

SCHOOL OF ECONOMICS AND MANAGEMENT

Beyond our Control

An examination on the impact that weather has on electricity prices in Denmark.

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Bachelor's thesis in Economics

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Abstract:

This paper is an empirical study on the effect that different weather conditions have on electricity prices in Denmark between the 29th of April 2023 and the 29th of April 2025. The study analyses how daily time series data for wind speed, temperature and solar exposure impacts daily electricity prices in respective bidding areas. The findings of this paper concludes that each of the measured weather variables has a significant impact on electricity prices in both bidding areas, with wind speed having the greatest impact, followed by temperature and solar exposure. As many countries move towards a greater reliance on weather based intermittent energy sources, the findings of this paper provides an insight into the impact that such a transition can have on electricity prices. As such the findings of this paper can be of particular interest to policymakers determining future energy policies.

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1.0 Introduction

The Danish government has committed themselves to having a domestic electricity supply consisting of 100% renewable sources by 2030. This transformation will largely depend on increased investments into intermittent sources such as solar and wind, whilst controllable sources such as gas and coal are gradually phased out. The increased reliance on weather dependent sources is expected to have consequences on the stability of the electricity supply and in extension on prices. (Danish ministry of Climate, Energy and Utilities, 2024) This paper aims to examine that relationship and investigate the impact between electricity prices and weather variations in Denmark.

1.1 Purpose and Research Question

The purpose of this paper is to provide an overview over the effect that variations in weather conditions have on electricity prices on the wholesale market through means of a statistical analysis. Denmark is especially suitable for this type of analysis given the small size of its bidding areas, which enables accurate estimation of the effect that measurements of weather data has on domestic production in specific bidding areas. The primary questions the paper aims to answer is (1) the effect that changes in solar exposure, wind speed and temperature have on electricity prices (2) how that relationship differs across bidding areas, and (3) how that relationship changes given the share of production that consists of renewable sources. By establishing a better understanding of this relationship, this paper can serve as support for decision makers when contemplating electricity policy.

1.2 Disposition

Section 2 begins with a thorough descriptive background regarding the price mechanisms that determine prices on the Danish wholesale electricity market and how they can be explained and understood using economic theory. The section also provides an overview over Danish electricity production, and how it has developed over time. Section 3 analyses previous

research regarding the effect that weather has on electricity prices. Section 4 presents the data used in the empirical analysis, and the methods employed in our statistical regression. Section 5 displays the results from the statistical analysis and how they compare to each other. Section 6 analyses the results from section 5, and discusses how the results relate to what we expected and to previous research. Section 7 expands on the insight from section 6 and discusses the impact they could have on policy. The paper concludes with a short summary and emphasises the main conclusions.

2.0 Background

2.1 Danish Electricity market

The Danish wholesale electricity market is today an integrated part of the larger European electricity market, which enables the free movement of trade across borders on the same conditions as within the country. (European Free Trade Association, 2014) The national monopoly with fixed rates which predated the current system was deregulated in the late nineties in order to allow for a competition based market-rate aimed at improving efficiency, innovation and lowered prices for consumers. This culminated when Denmark joined Nordpool, the first international power exchange in 1999. (Hauch, 2001)

Electricity has several unique characteristics, which separates it from other commodities and creates special market dynamics. Firstly, wholesale electricity is in practice unable to be stored, meaning that it's both produced and consumed instantly. This further implies that the infrastructure that facilitates the transfer of electricity must always be in balance in order to avoid power outages. As such the demand and supply of electricity must at all times be in equilibrium, which is why it's traded on an hourly basis, every day of the week. The transfer of electricity also presupposes the existence of sufficient infrastructure necessary for electricity transmission, as constraints in the transmission network limits the possibility of transfer. (Weron, 2014) It's against that background that countries traded on Nordpool are divided into different bidding areas, which operates as independent markets with individual prices. Denmark is divided into two bidding areas, Denmark West (DK1) and Denmark East (DK2). (Nord pool, n,d)

2.2 Price calculation

Electricity trading differs from other commodity markets as the spot price is determined in advance, this is typically done in a day-ahead market where consumers and suppliers place their bids and offers a day before scheduled delivery. The reason behind this is so that the operators of the transmission infrastructure can guarantee a balanced electric grid.

A separate intraday market exists for adjusting and additional balancing during the day of delivery. As the bulk of trading takes place on the day-ahead market, it will serve as this paper's benchmark for the price of electricity. (Nord pool, n.d)

2.3 Market Clearing Price & Merit Order

The market clearing price for each bidding area is derived on the day-ahead market by combining all hourly sales orders into an aggregate supply curve, and all hourly purchase orders into an aggregate demand curve. The intersection of these curves establishes the hourly MCP. (Nord pool, n.d) The demand curve is denoted by Q_D , it can be modelled using an intercept (α_1) representing the demand of electricity when the price is zero and a variable β_1 denoting the elasticity. β_1 is assumed to be < 0 meaning that demand is expected to drop if price increases. The supply is likewise denoted Q_S and modelled with an intercept (α_2), the quantity supplied when price is zero and a variable β_2 representing the elasticity of supply. β_2 is assumed to be greater than zero, indicating that the supply of electricity is expected to increase with price.

$$Q_{D(t)} = \alpha_1 + \beta_1 \times P_t$$

$$Q_{S(t)} = \alpha_2 + \beta_2 \times P_t$$

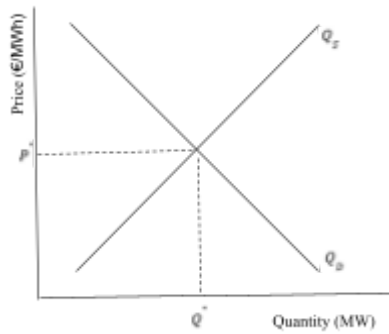


Figure 1: Relationship between aggregate supply & demand for hourly MCP on day-ahead market.

