key drivers of electricity prices are different across countries within the Nordics, as most of the existing literature focuses on different regions or individual national case studies, without fully capturing the cross-country heterogeneity in the Nordics.

This thesis addresses this gap by analyzing how renewable electricity generation, electricity consumption, cross-border electricity trade, and weather conditions affect day-ahead electricity prices in Denmark, Norway, and Sweden, and whether these effects show difference between the countries. The study uses fixed effects panel regression with instrumental variables and several robustness tests on a high-frequency dataset between 2020 and 2024. With the capturing of both region-wide and country-specific drivers, this study is aiming to provide a detailed understanding of price formation in the Nordic electricity market.

1.1 Problem statement

The increasing integration of renewable energy sources has significantly reshaped the electricity markets in Europe and in the Nordic region. While the merit-order effect suggests that renewable generation lowers electricity spot prices (Ketterer, 2014), the scale and consistency of this effect might be different between countries with different energy mixes. Denmark, Norway and Sweden have different renewable electricity generation portfolios, which might lead to different price responses to renewable output. Although previous research papers were studying the general impact of renewables in electricity market in Europe, there is limited empirical evidence that would compare the country-specific effects of renewable generation in these three Nordic countries. This thesis addresses the gap by investigating differences between the countries on how they react to renewable generation while controlling for different essential factors.

1.2 Questions

Research question: How do renewable electricity generation, alongside with electricity consumption, cross-border electricity trade, and weather conditions influence day-ahead electricity prices in Denmark, Norway and Sweden, and do these effects change across countries?

The below working questions were formulated to help to analyze and explore the topic and to be able to give an in-depth answer to the research question.

Working question I: Does electricity consumption, renewable energy generation, cross-border electricity trade, and weather conditions significantly affect day-ahead electricity prices in Denmark, Norway and Sweden?

With the first working question the goal is to explore the region-wide effects of the assumed main drivers of the electricity market which serves as the base for the rest of the analysis.

Working question II: Do the day-ahead electricity prices in Denmark, Norway, and Sweden respond differently to their own domestic renewable electricity generation?

The second working question was aimed to evaluate the main drivers of the market, but on a country level, to see whether there are any differences between the countries' responses to the different

Working question III: Do European natural gas prices, proxied by Dutch TTF day-ahead prices, have a significant influence on day-ahead electricity prices in the Nordic countries, beyond domestic supply, demand, and weather factors?

This working question was created with the focus to analyze if European gas prices proxied by the Dutch TTF day-ahead prices are having a price driving effect on the Nordic region's electricity prices.

Working question IV: Does the sensitivity of Nordic day-ahead electricity prices to European gas prices changes across Denmark, Norway and Sweden?

The rationale behind the fourth working question was to explore whether the previously mentioned European gas prices are affecting the prices differently in Denmark, Norway and Sweden.

Working question V: Do day-ahead electricity prices respond differently during hours of exceptionally high renewable energy generation (top 5% of RES output)?

The fifth working question was formulated to identify how does the renewable electricity generation affect the day-ahead electricity prices when it in the 95th percentile in the Nordic region.

Working question VI: Does the impact of extremely high renewable electricity generation (top 5% of RES output) on day-ahead prices differ across Denmark, Norway and Sweden?

The last working question's purpose was to assess if there is a heterogeneity in the countries' responses in their day-ahead electricity prices to the renewable production periods that are in the 95th percentile of their generation.

1.3 Limitations and delimitations

1.3.1 Limitations

Even though the paper provides a meaningful insight into the factors that are affecting the day-ahead electricity prices in the Nordic region on a short-term, there are several limitations that need to be acknowledged. These limitations are not invalidating the findings, but they are rather highlighting the contextual boundaries, the methodological constraints, and the broadness of the field that might influence the interpretation of the results, and the recognition of these limitations is important for transparency and for guiding future research.

The most important limitation to mention is endogeneity and omitted variable bias, even though IV methods were used for the RES generation to address endogeneity in the renewable electricity generation, the 4th and 5th robustness test results raised concerns about endogeneity when it comes to the high RES dummy variables, and therefore the causal interpretation of these two models is weaker.

Another limitation is the Dutch TTF gas price data, as the prices were only available in a daily frequency, while the rest of the data has hourly observations, therefore the daily TTF prices were assigned to all the 24 hours of the same day to match the granularity of the rest of the dataset. This mismatch might mask intraday price dynamics or volatility.

Omitted factors that might be affecting price volatility is also a constraint of this paper, these are grid stability, balancing costs, unexpected outages or storage behaviour and they were not included, which narrows down the scope of the thesis to price level drivers and not putting emphasis on volatility, which could also play a significant role in renewable-dominated systems.

Additionally, the generation from all types of renewable electricity sources were summed up into a single RES generation variable, however these differ in their predictability and their dispatchability, therefore it is possible that it might blurs the heterogenous effects. The country-specific models were partly accounting for this with their different generation mixes, but a source-specific model could have added a further depth to the analysis.

Moreover, the models do not account for policy shocks, fossil fuel price spikes, or COVID-related market shifts, while these events could affect supply and demand relationships, and their effects are different from purely market-driven dynamics, which is not captured in this analysis.

Lastly, for the weather data the countries' capital cities (Copenhagen, Oslo, Stockholm) were used, however renewable generation and consumption as well separated to several bidding zones in the three countries, which could introduce bias, especially in Norway and Sweden, where there are large differences in the weather conditions between the capital region and more rural areas.

1.3.2 Delimitations

The thesis also includes several delimitations, which are defining the scope and the focus of this research. The reasons behind these choices lie in the research objectives, and also in the data availability, and the delimitations are helping to clarify what was included in the study and in what way, and while these delimitations might be narrowing down the generalizability of the results in other markets, they were still very important to make to be able to create a manageable research design.

The study focuses on only three Nordic countries, which are Denmark, Norway and Sweden within the Nord Pool market, because these countries have different renewable mixes, which makes them ideal for a comparative analysis.

The thesis uses consumption-weighted country-level averaged data instead of using individual bidding zones, which allows to create a clear cross-country comparison, moreover it also uses a single renewable electricity generation variable to see the overall effect of renewables, instead of source-specific renewables.

The time frame for the analysis is five years, which is allowing for capturing any seasonal patterns. It focuses on hourly day-ahead electricity prices, which are very widely studied prices and they reflect the main market-clearing mechanism, moreover it uses specific control variables: consumption, renewable electricity generation, net imports, TTF gas prices, and weather-related variables, which were chosen based on theory and the availability of high-frequency data.

1.4 Disposition

The below table's goal is to show the overall structure of the research paper, and to help the reader with navigating the thesis more easily, therefore it outlines the main chapters and their content:

Disposition table	
Introduction	Introduction
	Problem statement
	Questions
	Limitations and delimitations
	Disposition
Literature review	Renewable Energy Integration, Electricity Demand and Price Volatility
	The Merit-Order Effect and Electricity Price Formation
	The Cross-Border and Spill-Over Effects in Renewable-Integrated Electricity Markets
Theory	The Merit-Order Effect
	Market Interconnectivity
	Market Coupling
	Cross-Border Spill-Over Effects
	Natural Gas Price Influence
Methodology	Research philosophy
	Research approach
	Research design and strategy
	Data collection, analysis and hypotheses
	Validity, reliability and representativity
Empirical Chapter	The Data
	The Variables
	Table of Variables
	Descriptive statistics of the variables
Analysis and Discussion	Analysis of all the models
	Discussion of all the models
Conclusion	Conclusion
	Future research

Table 1: Disposition table

2. Literature review

2.1 Renewable Energy Integration, Electricity Demand and Price Volatility

Renewable energy is taking on an intensified role when it comes to the power grids and it is shifting the electricity markets completely, with changes that are transforming how prices are set and bringing more volatility. Through different econometric and machine-learning methods empirical studies have analyzed the effects that are currently moving the electricity markets in relation to the renewable energy penetration and this section is presenting the key findings from recent literature.

Kohlscheen and Moessner (2022) with a random forest machine learning model analysed the EPEX (European Power Exchange) prices between 2012 and 2022. They found that wind power's effect was growing throughout the years, as in the beginning of the study it was only a minor factor, while by 2022 it became a significant influencing element of wholesale electricity prices. They also found that besides wind energy, solar energy's relevance was also increasing in the studied period, however it has a more minor effect than wind power, while natural gas prices have the strongest effect on electricity prices overall. (Kohlscheen and Moessner, 2022)

Féron et al. (2022) developed an equilibrium model to study the intraday electricity markets' price formation, with taking into account the variable renewable energy sources. They applied stochastic control theory and Nash equilibrium principles and used EPEX data between 2015 and 2017. Féron et al. (2022) found that the price volatility increases as delivery time approaches, moreover this volatility increases with the rise of intermittent renewable energy, which is due to the forecast uncertainty and weather conditions-related variability. (Féron et al., 2022)

Wolff and Feuerriegel (2018) were studying the short-term dynamics of prices in the German and Austrian electricity markets, and they found that the day-ahead market is less sensitive to renewable energy, than the intraday market, but even in the day-ahead market it lowers the prices. They did not find alternative fuel prices in general statistically significant on the short run. Furthermore, they also found that prices in general are lower during the weekends, and regarding monthly seasonality they saw that prices during summer months are usually lower when it comes to wind and solar power, while consumption was found to be a positive effect for prices. (Wolff and Feuerriegel, 2018)

2.2 The Merit-Order Effect and Electricity Price Formation

The presence of the Merit Order Effect has been confirmed by many researchers, across several different regions. These studies showed that significant reductions can be observed in wholesale electricity prices as a result of renewable energy sources (RES). (Ketterer, 2014; Cevik and Ninomiya, 2022; Loumakis et al., 2019; Owolabi et al., 2022)

Ketterer in her 2014 research focused on wind generation in Germany with the use of a GARCH model and demonstrated a significant drop in wholesale electricity prices. She emphasized the merit-order effect but highlighted the volatility increase, which is a threat to investment stability in electricity markets. She found that if wind power increases by 1%, then it leads to 0,09-010% drop in spot prices, however she also found that wind power has a weakened effect over the years. (Ketterer, 2014)

Cevik and Ninomiya (2022) found that in Europe the price reduction in electricity prices caused by the merit-order effect is 0.6% on average per 1 percentage point increase in renewable share and the more renewables added, the stronger the price lowering effect became. They had mixed findings regarding volatility, suggesting that it can be both increased or decreased by renewable energy depending on the analyzed quantiles: at high quantiles, where there were extreme prices, they found that renewable energy source integration actually leads to reduced volatility. (Cevik and Ninomiya, 2022)

Loumakis et al. (2019) studied Greece, and they reported that in the wholesale electricity prices there was a reduction caused by the merit-order effect, which was 14,2 EUR/MWh on average, and they also noted that the reduction depended on renewable energy source: solar generation had a more predictable daily generation with a peek around noon and it significantly lowered the prices at this time, which results in a highest merit-order effect during these hours. On the other hand, for example wind power has a more unpredictable generation pattern and it doesn't have sharp daily peaks in the merit-order effect like solar generation. (Loumakis et al., 2019)

Owolabi et al. (2022) were analyzing US markets, and they also confirmed the decrease in electricity prices across US markets caused by higher renewable energy generation and they highlighted that the price reduction is non-linear and it is particularly strong during price spikes. Their results are in contrast to Ketterer's findings, as they found that the increased renewable penetration in the US actually decreases price volatility in general, because of the portfolio effect from diversified energy sources, and with this they challenged the idea that high renewable integration raises volatility in the market. (Owolabi et al., 2022)

2.3 The Cross-Border and Spill-Over Effects in Renewable-Integrated Electricity Markets

The increased integration of renewable energy sources, like wind, solar or hydropower also has impacts beyond national borders through cross-border exchanges and spill-over effects. The dynamics of these and the understanding of them is important as the markets are getting more and more interconnected and complex, and these factors are significant when it comes to the determination of electricity price volatility, stability and market efficiency. Additionally, it is also essential for policymakers and market participants to understand how the renewable fluctuation affects interconnected markets and shapes cross-border electricity flows to optimize renewable energy integration and manage possible risks arising from its volatility

De Blauwe et al. (2024) studied the cross-border effects of renewable electricity generation, and they found that high renewable generation in one region, which is wind power generation in Germany in this research, has a significant influence on prices in smaller neighboring countries such as Denmark. The spill-over effect was found stronger in regions that are geographically closer and also in markets that has higher interconnectivity, however this effect in further away countries is weaker. (De Blauwe et al., 2024)

Keles et al. (2020) analyzed the cross-border electricity price dependencies and spill-over effects in Switzerland and its neighboring countries: Germany, France and Italy, with the highlight on how renewable energy generation and seasonal variability shape spill-over effects. They found that renewables in Germany have a strong downward pressure on the Swiss electricity prices during the summer, while in the winter, demand-side pressures from France and Italy are more significant. They also found that gas prices are driving the prices during all seasons. (Keles et al., 2020)

Schäfer et al. (2019) were analyzing hourly cross-border electricity flows in Europe, and they found that electricity is flowing across multiple borders very often and not just between neighboring countries. They also found that Germany and France are very important and central in the European trading patterns, and they also highlighted strong seasonal cycles in these flows, which supports the complexity of cross-border interactions and shows why the coordinated infrastructure is important in Europe. (Schäfer et al., 2019)

2.4 Conclusion

The literature shows that the integration of renewable energy is reshaping electricity markets by lowering wholesale prices and increasing price volatility, however the nature and the degree of these effects changes based on the energy mix of specific countries, the market design and regional characteristics. The merit-order effect is clearly confirmed by empirical research, as it shows significant price reductions that is coming from high renewable generation, while the impact of high renewable generation days on volatility is less consistent, since while some studies found increased unpredictability, other researchers pointed out that the volatility was less fluctuating with diversification. Furthermore, it was also pointed out, that the more interconnected the electricity markets are becoming, cross-border and spill-over effect are also becoming more relevant. Empirical evidence also shows that in case of large countries that also have high renewable shares, the fluctuations in their output can influence prices in smaller, neighboring countries, and that these factors are shaped by for example the energy type and the seasonality. The previous research provide a solid base for the analysis on how renewable production days are affecting electricity prices and they also show the importance of understanding of how different renewable energy mixes influence market dynamics.

3. Theory

In this chapter the key theoretical background and market mechanisms are presented that will help to interpret how the renewable energy production impacts electricity spot markets, while it also shows how changes in wind and solar generation are affecting the price formation through the merit-order effect, and how the more and more connected and coupled nature of power markets let these effects to spill over across country borders. It also examines how – besides other factors – natural gas prices also drive the electricity prices in Europe.

3.1 The Merit-Order Effect

The key theoretical concept for understanding how does the renewable electricity generation impact the electricity prices is the merit-order effect, which shows how the introduction of the low marginal cost generation, like solar or wind power is changing the supply curve in the electricity market, which leads to lower equilibrium prices. (Bahar and Sauvage, 2013) In competitive power markets, the generators offer to sell their output based on their production costs, which is starting from the cheapest and the market clearing price is determined by the last and most expensive unit that was needed to meet the demand. (Blume-Werry et al., 2021; Bahar and Sauvage, 2013)

The renewable energy sources, like wind and solar energy have very low marginal costs, which is basically near-zero fuel cost, which leads to that on days when the renewable generation is high, the electricity generated by the renewable energy sources (RES) is entering at the bottom of the supply curve, which leads to a shift in the curve and it pushes it to the right, by which it is displacing the mostly fossil-fuel based higher cost generation, which would set the price otherwise. In some cases, even negative prices can be reached if the system operators have limited transmission capacity to transfer the excess electricity to regions with higher prices. In case of these negative prices, the generators are the ones who have to pay, for which the reason is that stopping and restarting the generation is more costly, than paying for a consumer to use the generated electricity and also because of financial incentives, which are supporting the generation of these renewable plants even in those cases when the market prices are not high. (Bahar and Sauvage, 2013; Newbery et al., 2018) The result of this shift in the supply curve is a lower equilibrium spot price, which is the classic merit-order effect. (Sensfuß et al., 2007) Therefore in the short run the wind and the solar generation reduces the use of expensive peak units, which leads to lower wholesale electricity prices. (Newbery et al., 2018)

The merit-order effect as explained above creates a downward pressure on the spot prices (Würzburg et al., 2013), which might bring challenges for traditional fossil fuel-based electricity generators that has now reduced operating hours, however it is important to mention that the merit-order effect is a competitive system's normal market outcome, as lower marginal cost renewables push out higher cost plants, by this bringing a lower equilibrium price. (Newbery et al., 2018) However, possible policy incentives, like feed-in tariffs or priority dispatch can lead to a market distortion. (Ibid.) The merit-order effect with the increased renewable supply shifts the supply curve rightward and reduces the clearing price for all producers, which on the long term can significantly lower the revenues for traditional generators, which leads to the so called "missing money" problem where non-renewable plants struggle to cover their costs. (Newbery et al., 2018)

