WIND AND ELECTRICITY PRICES IN SWEDEN – A STATISTICAL ANALYSIS

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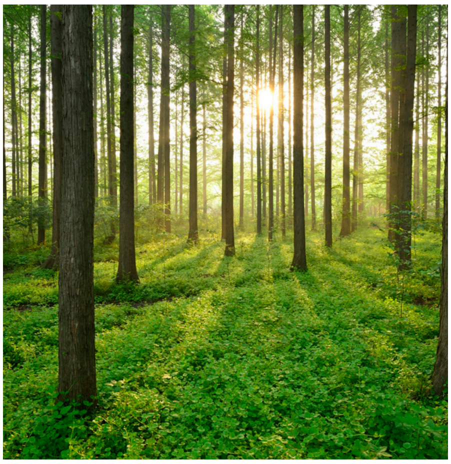

FUTURE ELECTRICITY MARKET DESIGN

Energiforsk

Wind and Electricity Prices in Sweden – a Statistical Analysis

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Foreword

This study, conducted by associate professor Rickard Sandberg at the Stockholm School of Economics, is an empirical study of how the wind and temperature conditions affected the development of electricity prices during the 2022 - 2023 season. The background is that the growing share of wind power in Swedish electricity production is expected to lead to increasingly volatile electricity prices. A main question therefore is how the current share of wind power, approximately 20 percent, affects the electricity price. The study indicates that a change in wind force by 1 m/s affects the electricity price more than a change in temperature by 1 degree C.

Increased knowledge about how and how much wind conditions affect electricity prices is important for both investors in wind power and electricity consumers' choice of contract with their supplier. The study is part of Energiforsk's program FemD "Future electricity market design". As with other projects within FemD, the author is solely responsible for the content of the report.

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Summary

Electricity prices in Sweden have displayed stable patterns for an extended period, with higher prices during winter and lower prices during summer. Historically, the primary sources of electricity have been water and nuclear power. However, with one-fifth of Sweden's current electricity production coming from wind power, we expect to experience an increased volatility in electricity prices due to fluctuations in wind conditions.

In this project, we utilize daily time series data for electricity prices, wind, and temperature over the past year (from September 2022 to August 2023) to examine the impact of wind and temperature on electricity prices across the four different bidding zones: SE1, SE2, SE3, and SE4. We also examine which of the two variables - wind or temperature - better predicts electricity prices.

To address our empirical questions, we employ various time series models to better understand the impact of wind and temperature on electricity prices. Formal testing reveals that the time series not only experience nonlinearities individually but also in their relationships. This complexity led us to consider using piecewise linear models to overcome these challenges.

Our findings indicate that both wind and temperature significantly impact prices. Specifically, for SE1, SE2, SE3, and SE4, when wind (temperature) increases by one unit, then prices decrease, on average, by: 6.4 (3.0) öre, 6.7 (4.6) öre, 14.6 (6.3) öre, and 11.2 (8.2) öre, respectively. Consequently, the effects of wind on prices are approximately two times larger than those of temperature. Regarding the relative predictive performance of wind and temperature, temperature is by far the strongest predictor of the two.

Concerning overall model performance, our linear and static models explain about 50% of the variation in electricity prices. When accounting for dynamic models, this percentage increases to 80%, indicating their suitability for predicting (forecasting) electricity prices.

Keywords

Electricity Prices; Wind Power; Temperature; Time-series Analysis; Regression Models; Structural Breaks; Wind and Temperature Impact Profiles; Relative Predictive Importance; Relative Driver Importance.

Sammanfattning

De svenska elpriserna har länge uppvisat ett starkt årstidsberoende, med höga priser under vintermånaderna och låga priser under sommarmånaderna. Inför den stora utbyggnad av vindkraft som väntas äga rum under de närmaste decennierna bedöms elpriserna att till följd av variationer i vindförhållandena bli mer volatila. Detta nya mönster väntas bli tydligare i takt med att vindkraftens andel av elproduktionen ökar.

Med hjälp av olika tidsseriemodeller undersöker vi i denna rapport vindens och temperaturens inverkan på elpriserna i de fyra zonerna SE1, SE2, SE3, and SE4 under säsongen 2022–23. Även om elpriserna fortfarande uppvisar ett starkt säsongsberoende, ser vi sammantaget att vinden har en större påverkan på elpriserna än temperaturen. Detta till trots att vindkraften i dagsläget ”bara” står för 20% av utbudet. Sammanfattningsvis ser vi en reducering av elpriser på grund av vindeffekter motsvarande: 6,4 öre i SE1, 6,7 öre i SE2 öre, 14,6 öre i SE3 samt 11,2 öre i SE4, medan reduceringen på grund av temperatur effekter motsvaras av: 3,0 öre i SE1, 4,6 öre i SE2, 6,3 öre i SE3, samt 8,2 öre i SE4. Effekten av vind i de olika zonerna är alltså ungefär dubbelt så stor som den för temperatur.

I rapporten finner vi även att elpriserna under helger är betydligt lägre än under veckodagar med en genomsnittlig skillnad om ca 25 öre. Vi finner också att begränsningar i kraftnätet ger lägre genomsnittliga elpriser motsvarande ca 15 öre i de zoner där ett överskott uppstår.