This guarantees that the market clearing price is the lowest price possible for each hour of the day, as price becomes equal to the marginal cost of the final unit of electricity needed to satisfy demand. This happens because the market operates through a system called “*merit order*” which orders all sales bids from lowest to highest and accepts them in order until demand is met, resulting in an area price represented by the marginal cost of the last accepted sales order. (Jacques Delors Institute, 2022) This system generates optimal social welfare, as it guarantees the price that maximizes consumer and producer surplus. (Nord pool, n.d) The process is illustrated by figure 2. The staples represent different sources of electricity with heights and width indicating marginal cost and quantity produced. The figure shows that all sales orders offered by source (A) and (B) are accepted, whilst only some of (C) and none of (D). The marginal cost of (C) hence becomes the market clearing price as it supplies the final unit needed to meet demand. (Jacques Delors Institute, 2022)

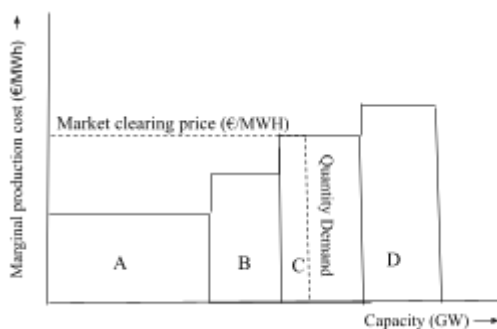


Figure 2: Illustrating marginal price setting.

2.4 Transmission & Trade

As a result of the Danish electricity market being integrated with the European market, electricity prices are not only determined by internal market conditions, but also that of neighbouring areas. After the MCP is calculated the *merit order* system is designed to maximise social welfare and as such guarantees that electricity will flow towards the area where the price is highest, leading to a negative supply shock resulting in a higher price for the area which electricity is being exported from, and a positive supply shock with lower prices for the area that is importing. This flow of electricity will continue until (1) full price convergence occurs or (2), the transmission infrastructure is not sufficient to meet (1) resulting in congestion and differing prices between areas. (Nord pool, n,d) See figure 3 & 4, for graphic illustration of electricity export from one area to another.

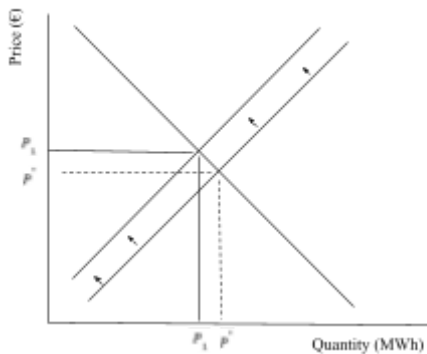


Figure 3: Surplus area generates export

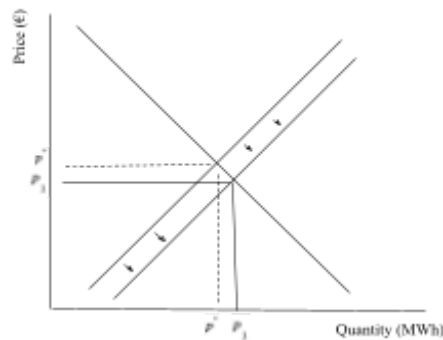


Figure 4: Deficit area generates imports.

Figure 5 displays the net export (total foreign exports - total foreign imports) in DK1 and DK2 during the past twenty years. Denmark has since 2011 been a net importer of electricity, indicating that the country consumes more electricity than domestically produced. DK2 has had a higher trade deficit than DK1 since 2021. DK1's biggest international trading partners are Norway (NO2) and Germany (GE), they are a net importer from NO2 and a net exporter to GE. DK2's biggest trading partners are Germany (GE) and Sweden (SE4), they are a net exporter towards GE and a net importer towards SE4. This indicates that Germany has an average positive effect on prices in both DK1 and DK2, whilst SE4 and NO2 has an average negative effect. (The Danish Energy Agency, 2025)

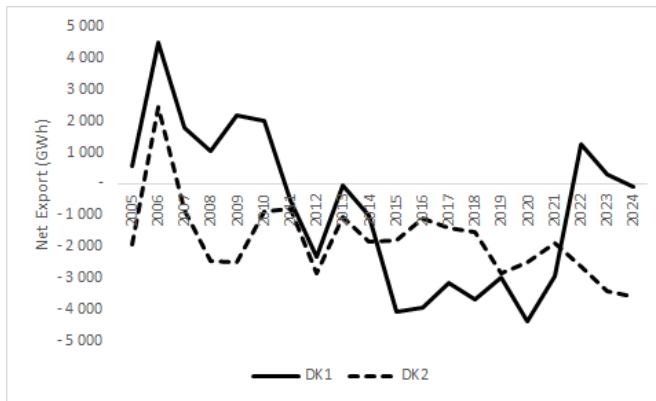


Figure 5: Net export for price area DK1 & DK2, (2005-2024)

Source: The Danish Energy Agency

2.5 Danish Electricity Production

Denmark's domestic electricity production has for the past twenty years gradually transitioned from electricity generated by non-renewable sources towards increasingly relying on renewable sources. Renewable electricity sources now represent more than 70% of the total electricity supply, this shift has primarily been possible through large investments into wind and solar photovoltaic based systems. Wind generated sources account for roughly 59% of total production, up from 20% in 2005. Solar derived sources account for approximately 10,5%, compared to nothing 15 years ago. The share of production generated from wind differs significantly in DK1 (63%) and DK2 (49%), solar based sources however is roughly equal in DK1 (11%) and DK2 (10%). The transition towards renewable electricity sources has not yielded an increase in total yearly electricity production over the past years. (The Danish Energy Agency, 2025)