Since large renewable shares are lowering wholesale prices, it causes the effect that for investors the incentives to build and maintain flexible backup generators based on fossil fuel has weakened, which is concerning when it comes to the supply's security, since even though they maybe face the "missing money" problem, fossil fuel based plants are still needed when due to the weather, the wind and solar plants are not generating, like in case of the Dunkelflaute that was mentioned in the introduction. (Newbery et al., 2018.) (Reuters, 2024a) This also leads to that when the renewables are not generating enough or at all, the reduced availability of low cost generation can drive the prices higher than how much they would be in a system that is supported by a more reliable back-up generation. As a result, the volatility of the wholesale prices can also increase in case of the growing renewable penetration and production. This volatility is coming from the renewables' output uncertainty and variability as they are highly affected by the weather. (Newbery et al., 2018)

3.2 Market Interconnectivity

The physical integration of the previously separate national and regional electricity markets is resulted in cross-border trade, which is allowed to happen through the connectedness of the separate markets. Market interconnectivity is another factor that significantly impacts market value, as this interconnectivity can be achieved through interconnector capacity, and it allows the electricity to be exported from areas that have surplus renewable generation. (Stewie et al., 2025)

Heavy interconnectedness contributes to price convergence, which can be defined as the electricity price alignment between markets due to increased interconnection capacity and market coupling, that lowers the price differentials through the cross-border flows. (Urquijo and Paraschiv, 2023) In an interconnected electricity system, the electricity flows naturally from regions which has renewables that generated surplus, therefore bringing lower prices towards areas that are experiencing supply shortages and higher prices. (Macedo et al., 2022)

The interconnections widen the merit-order effect across borders, which allows one area's cheap generation to replace more expensive generation in a different area, which therefore lowers the prices in the importing regions. (Abrell and Kosch, 2021) It is also important to note that cross-border trade is a key tool for managing the variability coming from renewable generation, since it gives access to a broader portfolio of mixed renewable sources. By having resources from a larger area, the interconnectivity with high renewable shares reduces the overall costs of balancing supply and demand, and it can also improve the reliability of the system, moreover a synergistic system can be created. (Bahar and Sauvage, 2013)

3.3 Market Coupling

While the market interconnectivity refers to the physical possibility to exchange electricity across borders, the market coupling represents the market design framework that allows this exchange to happen efficiently. Although they are closely related, market coupling is treated as a separate mechanism here, because it is managing how cross-border interconnection capacity is allocated. Market coupling determines how efficiently the physical cross-border trade's potential can be used, which is an essential mechanism that was designed to optimize the cross-border electricity trade within the European market. Before market coupling, the capacity and energy was traded separately, however now due to the market coupling there are simultaneous allocations through auctions. The core purpose of market coupling is to make sure that the interconnection capacity between bidding zones is allocated efficiently, and by this it is allowing electricity to flow from low to high price regions. With this the market coupling improves price convergence and social welfare, and it supports the integration of renewable energy sources. (EPEX SPOT, 2025)

Under the market coupling model, the electricity and the transmission capacity are not auctioned sequentially separately like they used to be, but they are optimized together through an implicit allocation mechanism. Market coupling lets electricity exchanges across countries to coordinate the matching of supply and demands on a single auction platform, Euphemia, which not only determines market prices, but also the cross-border net transfer positions. (Newbery et al., 2016) If the cross-border capacities are sufficient, then it leads to that prices are being harmonized through all regions and zones, while otherwise there are price differentials due to capacity constraints. (Newbery et al., 2019)

The background and foundation of market coupling in the European Union is rooted in the EU Third Energy Package, which introduced the integration of national electricity markets through market coupling mechanisms, like the European Day Ahead Market (DAM) auction platform, with the goal to improve trading efficiency, price convergence and the integration of renewable energy sources. As a part of this, the Target Electricity Model (TEM) was introduced to integrate electricity markets more effectively, which came into effect in 2014. (Newbery et al., 2019) Before the implementation of market coupling, traders were facing different risks, such as interconnectors that were not efficiently used or electricity flowing to the wrong direction: from high to low price region (Newbery et al., 2016, p. 254), therefore it is important to mention this as it is a barely 10-year-old framework. (Newbery et al., 2016)

When it comes to market coupling, different types can be mentioned, such as Single Day-Ahead Coupling (SDAC) or Single Intraday Coupling (SIDC). (EPEX SPOT, 2025) The SADC is operating through the previously mentioned implicit auctions by using a single algorithm, PCR Euphemia, which not only calculates clearing prices, but also matches trades and schedules the exchanges and by this it is supporting a unified and efficient European electricity market. (All NEMOs Committee, 2025) This is achieved through the Price Coupling of Regions (PCR) initiative, which is built on three key principles: the use of one single algorithm, a robust and decentralized data-sharing infrastructure and a service which is allowing power exchanges to share anonymized orders and network constraints that are helping with the determination of the bidding zone prices and the net positions. (EPEX SPOT, 2025)

3.4 Cross-Border Spill-Over Effects

Since the European systems are increasingly characterized by strong interconnections and market coupling, the renewable generation in one country can influence spot prices and even price volatility in neighboring countries. This can be identified as cross-border spill-over effect, which is the impact of high renewable output, that is reflecting this output’s effect as it lowers prices and increases volatlity. (Annan-Phan and Roques, 2018) Neighboring countries are not only “importing” the physical power, but also the price-lowering effects of those regions that have high renewable generation, as renewable production on average does not only lowers prices domestically, but also across borders in coupled markets. (Ibid.)

As mentioned, spill-overs impact price levels across interconnected electricity markets, which happens because of the surplus in renewable generation is often exported, which increases the supply and pushes down the demand beyond national borders, and the strength of these price spill-overs depends on the interconnector capacity. The interconnector can help to soften domestic price drops by allowing exports, however at the same time it can also increase exposure to cheap imported electricity, when the neighboring zones are having high renewable production, with this boosting the domestic price pressure, which is referred to as cross-border "cannibalization" and it leads to broader and deeper price drops across zones. This effect is especially visible in areas where renewables are mainly generated as solar energy, since the production patterns are highly synchronized across regions. (Stewie et al., 2025)

In addition to the direct price effects, the wind generators are increasing volatility as well in both domestic and interconnected markets. (Annan-Phan and Roques, 2018) Volatility spill-overs happen when volatility in one national market can affect the price dynamics in another market(s), which happens because of the strong interconnections and market coupling and national borders are not limiting it. (Cevik and Zhao, 2025) These volatility spill-overs are significant in interconnected markets because electricity, unlike gas and fossil fuels is not a storable commodity and therefore a mismatch between the supply and the demand immediately affects the prices and if this occurs in one country, it also immediately affects interconnected neighbors, moreover the degree of spill-overs are reflecting the level of the interconnectedness. (Cevik and Zhao, 2025; Weron, 2000)

The geometric asymmetries can be viewed as the barriers to balanced volatility spill-overs across European electricity markets, where mostly the central markets are acting like net transmitters of volatility, while markets that are further away are viewed as net receivers. These market asymmetries are linked to regional proximity and network centrality. Volatility spill-overs are stronger within the more central regions, which shows how the congestion and the limited cross-border capacity constrain deepens market integration. (Sikorska-Pastuszka and Papiez, 2023)

Lastly, hydro storages have a critical role in providing flexibility to electricity systems with high wind penetration, since even though wind generation reduces nodal prices, it increases price volatility, which is associated with spill-over effects on prices across the grid as it was previously discussed. However hydro, unlike wind, is dispatchable and can be stored, which allows it to absorb fluctuations and to stabilize prices. This flexibility is especially effective during wet seasons, when the availability of hydro power is high, and the opportunity cost of water use is low. In periods like this the hydro generation can mitigate both local and regional price volatility which is coming from the wind generation. On the other hand, during dry seasons, limited hydro availability reduces this buffering effect. (Wen et al., 2022)

3.5 Natural Gas Price Influence

In marginal cost-based electricity markets, the prices are set by the most expensive generator that is needed to meet the demand. Natural gas power plants many times fulfil this role because of their flexibility, and their dispatchability. Although variable renewable energy sources, like wind and solar are characterized by near-zero marginal costs and they are prioritized in dispatch, their volatility creates a need and holds a place for flexible backup capacity. Natural gas, with its easily dispatchable feature is increasingly concentrated at the margin, where they provide flexibility, especially during times when demand is high, but the renewable energy generators have low or zero generation. (Zakeri et al., 2023)

The marginal share concept captures this, which is the percentage of time, when a certain generation type sets market prices. Electricity prices are not only affected by renewable generation, but they are also significantly correlated with changes in the electricity output from natural gas fired power plants, which indicates the important role of gas as a marginal fuel in price formation. (Zakeri et al., 2023)

Natural gas prices are volatile because of their exposure to global markets, which are shaped by geopolitical events and international trade dynamics, and in electricity markets where the generation heavily relies on gas-fired plants, it does not only contribute to prices, but also to price volatility because of the strong coupling also with the natural gas market. Stringer et al. (2024) refers to it as "*electricity prices are at the mercy of the natural gas market*" (p.2), as the gas-based generation is often used to meet peak demand periods. And while gas offers flexibility and ease on one hand to power the generation, on the other hand its cost is driven by external factors, which can make electricity prices more sensitive and vulnerable to sudden fluctuations. (Stringer et al., 2024)

3.6 Conclusion

This chapter outlined the key theoretical mechanisms that are influencing the electricity spot prices when it comes to the context of growing renewable energy integration, in which the merit-order effect was found as a central price driving factor, which explains how do the low marginal cost renewables reduce the spot prices. Besides the merit-order effect, the role of market interconnectivity, market coupling, and cross-border spill-overs were also introduced as they are becoming more and more important in the European market. To make a clear distinction between the three, market interconnectivity refers to the physical cross-border links that allow the flow of electricity between countries, market coupling is governing how this interconnection capacity is allocated, while cross-border spill-overs describe the effects that are happening across borders due to the interconnection and market coupling. Finally, the importance of natural gas was also mentioned, as it is a marginal fuel and volatility driver.

Even though the effects of these factors are not all separately studied and analyzed in this report, they are all still important to understand the market and its mechanisms in Europe and in the Nordics, as together these concepts are the theoretical foundation for analyzing how renewable generation, consumption, trade, and external price factors are influencing the day-ahead electricity prices in the Nordic region.

4. Methodology

4.1 Research philosophy

The thesis ontologically is based on objectivism, as it assumes that the dynamics of the electricity market and the price patterns existence is not dependent on individual perception, and it can be observed and measured objectively. Variables like the renewable generation, electricity consumption, and market prices are treated as real occurrences, and they are reflecting the actual dynamics of the Nordic electricity market. (Saunders et al., 2023)

The epistemology of the research relies on a positivist perspective, as the knowledge is generated through empirical observation, measurement and statistical analysis, with aiming to identify generalizable causal relationships between electricity prices and their short-term drivers using hypotheses and econometric modeling that were created based on theory. (Ibid.)

4.2 Research approach

The research follows a deductive approach, which starts with establishing theories on electricity market behaviour, like the merit-order effect, market interconnectivity and cross-border trade, and the influence of natural gas prices, and based on these theoretical foundations, hypotheses were created to examine how the electricity consumption, renewable generation, cross-border trade, and the different weather conditions are affecting the day-ahead electricity prices. (Saunders et al., 2023)

The aim was to test whether these theoretical expectations are holding in the context of Denmark, Norway, and Sweden, which was done using fixed effect panel regression models, that were supported by instrumental variable methods and Driscroll-Kraay standard errors.

With the application of this theory-driven, deductive approach, this paper moves from general concepts to specific empirical testing to make sure that the results are linked to both theory and actual market data.

4.3 Research design and strategy

The paper is following a quantitative research design, as outlined by Creswell (2009), which is characterized by using numerical data, structured data collection, and statistical analysis to test the relationship between the chosen variables, with having the objective to examine how do the electricity consumption, renewable generation, cross-border trade, add weather conditions influence day-ahead prices in Denmark, Norway, and Sweden.

The design of the thesis is longitudinal, and it is using hourly panel data over a five-year period, which is allowing the analysis to capture cross-country dynamics in the Nordic electricity markets, while also using secondary data, therefore it only observes existing conditions without manipulating variables. (Leedy and Ormrod, 2015)

To control for country-specific effects, the analysis uses fixed effects regression models with instrumental variable method and robust standard errors to make sure that potential endogeneity is addressed, and the models' stability is consistent throughout the paper.

4.4 Data collection, analysis and hypotheses

4.4.1 Data collection

Secondary data collection methodology (Leedy and Ormrod, 2015) was used for the thesis, which is based on using previously recorded, structured datasets being obtained from official sources, which is in line with the quantitative nature of the research, that allows the analysis to happen without direct intervention or manipulation. (Ibid.)

The data covers a five-year period with hourly frequency (except the TTF gas prices as they were only available in daily frequency), which was collected from trusted data providers including Nord Pool, ENTSOE-E, EEX, and Open-Meteo. In case missing values were found in the datasets accessed from Nord Pool, they were double-checked against ENTSOE-E and in case the missing value was available through ENTSOE-E, they were manually filled based on that to ensure data continuity without synthetic data filling.

Bidding zone-level level data was summed up to country-level with consumption-weighted averages, to match the scope of the country-level analysis. The final dataset was then merged to a panel structure, with the three countries as cross-sectional units and the hourly observations over a five-year period as the time dimension.

During the data structuring process delivery IDs were created to uniquely identify each hourly observation, as this was a necessary step taking into consideration the daylight-saving time changes, because certain days had duplicated time stamps in the autumn period. By using consistent delivery IDs, the complications in the analysis coming from the duplicated values were avoided.

4.4.2 Data analysis method

To empirically evaluate the relationship between the renewable electricity generation and the day-ahead prices in the Nordic market, a fixed effects panel data framework was used. Taking into consideration the dataset's structure (high-frequency hourly observations for a small number of countries over a large time period), the fixed effects panel model was found suitable, because it allows for controlling for both unobserved country-specific heterogeneity and time varying factors that possibly influence electricity prices. (Wooldridge, 2013, p. 485)

The analysis is focusing on one main specification and five robustness tests (out of which the last two are in Appendix C), all of them are using fixed effects regression and all are adding additional explanatory variables or interaction terms to make the analysis deeper by taking into consideration different factors. Even though the Hausman test on the main model indicated that the random effects model could be consistent (result is in Appendix B), the fixed effects model was eventually chosen based on theoretical considerations and the nature of the dataset. Specifically, the small number of cross-sectional units (N=3), the possible correlation between unobserved individual effects and regressors, and diagnostic evidence of heteroskedasticity and serial correlation are all making the fixed effects regression more suitable, because the Driscroll-Kraay standard errors is an effective way to account for the complex errors in a fixed effects panel model with large T. The Driscroll-Kraay method in contrast with clustered standard errors, is valid even if the units are correlated across time and space and it applies a Newey-West type correction to cross-sectional averages, which provides a more reliable inference if there are unobserved common shocks. All the models were analyzed in Rstudio. (Wooldridge, 2013, p. 485; Hoechle, 2007)

The fixed effects approach controls for all time-invariant heterogeneity across countries by using within-unit variation over time, and the model specification assumes that unobserved unit-specific effects might be correlated with the explanatory variables. As mentioned, the within transformation was used for the estimation, which removes the unobserved effects by subtracting individual means from each observation, which allows the time-varying regressors to be consistently estimated, even if there are omitted variables that are constant over time. (Wooldridge, 2013, p. 485) Fixed effects is also useable for unbalanced panels as long as the unbalanced nature of it is not systematically related to the idiosyncratic error, u_{it}. (Wooldridge, 2013, p. 491)

The unobserved effects model is the following:

$$y_{iy} = \beta_1 x_{it1} + \beta_2 x_{it2} + \cdots + \beta_k x_{itk} + a_i + u_{it}, \qquad t = 1,2,\ldots,T$$

Equation 1: Unobserved effects model (Wooldridge, 2013, p. 485)

By applying the within transformation, the time-averaged values are being subtracted from each variable and the model becomes:

$$\ddot{y}_{it} = \beta_1 \ddot{x}_{it1} + \beta_2 \ddot{x}_{it2} + \cdots + \beta_k \ddot{x}_{itk} + \ddot{u}_{iy}, \qquad t = 1,2,\ldots,T$$

Equation 2: Time-demeaned equation (Wooldridge, 2013, p. 485)

This time-demeaned equation removes the unit-specific fixed effect a_i and by this it allows the slope coefficients β_j to be consistently estimated through pooled OLS on the transformed data. (Wooldridge, 2013, p. 485)

The fixed effects estimation has an important aspect when it comes to the treatment of degrees of freedom: although, the time-demeaned model has NT observations and k regressors, one degree of freedom is lost per unit due to the demeaning process (Wooldridge, 2013, p. 486):

$$df = NT - N - k = N(T-1) - k$$

Equation 3: Degrees of freedom (Wooldridge, 2013, p. 486)

The validity of the fixed effects assumptions lies on several key assumptions that make sure about the consistency and the unbiasedness of the estimation. These assumptions relate to both the error term and to the structure of the data itself and they are tested for the main model and for all the robustness models too. Assumptions for the fixed effects estimator as outlined by Wooldridge (2013, p. 509-510):

FE.1: Linear panel model with additive fixed effects

The fixed effects model is assuming a linear relationship between the dependent variable and the time-varying regressors, with an additional unobserved individual-specific effect. This defines the structure of the model and it not statistically testable, but it reflects the theoretical choice to account for unobserved fixed characteristics that might otherwise bias the estimation. (Wooldridge, 2013, p. 509)

$$y_{iy} = \beta_1 x_{it1} + \cdots + \beta_k x_{itk} + a_i + u_{it}, \qquad t = 1,2,\ldots,T,$$

Equation 4: FE1 assumption (Wooldridge, 2013, p. 509)

FE.2: Random sampling across cross-sectional units

The random sampling assumption relies on that the cross-sectional units, in this case the countries represent a random sample from a larger population. This assumption cannot be tested directly, however in this study, although the panel includes only Denmark, Norway and Sweden, they are treated as a representative sample of a broader Nordic electricity market. (Wooldridge, 2013, p. 509)

FE.3: No perfect collinearity

This requires that the explanatory variables are showing changes with time within each cross-sectional unit and they are not perfectly linearly related. (Wooldridge, 2013, p. 509) To verify this assumption, a multicollinearity check was done by estimating an OLS model with the same specification and then calculating Variance Inflation Factors (VIFs). VIFs show how one explanatory variable is correlated with the other explanatory variables, if the value of VIF is less than 10, then it indicates no severe multicollinearity. (Wooldridge, 2013, p. 98)

FE.4: Strict exogeneity

This assumption requires that the idiosyncratic error term, u_{it} is uncorrelated with the regressors in all time periods for each unit, meaning that nothing in the error term influences the regressors in any time period, including future, which is a strong assumption, however it is not directly testable. (Wooldridge, 2013, p. 509) In the context of this study, the regressors, like the electricity consumption, renewable generation, and weather-related variables are largely exogenous and predetermined by physical processes or operational rules and are not likely to be influenced by short-term pricing errors.