List of content

1 Introduction

1.1 BACKGROUND

Swedish electricity prices have long shown a strong seasonal dependence, with high prices during the winter months and low prices during the summer months. Added to this are variations between day and night, such as the diurnal fluctuations between day and night, as well as differences between weekdays and holidays. Additionally, there have sometimes been clear price differences between different years due to variations in temperature conditions and the availability of hydropower. This pattern has been very stable, and there have rarely been hours with very low prices during the winter or very high prices during the summer.

As we anticipate a significant expansion of wind power in the coming decades, electricity prices are expected to become more volatile due to variations in wind conditions; but the differences between day and night and weekdays and weekends are expected to persist. This new pattern is projected to become more evident as the share of wind power in electricity production increases. Such a pattern is expected to be even more pronounced as we simultaneously observe a steady increase in electricity demand. We can also expect varying wind conditions to have a different impact on electricity prices across the different bidding zones SE1, SE2, SE3, and SE4.

The total electricity production in Sweden marginally increased (0.5%) from 169 129 GWh in 2021 to 169 982 GWh in 2022, but wind power has increased by 20.3% from 27 483 GWh 2021 to 33 072 GWh 2022. A summary of Sweden's distribution of the different electricity power sources in 2022 is shown in Table 1.

***Table 1.* Electricity power distribution in Sweden for 2022.**

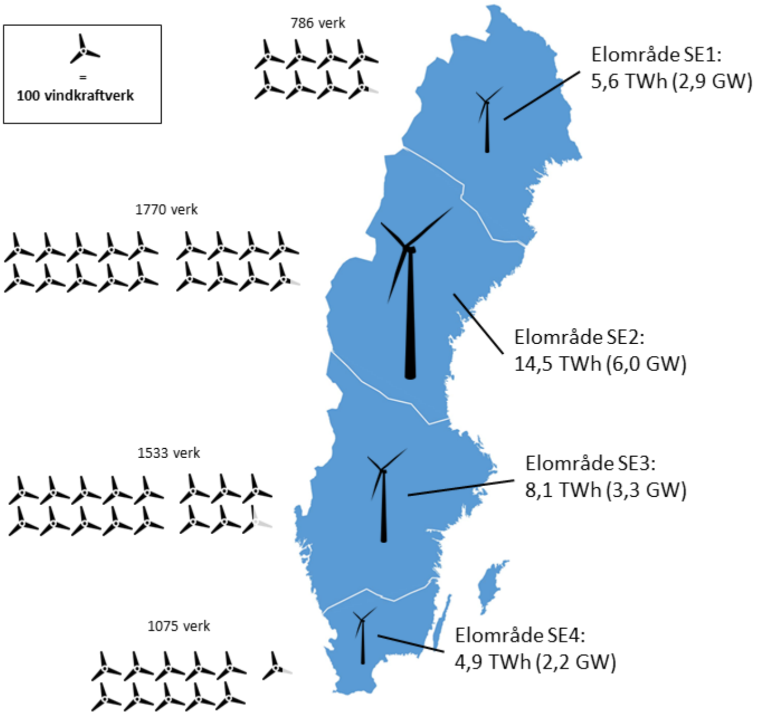
Source	GWh	Proportion of total production (%)
Water	69 587	40.9%
Wind	33 072	19.5%
Sun	1 968	1.2%
Nuclear	50 063	29.4%
Combined Heat and Power	15 292	9.0%
Total	169 982	100%

Source: The Swedish Energy Agency.

We observe in Table 1 that wind power constitutes approximately 20% of Sweden's total electricity production. The total supply (combining production and import) in 2022 amounted to 176,159 GWh, indicating an import of 6,177 TWh. On the demand side, 136,756 GWh were consumed, resulting in 39,403 TWh exported. The two primary consumers were Households and services with 74,044 GWh (54.1%) and Mining and manufacturing with 46,236 GWh (33.8%). It is noteworthy that household consumption strongly correlates with temperature and weekend effects, suggesting a substantial impact of temperature on demand and, consequently, on prices.

In Figure 1, an overview of the wind power supply in SE1, SE2, SE3, and SE4 is shown. We observe in this figure that SE2 produces the highest amount of wind power at 43.8%, followed by SE3 at 24.5%, SE1 at 16.9%, and SE4 at 14.8%.

***Figure 1.* The distribution of wind power in Sweden at the end of 2022.**



Source: The Swedish Energy Agency. "vindkraftverk" and "elområde" translate to windpower plant and bidding zone, respectively.

1.2 PURPOSE OF THE PROJECT AND EMPIRICAL QUESTIONS

The purpose of this project is to use statistical analysis to examine how wind and temperature affect the Swedish electricity price in the four bidding zones over the last year of daily data from September 2022 to August 2023. Based on the expectation that electricity prices become more volatile as a result of variations in wind conditions, the three main empirical questions we aim to answer by our statistical analysis are:

- Which effects do wind and temperature conditions have on Swedish electricity prices?
- How important are wind and temperature in predicting electricity prices?
- Which monthly effects do wind and temperature conditions have on Swedish electricity prices?