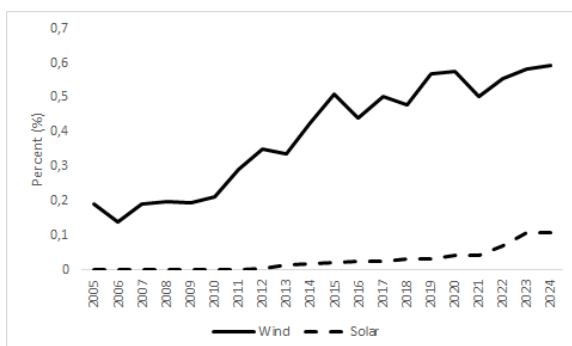


Figure 6: Share of solar and wind based electricity source in Denmark (2005-2024)

(1.0=100%) Source: The Danish Energy Agency

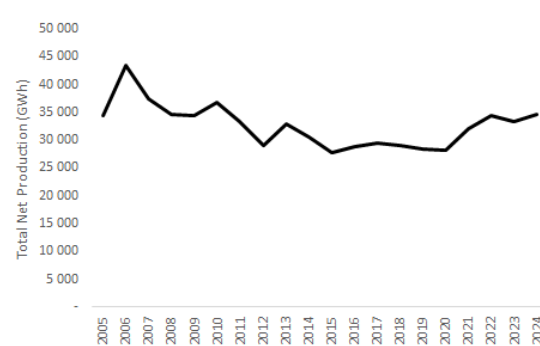


Figure 7: Total net production in Denmark (2005-2024)

Source: The Danish Energy Agency

2.6 Weather effect on pricing

In contrast to controllable energy sources such as coal and gas, intermittent energy sources are not consistently available as their supply depends on natural factors, as well as the limited capacity for storage. Changes to weather conditions that represent the underlying source of energy for intermittent sources such as wind and solar therefore result in supply shocks on the electricity market. (Sandberg, 2024) The size of the shocks depend on the size of the underlying share of total production that the weather condition affects. Meaning, an increase in wind should theoretically have a greater effect on price than an increase in solar exposure, as the share of total production is larger for wind based energy. Figure 8 and 9 illustrates this relationship. Given that the bulk of electricity trading is conducted on the day-ahead market, suppliers and consumers are forced to rely on meteorological observations to estimate the supply and demand of electricity. Meaning that it's the expectation of a certain weather condition rather than the actual weather condition that acts as a price determinant of the day-ahead market.

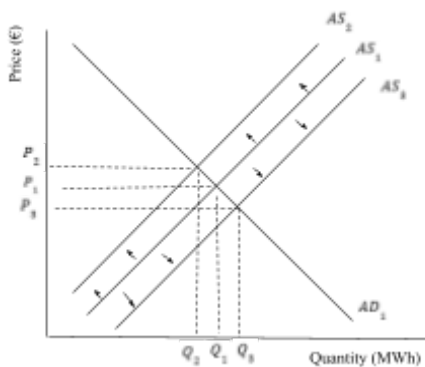


Figure 8: Solar supply shift

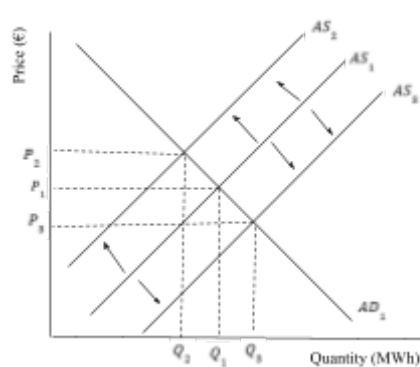


Figure 9: Wind supply shift

2.7 Demand of Electricity

So far, the paper has primarily focused on the effect that supply of electricity has on prices. But as previously stated, the price on the day-ahead market is determined by the intersection between the aggregate supply and demand curve. A considerable part of electricity consumed in Denmark is used for heating, meaning that temperature has an inverse effect on demand of electricity, i.e. a decrease in temperature yields an increase in demand. (The Danish Energy

Agency, n,d) Figure 10 illustrates a hypothetical scenario with slightly lowered temperature and a large decrease in wind speed then the previous day, resulting in a lowered output to a much higher price.

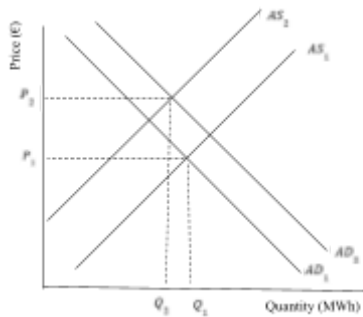


Figure 10: Positive demand shock and negative supply shock.

Another example of factors that effects demand is the day of the week. Weekends and holidays generally display a lower demand of electricity mainly due to a decrease in demand from business and industry. (Sandberg, 2024)

3.0 Previous Research

The report “*Weather conditions, climate change and the price of electricity*” by Mosquera-Lopez, Uribe and Joaqui-Barandica, estimates the effect that weather has on wholesale electricity prices in six different European countries, including Denmark. This enables a comparative approach between underlying circumstances, which allows for the results to be applicable for a larger set of circumstances. The variables used to estimate weather conditions are, temperature ($^{\circ}\text{C}$), precipitation (an integer in 100th mm), wind speed (m/s) and solar irradiance (Wh/m^2). The report examines daily data from the 1st of January 2015 to the 30th of December 2022. A limitation of examining such a time period is that it fails to consider changes in the generation mix during the measured period. A strength however is that it better captures time specific effects that otherwise might skew results. According to the study, the effect that weather conditions have on electricity prices mainly depends on (1) the underlying climate of the country, (2) the generation mix, meaning the distribution of different electricity sources in total production, (3) domestic policies. The results indicate that an increase in temperature has a negative impact on electricity prices.