FE.5: Homoskedasticity

The fifth assumption implies that the variance of the idiosyncratic error term u_{it} is constant across all time periods and units. (Wooldridge, 2013, p. 509) To test this, a modified Wald test for groupwise heteroskedasticity was used, which evaluates whether error variances differ systematically across units, and it is particularly suitable for panel data. (Baum, 2001)

FE.6: No serial correlation in the idiosyncratic errors

The sixth assumption requires the idiosyncratic errors u_{it} to be uncorrelated over time within each cross-sectional unit, which means that past shocks are not supposed to influence current error terms. (Wooldridge, 2013, p. 509) In this study, the Wooldridge test was applied to test the serial correlation. With this approach first-differenced residuals are regressed on their lagged residuals across all times and units, and a t-test is used to define the presence of serial correlation. (Wooldridge, 2001)

FE.7: Normality of idiosyncratic errors
The last assumption states that the idiosyncratic error term u_{it} is normally distributed with zero mean and constant variance, being conditional on the regressors and fixed effects. Since true errors are not observable, this assumption cannot be tested directly, but in large samples, the asymptotic inference remains valid even if the normality is not strictly satisfied. (Wooldridge, 2013, p. 509)

Since the Hausman test did not reject the null hypothesis of no systematic difference between fixed and random effects estimates, a random effects model was also estimated using the main specification, which was done to show how the results might differ under the random effects assumption, that the unobserved unit-specific effects are uncorrelated with the explanatory variables. However, given the nature of the data and theoretical expectations of these correlations, the fixed effects model remained the preferred approach, but the estimation output for the random effects model is shortly presented in Appendix A1. (Wooldridge, 2013)

All of the models are using instrumental variable methods within the fixed effects panel data model to address potential endogeneity in the one of the main explanatory variables, the renewable electricity generation (RES_generation), as outlined by Wooldridge (2013). (The need for IV methods is confirmed in Appendix A2.)

Endogeneity can arise if the RES generation is correlated with time-varying unobserved factors, which are also influencing electricity spot prices (DA_price). Even though the fixed effects estimation removes the time-invariant unobserved heterogeneity, it does not help with the correlation between the remaining idiosyncratic error term and the RES_generation if the second is endogenous, which violates the strict exogeneity assumption and can cause biased or inconsistent coefficients.

The model uses a two-stage least squares (2SLS) estimator, where sunshine and wind are used as instruments for RES_generation. These weather variables are the strongest predictors of renewable generation and since they are weather controls, they are not expected to be correlated with the structural error term in the electricity price equation.

The structural model estimated is:

$$\begin{aligned} DA\_price_{it} = {} & \beta_0 + \beta_1 \widehat{RES_{it}} + \beta_2 consumption_{it} + \beta_3 net\_import_{it} + \beta_4 temperature_{it} \\ & + \beta_5 rain_{it} + day\ dummies + month\ dummies + a_i + u_i \end{aligned}$$

Equation 5: Structural model (Based on Wooldridge, 2013. p. 524)

Where:
DA_price_{it} is the day-ahead electricity spot price in country i at time t,
RES_{it} is the predicted value of renewable generation from the first-stage regression,
X_{it} includes the explanatory variables such as consumption, net imports, temperature, and rain,
a_i captures unobserved country-level fixed effects,
u_i is the idiosyncratic error term.

The first-stage equation is:

$$RES_{it} = \pi_0 + \pi_1 sunshine_{it} + \pi_2 wind_{it} + \pi_3 consumption_{it} + \pi_4 net\_import_{it} + \pi_5 temperature_{it} + \pi_6 rain_{it} + day\ dummies + month\ dummies + v_{it}$$

Equation 6: First-stage equation (Based on Wooldridge, 2013, p. 525)

The two-stage least squares (2SLS) estimator for panel data models is used to get consistent estimates for the possibly endogenous variable, RES_generation. In the first stage, the variable that is possibly endogenous is regressed on all exogeneous variables. Then the fitted values from this first-stage regression, which by now are removed the endogeneity are then used in the second stage to estimate the structural model. While the included exogeneous regressors are present in both stages, some exogeneous variables, like sunshine duration and wind speed are excluded from the second stage and used only as instruments, which is based on the assumption, that they are affecting the electricity prices only through their influence on renewable generation. (Wooldridge, 2013)

"*It often happens that we have more than one exogenous variable that is excluded from the structural model and might be correlated with y_2, which means they are valid IVs for y_2.*" (Wooldridge, 2013, p. 528)

4.4.3 Hypotheses

Hypothesis I

To study the dynamics of electricity pricing in the Nordic region, it is important to take into consideration the drivers of it both on the demand and the supply side, as well as the external and environmental factors. The electricity consumption, which can be viewed as the demand has an effect on the marginal pricing along with the renewable energy generation, which is characterized by low marginal costs that affects market supply conditions and volatility. The net import captures the influence of external price signals, while weather variables, such as temperature and rain affect both renewable supply availability and demand patterns, and together these factors are providing a relevant set of explanatory variables for analyzing hourly price formation in the day-ahead electricity market of the Nordic countries. (Blume-Werry et al., 2021; Bahar and Sauvage, 2013; Newbery et al., 2018; Urquijo and Paraschiv, 2023; Wolff and Feuerriegel, 2018)

Working question I:

Does electricity consumption, renewable energy generation, cross-border electricity trade, and weather conditions significantly affect day-ahead electricity prices in Denmark, Norway and Sweden?

To address this question, fixed effects panel data regression with IV methods was estimated, with the use of hourly data over five years from three Nordic countries. The dependent variable is the hourly day-ahead electricity price, while the explanatory variables are the electricity consumption, total renewable electricity generation, net electricity imports, and two weather controls: temperature, and rainfall. Moreover, day-of-week and month dummies were also included as time controls.

The model is specified the following way:

$$DA\_price_{it} = \beta_1 * consumption_{it} + \beta_2 * RES_{generation_{it}} + \beta_3 * net_{import_{it}} + \beta_4 * tempreature_{it} + \beta_5 * rain_{it} + day\ dummies + month\ dummies + a_i + u_{it}$$

Equation 7: Main model specification

Where:
DA_price_{it} is the day-ahead electricity price for country i at time t,
a_i captures unobserved time0invariant country-specific effects,
u_{it} is the idiosyncratic error term,
and the explanatory variables represent time-varying market and environmental factors.

Hypothesis test:
For the evaluation of the effect of the above variables, the following hypothesis was tested:

- Null hypothesis (H_0): None of the explanatory variables have statistically significant effect on day-ahead electricity prices.
- Alternative hypothesis (H_1): At least one explanatory variable has statistically significant effect.

Hypothesis II

Day-ahead prices are set by the marginal price of the last unit that is needed to meet the demand in competitive electricity markets. Since renewable energy sources have near-zero marginal costs, an increase in their generation is expected to push down prices, however the magnitude of this price reducing effect can be different across countries, depending on the electricity system's structure and the flexibility of their generation. (Blume-Werry et al., 2021; Bahar and Sauvage, 2013; Newbery et al., 2018)

Working question II: Do the day-ahead electricity prices in Denmark, Norway, and Sweden respond differently to their own domestic renewable electricity generation?

To test this hypothesis, the main model was extended by interacting each country's own renewable generation with country dummies, which allows the marginal effect of RES generation on electricity prices to change by country.

The model is expressed as:

$$DA\_price_{it} = \beta_1 * consumption_{it} + \beta_2 * net_{import_{it}} + \beta_3 * tempreature_{it} + \beta_4 * rain_{it} + \beta_5 * (RES_{generation} * \ DK) + \beta_6 * (RES_{generation} * NO) + day\ dummies + month\ dummies + a_i + u_{it}$$

Equation 8: Robustness test 1 specification

Note: Sweden is used as a reference category, and it does not have its own RES interaction term to avoid the dummy variable trap.

Hypothesis test:

- Null hypothesis (H_0): The effect of the domestic RES generation on day-ahead prices is the same across the three countries.
- Alternative hypothesis (H_1): At least one country's day-ahead electricity prices respond differently to the changes in its own RES generation.

Hypothesis III

While electricity prices in the Nordic market are very much shaped by renewable energy and cross-border trade, natural gas remains a key marginal fuel across European power systems. Including TTF gas prices makes it possible to evaluate whether fluctuations in European gas markets influence the electricity prices in the Nordic region. (Zakeri et al., 2023; Stringer et al., 2024)

Working question III: Do European natural gas prices, proxied by Dutch TTF day-ahead prices, have a significant influence on day-ahead electricity prices in the Nordic countries, beyond domestic supply, demand, and weather factors?

To test this, the main model was expanded with the TTF gas price as an additional regressor, while all other model specifications remained the same.

The model:

$$DA\_price_{it} = \beta_1 * consumption_{it} + \beta_2 * RES_{generation_{it}} + \beta_3 * net_{import_{it}} + \beta_4 * tempreature_{it} + +\beta_5 * rain_{it} + \beta_6 * TTF\_price_{it} + day\ dummies + month\ dummies + a_i + u_{it}$$

Equation 9: Robustness test 2 specification

Hypothesis test:

- Null hypothesis (H_0): The Dutch TTF gas price has no statistically significant effect on day-ahead electricity prices in the Nordic market.
- Alternative hypothesis (H_1): The Dutch TTF gas price has a statistically significant effect on day-ahead electricity prices in the Nordic market.

Hypothesis IV

As it was mentioned in the previous hypothesis, even though electricity prices in the Nordic market are very much affected by renewable energy and cross-border trade, marginal fuel prices are also affecting the electricity prices, however the sensitivity to the gas prices can vary by countries. (Zakeri et al., 2023; Stringer et al., 2024)

Working question IV: Does the sensitivity of Nordic day-ahead electricity prices to European gas prices changes across Denmark, Norway and Sweden?

To test this hypothesis, interaction terms between the TTF gas price and the country dummies for Denmark and Norway were added to the main model, while Sweden was excluded and it serves as the reference category to avoid the dummy variable trap. This specification allows the marginal effect of gas process on electricity prices to be different across countries, while all other variables from the main model remained the same.

Model specification:

$$DA\_price_{it} = \beta_1 * consumption_{it} + \beta_2 * RES_{generation_{it}} + \beta_3 * net_{import_{it}} + \beta_4 * tempreature_{it} + \beta_5 * rain_{it} + \beta_6 * (TTF + rice * DK) + \beta_7 * (TTF + rice * NO) + day\ dummies + month\ dummies + a_i + u_{it}$$

Equation 10: Robustness test 3 specification

Hypothesis test:

- Null hypothesis (H_0): There are no significant differences between the countries in how TTF gas prices affect electricity prices.
- Alternative hypothesis (H_1): At least on country responds differently to TTF gas prices compared to Sweden.

Hypothesis V

Renewable energy generation, particularly wind and solar can have downward pressure on electricity prices due to their non-zero marginal cost. However, the price effects might be non-linear, especially during hours when there is exceptionally high renewable output. This hypothesis explores whether price behaviour is significantly different during these extreme production hours. The identification of these non-linear price effects is very important to understand market dynamics in countries where renewable penetration is high. (Owolabi et al., 2022; Würzburg et al., 2013; Bahar and Sauvage, 2013)

Working question V: Do day-ahead electricity prices respond differently during hours of exceptionally high renewable energy generation (top 5% of RES output)?

To test this hypothesis, a dummy variable was created for the top 5% hourly renewable generation values across the entire sample, and this binary variable was added to the main fixed effects panel regression alongside all the original controls.

This model is expressed as:

$$DA\_price_{it} = \beta_1 * consumption_{it} + \beta_2 * RES_{generation_{it}} + \beta_3 * net_{import_{it}} + \beta_4 * tempreature_{it} + \beta_5 * rain_{it} + \beta_6 * high\_RES\_dummy_{it} + day\ dummies + month\ dummies + a_i + u_{it}$$

Equation 11: Robustness test 4 specification

Where:
high_RES_dummy = 1 if RES_generation ≥ 95^{th} percentile,
high_RES_dummy = 0 otherwise.

This specification allows to test for non-linear or amplified price effects during extreme RES output hours.

Hypothesis test:

- Null hypothesis (H_0): High renewable output hours do not lead to additional price effects beyond the linear RES_generation effect.
- Alternative hypothesis (H_1): High renewable output hours are associated with statistically significant shifts in day-ahead electricity prices.

The analysis and the discussion for this hypothesis is in Appendix C1.1.

Hypothesis VI

While the previous analysis tested whether electricity prices respond differently during hours of exceptionally high renewable generation, this hypothesis deepens the question by exploring whether the non-linear price effects are different across countries. Each Nordic country has a different energy mix and level of exposure to renewable generation, which all might influence how extreme RES output translates into price dynamics. By identifying country-specific effects, this test identifies whether high RES penetration leads to asymmetric price responses across Denmark, Norway and Sweden. (Owolabi et al., 2022; Würzburg et al., 2013; Bahar and Sauvage, 2013)

Working question VI: Does the impact of extremely high renewable electricity generation (top 5% of RES output) on day-ahead prices differ across Denmark, Norway and Sweden?

To test this hypothesis, the model used country-specific dummy variables that equal to 1 when the country's own RES output reaches or exceeds the 95th percentile, and these dummies were interacted with the country dummies and added to the main fixed effects estimation. Sweden is excluded from the interaction to avoid the dummy variable trap, and it serves as a baseline.

The model is specified as:

$$DA\_price_{it} = \beta_1 * consumption_{it} + \beta_2 * RES_{generation_{it}} + \beta_3 * net_{import_{it}} + \beta_4 * tempreature_{it} + \beta_5 * rain_{it} + \beta_6 * high\_res\_dk + \beta_7 * high\_res\_no + day\ dummies + month\ dummies + a_i + u_{it}$$

Equation 12: Robustness test 5 specification

Hypothesis test:

- Null hypothesis (H_0): There is no difference in the price impact of extremely high renewable output across countries
- Alternative hypothesis (H_1): At least one country exhibits a significantly different price response during high-RES periods compared to Sweden.

The analysis and the discussion for this hypothesis is also in Appendix C1.2.

4.5 Validity, reliability and representativity

4.5.1 Validity

Construct validity (Saunders et al., 2012) is accounted for by matching the variables in the dataset with theoretical concepts that were discussed in the literature reviews and in the theory chapter. Electricity consumption, renewable energy generation, net imports, and weather-related factors were selected and defined taking into consideration theoretical bases, like the merit-order effect or market coupling, therefore the explanatory variables that were used in the model are in line with the price formation mechanisms that the research aims to analyze.

Regarding internal validity (Saunders et al., 2012), the fixed effects panel regression models were used to control for unobserved time-invariant differences across countries, which helps to isolate the impact of the main independent variables on the electricity prices. Moreover, to address potential endogeneity in renewable electricity generation, instrumental variable methods were used in all the models, however in robustness tests 4 and 5 endogeneity might still be present, therefore these results are interpreted with caution, and they were placed in Appendix C, and they are not part of the main conclusion.

Lastly, when it comes to external validity (Saunders et al., 2012), the results are considered relevant within the Nordic context, as the data and the analysis covers three countries over a five-year period. However, the findings might not be generalizable in markets that have different structures, for example those that are fossil-fuel dominated.

4.5.2 Reliability

The reliability of the analysis is secured by the use of standardized, high-frequency datasets from official and trusted platforms such as Nord Pool, ENTSOE-E, EEX, and Open-Meteo, which are commonly used in academic and market research, and which makes sure about the dataset's the credibility and repeatability. (Saunders et al., 2012)

The data processing steps, which are including timestamp alignment and making sure that every unit is harmonized, and the fact that missing values were filled from other reliable source are documented and were consistently done throughout the whole dataset, and no artificial or statistical imputation methods were used, are all contributing to the reliability. If the same data was sourced and the same regression techniques were used by another researcher, the results would be replicable, especially since the cleaned and structured dataset was constructed with reproducible steps. (Saunders et al., 2012)

4.5.3 Representativity

The dataset that is used in this thesis contains hourly observations across three countries during a five-year period, which makes it highly representative of the Nordic electricity markets. The use of country-level averages ensures that the price patterns are reflecting the whole country's market behaviour.