To address these empirical questions, some statistical challenges arise due to the rather complex time series properties of the series studied. In this regard, it is exceedingly important to use statistical models that are able to capture these properties, at least approximately, to render valid estimation results and conclusions. Moreover, since we have data for the four different bidding zones, the same empirical questions and statistical concerns apply to all zones.

The above questions can be answered using different statistical measures and methods. In this project, we will rely on so-called reduced form time series modeling, where electricity prices are modeled as a function of wind and temperature.[1] The first empirical question is addressed by comparing the estimated model effects that wind and temperature have on prices. The second empirical question is addressed by comparing the so-called coefficient of determination (or the R^2-value) to assess which of the two variables has the strongest predictive power on electricity prices. The last empirical question is addressed in the same way as the first one but now on segments of monthly data.

1.3 WHAT IS CAUSING PRICE CHANGES AND PRICE VOLATILITY?

When analyzing the empirical findings in our results section, it is useful to consider a list of factors that explain electricity prices and volatility changes

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[1] Reduced form time series modeling captures the statistical relationship between variables, as opposed to structural modeling derived from economic theory and equilibrium models.

over time. Such a list is presented in Table 2 below. Additionally, in Figure 2, different supply-demand scenarios are illustrated to explain not only how price changes when supply and demand change but also how price volatility may change. It is also important to note that the factors listed in Table 2 can have a different impact in different bidding zones, as well as a different impact at different times of the year; the slope of the supply and demand curves varies over the year, causing the price elasticity to vary throughout the year.

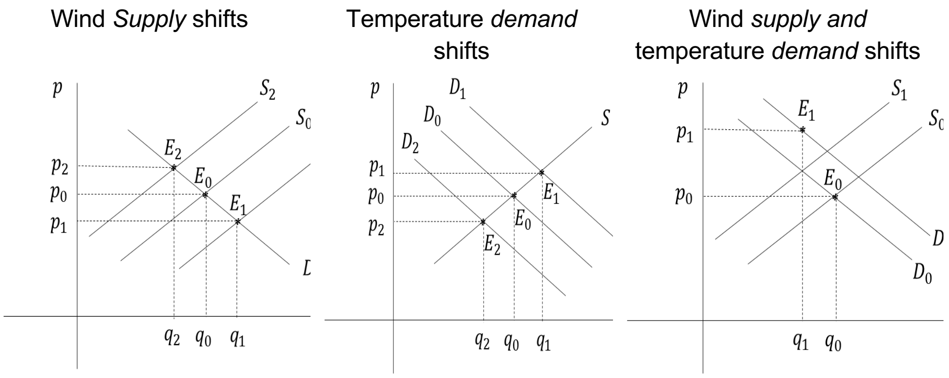
***Table 2.* Factors that affect the price of electricity.**

Demand	Supply
• Lower (higher) temperature increases (decreases) demand.	• Rainy periods increase supply due to more waterpower, filling up reservoirs.
• Weekdays (weekends): higher (lower) demand.	• More (less) wind increases (decreases) supply.
• Sun power decreases demand in summertime.	• Network constraints (bottlenecks) may cause excess supply due to failure in distributing excess power.
• Changes in European demand via market coupling, e.g., German nuclear plants were shut down in 2022, causing prices to increase in Sweden.	• Changes in European supply via market coupling, e.g., the wind supply in Germany affects Swedish prices (particularly in SE4).

We observe the obvious yet crucial fact in Table 2 that the key variables in this project, viz. wind and temperature, impact electricity prices from the supply side and the demand side, respectively.

The leftmost part of Figure 2 illustrates how prices change due to a shift in supply. Specifically, let E_0 designate an equilibrium at an average windy day with quantity q_0 and price p_0. On a windier day, the wind supply of electricity increases, and the supply curve shifts to the right to S_1, resulting in a new equilibrium point E_1 with quantity q_1 and price p_1. It is noticed that $p_1 < p_0$, so the price has decreased. Conversely, on a less windy day, the wind supply of electricity decreases, and the supply curve shifts to the left to S_2. A new equilibrium E_2 is obtained with quantity q_2 and price p_2. It is noticed that $p_2 > p_0$, so the price has increased.