Changes in wind speed also display a significant negative effect on prices, this relationship is amplified when wind speed measures between 15-20 m/s. Precipitation has a significant negative impact on prices, but only when daily precipitation is above 90% of the maximum recorded rainfall during the time period. Solar irradiance does not have a significant impact on electricity prices. Through a comparative analysis spanning several years, the paper provides an insight on how weather can influence prices of electricity depending on the natural and political conditions of a country.

In the report “*Wind and Electricity Prices in Sweden - a statistical analysis*”, Rickard Sandberg examines and compares the impact changes in wind speed and temperature have on prices of electricity in different bidding areas across Sweden. The study analyses daily data of average wind speed (m/s), temperature (°C) and average price on the day-ahead market, for each bidding area. According to the study, both wind speed and temperature has a significant impact on prices across all areas, concluding that changes of one unit (m/s) in wind has roughly a twice as large effect on prices then one unit change (°C) of temperature. Sandberg concludes that as investments into wind power increases, this impact will grow larger and result in more volatile electricity prices.

4.0 Method

4.1 Description of Data

The data in this report comprises 732 daily observations gathered from the 29th of April 2023 until the 29th of April 2025. The rationale behind limiting the report to this specific time period is based upon two assumptions, (1) it allows for seasonal effects and yearly shocks to be taken into consideration and (2) it guarantees that the results will be up-to-date and relevant. The data is structured as a univariate time series, as such before continuing with the statistical analysis we determine whether any of the time series are non-stationary. This is done by employing the Augmented-Dickey-Fuller (ADF), to investigate if the time series has a unit root. Where H_0 = the time series has a unit root (non-stationary), and H_A = the time series does not have a unit root (stationary).

4.2 Electricity Prices

The data used to estimate electricity prices is the daily aggregate on the day-ahead market for each bidding area, i.e. the average value of all hourly prices in DK1 and DK2 and it's measured in units of (€/MWh). The data is gathered from the power exchange Nordpool. Figure 11 and 12 displays electricity prices for each bidding area, prices exhibit a similar pattern and appear stationary. This is confirmed by the ADF-test, meaning the null is rejected and stationarity is assumed.

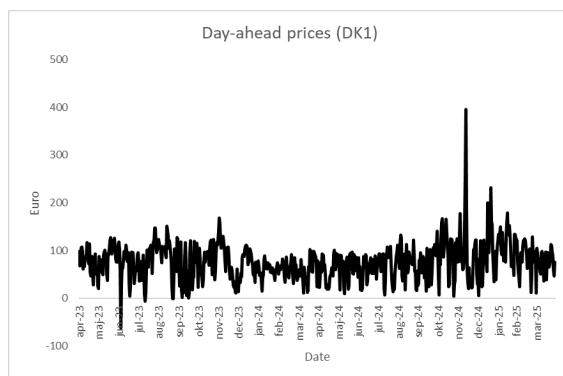


Figure 11: Day-Ahead (DK1)

Source: Nord pool

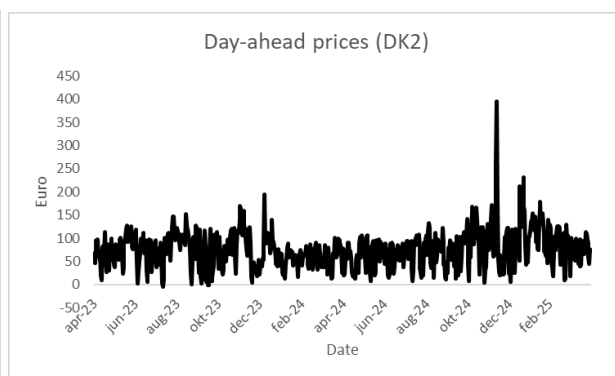


Figure 12: Day-ahead DK2.

Source: Nord pool

4.3 Weather Data

Meteorological observations are sourced from the Danish Meteorological Institute (DMI), which is a Danish government department responsible for gathering meteorological data. Two climate stations have been selected to represent the different bidding areas. The climate station located at Aalborg represents weather conditions in DK1 and the station located in Copenhagen represents DK2.

4.4 Wind

The parameter used to estimate wind is the daily mean wind speed (m/s) from each representative climate station, it's calculated by measuring the average of all hourly values per day. (DMI, 2025) After performing the ADF-test, we can confidently reject the null hypothesis and assume stationarity. Wind speed is expected to have a negative effect on prices, as increased wind speeds will increase electricity production leading to an outward

shift of the supply curve resulting in lower prices. Wind speed is also expected to have a bigger effect on prices in DK1 than DK2, given that wind power has a larger share of the generation mix. Furthermore, we expect wind to have the biggest effect on prices of the measured weather conditions, since wind power represents more than half of total yearly production in both areas.

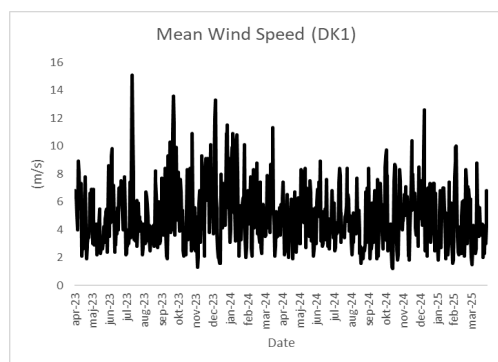


Figure 13: Mean Wind Speed (Aalborg).
Source: DMI (2025)