Even though the dataset does not include bidding-zone level analysis, the national level averages are able to capture key differences between the countries. Weather data was based on capital cities, which is a geographic simplification, especially in case of Norway and Sweden, but this was based on practicality, however using different regions' weather data could have made it more representative.

When it comes to the representativity, it is also an important factor that since the complete population data was used instead of a sample, it strengthens this study, since by this sampling bias were completely avoided, therefore the dataset is representative, besides the geographical simplification in the weather data. (Saunders et al., 2012) However, since it is a specific Nordic study, it might not be generalizable without caution for different markets.

5. Empirical Chapter

In this chapter the data sources and the variables are presented that will guide the empirical discovery of how the different theory-based factors are influencing the electricity spot prices across Denmark, Norway and Sweden. In the following sections the dataset's nature, structure and role will be discusses, before presenting the descriptive characteristics of the main variables.

5.1 The Data

The data that was used in the paper was collected from secondary sources, using official platforms, with the primary source for electricity-related data being Nord Pool, which provided hourly observations on day-ahead electricity prices, electricity consumption, and renewable electricity generation for each bidding zone in Denmark, Norway, and Sweden. These values were summed up to country level using consumption-weighted averages to match the analytical scope of the study.

Data on cross-border electricity trade (net imports) were retrieved from ENTSOE-E Transparency Platform, which provides hourly bilateral trade flows between countries, and the net imports were calculated as the difference between imports and exports at each hour for all sides, and then summed to get country-level values.

Weather data, which includes temperature, sunshine duration, wind speed, and rainfall were collected from Open-Meteo, and for consistency and geographic simplification, the capital cities were used as proxies of each country for national weather conditions.

Daily Dutch TTF gas prices were used as proxy for the broader European gas market, which were requested from European Energy Exchange (EEX), however these were only available in daily frequency, therefore each daily value was assigned to all 24 hours of the same day to match the structure of the electricity dataset.

All datasets were downloaded and merged to a panel format, structured with hourly observations across the three countries over the five-year period, by which a high-frequency dataset was created, which allows for a detailed and consistent empirical analysis.

5.2 The Variables

5.2.1 Dependent variables

DA_price:

The dependent variable in all models is the hourly electricity day-ahead price for Denmark, Norway and Sweden for the studied 5-year period. It is the core outcome variable, as day-ahead prices are widely used in electricity market research due to their transparency, and it reflects the market equilibrium price that is determined by the supply-demand bidding behaviour. (Bahar and Sauvage, 2013, Newbery et al., 2018, Blume-Werry et al., 2021)

Since Denmark, Norway and Sweden are having separate bidding zones in their electricity markets, with different prices for each zone, to be able to conclude a country-level analysis, consumption weighted average prices were created following a similar approach that is used by Eurostat in their electricity price statistics. (Eurostat, 2024) The hourly day-ahead prices and the consumption data for each bidding zone were retrieved from Nord Pool, and they are in EUR/MWh. The country-level day-ahead prices were calculated with the below formula:

$$Country - level\ price = \frac{(Bidding\ zone\ 1\ price * Consumption\ zone\ 1 + Bidding\ zone\ 2\ price * Consumption\ zone\ 2 + \cdots + Bidding\ zone\ n\ price * Consumption\ zone\ n)}{(Consumption\ zone\ 1 + Consumption\ zone\ 2 + \cdots + Consumption\ zone\ n)}$$

Equation 13: Country-level DA price

5.2.2 Explanatory and control variables

consumption:

One of the independent variables is the consumption, for which the hourly volumes were used of Denmark, Norway and Sweden. The electricity market's real-time balancing nature makes consumption an effective representation of the demand, and it controls for that side of the price formation. For this Nord Pool was used as a source and the bidding zone level consumptions were summed to create a country-level consumption and the volumes are in MWh. (Blume-Werry et al., 2021; Bahar and Sauvage, 2013; Wolff and Feuerriegel, 2018)

RES_generation:

The generation of renewable energy sources (RES) is the one of the most important explanatory variables, and it is included in every model as it is essential for testing the merit-order effect (how the renewable energy output drives the electricity prices). For this renewable production data was accessed from Nord Pool for every country from different sources of renewable generation, such as wind, solar, hydro and other renewables on a bidding zone-level, which were added together on a country level, then all types were summed into on total renewable production output, and they are in MWh. (Würzburg et al., 2013; Bahar and Sauvage, 2013)

To illustrate the differences in the renewable energy mixes between Denmark, Norway and Sweden, the following pie charts show the share of wind, solar, hydro, and other renewables in the total renewable electricity generation during the studies period in the three countries:

It can be seen that Norway is hydro-dominant, as more than 90% of its renewable electricity generation is coming from hydro generation, while it has 8,4% wind generation and a minor solar and other type of renewable generation.

Sweden has a much higher balance between hydro and wind, as it has 55,3% hydro generation and 43,47% of wind generation, while it also has a minor 1,22% solar generation.

Denmark is clearly wind-dominated, as its renewable generation is coming from 88,85% wind generation and 11,15% solar generation.

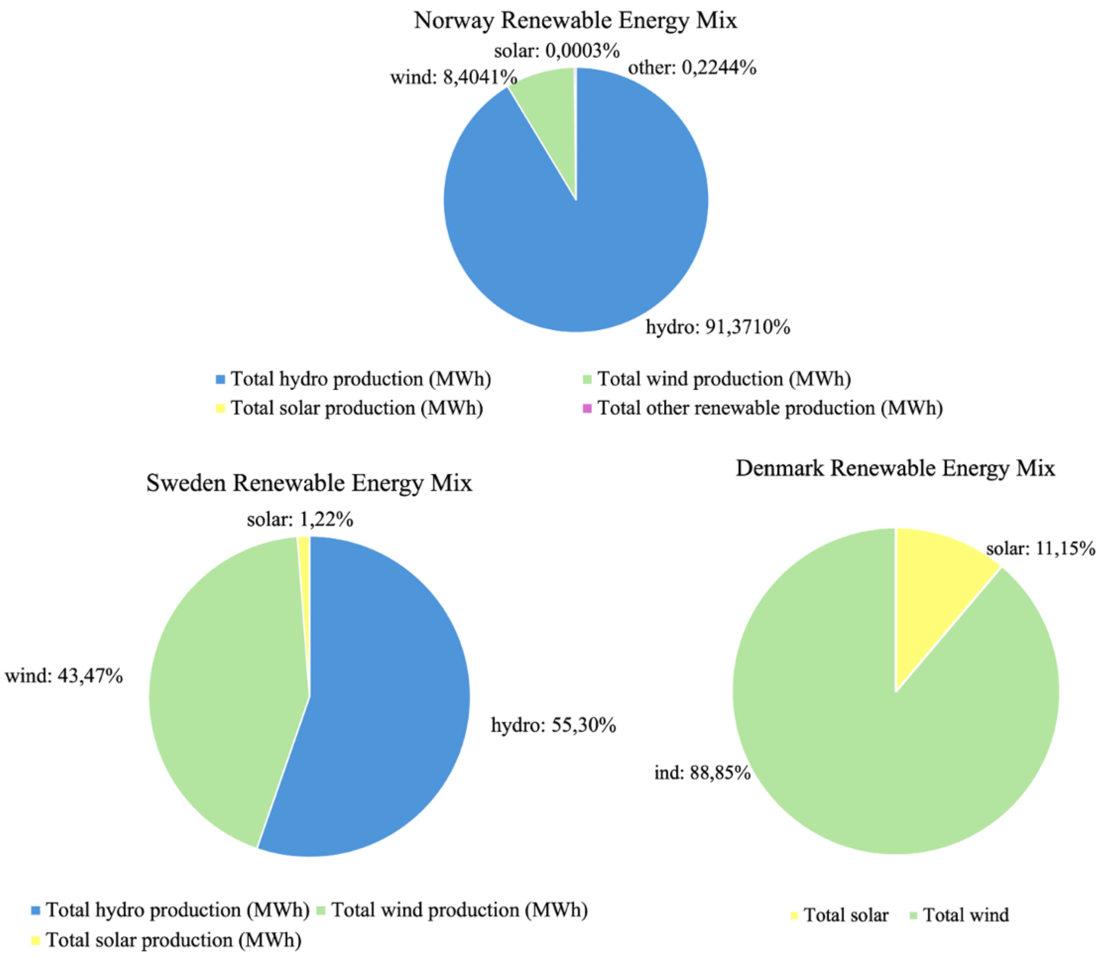

Figure 1: Countries' Renewable Energy Mix (data source: Nord Pool)

net_import:
Net import, which is another hourly dependent variable, shows the net electricity imports per country, and it also linked to the effects of market coupling, cross-border flows and market interconnectivity. It is also present in every model, and it was sourced from ENTSOE-E Transparency Platform as cross-border flows per country. It was calculated for each country based on bilateral trade flows with all active trading partners, first the partner-level net imports were calculated for each country-partner pair by subtracting the export amounts from the import amounts on an hourly level. Then to obtain the total net imports for each country at each point in time, these partner-level net imports were summed on a country-level. Volumes are reported in MWh. (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021)

temperature:
Temperature was included as a demand side control variable, as it directly affects the heating and cooling needs. In colder periods electricity demand naturally rises, especially in the Nordic region. Temperature is in Celsius degrees, and it was retrieved from Open-Meteo and the capital cities were used as proxies for the countries, so for Denmark Copenhagen's weather, for Norway Oslo's weather, and for Sweden Stockholm's weather.

sunshine:
Sunshine was included as an instrument for the RES generation, and it is assumed to be correlational with it. Longer sunshine hours are generally leading to higher electricity output from solar panels, by this increasing the renewable supply and possibly pushing down the spot

prices due the merit-order effect. This control is important during daylight hours, especially around the middle of the day, when solar generation is usually the highest. Sunshine duration was also sourced from Open-Meteo and it is measured in seconds of sunshine observed per hour. The capital cities were used again as proxy locations for the sunshine duration. (Loumakis et al., 2019)

wind:
Wind speed was another instrument for RES generation, since wind-generation is highly sensitive to wind speed, therefore by controlling for the wind, which can significantly influence the merit-order effect. Wind speed is in km/h, it is accessed from Open-Meteo and the capital cities were used as proxy locations for the three countries. (Ketterer, 2014)

rain:
Rain was added as a control variable for the hydropower generation, which is a present in all three countries, but it is the heaviest in Norway. Rain increases the reservoir levels, and it boost the hydro generation, and its effect is direct and immediate. Rain is measured in millimeters, and it is sourced from Open-Meteo and capital cities of the three countries were used for the locations as proxies. (Wen et al., 2022)

TTF_price:
In the theory section it was explained that electricity prices can be highly affected by alternative fuel, especially gas prices. To control for these, in two robustness tests the Dutch TTF day-ahead gas prices were introduced as a proxy for gas prices across Europe as the Dutch TTF is the largest and most traded gas hub in Europe. (The Oxford Institute for Energy Studies, 2021) The prices were requested from EEX and they were in daily frequency, therefore to match the hourly granularity of the rest of the data, the corresponding daily gas prices were assigned to all 24 hourly observations within the same day, and the prices are in EUR/MWh. (Zakeri et al., 2023; Stringer et al., 2024)

5.2.3 Dummy variables

In case of dummy variables, to avoid perfect multicollinearity and the dummy variable trap, in case of n number dummy variables, always n-1 dummies were included in the model estimations. (Verbeek, 2004, p. 73)

dk, no, se:
Country dummies were added to control for the unobserved and time-invariant heterogeneity across Denmark (dk), Norway (no) and Sweden (se), which are capturing the structural differences in the markets, energy mixes and regulatory conditions that are time-constant, but change between the countries.

high_res_dummy:
A binary variable was created for the renewable electricity production if the hourly generation fell into the top 5% of all observed RES generation values in the dataset. The purpose of this dummy is to test whether the price dynamics change and show non-linearity during those periods when the production was exceptionally high and if it intensifies the merit-order effect. (Owolabi et al., 2022)

high_res_dk_dummy, high_res_no_dummy, high_res_se_dummy:
A binary variable was created if the hourly renewable electricity generation exceeds the 95th percentile within that specific country's own distribution, and 0 otherwise. This version defines the high RES output relative to each country's typical generation levels and it allowing the model to test the dynamics between high renewable generation and prices on a country level.

month:
The month dummy was one of the time-control dummies, it was used to account for seasonal effects, as electricity markets are very much affected by seasonality, and it controls for recurring seasonal patterns both in production and consumption due to weather conditions. By including these dummies it is easier to isolate the impact of other regressors by absorbing fixed seasonal variation. (Wolff and Feuerriegel, 2018)

day:
Day of the week was the other time-control dummy, it was added to capture systematic differences between weekdays and weekends, as on weekends there might be lower industrial related demands or changes on the consumer side. (Wolff and Feuerriegel, 2018)

5.2.4 Interaction terms

Robustness test 1: RES_generation x country
This interaction term was used to test how does the impact of renewable energy generation on spot prices differs between the Nordic countries, therefore separate terms were created for each country by multiplying the country dummies with their own RES_generation. With this the model can estimate the country-specific coefficients for the price effect of renewable energy supply by taking into account the differences between the renewable energy mixes of the countries.

Robustness test 3: TTF_price x country
To test whether the electricity prices in the three countries show different sensitivities to the market dynamics of European gas market, an interaction term was created between the country dummies and the Dutch TTF day-ahead prices. These constructed variables allow the model to estimate how each country's spot prices react to changes in gas prices.

Robustness test 5: high_res country dummy x country
This interaction term was created to test whether the price effect of exceptionally high renewable generation differs between Denmark, Norway, and Sweden. The high RES country dummy was defined separately for each country based on their own 95th percentile threshold. By interacting this with the respective country dummies, the model can capture country specific price effects during extreme domestic renewable output conditions.

5.3 Table of Variables

Variable	Description	Type	Unit	Used in	Source
DA_price	Day-ahead electricity price	Dependent	EUR/MWh	All models	Nord Pool
consumption	Electricity demand	Explanatory	MWh	All models	Nord Pool
RES_generation	Renewable electricity generation	Explanatory	MWh	All models	Nord Pool
net_import	Net electricity imports	Explanatory	MWh	All models	Constructed (Entsoe-E Transparency Platform)
temperature	Hourly temperature	Explanatory	°C	All models	Open-Meteo
sunshine	Sunshine duration	Instrument	Seconds	All models	Open-Meteo
wind	Wind speed	Instrument	km/h	All models	Open-Meteo
rain	Rainfall	Explanatory	Milimetres	All models	Open-Meteo
TTF_price	Dutch gas price	Explanatory	EUR/MWh	Robustness test 2, 3	EEX
high_res_dummy	Dummy for top 5% renewable generation hours	Dummy	Binary	Robustness test 4	Constructed
high_res_dk_dummy high_res_no_dummy high_res_se_dummy	Dummy for top 5% renewable generation hours of each country	Dummy	Binary	Robustness test 5	Constructed
dk no se	Country dummies for interaction terms	Dummy	Binary	Robustness test 1, 3, 5	Constructed
month	Month dummies	Dummy	Binary	All models	Constructed
day	Day dummies	Dummy	Binary	All models	Constructed
RES_dk RES_no RES_se	Interaction: RES generation x country	Interaction	-	Robustness test 1	Constructed
TTF_dk TTF_no TTF_se	Interaction: TTF x country	Interaction	-	Robustness test 3	Constructed

Table 2: Table of Variables

5.4 Descriptive statistics of the variables

	mean	sd	min	median	max	n
DA_price	72,4	81,07	-298,97	49,5	936,29	131 539
consumption	11 536,96	5 945,24	2 148,00	12 696,00	25 756,00	131 539
RES_generation	9 304,97	7 115,08	0	9 521,00	27 715,00	131 539
net_import	-1 576,80	2 482,12	-8 369,89	-1 713,89	8 568,87	131 539
tempreature	8,34	7,74	-28,1	8,1	31,4	131 539
sunshine	1 092,44	1 602,33	0	0	3 600,00	131 539
wind	13,61	7,68	0	12,3	58,7	131 539
rain	0,08	0,36	0	0	13,3	131 539
TTF_price	42,76	39,43	3	33,67	304,98	114 043

Table 3: Descriptive statistics of the dependent variable and explanatory variables

The above table shows the descriptive statistics for dependent variable (DA_price) and the explanatory, instument and control variables that were used in the analysis. The dataset has 131 539 hourly observations for Denmark, Norway and Sweden for the five-year period, with the exemption of TTF_price, which only have 114 043 observations due to the fact that on some days it was not traded.

The dependent variable, the DA_price has a mean of 72,40 EUR/MWh with a standard deviation of 81,07, which shows a significant variation in the hourly prices. The price range is between -298,97 EUR/MWh and 936,29 EUR/MWh, which captures extreme market events, like price strikes or negative prices (as mentioned in the theory section), which are typically associated with renewable overproduction or transmission constraints. The volatility underlines the dynamic nature of the electricity spot market, especially when it comes to systems where renewable penetration is high.