***Figure 2.* Supply and demand curves for electricity prices.**


Wind *Supply* shifts

Temperature *demand* shifts

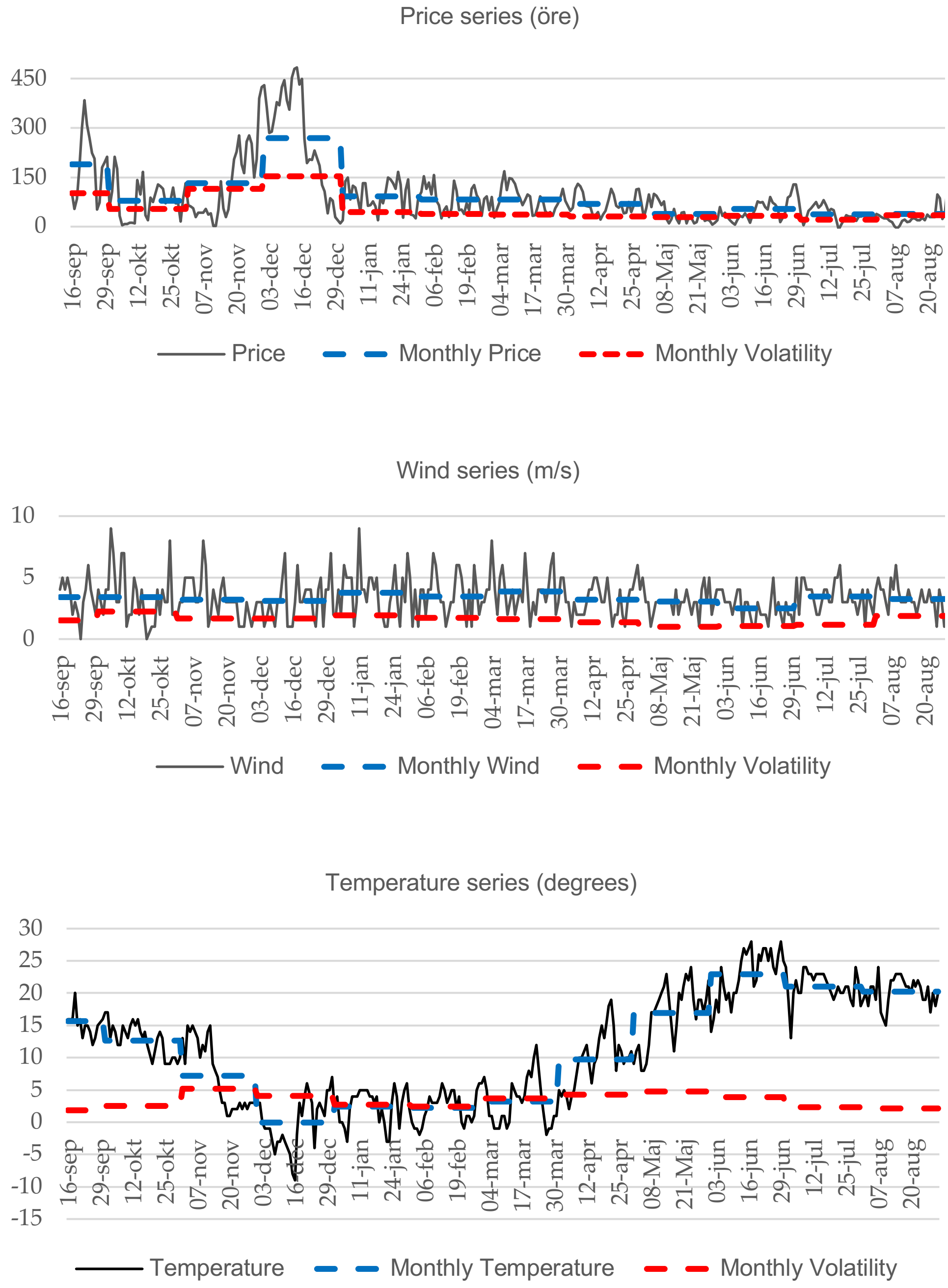
Wind *supply and* temperature *demand* shifts

Moving on to the supply-demand curves in the center of Figure 2, illustrating how prices may change due to a shift in demand. Specifically, let E_0 denote the equilibrium at an average warm day with quantity q_0 and price p_0. On a colder day, the demand for electricity increases (this is largely due to the fact that electric heating is so common in Swedish homes and commercial premises), shifting the demand curve to the right to D_1. A new equilibrium point E_1 is obtained with quantity q_1 and price p_1. It is noticed that $p_1 > p_0$, so the price has increased. On a warmer day, conversely, the demand for electricity decreases, and the demand curve shifts to the left to D_2. The new equilibrium E_2 is obtained with quantity q_2 and price p_2. It is noticed that $p_2 < p_0$, so the price has decreased.

Lastly, considering the supply-demand curves in the rightmost part of Figure 2, illustrating how prices may change due to a shift in supply and demand. Specifically, let E_0 signify an equilibrium at an average warm and windy day with quantity q_0 and price p_0. On a colder day that is less windy, a common scenario in winter, the demand for electricity increases simultaneously with the supply decrease, causing the demand curve to shift to the right to D_1 and the supply curve to shift to the left to S_1. A new equilibrium point E_1 is obtained with quantity q_1 and price p_1. It is noticed that $q_1 < q_0$ and $p_1 > p_0$, so less quantity is available at a (potentially) much higher price.

Having conceptualized how electricity prices may change at different points in time, real-time series data are presented in Figure 3. Specifically, daily time series data for price, wind, and temperature (black solid lines) in Zone 3, as measured by Stockholm data observations, are shown. Monthly averages (blue dashed line) and monthly volatility (red dashed line) are also displayed.

***Figure 3.* The time-varying behavior of price, wind, and temperature series in Zone 3 (Stockholm).**



Note: The observations for the monthly series are the ones reported for SE3 in Tables 4 and 5.

The price series in this figure exhibits a nonlinear monthly time-varying behavior for both the level and the volatility, particularly during the months of September to January 2022. It is evident that electricity prices are at higher (lower) levels during the winter (summer), with relatively high prices observed in September as well. The former observation is simply attributed to higher demand during the winter and colder months. The latter observation is influenced by a (much) higher demand in Germany (due to the temporarily shutdown of several nuclear plants) and the interlinked electricity price markets.