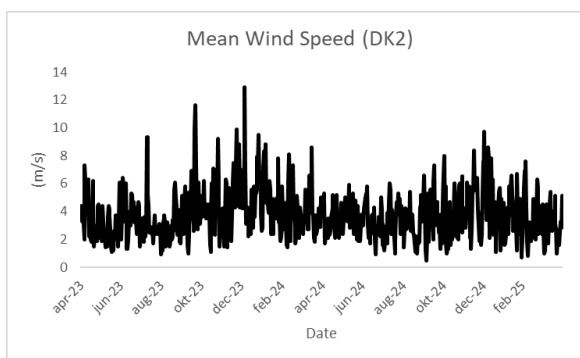


Figure 14: Mean Wind Speed (Copenhagen).
Source: DMI (2025)

4.5 Sunshine

The parameter used to estimate sunshine is the number of hours of bright sunshine per day measured from each representative climate station, it's estimated by measuring global radiation and is calculated by taking the sum of all hourly values. Minutes are converted to hours, i.e. 1 hour and 30 minutes of bright sunshine equals 1,5. (DMI, 2025) The ADF-test allows us to confidently assume stationary at the 0.05 level in DK1, we assume weak stationary in DK2 at the 0.1 level. Sunshine is expected to have a roughly equal negative effect on price in both areas, as increased hours of bright sunshine will increase the electricity production of solar based sources, leading to an outward shift of the supply curve resulting in lower prices. Sunshine is expected to have the smallest impact on prices out of our measured weather variables given the relatively small share of solar derived energy sources in the generation mix.

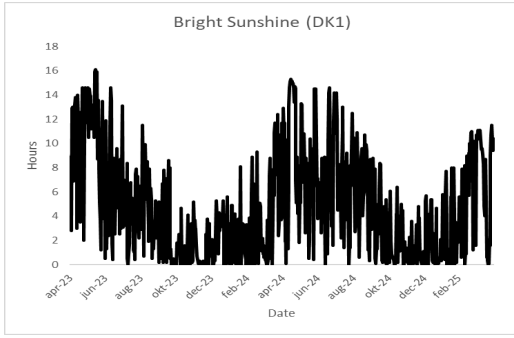


Figure 15: Bright Sunshine hours (Aalborg).

Source: DMI (2025)

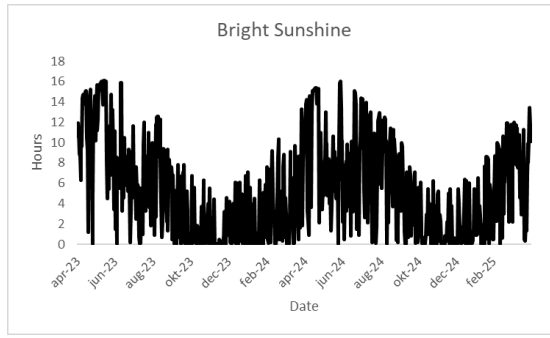


Figure 16: Bright Sunshine Hours (Copenhagen).

Source: DMI (2025)

4.6 Temperature

The parameter used to estimate temperature is the mean temperature measured from each representative climate station, it's measured by calculating the average of all hourly values per day. It's expressed in celsius (°C). (DMI, 2025) The result from the ADF-test indicates the presence of a unit-root, i.e. we fail to assume stationary. The time series is therefore transformed by taking its first difference, see equation (1), this removes trends and allows for the time series to become stationary. After testing the transformed series we can confidently reject the null hypothesis.

$$\Delta y_i = (y_{i,t} - y_{i,t-1}) \text{ (Equation 1)}$$

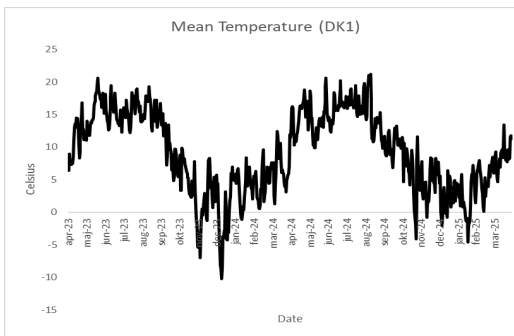


Figure 17: Mean Temperature (Aalborg).

Source: DMI (2025)

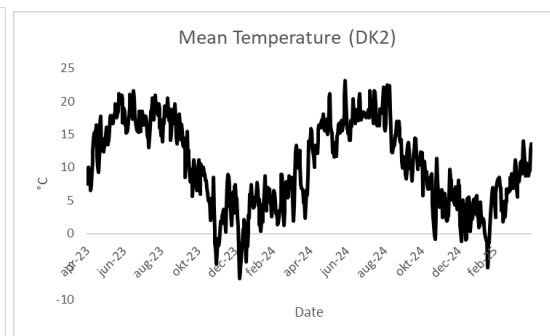


Figure 18: Mean Temperature (DK2).

Source: DMI (2025)

The first difference of average daily temperature is expected to have a negative effect on prices, as we expect lower temperatures to increase demand which will shift the demand curve outwards and vice versa for hot temperatures.

4.7 Control Variables

In order to capture non-weather related exogenous factors that might affect prices, two dummy variables are included. A dummy variable indicating if the observation is observed on a weekend is included to capture time specific demand effects. Another dummy variable indicating if prices in Germany (GE) is higher than the observed price (Nord pool, n,d) which would indicate (1) existence of transmission constraints and (2) a negative supply shock in DK 1 & 2. Weekends are expected to be associated with lower demands of electricity, meaning that we expect the dummy variable indicating the presence of weekends to have a negative impact on prices. In contrast we expect the dummy variable indicating if prices in Germany are higher than that in Denmark to have a positive effect, as the merit order allows for electricity to flow from areas with lower prices to areas with higher prices. If two areas end up with differing prices, then it's an indication that the transmission capabilities between areas are exhausted.