The hourly electricity consumption (consumption) has an average of 11 537 MWh, ranging from 2 148 MWh to 25 756 MWh. This variable represents the total national electricity usage of each country in every hour summed up from bidding-zone level.

The renewable electricity generation variable (RES_generation) includes wind, hydro, solar and other sources and it averages at 9 305 MWh, with a minimum of 0 representing that renewables are not generating always, and it reaches up to 27 715 MWh. This is a significant range, and it shows the fluctuating nature of RES production in the Nordics, which is a central point in the analysis given its influence on price formation through the merit-order effect.

Net import (net_import) has a negative mean of -1 577,80 MWh, which implies that on average across the three countries, they were exporters of electricity. However, the range is between -8 361 MWh and 8 569 MWh, which shows the flexibility of cross-border flows, which is in line with the high level of market integration within the Nordic and in the broader European region. This variable is a key in capturing the market coupling and cross-border flows, which influence the domestic price signals.

Tempreature (tempreature) was added to control for the demand-side dynamics, and it is ranged between -28,1°C and 31,4°C, with an average of 8,34°C, which captures seasonal variations in the Nordic region. Naturally, colder temperatures typically increase electricity demand especially for heating.

Sunshine duration (sunshine) was used as a proxy for solar energy production, and it averaged 1 092 seconds per hour, with a maximum of 3 600 seconds, which represents full sun exposure for an hour. Taking into consideration that solar production is most active during midday and in summer months, this variable is key for instrumenting price impacts that are related to solar availability and seasonal changes.

Wind speed (wind) averaged at 13,61 km/h, with reaching a maximum of 58,7 km/h, which highlights a significant variability in the potential for wind generation. Since wind is a “key player” in the renewable supply, especially in Denmark, this variable is used as an instrument for the RES generation.

Rainfall (rain) is included as a control hydropower generation, it has a low mean of 0,08 mm/hour with a maximum of 13,3 mm/hour. While rain is not a perfect proxy for hydro generation, it is still the best short-term indicator of hydro potential, especially in Norway where hydropower dominates, since even though in the winter months snow would be a better indicator, however it doesn’t have an immediate effect and maybe no effect at all for weeks or months due to low temperatures and no melting.

Lastly, the Dutch TTF hub’s day-ahead gas prices (TTF_price), which was used to control for European gas market conditions has an average price of 42,76 EUR/MWh, which ranges from

3 EUR/MWh to 304,98 EUR/MWh. The inclusion of this takes into account the external fuel price pressures that influence electricity spot prices even in systems with high renewable generation.

The descriptive statistics shows that the dataset has significant variation both in prices and explanatory factors, which provides a robust base for testing the price effects of renewable generation, market interconnectivity, and weather factors.

6. Analysis and Discussion

6.1 Analysis

6.1.1 Main model

With the main model the first working question is aimed to be answered: Does electricity consumption, renewable energy generation, cross-border electricity trade, and weather conditions significantly affect day-ahead electricity prices in Denmark, Norway and Sweden?

The main regression model uses a fixed effects (FE) panel regression with instrumental variables (IV) method to analyze the determinants of hourly day-ahead electricity prices across Denmark, Norway and Sweden over a five-year period, between 01.01.2020 and 31.12.2024, as mentioned in the previous sections. With the dataset's high frequency, having few cross-sectional units (N=3) and many times periods, the FE estimator is appropriate for isolating within-country variation while also controlling for unobserved, time-invariant heterogeneity like the energy mix, the market design or the regulatory features. Driscroll-Kraay standard errors were used in the estimation to account for heteroskedasticity, autocorrelation and multicollinearity, which are all common features in electricity market data.

Variable	Estimate	Std. Error	t-statistic	p-value
consumption	0,043	0,005	8,541	< 2,2E-16
net_import	-0,056	0,008	-7,410	0,000
temperature	-4,405	0,416	-10,593	< 2,2E-16
rain	-12,127	2,081	-5,826	0,000
RES_generation	-0,053	0,007	-7,678	0,000
dayMonday	6,023	5,847	1,030	0,303
daySaturday	-10,699	5,192	-2,060	0,039
daySunday	-8,882	5,406	-1,643	0,100
dayThursday	5,289	5,522	0,958	0,338
dayTuesday	6,203	5,878	1,055	0,291
dayWednesday	5,288	5,832	0,907	0,365
month02	-6,329	9,480	-0,668	0,504
month03	9,147	9,390	0,974	0,330
month04	28,607	8,922	3,206	0,001
month05	69,191	9,706	7,129	0,000
month06	108,445	10,873	9,974	< 2,2E-16
month07	104,356	10,777	9,683	< 2,2E-16
month08	138,988	11,893	11,687	< 2,2E-16
month09	130,393	11,052	11,798	< 2,2E-16
month10	67,227	9,425	7,133	0,000
month11	48,662	9,072	5,364	0,000
month12	76,936	10,091	7,624	0,000

Table 4: Main model regression output (Driscroll-Kraay, IV methods)

Coefficients and their economic meaning
The coefficient for the electricity consumption is positive and statistically significant (β = 0,042, $p < 2,2*10^{-16}$), which means that the increased consumption correlates with higher day-ahead prices. To quantify it, a 1 unit, therefore 1 MWh increase in consumption raises the day-ahead prices by 0,042 EUR/MWh, holding all else equal.

Renewable electricity generation's coefficient (RES_generation) shows a negative and significant effect (β = -0,053, $p = 1,63*10^{-14}$), which implies that the renewable electricity generation lowers the prices: 1 MWh increase in RES generation lowers the day-ahead prices by 0,053 EUR/MWh, holding everything else equal.

Net import shows a significantly negative impact on prices (β = -0,056, $p = 1,27 * 10^{-13}$), which means that net imports are having a price lowering effect, one unit (MWh) increase in net imports decreases the prices by 0,053 EUR/MWh, holding everything else constant.

Temperature has a negative and strong effect (β = –4,41, $p < 2,2*10^{-16}$), this implies that that temperature raises are decreasing the day-ahead electricity prices. The result shows that a 1 Celsius degree increase in the temperature leads to a 4,41 EUR/MWh decrease in the day-ahead prices. Rain also has a negative and statistically significant effect (β = –12,13, $p = 5,68 * 10^{-9}$), this means that a 1mm increase in rainfall leads to a decrease in day-ahead electricity prices by 12,13 EUR/MWh on average, with everything else being equal.

Out of the day-of-week dummies only Saturday shows statistical significance and it has a negative coefficient (β = –10,70, p = 0,039), while the rest of the days are not statistically significant. On average day-ahead prices are 10,70 EUR/MWh lower on Saturdays compared to Fridays (reference category). Out of the month dummies February and March are not statistically significant, while from April to December month dummies are significant and they all have positive effects. For example, in April (β = 28,61, p = 0,001), prices are 28,61 EUR/MWh higher on average than in January (reference category), while August (β = 138,99, $p < 2,2*10^{-16}$) is having the largest difference, when prices are 138,99 EUR/MWh higher on average than in January.

Model diagnostics
The fixed effects assumption tests are confirming the use of the Driscroll-Kraay robustness standard errors as the Modified Wald test rejects the null of homoskedasticity (χ^2 =118 898, p = 0), which indicates groupwise heteroskedasticity, however the value is extremely high and might be inflated, the result still supports the need for robust standard errors. The Wooldridge test shows first-order serial correlation (β = 0,992, $p < 2,2*10^{-16}$), however multicollinearity is not an issue as all VIFs were below 10, with the highest being 5 for temperature. The overall model chi square is 3960, with $p < 2,2*10^{-16}$, which confirms that the explanatory variables are jointly significant. The F-statistic of the first-stage IV regression of RES generation on the exogeneous variables and instruments yielded a value of 5982,7, which exceeds the recommended threshold of 10 (Staiger and Stock, 1997), which confirms the relevance and strength of the instruments of wind speed and sunshine duration, and the same instruments were used in all robustness tests. (Outputs are in Appendix B)

Result
Since almost all main variables in the main regression model are statistically significant, therefore the null hypothesis, which says that none of the explanatory variables have statistically significant effect on day-ahead prices is rejected.

6.1.2 Robustness test 1

The first robustness test is aimed to answer the following working question: Do the day-ahead electricity prices in Denmark, Norway, and Sweden respond differently to their own domestic renewable electricity generation?

To test this, the total renewable electricity generation was replaced with country-specific components: RES_dk (Denmark) and RES_no (Norway). This separation allows the report to have a more in-depth evaluation of whether the average price effect of renewables is changing by the countries' renewable energy mix. The fixed effects model is again estimated with Driscoll-Kraay standard errors with instrumental variables method.

Variable	Estimate	Std. Error	t-statistic	p-value
consumption	0,013	0,002	8,019	1,075E-15
net_import	-0,009	0,002	-3,996	6,45E-05
temperature	-1,785	0,210	-8,500	< 2,2E-16
rain	-8,663	1,208	-7,171	7,511E-13
RES_dk	-0,028	0,002	-15,417	< 2,2E-16
RES_no	-0,010	0,003	-3,563	0,000
dayMonday	4,592	2,605	1,763	0,078
daySaturday	-9,049	2,237	-4,044	0,000
daySunday	-12,302	2,291	-5,370	7,89E-08
dayThursday	3,416	2,490	1,372	0,170
dayTuesday	6,882	2,673	2,575	0,010
dayWednesday	4,400	2,637	1,668	0,095
month02	-7,455	2,255	-3,306	0,001
month03	10,489	2,788	3,762	0,000
month04	19,634	2,950	6,657	2,813E-11
month05	36,327	4,394	8,267	< 2,2E-16
month06	60,724	5,983	10,149	< 2,2E-16
month07	63,935	5,962	10,723	< 2,2E-16
month08	89,675	6,417	13,974	< 2,2E-16
month09	78,379	6,099	12,852	< 2,2E-16
month10	28,653	3,743	7,655	1,948E-14
month11	25,250	3,314	7,618	2,59E-14
month12	46,104	4,115	11,203	< 2,2E-16

Table 5: Robustness test 1 regression output (Driscroll-Kraay, IV methods)

Coefficients and their economic meaning

In this specification the consumption keeps being a strong and highly significant predictor of day-ahead electricity prices ($\beta = 0{,}013$, $p = 1{,}08 * 10^{-15}$), however, the scale is smaller, as in this robustness test 1 MWh increase in consumption still raises the prices, but by only 0,01 EUR/MWh, holding all else equal.

Net import is still statistically significant with a negative effect on prices ($\beta = -0,009$, $p = 6,5 * 10^{-5}$), which is similarly as with the consumption also a smaller magnitude change compared to the main model, as net import increase by one MWh, here the prices are decreasing by 0,01 EUR/MWh.

The temperature's coefficient stays significant and negative ($\beta = -1,79$, $p < 2,2*10^{-16}$), which also has a lowered magnitude: 1 Celsius degree increase lowers the prices by 1,79 EUR/MWh. Rainfall also keeps its significantly negative sign ($\beta = -8,67$ $p = 7,51 * 10^{-13}$), meaning that 1mm increase in rainfall leads to a 8,67 EUR/MWh decrease on average in the spot prices.

RES_dk (Denmark) shows a significant negative effect on prices ($\beta = -0,03$, $p < 2,2*10^{-16}$), which is interpreted in a way that a 1MWh increase in renewable generation in Denmark leads to a 0,028 EUR/MWh decrease in day-ahead prices compared to Sweden (reference category). While RES_no (Norway) is also negative and statistically significant ($\beta = -0,01$, $p = 0,00$), where 1 MWh increase in renewable generation is associated with a 0,01 EUR/MWh decrease in prices relative to Sweden.

Out of the day-of-week dummy variables Saturday ($\beta = -9,05$, $p = 0,00$), Sunday ($\beta = -12,30$, $p = 7,89*10^{-8}$) and Tuesday ($\beta = 6,89$, $p = 0,01$) are statistically significant at a 5% percent level. On Saturdays the day ahead prices on average 9,95 EUR/MWh, while on Sundays they are 12,30 lower than on Fridays (reference category), however on Tuesdays on average the day-ahead prices are 6,89 EUR/MWh higher compared to Fridays. The month dummies are all statistically significant in this model, with February ($\beta = -7,46$, $p = 0,001$) having a negative effect compared to January (reference category), while the rest of the months are having positive effects compared to January, with the strongest effect again in August ($\beta = 89,68$, $p < 2,2*10^{-16}$). This means that in February the prices on average are 7,46 EUR/MWh lower compared to January, while in August prices are 89,68 EUR/MWh higher, than in January.

Model diagnostics
The Modified Wald test again rejects homoskedasticity ($\chi^2 = 2424,87$, $p = 0$), and the Wooldridge test confirms the presence of first-order serial correlation ($\beta = 0,978$, $p < 2,2*10^{-16}$). All VIF values are well below 10, with the maximum at 5 (temperature), indicating that multicollinearity is not an issue. These findings are confirming the use of Driscoll-Kraay standard errors. The overall model has a chi square of 21 652 ($p < 2,2*10^{-1}$), which indicates that the explanatory variables show joint significance. In this robustness test RES_dk and RES_no were instrumented separately, however the instruments (wind speed and sunshine duration) are relevant here as well, as the first-stage IV F-statistics for Denmark is 8995,4, and for Norway it is 8537,8, which are both well above the threshold of 10 (Staiger and Stock, 1997). (Outputs are in Appendix B)

Result
The null hypothesis is rejected, as Denmark and Norway are responding differently to total Nordic RES generation, than the baseline Sweden.

6.1.3 Robustness test 2

The second robustness test was created to answer the following working question: Do European natural gas prices, proxied by Dutch TTF day-ahead prices, have a significant influence on day-ahead electricity prices in the Nordic countries, beyond domestic supply, demand, and weather factors?

To test this working question, this robustness test adds Dutch TTF day-ahead natural gas price as an additional control variable, that is accounting for natural gas-related marginal price pressures in the Nord Pool spot market. As the previous ones, this robustness model uses fixed effects panel estimation and Driscoll-Kraay standard errors with IV method.

Variable	Estimate	Std. Error	t-statistic	p-value
consumption	0,039	0,004	10,207	< 2,2E-16
net_import	-0,051	0,006	-8,679	< 2,2E-16
temperature	-3,549	0,360	-9,853	< 2,2E-16
rain	-6,166	1,671	-3,689	0,000
TTF_price	1,765	0,068	26,007	< 2,2E-16
RES_generation	-0,049	0,005	-9,168	< 2,2E-16
dayMonday	-1,663	4,925	-0,338	0,736
daySaturday	-9,005	4,134	-2,192	0,028
daySunday	-8,888	4,327	-2,054	0,040
dayThursday	-1,912	4,620	-0,414	0,679
dayTuesday	-1,894	4,910	-0,386	0,700
dayWednesday	-3,163	4,861	-0,651	0,515
month02	5,650	8,157	0,693	0,489
month03	5,297	7,904	0,670	0,503
month04	22,716	7,502	3,028	0,002
month05	61,400	8,010	7,665	0,000
month06	86,299	8,933	9,661	< 2,2E-16
month07	90,105	8,719	7,926	0,000
month08	75,712	8,809	8,594	< 2,2E-16
month09	68,925	8,392	8,213	< 2,2E-16
month10	32,276	7,845	4,242	0,000
month11	16,479	7,752	2,126	0,034
month12	25,982	7,948	3,269	0,001

Table 6: Robustness test 2 regression output (Driscroll-Kraay, IV methods)

Coefficients and their economic meaning

Electricity consumption keeps being positive and statistically significant ($\beta = 0{,}04$, $p < 2{,}2*10^{-16}$), which means in this model that 1 MWh increase in consumption is associated with 0,04 EUR/MWh increase in the day-ahead prices, holding all else equal.

Renewable electricity generation (RES_generation) has a negative and highly significant coefficient ($\beta = -0{,}05$, $p < 2{,}2*10^{-16}$), this means that 1 MWh increase in renewable electricity generations leads to a 0,05 EUR/MWh decrease in the spot prices, with everything else being constant.

Net import still has a statistically significant negative effect ($\beta = -0{,}05$, $p < 2{,}2*10^{-16}$), 1 MWh increase in net import result in a -0,05 EUR/MWh decrease in prices on average.

Temperature still has a negative and statistically significant effect on the day-ahead prices ($\beta = -3{,}55$; $p < 2{,}2*10^{-16}$), meaning that a 1 Celsius degree increase in temperature leads to a 3,55 EUR/MWh decrease in day-ahead prices on average. Rain is also still negative and significant ($\beta = -6{,}17$; $p = 0{,}00$), resulting in a 6,17 EUR/MWh decrease in the prices in case of a 1mm increase of rainfall.

The TTF natural gas price turned out to be a positive and highly significant price determinant ($\beta = 1{,}765$, $p < 2{,}2*10^{-16}$), which indicates that a 1 EUR/MWh increase in the Dutch TTF natural gas price leads to a 1,77 EUR/MWh increase on average in the day-ahead electricity price.

From the day-of-week dummies only Saturday ($\beta = -9{,}00$; $p = 0{,}028$) and Sunday ($\beta = -8{,}89$; $p = 0{,}04$) are statistically significant, with Saturday having on average 9 EUR/MWh lower prices compared to Friday, while Sunday is having on average 8,89 EUR/MWh lower prices relative to Friday.