Examining the wind series in Figure 3 (a black solid line), seemingly more stable monthly average and volatility patterns are displayed, albeit with slow variations over time.

For the temperature series in Figure 3, we observe a pattern that varies with the time of the year, but the volatility of the series appears to be more stable. Additionally, we can observe strong co-movements in opposite directions between the price and temperature series, but less so between the price and wind series. In this regard, by examining the time series graphs of the data in Zone 3, it becomes apparent that all series exhibit a nonlinear time-varying behavior. Furthermore, it is worth considering the possibility that wind and temperature may have different effects on prices depending on the time of the year. These conjectures about time-varying characteristics are formally confirmed by statistical tests in Subsection 4.2. Such considerations are crucial when selecting appropriate models to address our empirical questions, and therefore, several candidate models are introduced in Section 2.

1.4 SCOPE FOR FURTHER RESEARCH

It would be interesting to study the same empirical questions raised above using data over a much longer time period, starting from when wind power was introduced as a power source (around 1990). With such data, it would be possible to assess the gradual impact that wind has had over time on electricity prices.

In this report, preliminary conclusions are presented, indicating that there are factors other than wind and temperature that affect electricity prices. For example, nuclear and hydroelectric data are not accounted for, and we have already mentioned that German wind conditions have a strong impact on Swedish electricity prices, particularly in Zone 4. Therefore, in future studies, it would be interesting to also include these types of data in the analysis.

Although several time series models are utilized in this project, there are yet other models and statistical methods that can be used to shed further light on our empirical questions. One example to consider is a family of parametric models called time-varying mean and conditional heteroscedasticity models. However, to obtain accurate estimation results, these models are typically applied to longer time series than the ones in this project. Another example would be to use multivariate models to simultaneously model price series and other factors not only from Sweden but also from neighboring countries, which obviously have a mutual impact on each other due to the interlinked electricity price markets. Such an approach would also open up a broad range of additional empirical questions to be examined.

1.5 DISPOSITION OF THE REPORT

The rest of this report is structured as follows. Section 2 introduces various time series models. The data and summary statistics are presented in Section 3. Estimation results and analysis are provided in Section 4. Section 5 gives a summary of estimation results and concludes.

2 Modelling Electricity Prices

2.1 REDUCED TIME-SERIES MODELLING

The above empirical questions on how wind and temperature impact daily electricity prices over time in the different zones are examined using time series-analysis and reduced-form models. As such, electricity prices in any of the four zones, P_t, can be viewed as a function of temperature, T_t, wind, W_t, other factors, X_t, and a stochastic term ϵ_t:

$$P_t = f(W_t, T_t, X_t; \theta) + \epsilon_t,$$

where $f(\cdot)$ designates the functional form, and θ is a vector of unknown parameters, different for the various zones, to be estimated using data. It is noticed that a linear functional form is a predominant choice in most empirical cases, but, as we will show, it is critical to also consider other functional forms because wind and temperature may have a nonlinear impact on electricity prices; in this case, different impacts in different time periods. X_t is a vector of exogenous variables also affecting prices, such as weekends and monthly effects, but also includes effects that we cannot explicitly control for, such as the wind factors and electricity prices in Germany. Lastly, the stochastic term ϵ_t is a disturbance term with properties $E\epsilon_t = 0$ and $V\epsilon_t = \sigma_\epsilon^2 \in (0, \infty)$.

The choice of exogenous factors X_t in this project includes various dummies such as weekends and when Swedish nuclear plants are temporarily shut down. Additionally, for some time series models, we have also introduced monthly dummies (time-fixed effects) to capture remaining effects on prices that Swedish wind and temperature cannot explain, as well as dummies as proxies for network constraints.

2.2 REFERENCE MODELS

A reference model for each zone is provided by the linear multiple regression model:

$$P_t = \alpha + \beta_1 W_t + \beta_2 T_t + \delta_1 Weekend_t + \delta_2 D_t + \delta_3 NR_{(ij)t} + \epsilon_t, \qquad \text{[RM1]}$$

where P_t, W_t, and T_t are the time series of interest, defined as above. D_t is a dummy variable taking on the value one if a nuclear plant is temporarily shut down and zero otherwise, and $Weekend_t$ is another dummy variable equal to one for Saturdays and Sundays and zero otherwise. As a final dummy, we consider a proxy for power network constraints (bottlenecks) $NR_{(ij)t}$. This dummy is equal to one if the discrepancies in daily prices between adjacent zones ($i = 1,2,3$ and $j = i + 1$) differ by more than 1 öre, and zero otherwise. Moreover, the set of unknown parameters to be estimated is $\theta = (\alpha, \beta_1, \beta_2, \delta_1, \delta_2, \delta_3, \sigma_\epsilon^2)'$. Variables of main interest in this model are wind and temperature, and their impact on electricity prices are measured by the parameters β_1 and β_2, respectively. The parameters δ_1 and δ_2 measure the impact that a shutdown nuclear power plant and weekdays, respectively, have on electricity prices. The δ_3 parameter is a measurement proxy for the impact that bottlenecks have on prices.