4.8 Summary Statistics

	Mean	Median	S.D	Min-value	Max-value
Price	76,434	76,690	37.351	-61.410	395.340
Wind	4.972	4.600	2.185	1.200	15.100
Sunshine	4.818	3.800	4.314	0.000	16.100
Weekend	0.318	0	0.466	0.000	1.000
DK1_Lag	76.479	76.735	37.366	-61.410	395.340
Δ Temperature:	0.005	0.000	1.798	-6.000	6.600
GE	0.744	1.000	0.436	0.000	1.000

Table 1 Summary statistics for values observed representing DK1

	Mean	Median	S.D	Min-value	Max-value
Price	76.063	75.955	38.894	-3.950	395.360
Wind	3.782	3.600	1.755	0.500	12.900
Sunshine	5.333	4.800	4.658	0.000	16.100
Weekend	0.286	0.000	0.452	0.000	1.000
DK2_Lag	76.107	76.075	38.908	-3.950	395.36
Δ Temperature:	0.006	0.000	1.740	-6.500	6.200
GE	0.693	1.000	0.461	0.000	1.000

Table 2 Summary statistics for values observed for representing DK2

From the values displayed in table 1 and 2 we observe large standard deviations in prices and weather data, indicating substantial degrees of variability in the data. This means that daily electricity prices fluctuate considerably relative to their average, indicating significant volatility in daily prices. Weather conditions likewise display significant day-to-day fluctuations.

4.9 Regression Specification

The relationship between electricity prices and weather conditions are analyzed by means of a multiple linear regression model using the Ordinary Least Squares model. The OLS model was chosen based upon the existence of a linear relationship between the dependent variable (price) and the explanatory variables, see appendix for correlation matrix. The OLS model is formally specified as follows.

$$Y_{t,i} = \beta_{0,i} + \beta_{2,i} X_{2,t,i} + \beta_{3,i} X_{3,i,t} + \dots \beta_{p,i} X_{p,i,t} + \varepsilon_{i,t}$$

In our case $t = 1, \dots, 731$, i.e. the number of observations, and $i \in \{1, 2\}$, i.e. indicating that the regression is performed for two different regions (DK1 and DK2). Separate regression was chosen in favour of panel data by observing the correlation between weather data in DK1 and DK2, i.e. measured weather conditions in one bidding area tends to follow the same

pattern as in the other. Y and X indicates dependent and explanatory variables respectively, β_0 stands for the constant of the regression and β_p represented the coefficient for variable p .

4.10 Regression

A regression model (1) is created for each bidding area, where $price_{t,i}$ is the dependent variable, and $wind_{t,i}$, $sunshine_{t,i}$ and $\Delta temperature_{i,t}$ representing the weather conditions that are of interest in explaining prices. The explanatory variable $weekend_{i,t}$ is the dummy variable equal to one for observations on Saturdays and Sundays and zero for all other observations. $GE_{i,t}$ is equal to one if prices in the German bidding area (GE) are greater than prices in i .

$$price_{t,i} = \beta_{0,i} + \beta_{2,i} wind_{t,i} + \beta_{3,i} sunshine_{t,i} + \beta_{4,i} \Delta temperature_{i,t} + \beta_{5,i} weekend_{i,t} + \beta_{6,i} GE_{i,t} + \varepsilon_{i,t}$$

(regression model 1)

After estimating the regression, the Breusch-Godfrey Test was conducted which indicated first order autocorrelation in the time series for electricity prices in both bidding areas, meaning that yesterday's prices is a strong estimator for the prices of today. As such we included a new explanatory variable $price_{t-1}$, representing lagged prices, and performed a second regression.

$$price_{t,i} = \beta_{0,i} + \beta_{2,i} wind_{t,i} + \beta_{3,i} sunshine_{t,i} + \beta_{4,i} \Delta temperature + \beta_{5,i} weekend_{t,i} + \beta_{6,i} GE_{t,i} +$$

$$\beta_{7,i} price_{(t-1),i} + \varepsilon_{i,t} \quad (\text{Regression model 2})$$

The inclusion of lagged prices created heteroskedastic error terms in both regressions, this was accounted for by implementing robust standard errors. A variance inflation factor test to check for multicollinearity was applied on both regressions, and the results showed that we could discard it being an issue. A Q-Q plot was also created indicating that the residuals are normally distributed.

5.0 Results

5.1 Regression results

Bidding Area	DK1	DK2
<i>Variables</i>	<i>Price</i>	<i>Price</i>
Constant	79.4771*** (4.97962)	84.6598*** (5.03102)
Wind	-6.63666*** (0.558590)	-8.99836*** (0.784861)
Sunshine	-0.424791* (0.258819)	-0.702448*** (0.218128)
Δ Temperature	-2.07239*** (0.493158)	-2.17111*** (0.629653)
Weekend	-18.6006*** (1.96833)	-20.2780*** (1.84502)
GE	2.61299 (2.18197)	-1.08602 (2.51220)
$price_{(t-1),DK1}$	0.473121*** (0.0366151)	
$price_{(t-1),DK2}$		0.470077*** (0.0370037)
Observations	731	731
R-Squared	0.575021	0.598038

Table (3): Results for Regression model 2

Robust Standard Errors in Parentheses

*** = $p < 0.01$, ** = $p < 0.05$, * = $p < 0.1$

Table 3 contains the results from regression model 2 conducted on each bidding area. Wind speed displays a highly statistically significant negative effect on prices across both bidding areas; the effect is more prevalent in DK2 than in DK1. Bright sunshine hours displays a

highly significant negative effect on price in DK2, whilst displaying weak significance on DK1. The first difference of average daily temperature has a largely similar negative impact on prices in DK1 and DK2. Weekends demonstrate the biggest effect on prices in both areas, indicating that weekends are expected to have a lower price than weekdays. The existence of higher prices in Germany appears to not have an impact on prices according to the regression. Yesterday's prices is the only variable that exhibits a positive relationship with prices, showing that prices are expected to increase by roughly 0.5 units if the price of yesterday increased by one.