In this specification February and March are again insignificant, while the rest of the months are statistically significant and all have positive effects, with July ($\beta = 90{,}11$; $p = 0{,}00$) having the strongest effect, which means that compared to January prices in July are 90,11 EUR/MWh higher on average.

Model Diagnostics
Multicollinearity is still within acceptable limits, since all VIF values are well below 10, with the highest value for temperature being VIF = 4,9. The groupwise heteroskedasticity is rejected by the Modified Wald test ($\chi^2 = 214\ 654$; $p = 0$), that is confirming the use of robust standard errors, however this value is very high again which might imply that it's inflated. First-order autocorrelation is confirmed by the Wooldridge test ($\beta = 0{,}99$; $p < 2{,}2*10^{-16}$), again supporting the use of the Driscoll-Kraay adjustment. The overall model has a 17 956 ($p < 2{,}2*10^{-16}$) chi square value, which confirms the joint significance of the explanatory variables. (Outputs are in Appendix B)

Result
The null hypothesis is rejected, as the Dutch TTF gas price has a statistically significant effect on the day-ahead electricity prices in the Nordic market.

6.1.4 Robustness test 3

With this robustness test the aim was to answer the working question regarding whether the countries have different response to the TTF gas prices: Does the sensitivity of Nordic day-ahead electricity prices to European gas prices change across Denmark, Norway and Sweden?

This robustness test is deepening the gas price control by separating the Dutch TTF index into two proxies: TTF_DK and TTF_NO, which is reflecting country-specific sensitivity to international gas prices. This model's estimation is also based on fixed effects with Driscoll-Kraay standard errors with IV method.

Variable	Estimate	Std. Error	t-statistic	p-value
consumption	0,033	0,003	9,500	< 2,2E-16
net_import	-0,043	0,005	-7,995	1,31E-15
temperature	-3,905	0,346	-11,284	< 2,2E-16
rain	-7,484	1,532	-4,884	1,04E-06
RES_generation	-0,040	0,005	-8,303	< 2,2E-16
TTF_dk	1,452	0,054	26,667	< 2,2E-16
TTF_no	1,112	0,030	36,883	< 2,2E-16
dayMonday	-10,603	4,682	-2,265	0,024
daySaturday	-8,466	3,904	-2,169	0,030
daySunday	-7,779	4,089	-1,902	0,057
dayThursday	-10,106	4,367	-2,314	0,021
dayTuesday	-10,322	4,710	-2,192	0,028
dayWednesday	-11,857	4,609	-2,572	0,010
month02	-0,709	7,591	-0,093	0,926
month03	2,805	7,458	0,376	0,707
month04	20,549	7,077	2,904	0,004
month05	55,122	7,356	7,493	6,77E-14
month06	85,601	8,195	10,446	< 2,2E-16
month07	78,084	8,154	9,576	< 2,2E-16
month08	93,321	8,572	10,886	< 2,2E-16
month09	84,437	8,216	10,278	< 2,2E-16
month10	41,151	7,182	5,730	1,01E-08
month11	26,265	6,985	3,760	0,000
month12	38,974	7,719	5,049	4,45E-07

Table 7: Robustness test 3 regression output (Driscroll-Kraay, IV methods)

Coefficients and their economic meaning

The electricity consumption keeps a statistically significant and positive relationship with day-ahead prices ($\beta = 0,033$, $p < 2,2*10^{-16}$), meaning that in this model 1 MWh in consumption leads to a 0,03 EUR/MWh price increase in day-ahead prices, holding all other variables constant.

Renewable electricity generation has now again a negative and significant coefficient ($\beta = -0,04$, $p < 2,2*10^{-16}$), which implies that an extra 1 MWh renewable electricity generation is associated with a 0,04 drop in spot prices.

Net imports show a statistically significant and negative association with prices ($\beta = -0,04$, $p = 1,3*10^{-15}$), leading to that a 1 MWh increase in net imports implies a 0,04 EUR/MWh decrease in the prices, holding everything else constant.

Temperature keeps being highly significant with a negatively sign ($\beta = -3,91$, $p < 2,2*10^{-16}$), which means that a 1 Celsius degree increase leads to a 3,91 EUR/MWh price drop on average. Rainfall continues to be negative and statistically significant ($\beta = -7,48$, $p = 1,04*10^{-6}$), leading to a 7,48 EUR/MWh decrease in spot prices in case of a 1 mm increase of rain, holding everything else equal.

Both gas price proxies are positively and strongly significant: TTF_DK ($\beta = 1,45$, $p < 2,2*10^{-16}$), and TTF_NO ($\beta = 1,11$, $p < 2,2*10^{-16}$). Therefore, Danish electricity prices show a 1,45 EUR/MWh increase in case of a 1 EUR/MWh increase in the TTF gas prices compared to Sweden, while Norway shows a smaller sensitivity as its day-ahead electricity prices increase by 1,11 EUR/MWh in case of a 1 EUR/MWh increase in the TTF prices compared to Sweden (reference group).

Day-of-week effects are showing a big difference compared to the previous models' weekend significance, as now all days except Sunday show significance at a 5% level and they are all negatively affecting the prices compared to Friday (reference group), with Wednesday ($\beta = -11,86$, $p = 0,01$) having the strongest effect: on average prices are 11,86 EUR/MWh lower than on Fridays.

Month dummies are not significant for February and March, while they are significant for the rest of the month compared to January, with August having the most intensive difference, as prices are 93,32 EUR/MWh higher on average than in January.

Model Diagnostics

Multicollinearity stays within acceptable limit, with all VIFs below 10 (maximum: 5 for temperature). The Modified Wald test confirms groupwise heteroskedasticity ($\chi^2 = 207\,790$, $p = 0$), which is again a very high value, but it confirms the use of Driscoll-Kraay corrections. The Wooldridge test for serial correlation confirms strong first-order autocorrelation ($\beta = 0,999$, $p < 2,2*10^{-16}$), further supporting the use of robust standard errors. The overall model's chi square is 19 486 ($p < 2,2*10^{-16}$), which underscores the joint significance of the explanatory variables. (Outputs are in Appendix B)

Result

The null hypothesis is rejected, as both Denmark's and Norway's day-ahead prices respond positively and statistically significantly compared to Sweden.

6.2 Discussion

6.1.1 Main model

With the main model the aim is to analyze whether the electricity consumption, renewable energy generation, cross-border electricity trade, and weather conditions significantly affect day-ahead electricity prices in Denmark, Norway and Sweden?

In the theory section it was mentioned that the market clearing price is determined by the unit that was last sold on the market – which is also the most expensive – to meet the demand expectations (Blume-Werry et al., 2021; Bahar and Sauvage, 2013), therefore consumption, which is the actual demand, is expected to have a positive price driving effect. In the main model it was found that a 1 MWh increase in consumption leads to 0,043 EUR/MWh increase in the day-ahead prices, therefore it is visible that consumption actually drives up the prices.

Through market interconnectivity, market coupling and cross-border flows it is expected from a theoretical perspective that cheap generation in one area replaces the more costly generation in another area (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021). This was tested through net import, which in this main specification shows a negative price effect, as a 1 MWh increase in net imports lowers the prices by 0,06 EUR/MWh on average, therefore it is confirmed that it affects the prices.

According to the merit-order effect has a downward pressure on prices, as the low marginal cost renewables enter the electricity market, and they are lowering the equilibrium prices. (Würzburg et al., 2013; Bahar and Sauvage, 2013) The renewable electricity generation was found to have a significant negative effect, as a 1 MWh increase in RES generation leads to a 0,053 EUR/MWh decrease in the day-ahead electricity prices, therefore the merit-order effect is confirmed in the model, since it shows a downward pressure on the prices. The applied IV method helps to make sure that the observed effects are not biased.

Temperature was found to have a negative effect as well, as it was found in the analysis section that a 1 Celsius degree increase lowers the prices by 4,41 EUR/MWh, which is logical as heating demand goes down in the milder weather and therefore there is no need for the same amount of electricity for the heating.

Rain seems to be also a negative driver for the prices, as it was explained in the analysis, a 1 mm increase in rainfall leads to a 12,13 EUR/MWh drop in the day-ahead prices on average, which can be tied to the low marginal cost of hydro and the dispatchable feature of it (Wen et al., 2022), as the increased hydro generation can lower the prices due to the merit-order effect. Therefore, during higher water availability, hydropower replaces the more expensive generation technologies, which leads to lower prices on the market.

When it comes to the seasonality, Saturday showed a statistically significant effect compared to Fridays, which was the reference category in the regression to avoid the dummy variable trap, and it has on average 10,70 EUR/MWh lower prices than Fridays, which is line with Wolff and Feuerriegel's (2018) findings that prices are lower during weekends, what can be caused by reduced industrial demand. However, when it comes to monthly seasonality the results are unexpected, as Wolff and Feuerriegel's (2018) found that electricity prices are in general lower in the summer due to lowered heating demand, but the main regression specification found that the summer month, especially August is having the greatest statistically significant and positive difference compared to January, which was the reference category. This result is counterintuitive taking into consideration that it is also logical that solar generation is peaking in these months and theoretically it should lower the prices due to the merit-order effect. However, it is important to note, that month dummies are not causing electricity price changes directly, but they can absorb residual seasonal variation that is not fully controlled for by the included explanatory variables. Therefore, even though the month dummies do not reflect a causal seasonal effect, they still show the presence of a complex and time-related price dynamics that would require further studying, and since the main focus of this thesis is the short-term price effect of renewable production, net import and consumption, the seasonal fixed effects are viewed as controls.

To answer the working question, the electricity consumption, renewable energy generation, cross-border electricity trade, and weather conditions are all significantly affecting day-ahead electricity prices in Denmark, Norway and Sweden, however in different direction, as consumption drives the prices up, while net import, RES generation, temperature and rain are lowering the day-ahead prices in this specification.

6.2.2 Robustness test 1

With the first robustness test the aim was to answer whether the day-ahead electricity prices in Denmark, Norway, and Sweden respond differently to their own domestic renewable electricity generation? This question was designed to evaluate whether there is a difference between the general Nordic response and the country-specific price response to their own renewable electricity generation.

In this model the countries' own RES generation variables were interacted with the constructed country dummies to see the country specific effects, with Sweden being the reference group, therefore in this model it will be presented how Denmark and Norway respond differently compared to Sweden to RES generation outputs.

As it was mentioned at the main model, the expectation based on the theory was that consumption positively affects the prices. Here a 1 MWh increase in consumption drives the prices up by 0,01 EUR/MWh, which is a lower magnitude than what the main model resulted in, but it still confirms the price driving effect of the demand, so it's in line with the theory (Blume-Werry et al., 2021; Bahar and Sauvage, 2013).

Market interconnectivity, market coupling and cross-border flows were controlled for again through net import, which should lower the prices in theory (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021), and net import again showed a price lowering effect, however with a smaller magnitude than at the main model, as here a 1 MWh increase in net imports only lowers the prices on average by 0,01 EUR/MWh. This is still in line with the theory, but the effect is smaller.

Temperature and rain are both still in line with the logical expectation and theory (Wen et al., 2022), that they should be having negative effects on the prices, which is still underscored by the results, as 1 Celsius degree temperature increase is causing a 1,79 EUR/MWh price decrease on average, while 1 mm rain increase shows a 8,67 EUR/MWh decrease in the day-ahead prices, which are also smaller magnitude results compared to the main specification.

The coefficient for Denmark's country-specific marginal effect of renewable electricity generation on spot prices relative to Sweden indicates a 1 MWh increase in Denmark's RES generation leads to a 0,03 EUR/MWh decrease in the day-ahead prices, which is in line with the expectations from the merit-order effect. Norway's RES generation shows a smaller scale, 0,01 EUR/MWh decrease in the day-ahead prices in case of the RES generation increases by 1 MWh compared to Sweden. Through these country specific interactions, it becomes clear that there is heterogeneity across the countries' responses and that even though the merit-order effect is present in the region, the strength of it depends on the characteristics of the specific countries. Denmark's effect is stronger possibly due the high percentage of wind power in its energy mix, while Norway's hydro power-based system is more storable and it can buffer fluctuations as it was explained in the theory section (Würzburg et al., 2013; Bahar and Sauvage, 2013).

In this specification Saturday and Sunday are both showing significant negative price effects, while Tuesday has a positive effect compared to Friday, which is perfectly in line with the theoretical expectation that during weekends prices are lower due to decreased industrial consumption (Wolff and Feuerriegel, 2018). The month dummies are lower in magnitude compared to the main model, but they show similar positive price effects during the summer months compared to January, which is contradictory when it comes to previous empirical findings. (Wolff and Feuerriegel, 2018)..

To answer the working question, Denmark, Norway and Sweden are in line with the price-reducing expectations of the merit-order effect, but they are affected by it on a different scale, Denmark is found the be the most affected compared to Sweden, then Norway, but since Sweden was used as a reference category and its interaction term is omitted it is only possible to state that Sweden is affected the least by its own RES generation.

6.2.3 Robustness test 2

With this robustness test the aim was to study if European natural gas prices, proxied by Dutch TTF day-ahead prices, have a significant influence on day-ahead electricity prices in the Nordic countries, beyond domestic supply, demand, and weather factors?

This model uses the main model as a base and adds Dutch TTF day-ahead gas prices as a proxy for European gas prices to see whether they are also drivers of the electricity prices as the theory suggested.

With the addition of the gas prices the relevance of the consumption barely changed compared to the main model, as a 1 MWh increase in consumption leads to a 0,039 EUR/MWh increase in the prices, which is very close to the main model's effect, therefore it is in line with the theory (Blume-Werry et al., 2021, Bahar and Sauvage, 2013).

Net import is also very similar to the main model, it is now 0,05 EUR/MWh price drop in case of a 1 MWh net import, which implies that if the gas prices are also taken into account, then the net electricity imports are having a little bit lower price decreasing effect.

Renewable electricity generation is also having a very similar effect as in the main model, since in the main specification a 1 MWh increase lead to a 0,053 EUR/MWh decrease in spot prices, while in this model it leads to a 0,049 EUR/MWh decrease in the spot prices, which is just a minor magnitude change. (Würzburg et al., 2013; Bahar and Sauvage, 2013)

Temperature and rain are both significantly lowering the day-ahead electricity prices still, however compared to the main model in case of a 1 Celsius degree temperature increase, the prices in the main model drop by 4,41 EUR/MWh, while in this one by a little bit less, 3,55 EUR/MWh, however in case of a 1 mm increase of rain in the main model caused a 12,13 EUR/MWh price drop, while here the magnitude is half of it, as it is only 6,17 EUR/MWh price decrease, but they are still in line with the logical and theoretical expectations (Wen et al., 2022).

A 1 EUR/MWh raise in TTF prices leads to a 1,77 EUR/MWh increase in the day-ahead electricity prices on average across Denmark, Norway and Sweden. Theory states that natural gas-based generators are often used due to their flexibility in case the RES generation is not enough to meet the demand, however natural gas does not have a near-zero marginal cost, and it is also very volatile because of its exposure to global markets. Therefore, since the market clearing price is set by the most expensive generator that is needed to fulfill the demand, it is expected that TTF prices are increasing the prices, which is in line with the results of this model. (Zakeri et al., 2023; Stringer et al., 2024; Newbery et al., 2018)

The day dummy variables in this specification are only significant on Saturday and Sunday, which are both having a negative effect compared to Friday, that is in line with the theory (Wolff and Feuerriegel, 2018) and similar to the main specification. While the months are also having almost identical results like the main model, the only difference is that they are showing a smaller scale seasonality, however not aligned with the expectations based on results of Wolff and Feuerriegel (2018).

To answer the working question, the Dutch day-ahead gas prices changes are showing a significant positive change in the electricity prices throughout the Nordic countries, thereby the theory is confirmed that gas prices are significant price drivers in the electricity market.

6.2.4 Robustness test 3

The third robustness test is aimed to test whether the sensitivity of Nordic day-ahead electricity prices to European gas prices change across Denmark, Norway and Sweden?

In this model interaction terms were created between the country dummies and the Dutch TTF day-ahead gas prices, which allows to analyze whether the marginal effect of prices on electricity spot prices differ between Denmark, Norway and Sweden.

The consumption remained to be a positive price driver, which is in line with the previous models and the theory (Blume-Werry et al., 2021; Bahar and Sauvage, 2013). In this specification it causes a 0,033 EUR/MWh increase in prices in case of a 1 MWh increase in consumption.

Net import is still a negative factor, which is also in line with the main model and the theory (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021), which in this case is decreasing the prices by 0,043 EUR/MWh in case of a 1 MWh increase in net import.

RES generation is remained to be in line with the merit-order effect expectation (Würzburg et al., 2013; Bahar and Sauvage, 2013) and all the previous models, as prices on average are dropping by 0,04 EUR/MWh in case of a 1 MWh increase in renewable electricity generation.

Temperature and rain are also continue having negative effect on the prices, therefore they did not change significantly compared to the previous specifications, prices are decreasing by 3,91 EUR/MWh if the temperature raises by 1 Celsius degree, and they are decreasing by 7,48 EUR/MWh in case of a 1 mm increase of rainfall which is in line with the theory(Wen et al., 2022).