A second reference model for each zone is the same as the model in RM1 but augmented with monthly dummies:

$$P_t = \alpha + \beta_1 W_t + \beta_2 T_t + \sum_{\tau=1}^{11} \theta_\tau M_\tau + \delta_1 Weekend_t + \delta_2 D_t + \delta_3 NR_{(ij)t} + \epsilon_t, \qquad \text{[RM2]}$$

where M_τ abbreviates a monthly dummy (with December set as the baseline month). The θ_τ parameters, also referred to as time-fixed effects (TFE), measure monthly exogenous variation and seasonal effects in prices not captured by the wind and temperature variables. The set of unknown parameters to be estimated for this model is $\theta = (\alpha, \beta_1, \beta_2, \theta_1, \dots, \theta_{11}, \delta_1, \delta_2, \delta_3, \sigma_\epsilon^2)'$ (a total of 18 parameters).

A primary motivation for introducing the second reference model RM2 is that there are many factors not controlled for in RM1, and allowing for TFE, as in RM2, serves as crude proxies for these omitted factors.

2.3 REFERENCE MODEL SWEDEN

As a last reference model, we consider a fixed effects (FE) panel data model (PDM). The purpose of this model is to provide an overview of how wind and temperature, in a more general sense (not zone specific), influence electricity prices in Sweden. This model features homogeneous slope coefficients but accommodates zone-specific effects, denoted as fixed effects (FE). Such a model is specified as:

$$P_{it} = \alpha_i + \beta_1 W_{it} + \beta_2 T_{it} + \delta_1 Weekend_{it} + \delta_2 D_{it} + \epsilon_{it}, \qquad \text{[PDM]}$$

and it is a close analog of the RM1, excluding the dummy variable for power network constraints. In this model, a zone-specific index, i, is added to both the dependent and all explanatory variables, as well as the error term. The zone fixed effects are captured by α_i, and it is noted that the wind (β_1) and temperature (β_2) parameters are assumed to be the same for all zones (i.e., slope homogeneity). Weekend and dummy effects are also assumed to be the same across all zones. The set of estimated unknown parameters reported for this model is $\theta = (\beta_1, \beta_2, \delta_1, \delta_2, \sigma_\epsilon^2)'$ (i.e., the FE are not reported).

2.4 PIECEWISE LINEAR MODEL

As illustrated in Figure 3 and summarized in Tables 4 and 5 in Section 3.2 below, time-varying mean and volatility appear to be key characteristics of the time series under study. In Subsection 4.2, we further substantiate these observations by conducting formal statistical tests. Although all series exhibit apparent nonlinearity, it is still possible that the relationship between these variables is linear. Consequently, we conducted statistical tests for a linear relationship, as detailed in Subsection 4.2. Preceding the outcomes of these tests, strong evidence in favor of a nonlinear relationship was found.

The identified nonlinear characteristics, both within the series themselves and in their relationships, may lead to spurious ordinary least squares (OLS) estimation results due to non-stationarity and nonlinearity in the functional form. To address these issues, we adopt a so-called piecewise linear model.[2] In our case, this entails applying the RM1 on each segment of monthly data to achieve, at least approximately, segments of stationary data and linear relationships, thereby opting at enhancing the accuracy of the estimation results.

A model that is linear for each segment of monthly data within each zone is given by:

$$P_t = \alpha_\tau + \beta_{1\tau} W_t + \beta_{2\tau} T_t + \delta_{1\tau} Weekend_t + \delta_{2\tau} D_t + \epsilon_t, \qquad \text{[PWLM]}$$

where α_τ, $\beta_{1\tau}$, $\beta_{2\tau}$, $\delta_{1\tau}$, and $\delta_{2\tau}$ denote segment-specific parameters, i.e., parameters that change over months, where the time index τ spans from September 2022 to August 2023, covering a total of 12 months. The set of estimated unknown parameters reported for each month in this model are the effects that wind and temperature have on prices, i.e., the set $\theta = (\beta_{1\tau}, \beta_{2\tau})'$.

2.5 DYNAMIC MODEL

When modeling a price series in general, it is common to incorporate dynamics.[3] This is done to capture potential issues with serially correlated error terms. Motivated by the observation that electricity price series for all

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[2] See "Introduction to the Piecewise Regression Model" by Chow, G. C., 1960.

[3] See "Dynamic Econometrics" by Hendry, D. F., 1995.

zones exhibit a strong positive first-order autocorrelation[4], we include the lagged price variable, P_{t-1}, as an explanatory variable in the RM1 model (excluding the dummy for network constraints, as they were found to be nonsignificant) to obtain:

$$P_t = \alpha + \beta_1 W_t + \beta_2 T_t + \rho P_{t-1} + \delta_1 Weekend_t + \delta_2 D_t + \epsilon_t. \qquad \text{[DM]}$$

In this model, the parameter ρ measures the persistence or memory in the price series. It is assumed that $\rho \in (-1,1)$ to ensure that the price series are not nonstationary (i.e., not random walks). A value close to one, as observed in the series at hand (as is shown in Table 11 below), indicates that yesterday's electricity spot price is a good predictor for today's electricity spot price. Moreover, the marginal effects that wind and temperature, denoted by β_1^* and β_2^*, respectively, on prices can be solved for recursively to yield: $\beta_1^* = \beta_1/(1-\rho)$ and $\beta_2^* = \beta_2/(1-\rho)$.[5] The set of unknow parameters to be estimated for this reference model is $\theta = (\alpha, \beta_1, \beta_2, \rho, \delta_1, \delta_2, \sigma_\epsilon^2)'$.