Both regression displays a similar R^2 , with 0.575 and 0.598. Indicating that about 57% of the price variance in DK1 and 60% of the price variance in DK2 is explained by our models.

5.2 Standardised results

The different units of measure in the weather data complicates the process of comparing their estimated effects with each other. By standardizing the coefficients, meaning that instead of displaying the unit change, standardized coefficients display the change in standard deviations of the dependent variable per change in standard deviation of the explanatory variable. This makes the explanatory variables “unitless” which allows for a more pedagogical comparison. (Sandberg, 2024) The standardized coefficient are denoted by β^* and calculated according to equation (2). Only coefficients estimating weather data are standardized as it's the effect of them that the paper is investigating.

$$\beta x^* = \frac{\sigma_x}{\sigma_y} \beta x \quad (\text{Equation 2})$$

Variable	Standardized Coefficient
Wind	-0,388
Sunshine	-0,049
Δ Temperature	-0,099

Table (4) Standardized coefficients for DK1

Variable	Standardized Coefficient
Wind	-0,406
Sunshine	-0,084
Δ Temperature	-0,097

Table (5) Standardized coefficients for DK2

The standardized coefficients have the same sign and follow the same hierarchical structure as the unstandardized coefficients, i.e. mean wind speed has the greatest effect on prices, followed by average temperature and hours of bright sunshine. By dividing the standardized coefficients with each other their relative effect on price can be estimated.

$$\frac{\beta_{2,2}^* wind}{\beta_{3,2}^* sunshine} = 4.833 \quad \frac{\beta_{2,2}^* wind}{\beta_{4,2}^* \Delta temperature} = 4.185 \quad \frac{\beta_{4,2}^* \Delta temperature}{\beta_{3,2}^* sunshine} = 1.154$$

$$\frac{\beta_{2,1}^* wind}{\beta_{3,1}^* sunshine} = 7.918 \quad \frac{\beta_{2,1}^* wind}{\beta_{4,1}^* \Delta temperature} = 3.919 \quad \frac{\beta_{4,1}^* \Delta temperature}{\beta_{3,1}^* sunshine} = 2,020$$

Given the results from the equations above we can observe and compare the relative effects of the standardized coefficients. The estimate for the standardized mean wind speed coefficients has a roughly 5 times greater effect in DK2 and 8 times in DK1 on electricity prices than the standardized coefficients for bright sunshine hours, and roughly 4 times greater effect than the first difference of average temperature in both DK2 and DK1, though slightly greater in DK2. The first difference of temperature has in turn roughly a 1.1 times greater relative effect on prices than hours of bright sunshine in DK2 and 2 times in DK1.

6.0 Analysis

This analysis begins by examining the results from the regressions and interpreting if they displayed what we anticipated, how they relate to results from previous research, and how well they agree with the theoretical background accounted for in section 2.

The observed impact of wind speed on electricity prices is largely in line with our expectations, it displays both the highest unit and standardized effect on prices in both bidding areas. This is in accordance with theory discussed in section 2.6, which establishes that the size of the effect that an increase in a certain weather condition will have on prices depends on the share of the generation mix that consists of sources that has the ability to harness its energetic power. This further confirms the results estimated in the reports created by Uribe et al, and Sandberg. One aspect of the relationship between wind and prices that contradicted our expectations was that wind speed displayed a larger impact on prices in DK2 in DK1, even though the yearly share of wind power in total electricity production is greater in DK1 than in DK2. One potential explanation for this apparent contradiction is that DK2 is in contrast to DK1 a net importer of electricity, meaning that the price depends on the electricity generated from other areas to a larger extent. This relationship is further explained in figure 2.4, which displays that areas depended on imports will have lowered prices then what the internal production would achieve assuming no transmission capabilities.

The estimated impact of sunshine on prices is also aligned with our expectations, as it demonstrates negative effects on prices in both bidding areas. The effect is also lower than that of wind, both in terms of units and standardized impact. Further confirming the theoretical assumption presented in section 2.6. The result that sunshine has a significant effect on prices stands in contrast to the results estimated by Uribe et al, which displayed no significant effect. By comparing the different time periods examined with figure 6 in section 2.5 differing results are expected, as total energy production from solar based sources has increased significantly since their report was published.

The observed effect of temperature and weekends demonstrates expected results, confirming the theoretical assumptions of electricity demand presented in section 2.7. The impact

confirms the results of temperature presented by both Sandberg and Uribe et al. The weekend effect is also in line with the estimation concluded by Sandberg.

The variable meant to incorporate the effect that cross-area trade has on prices yielded as previously mentioned no significant results. The reasoning for choosing German prices as a reference was based on the observation that both areas are net exporters towards it. This was probably an oversimplification that failed to incorporate the full scope that cross-area trading has on prices, since each area has transmission capabilities to several other areas. Hence by only comparing danish prices with german, only a part of the effect was captured and insignificant results are not surprising.

In section 4.8 we observed substantial degrees of variability for electricity prices and weather data across both bidding areas during the measured time period, and in section 2.6 we concluded that changes to weather acts as repeated supply shocks. Given the fact that intermittent renewable energy sources comprises upwards of 70% of Danish electricity production, a significant part of the volatility in prices can be attributed to the large fluctuations in underlying weather conditions. This effect can further be assumed to become more distinct in the future as investments into solar and wind based sources are expected to increase. This can be illustrated by examining the theoretical assumptions presented in section 2.3, which specified that the *merit order* mechanism guarantees that the cheapest electricity will be prioritized. As intermittent sources such as solar and wind have a near zero marginal cost, meaning that an increased share in the generation mix will yield lower prices than today on days with favourable conditions and higher prices than today on days with unfavourable conditions. In essence, increasing the variability and volatility of prices.