The main effect that this model examines is that how do the different countries electricity price reactions to TTF gas price differ: The analysis showed that compared to Sweden, Denmark's day-ahead electricity price increase by 1,45 EUR/MWh as a reaction to a 1 EUR/MWh raise in the TTF prices, while in Norway the electricity prices increase by 1,11 EUR/MWh in response to the TTF prices compared to Sweden. (Zakeri et al., 2023; Stringer et al., 2024)

Day dummies in this section show a more significant difference compared to the previous findings, as all days but Sunday are significant, and all are showing negative effects relative to Friday. This pattern differs a lot from the previous models and the theory (Wolff and Feuerriegel, 2018), for which a possible explanation is that this model captures country-specific gas price sensitivities, which allows to isolate the weekly price structure, which shows that Friday tends to have higher prices. The month dummy variables are consistent with the previous models with moderate magnitude differences, but they are not in line with the findings of Wolff and Feuerriegel (2018).

To answer the working question, Denmark, Norway and Sweden show different sensitivities to the TTF gas prices, while they are still being in line with the theory, it is visible that Denmark is more affected by gas prices as Norway and Sweden, possibly because of the higher wind share in its renewable electricity mix, which is much more volatile, than hydro generation – which take up more than 50% of Sweden's and more, than 90% of Norway's renewable mix – therefore it can be assumed that Denmark relies more on gas-based electricity generation.

6.2.7 Research question

This section aims to answer the research question of whether and how do electricity consumption, renewable generation, cross-border trade, and weather conditions influence day-ahead electricity prices across Denmark, Norway, and Sweden. The results of the main model and the three robustness tests are being used to help answering this question.

Electricity consumption is confirmed to be a positive price driver through all the models as expected. In all model specifications the increases in demand significantly raise day-ahead electricity prices, no matter whether it was a region-wide or country-specific model, which validates the role of consumption as a central upward force in the formation of market price (Blume-Werry et al., 2021; Bahar and Sauvage, 2013).

Renewable electricity generation was found to have a negative effect on prices across all models, which is in line with the merit-order effect (Würzburg et al., 2013; Bahar and Sauvage, 2013). In the main model a 1 MWh increase in RES generation leads to a 0,053 EUR/MWh decrease in prices.

Net imports are consistently reducing prices, which supports the theoretical expectations from market coupling and interconnectivity literature (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021) and it confirms that cross-border inflows are helping to reduce domestic prices.

Temperature was found to decrease prices, which is likely due to the reduced heating demand in warmer periods, while rainfall also show strong negative effects in all models, which is in line with the hydro generation's ability to replace more expensive sources as expected based on the theory (Wen et al., 2022).

When RES generation was broken down by country, heterogeneity was clearly visible, as Denmark experiences the strongest price-reducing effect (-0,03 EUR/MWh), which is consistent with its wind dominated system, while Norway followed it (-0,01 EUR/MWh), with its flexible hydropower-heavy system, and Sweden, which was the reference group, appears to be the least affected by its own RES generation, which confirms that the merit-order effect is consistent, and it was found that the magnitude depends on the characteristics of the national systems. (Würzburg et al., 2013; Bahar and Sauvage, 2013)

The Dutch TTF day-ahead gas prices were also found to be significant positive drivers of the electricity prices in the Nordic region. When looking at the country-specific effects, Denmark appears to be the most sensitive to gas price fluctuations, possibly due to the wind-dominated system which is highly volatile and unpredictable, which was followed by Norway, then Sweden, which highlights the differences between the countries' generation mix and reliance on natural gas. (Zakeri et al., 2023; Stringer et al., 2024)

To answer the research question, electricity day-ahead prices in Denmark, Norway, and Sweden are shaped by a combination of domestic consumption, renewable output, cross-border electricity trade, and weather condition, with results that are in line with theoretical expectations. However, the analysis also identifies significant cross-country differences, especially in how electricity prrices respond to renewable generation and to natural gas prices. The found differences reflect each country's generation mix, flexibility and exposure to external markets, which underscores the importance of country-specific modeling within a regional electricity market like the Nord Pool.

7. Conclusion

This thesis was aimed to understand how electricity consumption, renewable generation, cross-border electricity trade, and weather conditions affect day-ahead electricity prices in Denmark, Norway, and Sweden, and whether these effects are different between the three countries. The analysis was based on a five-year panel dataset and used fixed effects panel regression with instrumental variables and Driscroll-Kraay standard errors to account for potential biases and provide robustness.

The results from the main model confirmed what was expected based on the theory: consumption pushes prices up, while renewable generation, net imports, temperature, and rainfall have significant price-lowering effects. These findings are consistent with the merit-order effect and the role of market interconnectivity and cross-border spillovers, where lower-cost electricity is replacing the more expensive generation across borders.

The first robustness test made it clear that the price effects of renewables are not the same in every country, as Denmark showed the strongest price-lowering effect as a response to its own renewable generation, followed by Norway, while Sweden, which was used as a reference category seemed to be the least affected, which is not surprising taking into consideration the countries' renewable generation mixes and the fact that Denmark is heavily relying on wind, which is has the most variability and unpredictability, while Norway and Sweden are relying more heavily on hydro generation, which is storable and therefore its dispatchability is also more flexible.

The analysis also showed that European gas prices, measured by the Dutch TTF day-ahead index, are significantly influencing electricity prices in the Nordic region, and on a country-specific level, Denmark showed the highest sensitivity to gas prices, followed by Norway and then Sweden, which reflects how dependent the three countries are on gas prices.

The results show that while there are regional patterns and shared mechanisms across the Nord Pool market, the country-level characteristics play a major role in shaping the price dynamics, and even in a highly integrated electricity market, national differences still matter and should be taken into account when thinking about future energy transitions or investments.

Future research

While this thesis gave an insights into the drivers of the day-ahead electricity prices in the Nordic region, it also showed how wide the topic is which implies that there are several ways how future research could deepen this analysis.

A possible direction for future research is using source-specific renewable generation in the models, rather than a common summed up RES generation variable to see the distinct impacts of the different sources on the day-ahead prices.

Another way to deepen the understanding of the dynamics in the Nordic market would be a bidding-zone level analysis instead of country-level averages, since price formation is happening on a bidding zone-level, and it could shed light to differences inside the certain countries.

Further research could be also shifting the focus to price volatility and using price variance as the dependent variable instead of the price level, since the growing share of renewables could also increase volatility due to their unpredictability.

By taking into consideration these dimensions, future studies could provide an even deeper and more nuanced understanding of the Nordic electricity market.

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Production:
Report type: Production, year: 2020, 2021, 2022, 2023, 2024, area: DK1, DK2, NO1, NO2, NO3, NO4, NO5, SE1, SE2, SE3, SE4, aggregation level: none, unit: MWh

Consumption:
Report type: Consumption, year: 2020, 2021, 2022, 2023, 2024, area: DK1, DK2, NO1, NO2, NO3, NO4, NO5, SE1, SE2, SE3, SE4, aggregation level: none, unit: MWh

ENTSOE-E Transparency platform
https://newtransparency.entsoe.eu/transmission/physicalFlows?appState=%7B%22sa%22%3A%5B%22CTY%7C10Y1001A1001A65H%22%5D%2C%22st%22%3A%22CTY%22%2C%22mm%22%3Atrue%2C%22ma%22%3Afalse%2C%22sp%22%3A%22HALF%22%2C%22dt%22%3A%22TABLE%22%2C%22df%22%3A%222025-05-30%22%2C%22tz%22%3A%22CET%22%7D

Transmission - Cross-border Physical Flows
Denmark (01.01.2020 – 31.12.2024)
Norway (01.01.2020 – 31.12.2024)
Sweden (01.01.2020 – 31.12.2024)

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Appendix

Appendix A

The choice of the fixed effects estimation was explained in the 4.4.2 Data analysis method section, however random effects regression was estimated as well for transparency, for which the results will be presented in Appendix A1. Moreover, to confirm the need of instrumental variables method, the fixed effects model's estimation without IV method will be presented Appendix A2.

A1. Random effects main model

The random effects model was also estimated to compare it with the fixed effects model, which was eventually preferred based on theoretical considerations, moreover the assumption checks of the random effects model showed significant violations, including serial correlation, and groupwise heteroskedasticity, for which the fixed effect model's Driscroll-Kraay robust standard errors is a better solution, as it corrects for heteroskedasticity, serial correlation and for also cross-sectional dependence, however it is not appropriate for random effects models, and random effect model does not have a standard error option that would fix all of the assumption breaks. (Hoechle, 2007)

The Hausman test (Wooldridge, 2013) showed a p-value of 1, which suggests no systematic difference between the fixed and random effects estimators.

Hausman Test	
chi square	9,548
df	24
p-value	0,9962

Table 8: Hausman test for Random effects model

The Breusch-Pagan test (Verbeek, 2004) for heteroskedasticity rejects the null-hypothesis, which implies the presence of heteroskedasticity.

Breusch-Pagan heteroskedasticity test	
LM statistic	10689,45
df	24
p-value	0

Table 9: Breusch-Pagan test for Random effects model

The Durbin-Watson test (Verbeek, 2004) shows strong first-order autocorrelation with the DW value being 0,05 with a statistical significance:

Durbin-Wattson serial correlation test	
DW	0,0049786
p-value	< 2,2E-16

Table 10: Durbin-Wattson test for Random effects model

However, multicollinearity does not seem to be an issue as all the results are below 10, which is the threshold according to Wooldridge (2013).

Mutlicollinearity (VIF)	
	VIF
consumption	2,9
RES_generation	2,3
net_import	1,5
temperature	5,0
sunshine	1,4
wind	1,4
rain	1,0
hour	1,0
month	4,5

Table 11: Multicollinearity for Random effects model

And the estimation can be seen below, the overall model is statistically significant:

```
Coefficients:
                 Estimate  Std. Error  z-value  Pr(>|z|)
(Intercept)    2.3021e+01  1.9621e+01   1.1733    0.2407
consumption    4.6549e-03  1.3703e-04  33.9702 < 2.2e-16 ***
RES_generation 2.0831e-03  7.7501e-05  26.8790 < 2.2e-16 ***
net_import     3.5127e-03  1.3705e-04  25.6298 < 2.2e-16 ***
temperature   -1.5535e+00  6.0764e-02 -25.5666 < 2.2e-16 ***
sunshine       2.3972e-03  1.5488e-04  15.4773 < 2.2e-16 ***
wind          -2.4659e+00  3.1861e-02 -77.3947 < 2.2e-16 ***
rain          -3.0896e+00  5.7198e-01  -5.4016 6.603e-08 ***
dayMonday      4.0306e+00  7.5077e-01   5.3687 7.930e-08 ***
daySaturday   -9.1257e+00  7.5676e-01 -12.0590 < 2.2e-16 ***
daySunday     -1.3211e+01  7.6006e-01 -17.3821 < 2.2e-16 ***
dayThursday    3.9636e+00  7.5088e-01   5.2786 1.302e-07 ***
dayTuesday     5.6817e+00  7.5114e-01   7.5641 3.907e-14 ***
dayWednesday   4.3251e+00  7.5079e-01   5.7607 8.374e-09 ***
month02       -8.5329e+00  9.9729e-01  -8.5561 < 2.2e-16 ***
month03        6.9677e+00  9.9680e-01   6.9901 2.747e-12 ***
month04        9.8443e+00  1.0645e+00   9.2481 < 2.2e-16 ***
month05        1.7876e+01  1.1975e+00  14.9285 < 2.2e-16 ***
month06        3.7005e+01  1.3768e+00  26.8776 < 2.2e-16 ***
month07        4.3589e+01  1.3870e+00  31.4266 < 2.2e-16 ***
month08        7.0582e+01  1.3787e+00  51.1959 < 2.2e-16 ***
month09        6.1325e+01  1.2760e+00  48.0605 < 2.2e-16 ***
month10        1.8425e+01  1.1149e+00  16.5268 < 2.2e-16 ***
month11        1.9974e+01  1.0220e+00  19.5445 < 2.2e-16 ***
month12        3.9991e+01  9.7788e-01  40.8950 < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Total Sum of Squares:    824400000
Residual Sum of Squares: 695950000
R-Squared:      0.15582
Adj. R-Squared: 0.15566
Chisq: 24274.2 on 24 DF, p-value: < 2.22e-16
```

Table 12: Random effects model estimation output (Rstudio)

A2. Fixed effects main model without endogeneity treatment

To validate the use of instrumental variables in the thesis, the fixed effects estimation without IV method, but with Discroll-Kraay standard errors is presented below:

t test of coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
consumption	4.6676e-03	4.1413e-04	11.2707	< 2.2e-16	***
RES_generation	2.0838e-03	2.1253e-04	9.8045	< 2.2e-16	***
net_import	3.5089e-03	4.0469e-04	8.6707	< 2.2e-16	***
temperature	-1.5515e+00	1.8999e-01	-8.1660	3.215e-16	***
sunshine	2.3925e-03	3.7269e-04	6.4195	1.372e-10	***
wind	-2.4667e+00	1.0429e-01	-23.6520	< 2.2e-16	***
rain	-3.0878e+00	1.0822e+00	-2.8532	0.004329	**
dayMonday	4.0300e+00	2.5363e+00	1.5889	0.112078	
daySaturday	-9.1156e+00	2.1898e+00	-4.1628	3.146e-05	***
daySunday	-1.3199e+01	2.2378e+00	-5.8982	3.684e-09	***
dayThursday	3.9621e+00	2.4264e+00	1.6329	0.102485	
dayTuesday	5.6795e+00	2.6053e+00	2.1799	0.029264	*
dayWednesday	4.3231e+00	2.5643e+00	1.6859	0.091823	.
month02	-8.5313e+00	1.8765e+00	-4.5464	5.461e-06	***
month03	6.9797e+00	2.5099e+00	2.7809	0.005421	**
month04	9.8717e+00	2.4248e+00	4.0711	4.681e-05	***
month05	1.7912e+01	3.0804e+00	5.8147	6.087e-09	***
month06	3.7039e+01	3.7765e+00	9.8077	< 2.2e-16	***
month07	4.3627e+01	4.2190e+00	10.3405	< 2.2e-16	***
month08	7.0613e+01	5.2045e+00	13.5675	< 2.2e-16	***
month09	6.1355e+01	4.6768e+00	13.1190	< 2.2e-16	***
month10	1.8448e+01	2.6392e+00	6.9899	2.764e-12	***
month11	1.9982e+01	2.7596e+00	7.2410	4.480e-13	***
month12	3.9992e+01	3.7651e+00	10.6219	< 2.2e-16	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 13: Driscroll-Kraay robust standard error estimation coefficients for Fixed effects model (Rstudio)

It is clear, that without the IV methods the RES_generation has a positive effect, which is in contrast with the theoretical findings, therefore the use of the IV methods is justified.

Appendix B

The outputs for assumption tests of the main model and the three robustness tests are shown below, they are analyzed in the analysis section, therefore here are only the tables are shown:

B1. Main model

Hausman Test	
chi square	9,548
df	24
p-value	0,9962

Table 14: Hausman test for main model

Modified Wald test for groupwise heteroskedasticity	
chi square	118898
p-value	0

Table 15: Modified Wald test for main model

Wooldridge serial correlation test				
	estimate	std. error	t-value	p-value
intercept	0,002	0,056	0,032	0,975
lag_resid	0,992	0,001	1739,981	< 2,2E-16

Table 16: Wooldridge test for main model

Mutlicollinearity (VIF)	
	VIF
consumption	2,9
RES_generation	2,3
net_import	1,5
temperature	5,0
rain	1,0
day	1,0
month	4,5
sunshine	1,4
wind	1,4

Table 17: Multicollinearity test for main model

First stage IV F-statistic	
F	5982,70
p-value	< 2,2E-16

Table 18: First stage IV statistic for main model

B2. Robustness test 1

Modified Wald test for groupwise heteroskedasticity	
chi square	2424,87
p-value	0

Table 19: Modified Wald test for RT1

Wooldridge serial correlation test				
	estimate	std. error	t-value	p-value
intercept	-0,001	0,043	-0,026	0,979
lag_resid	0,978	0,001	721,427	< 2,2E-16

Table 20: Wooldridge test for RT1

Mutlicollinearity (VIF)	
	VIF
consumption	4,3
net_import	1,4
temperature	5,0
sunshine	1,0
wind	2,2
rain	1,0
RES_dk	3,7
RES_no	1,5
day	1,0
month	4,6

Table 21: Multicollinearity test for RT1

First stage IV F-statistic Denmark	
F	8995,40
p-value	< 2,2E-16

Table 22: First stage IV statistic for RES_dk

First stage IV F-statistic Norway	
F	8537,8
p-value	< 2,2E-16

Table 23: First stage IV statistic for RES_no

B3. Robustness test 2

Modified Wald test for groupwise heteroskedasticity	
chi square	214654
p-value	0

Table 24: Modified Wald test for RT2

Wooldridge serial correlation test				
	estimate	std. error	t-value	p-value
intercept	0,001	0,053	0,024	0,981
lag_resid	0,990	0,001	1480,789	< 2,2E-16

Table 25: Wooldridge test for RT2

Mutlicollinearity (VIF)	
	VIF
consumption	2,9
RES_generation	2,2
net_import	1,5
temperature	4,9
sunshine	1,4
wind	1,4
rain	1,1
TTF_price	1,1
day	1,0
month	4,7

Table 26: Multicollinearity test for RT2

B4. Robustness test 3

Modified Wald test for groupwise heteroskedasticity	
chi square	207790,1
p-value	0

Table 27: Modified Wald test for RT3

Wooldridge serial correlation test				
	estimate	std. error	t-value	p-value
intercept	0,001	0,050	0,020	0,984
lag_resid	0,999	0,001	1355,429	< 2,2E-16

Table 28: Wooldridge test for RT3

Mutlicollinearity (VIF)	
	VIF
consumption	3,6
RES_generation	2,9
net_import	1,7
temperature	5,0
sunshine	1,4
wind	1,4
rain	1,0
TTF_dk	1,7
TTF_no	1,6
day	1,0
month	4,6

Table 29: Multicollinearity test for RT3

Appendix C

Additional analysis

The two additional robustness tests' analysis and discussion are presented in this appendix, which were exploring the impact of extremely high renewable electricity generation periods in the whole region, then separately by countries, however due to concerns about potential endogeneity in the high RES dummy variables, the results of these models are not mentioned in the main analysis and they are not part of the general conclusion, but they are included here for transparency.