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[4] First-order autocorrelations for the price series in the four Zones are: 0.89, 0.89, 0.90, and 0.88, respectively.

[5] One can show that the marginal effects can be calculated as a sum of the geometric series: $\beta_i \sum_{i=0}^{\infty} \rho^i = \beta_i/(1-\rho)$, for $i = 1,2$, assuming that $\rho \in (-1,1)$.

3 Data and Summary Statistics[6]

3.1 DATA

The data used in our analysis were obtained from a weather app called "Weather data." These daily observations include electricity prices, temperature, and wind for the cities of Luleå, Sundsvall, Stockholm, and Malmö, representing the four zones SE1, SE2, SE3, and SE4, respectively. This results in 350 time series observations for each variable, as illustrated in Figure 3.[7]

Furthermore, the electricity price series is measured in Swedish öre, while temperature and wind are measured in degrees Celsius and meters per second (m/s),[8] respectively. Wind strength data corresponds to 10:00 AM each day, and temperature reflects the daily highest reported temperature. The electricity prices for each Zone are based on the average value of the "day-before-market" (the Elspot market).

In addition to these primary data, we introduce dummy variable data for when the nuclear reactor Oskarshamn 3 is shut down. Dummy variables are also created for weekends and months. Finally, the notation for price, wind, and temperature data in the four different zones is as follows: SE1P, SE2P, SE3P, SE4P; SE1W, SE2W, SE3W, and SE4W; and SE1T, SE2T, SE3T, and SE4T, respectively.

3.2 SUMMARY STATISTICS

The summary statistics reported in Table 3 reveal similarities between Zones 1 and 2, particularly in the price series, as expected. For Zone 3, prices are approximately 25% higher and about 20% more volatile compared to Zones 1 and 2. In Zone 4, the highest prices are observed, approximately 35% higher than in Zones 1 and 2, and about 13% higher than in Zone 3. Price volatility is comparable to Zone 3. Notably, Zone 4 is, on average, the windiest zone. Lastly, it is observed that prices have been negative in all zones, occurring a few times during the summer.[9]

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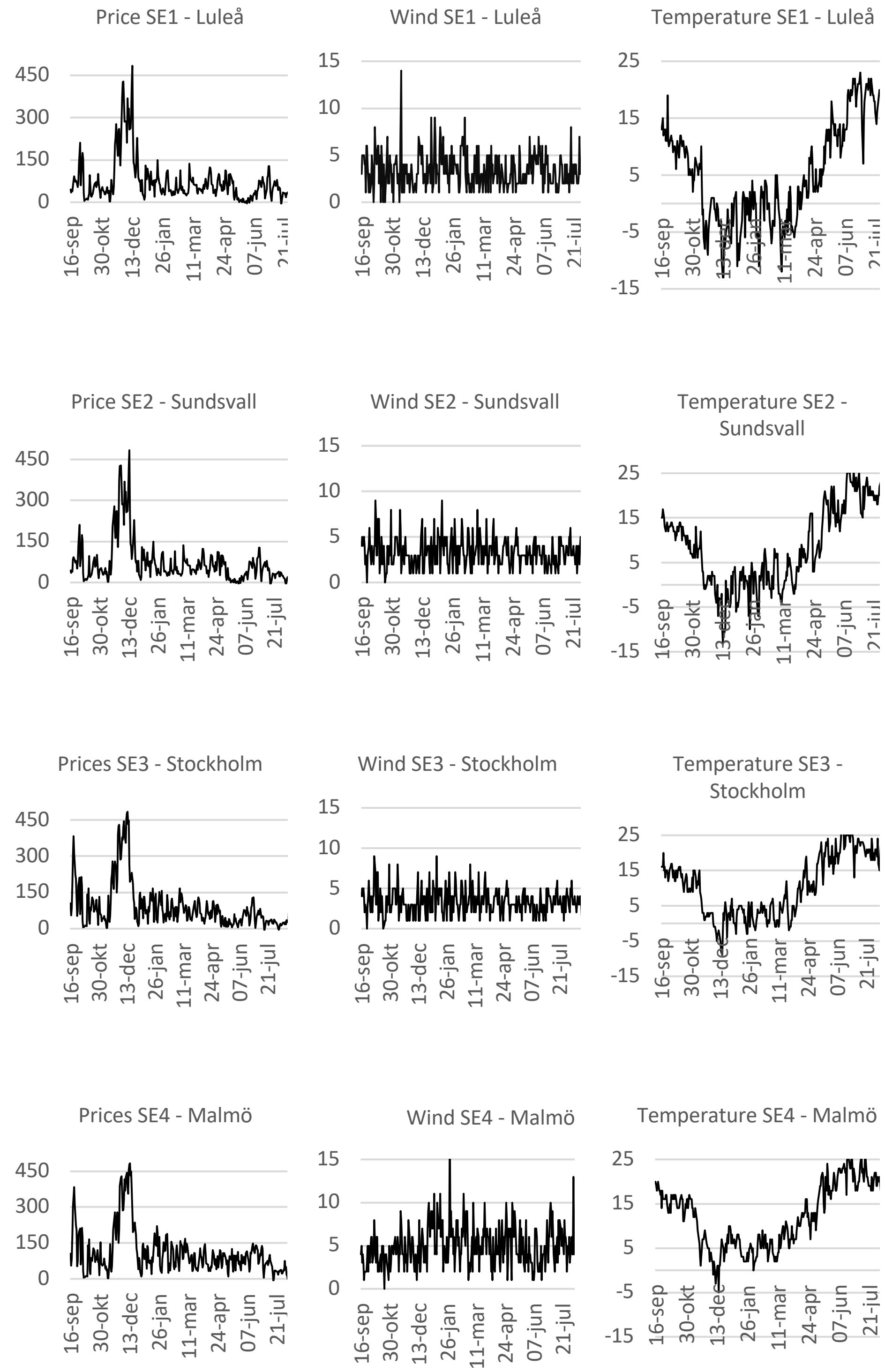
[6] Most of the data analysis is conducted using the Stata software program. More advanced analyses, such as implementing various tests for structural breaks, are performed in Python.