7.0 Discussion

This paper began by discussing the mechanisms that determine the price of electricity in Denmark from a theoretical perspective, this presentation was further expanded by including an empirical analysis on the role weather has as a price determinant. After analysing the results from our empirical investigation with established economic theory and previous research into the subject, we believe that the insights derived from our results can be of interest to actors operating on the electricity markets, and especially to policy makers.

7.1 Policy implications

The transition away from fossil fuels towards renewable energy sources is imperative, not only for Denmark but for all countries that have agreed to achieve the goals established by the Paris agreement. This paper has illustrated that such a transition is not entirely straightforward. Denmark has increased their share of renewable energy sources from around 20% of total production to more than 70% in less than 20 years, but this transition has not however increased the total electricity production, and since electricity demand has increased during this time period, Denmark has gone from a net exporter to a net importer of electricity. This can be attributed to an increased reliance on intermittent weather based sources of electricity, especially solar and wind. As such, during favourable weather conditions electricity prices drops significantly, which is further exacerbated by limitations in the transmission infrastructure, i.e. Denmark exports less than ideally. During unfavourable weather conditions the opposite is true, the country does not produce enough electricity to meet demand and as such relies on imports, transmission constraints also prohibit the ideal import size resulting in even higher prices. It can hence be concluded that an increased reliance on intermittent weather based sources of electricity brings about more volatile prices and a less predictable supply. From the analysis we also observe that the low marginal costs of renewable sources will on days with favourable conditions result in prices that are lower than the marginal cost of controllable sources. Meaning that there will be little financial incentives to invest in non-renewable sources. As such it appears that policy makers are faced with a dilemma, clean or stable electricity.

Another issue that can be attributed to the Danish model, is that it can be interpreted as an environmental free-riding problem. That is, Denmark is not willing itself to invest in controllable energy sources but willingly imports electricity derived from such sources from other countries. Denmark has previously expressed a target of achieving an electricity supply composed of 100% renewable electricity sources. But if that entails that a significant portion of electricity consumed is composed of non-renewable imported sources, then the target appears disingenuous. A more responsible target would instead be to strive to achieve 100% renewable sources in domestically consumed electricity, as it more clearly demonstrates the actual environmental burden of the country.

From the report, it appears that this dilemma could primarily be resolved through increased investments into transmission infrastructure. Increased transmission capabilities will allow for more electricity to travel a further distance. This will serve to stabilize prices through enabling export and import when an area experiences a surplus or deficit. It will also allow for a larger share of consumption to be composed of renewable sources as it will connect the area with areas further away. In the case of Denmark, such investment into transmission infrastructure would allow the country to increase their import of electricity derived from hydropower in Norway and Sweden during times of low domestic production.

8.0 Conclusion

The purpose of this paper has been to examine the impact that changes to weather conditions has on prices of electricity in Denmark. Through a statistical analysis we have concluded that wind speed, solar exposure and temperature each has significant effects on electricity prices. Indicating that the price of electricity in Denmark is currently to a significant extent determined by forces beyond human control.

By combining the results from the empirical analysis with contemporary economic theory, we have been able to explain the reasons behind this relationship and speculate how it can further develop in the future.

Furthermore, we have applied our insights into that relationship to discuss potential implications for environmental policies. Concluding that knowledge concerning the impact that weather has on intermittent energy sources is paramount in order to craft a pragmatic and sustainable electricity policy.

Further research into the subject would profit from increased insight into daily cross-border trading patterns, which would assist in further estimating the effect that weather has on prices. A larger time period and the inclusion of more countries could also deepen the analysis and assist in identifying the effect of underlying circumstances.

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10.0 Appendix:

10.1 Redogörelse för användning av generativ AI

Verktyg: ChatGPT

Användning: Generativ AI har primärt använts för vägledning inom dataprogram som Gretl och Excel. Generativ AI har i begränsad utsträckning varit behjälplig med feedback på förslag till källförteckning.

10.2 Correlation Matrix

Price	Wind	Sunshine	DK2_Lag	Weekend	Δ Temperature	GE	
1.0000	-0.5531	-0.0645	0.6266	-0.2614	-0.0966	-0.1696	Price
	1.0000	-0.2400	-0.3381	-0.0130	0.0813	0.2507	Wind
		1.0000	-0.1231	0.0407	0.1038	0.0119	Sunshine
			1.0000	-0.0622	0.0840	-0.1730	DK2_Lag
				1.0000	-0.0091	-0.0966	Weekend
					1.0000	-0.494	Δ Temperature
						1.0000	GE

Table A1: Correlation Matrix (DK2)

Price	Wind	Sunshine	DK1_Lag	Weekend	Δ Temperature	GE	
1.0000	-0.5334	-0.0381	0.6178	-0.2784	-0.1018	-0.0617	Price
	1.0000	-0.1917	-0.3328	-0.090	0.0939	0.2656	Wind
		1.0000	-0.1131	0.0124	0.0297	0.0136	Sunshine
			1.0000	-0.0861	0.1002	-0.0614	DK1_Lag
				1.0000	0.0488	-0.1713	Weekend
					1.0000	-0.0016	Δ Temperature
						1.0000	GE

Table A2: Correlation Matrix. (DK1)

10.3 Dickey-Fuller-Test Results:

DK1

Variable	P-Value
Price (DK1)	<0,001
Wind	<0,001
Sunshine	<0,05
Price Lag (DK1)	<0,001
Δ Temperature	<0,001

DK2

Variable	P-Value
Price (DK2)	<0,001
Wind	<0,001
Sunshine	<0,1
Price Lag (DK2)	<0,001
Δ Temperature	<0,001

Augmented Dickey-Fuller-Test Results.