C1. Analysis of Robustness test 4 and 5

C1.1 Robustness test 4

This robustness test was designed to answer the fifth working question: Do day-ahead electricity prices respond differently during hours of exceptionally high renewable energy generation (top 5% of RES output)?

The fourth robustness test introduces a binary indicator, the high_res_dummy for hours that are considered high renewable production period, by being in the top 5% of all renewable production to see whether these periods have a different effect on day-ahead electricity prices, while controlling for continuous RES generation and Driscroll-Kraay standard errors with IV method were used for the estimation.

Variable	Estimate	Std. Error	t-statistic	p-value
consumption	0,040	0,004	9,415	< 2,2E-16
net_import	-0,055	0,007	-8,393	< 2,2E-16
temperature	-3,887	0,412	-9,437	< 2,2E-16
rain	-11,283	2,103	-5,365	8,10E-08
RES_generation	-0,055	0,006	-8,802	< 2,2E-16
high_res_dummy	98,512	11,227	8,774	< 2,2E-16
dayMonday	5,286	5,968	0,886	0,376
daySaturday	-11,940	5,311	-2,248	0,025
daySunday	-10,630	5,515	-1,927	0,054
dayThursday	5,370	5,631	0,954	0,340
dayTuesday	5,628	6,002	0,938	0,348
dayWednesday	5,520	5,952	0,928	0,354
month02	-4,342	9,696	-0,448	0,654
month03	9,188	9,577	0,959	0,337
month04	27,870	9,156	3,044	0,002
month05	60,865	9,791	6,216	5,11E-07
month06	94,400	10,799	8,742	< 2,2E-16
month07	89,482	10,940	8,179	2,88E-13
month08	125,101	11,771	10,628	< 2,2E-16
month09	119,997	10,875	11,034	< 2,2E-16
month10	63,297	9,398	6,735	1,65E-08
month11	45,696	9,224	4,954	7,29E-04
month12	74,421	10,134	7,343	2,09E-10

Table 30: Robustness test 4 regression output (Driscroll-Kraay, IV methods)

Coefficients and their economic meaning
The electricity consumption stayed significantly positive (β = 0,04, p < $2{,}2*10^{-16}$), which implies that a 0,04 EUR/MWh increase is the result on average of a 1 MWh increase in consumption, holding everything else constant.

Renewable electricity generation continues resulting in a statistically significant negative effect (β = -0,06, p < $2{,}2*10^{-16}$), leading to a 0,06 EUR/MWh price drop in spot prices in case of a 1 MWh increase in RES generation.

Net import is again showing a negative and significant impact (β = -0,06, p < $2{,}2*10^{-16}$), meaning that on average day-ahead prices are decreasing by 0,06 EUR/MWh as a result of a 1 MWh increase in net import, holding all else equal.

Temperature keeps having a strong and negative effect on the prices (β = –3,887, p < $2{,}2*10^{-16}$), leading to a 3,887 EUR/MWh price fall in case of a 1 Celsius degree increase.

Rainfall is also still negatively significant. (β = –11,28, p = $8{,}1*10\text{-}^{8}$), which implies a 11,28 EUR/MWh price drop on average in case of a 1 mm increase of rain.

The high renewable generation dummy is statistically significant and positive ($\beta = 98{,}512$, $p < 2{,}2 \cdot 10^{-16}$), which implies that on days with exceptionally high renewable generation (top 5% of the distribution), the day-ahead price is on average 98,51 EUR/MWh higher, than on other days.

In this specification out of the day-of-week dummies Saturday ($\beta = -11{,}94$, $p = 0{,}025$) is the only that's statistically significant at 5% and it has a negative effect, which means that spot prices on Saturday are on average 11,94 EUR/MWh lower than on Fridays (reference category).

Out of the month dummy variables February and March have no statistical significance at 5%, however the rest of the months are significant, with the strongest effect again in August, when the prices are on average 125,10 EUR/MWh higher compared to January.

Model diagnostics

There's no multicollinearity in the model as all VIF values are below 10, with the highest value of 5,2 for the temperature. Heteroskedasticity is present as it was shown by the Modified Wald test ($\chi^2 = 143\ 710{,}5$, $p = 0$), which is again a very high value and might be inflated, but it still confirms heteroskedasticity, while serial correlation is confirmed by the Wooldridge test ($\beta = 0{,}991$, $p < 2{,}2 \cdot 10^{-16}$), which results are validating the use of the Driscroll-Kraay robust standard error estimation. The overall model has a chi square of 3984,1 ($p < 2{,}2 \cdot 10^{-16}$), which means the explanatory variables are jointly significant.

Assumption tests – tables:

Modified Wald test for groupwise heteroskedasticity	
chi square	143710,5
p-value	0

Table 31: Modified Wald test for RT4

Wooldridge serial correlation test

	estimate	std. error	t-value	p-value
intercept	0,002	0,061	0,030	0,973
lag_resid	0,991	0,001	1768,029	< 2,2E-16

Table 32: Wooldridge test for RT4

Mutlicollinearity (VIF)	
	VIF
consumption	3,0
RES_generation	2,6
net_import	1,5
temperature	5,2
sunshine	1,4
wind	1,4
rain	1,0
high_res_dummy	1,4
day	1,0
month	4,6

Table 33: Multicollinearity test for RT4

Result
The null hypothesis is rejected because the coefficient for the high renewable generation dummy is statistically significant and positively affecting the day-ahead prices.

C1.2 Robustness test 5

The fifth robustness test was created to answer the last working question: Does the impact of extremely high renewable electricity generation (top 5% of RES output) on day-ahead prices differ across Denmark, Norway and Sweden?

At the last robustness test separate dummy variables were created for high renewable production days in Denmark (high_res_dk) and Norway (high_res_no) to analyze possible country-specific nonlinear effects in the Nord Pool market. As in all previous models, the Driscroll-Kraay standard errors and instrumental variables were used for the estimation.

Variable	Estimate	Std. Error	t-statistic	p-value
consumption	0,038	0,005	8,018	1,08E-15
net_import	-0,050	0,007	-6,919	4,57E-12
temperature	-3,974	0,398	-9,973	< 2,2E-16
rain	-11,752	1,963	-5,988	2,13E-06
RES_generation	-0,049	0,007	-7,186	6,70E-13
high_res_dk	-7,935	5,423	-1,463	0,143
high_res_no	95,737	12,000	7,978	1,50E-15
dayMonday	5,866	5,490	1,069	0,285
daySaturday	-11,145	4,870	-2,289	0,022
daySunday	-10,073	5,064	-1,989	0,047
dayThursday	4,939	5,186	0,952	0,341
dayTuesday	6,141	5,525	1,112	0,266
dayWednesday	5,483	5,485	1,000	0,318
month02	-4,983	8,786	-0,558	0,577
month03	12,263	8,730	1,405	0,160
month04	27,908	8,314	3,357	0,001
month05	62,640	9,122	6,867	6,58E-12
month06	98,132	10,297	9,530	< 2,2E-16
month07	94,350	10,203	9,247	< 2,2E-16
month08	128,842	11,346	11,356	< 2,2E-16
month09	121,348	10,535	11,518	< 2,2E-16
month10	62,625	8,938	7,007	2,46E-12
month11	47,092	8,585	5,583	2,37E-08
month12	72,758	9,489	7,668	1,76E-14

Table 34: Robustness test 5 regression output (Driscroll-Kraay, IV methods)

Coefficients and their economic meaning

As in all previous models, in the last one as well the electricity consumption keeps being a significant and positive estimator of the day-ahead prices ($\beta = 0,04$, $p = 1,08*10^{-15}$), implying a 0,04 EUR/MWh price raise if the consumption increases by 1 MWh, holding all other variables constant.

Renewable electricity generation in this last specification also shows a significant negative coefficient ($\beta = -0,05$, $p = 6,70*10\text{-}^{13}$), with having a 0,05 EUR/MWh price lowering effect in case the renewable generation raises by 1 MWh.

The net import stays a negative and statistically significant coefficient ($\beta = -0,05$, $p = 4,57 * 10^{-12}$), implying a 0,05 decrease in spot prices if the net import raises by 1 MWh.

The temperature variable keeps being statistically significant and negatively correlated with the prices ($\beta = –3,97$, $p < 2,2*10^{–16}$), leading to a 3,97 EUR/MWh price decrease on average in case of a 1 Celsius degree temperature increase, holding all else equal.

Rainfall in this robustness test has still a negative sign while being significant ($\beta = –11,75$, $p = 2,13*^{10\text{-}6}$), which is associated with a 11,75 EUR/MWh price drop in case of a 1 mm increase in rain.

The high RES dummy for Denmark is negative, however statistically not significant ($\beta = -7{,}935$, $p = 0{,}143$) compared to Sweden. While the high RES dummy for Norway is positive and statistically significant ($\beta = 95{,}74$, $p = 1{,}50 \cdot 10^{-15}$), by this suggesting that high RES days in Norway are causing price increases by 95,74 EUR/MWh on average compared to Sweden.

When it comes to the day-of-week dummies, only Saturday ($\beta = -11{,}15$, $p = 0{,}02$) and Sunday ($\beta = -10{,}07$, $p = 0{,}05$) are having significant effects which are having negative signs compared to Friday, while the weekdays are statistically not significant.

The month dummies, like in almost all of the previous models are statistically significant and positive compared to January for almost all models except for February and March, with August having the strongest effect ($\beta = 128{,}84$, $p < 2{,}2 \cdot 10^{-16}$), meaning that compared to January, prices are on average 128,84 EUR/MWh higher in August.

Model diagnostics

As all VIF values are under 10, with temperature being the highest with 5,1, therefore multicollinearity is not an issue in this model. The Modified Wald test rejected again the null hypothesis of homoskedasticity ($\chi^2 = 115\ 953{,}4$, $p = 0$) and the Wooldridge test detected serial correlation ($\beta = 0{,}991$, $p < 2{,}2 \cdot 10^{-16}$), therefore using the Driscroll-Kraay corrections is again valid. The model's chi square is 4589,5 with $p < 2{,}2 \cdot 10^{-16}$ which confirms that the model is jointly statistically significant.

Assumption tests – tables:

Modified Wald test for groupwise heteroskedasticity	
chi square	115953,4
p-value	0

Table 35: Modified Wald test for RT5

Wooldridge serial correlation test

	estimate	std. error	t-value	p-value
intercept	0,002	0,057	0,029	0,977
lag_resid	0,991	0,001	1676,375	< 2,2E-16

Table 36: Wooldridge test for RT5

Mutlicollinearity (VIF)	
	VIF
consumption	3,0
RES_generation	2,4
net_import	1,5
temperature	5,1
sunshine	1,4
wind	1,5
rain	1,0
day	1,0
month	4,6
high_res_dk	1,1
high_res_no	1,1

Table 37: Multicollinearity test for RT5

Result
The null hypothesis is rejected, as Norway shows significantly different responses in their high RES dummy price response compared to Sweden.

C2. Discussion of Robustness test 4 and 5

C2.1 Robustness test 4

This robustness test studies whether day-ahead electricity prices respond differently during hours of exceptionally high renewable energy generation (top 5% of RES output)?

In this model a dummy variable was created for the top 5% of the renewable generation to account for high renewable production periods to analyze how do the electricity prices behave in case of RES output spikes.

Consumption remains similar as in the previous models and being in line with the theory (Blume-Werry et al., 2021; Bahar and Sauvage, 2013), by reacting with a 0,04 EUR/MWh price increase to a 1 MWh increase in consumption.

Net import also similar to the previous models, with slight magnitude change, therefore the theory is still confirmed (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021). In this specification prices react with a 0,055 EUR/MWh decrease to a 1 MWh increase in net import.

RES generation was kept as a control variable in this specification, and it remains being theoretically sound as the result underscores the merit-order effect, in this scenario its price suppressing effect is 0,055 EUR/MWh in case of a 1 MWh increase in RES output. (Würzburg et al., 2013; Bahar and Sauvage, 2013)

Rain and temperature are in line with the theoretical and logical expectations and with the previous models, as 1 mm increase in rainfall leads to a 11,28 EUR/MWh price drop, that is aligned with the theory (Wen et al., 2022), while a 1 Celsius degree change in temperature is associated with a 11,28 EUR/MWh price decrease.

The high RES dummy shows an unexpected and extremely high positive result, as the model implies that a during hours of exceptionally high RES generation, the day-ahead electricity price on average is 98,51 EUR/MWh higher, than during other hours, while controlling for continuous RES generation and other variables which is contrary to the merit-order effect (Würzburg et al., 2013; Bahar and Sauvage, 2013), and while it might reflect nonlinear effect, such as grid congestion or balancing costs or curtailment events, it also raises concerns of possible endogeneity caused by unobserved factors, which should be treated with an IV approach to get more reliable estimates. This could be done by instrumenting the high RES dummy with exogeneous weather-related variables, such as extreme wind speeds or sunshine duration threshold to moderate the bias coming from reverse causality or omitted variables, and to isolate better the causal effect of extreme renewable output on electricity prices, however in this form the coefficients should be interpreted with caution.

Day of week dummies are showing significance only for the weekends compared to Friday with a negative effect, which is in line with most of the models and the theory (Wolff and Feuerriegel, 2018), while month dummies are showing similar results and scale as the main model, which is not in line with the expectations based on Wolff and Feuerriegel's findings (2018).

To answer the working question, day-ahead prices respond differently to exceptionally high-renewable periods, however the results are the opposite of what is expected based on the merit-order effect, which could be caused by endogeneity, therefore these results are not reliable indicators of the specific effect of these high renewable production days and they should be cautiously interpreted.

C2.2 Robustness test 5

The last robustness test is aimed to answer if the impact of extremely high renewable electricity generation (top 5% of RES output) on day-ahead prices differs across Denmark, Norway and Sweden?

In this model country-specific dummy variables were created that are equal to 1 in case of the country's own RES output is in the top 5% of its renewable generation, then these were interacted with the country dummies, and these were added to the main model to analyze if there is a difference between the countries' responses to RES output spikes. Sweden was omitted to avoid the dummy variable trap, and it was considered as a baseline.

Consumption is having a similar response as the rest of the models with 0,04 EUR/MWh increase as a response to a 1 MWh increase in consumption, which is in line with the theory (Blume-Werry et al., 2021; Bahar and Sauvage, 2013).

Net import is also in line with all the previous models and with the theory (Urquijo and Paraschiv, 2023; Abrell and Kosch, 2021), as a 1 MWh increase in net import decreases the day-ahead electricity prices by 0,055 EUR/MWh.

RES generation throughout all the models show similar scale effects as the net import, and now it also decreases by 0,055 EUR/MWh in case of a 1 MWh increase in RES generation, which is also similar effect as the previous models, and it underscores the merit-order effect theory (Würzburg et al., 2013; Bahar and Sauvage, 2013).

Temperature and rain effects are consistent with the main and with the previous model, and therefore also with the theory with minor magnitude differences, as in this model 1 Celsius degree temperature increase is associated with a 3,97 EUR/MWh electricity day-ahead price decrease, while a 1 mm increase in rainfall is associated with a 11,752 EUR/MWh drop in the spot prices which is consistent with the theory (Wen et al., 2022).

The focus of this model is the effect of the high RES output in the specific countries: Denmark does not have a statistically significant difference compared to Sweden, which is the reference group here, however in Norway extremely high renewable production periods are raises the prices by 95,737 EUR/MWh on average compared to Sweden, which is also an unexpected result, like the previous specification, as it is contradictory to the merit-order effect expectation (Würzburg et al., 2013; Bahar and Sauvage, 2013), based on which it would be assumed that extremely high production days are also having price lowering effects. As it was explained in the previous model, this result can be cause by nonlinear effects, but at the same time endogeneity could be the actual reason behind this result, for which IV method should be used with instruments such as extreme weather-related explanatory variables, therefore the current coefficient results should be taken into consideration with caution.

The day-of-week dummies are almost identical as in the previous model, showing significance only during the weekends with negative effect, which is underscoring the findings of Wolff and Feuerriegel (2018). The month dummy variables are showing similar significance and positive effects as the previous models, which is again, contradictory to the findings of Wolff and Feuerriegel (2018).

To answer the working question, the price responses differ between countries, or at least between Norway and the rest of the observed countries, as Denmark did not show a significance compared to Sweden, however the result is showing an opposite sign effect of what is expected based on the merit-order effect, which can be caused by nonlinear effect or endogeneity, therefore this result should be treated with caution as it might be biased.