[7] The data have been collected by Professor Lars Bergman at the Stockholm School of Economics.

[8] One SEK corresponds to 100 öre.

[9] The most negative price, -9.57 öre, was observed on June 16 in all zones.

Figure 4. **The price, wind, and temperature series for the four zones.**



Price SE1 - Luleå

Wind SE1 - Luleå

Temperature SE1 - Luleå

Price SE2 - Sundsvall

Wind SE2 - Sundsvall

Temperature SE2 - Sundsvall

Prices SE3 - Stockholm

Wind SE3 - Stockholm

Temperature SE3 - Stockholm

Prices SE4 - Malmö

Wind SE4 - Malmö

Temperature SE4 - Malmö

***Table 3.* Summary statistics for wind, temperature, and price series in the four zones.**

Series	Mean	Std.	Min.	Max.
SE1W	3.39	1.86	0.00	14.00
SE1T	6.44	9.25	-13.00	25.00
SE1P	70.18	76.23	-9.57	483.78
SE2W	2.94	1.60	0.00	8.00
SE2T	9.18	9.11	-13.00	26.00
SE2P	70.19	76.31	-9.57	483.78
SE3W	3.31	1.56	0.00	9.00
SE3T	11.01	8.68	-9.00	28.00
SE3P	92.65	94.26	-9.57	483.78
SE4W	4.91	2.35	0.00	19.00
SE4T	12.64	7.25	-5.00	27.00
SE4P	106.35	91.90	-9.57	483.78
SEW	3.64	2.02	0.00	19.00
SET	8.90	8.90	-13.00	28.00
SEP	84.87	86.37	-9.57	483.78

Notes: Std. signifies standard deviations. SEW, SET, and SEP denote aggregated series from the four zones to a "national" level.

Refining the statistics in Table 3, monthly averages and volatilities for the wind, temperature, and price series are reported in Tables 4 and 5, respectively.

In Table 4, it is observed that December, the coldest month across all zones, is also associated with the highest prices. Additionally, July and August consistently exhibit the lowest prices for all zones, and we notice a spike in prices in Zone 4 during June. It is worth mentioning that Zone 4 is the windiest and warmest zone for almost all months. An erroneous analysis based solely on this information might suggest that Zone 4 should experience more supply due to higher wind and less demand due to warmer months compared to other zones, thereby, ceteris paribus, resulting in lower prices. However, as evident, this is not the case. One contributing factor to higher prices in September is increased demand in Germany, influencing Swedish prices due to the interconnected electricity price market.

***Table 4.* Monthly average observations for wind, temperature, and prices in the four zones.**

Series	Sep	Oct	Nov	Dec	Jan	Feb	Ave
SE1W	3.43	3.50	**2.95**	3.74	**4.10**	3.54	3.39
SE1T	12.63	8.61	0.98	**-4.02**	-2.03	-1.89	6.44
SE1P	85.31	50.00	122.06	**205.39**	70.39	52.03	70.18
SE2W	3.50	2.63	2.77	2.74	3.19	**5.36**	2.94
SE2T	13.90	10.90	4.42	**-3.03**	-0.32	1.11	9.18
SE2P	85.91	51.19	122.06	**205.44**	70.39	52.03	70.19
SE3W	3.40	3.40	3.23	3.10	3.77	3.46	3.31
SE3T	15.67	12.69	7.23	**-0.05**	2.42	2.21	11.01
SE3P	188.52	79.27	131.10	**269.01**	92.58	82.51	92.65
SE4W	**3.20**	3.65	4.70	4.64	**6.61**	5.79	4.91
SE4T	17.53	14.97	10.13	**3.11**	5.16	5.04	12.64
SE4P	188.53	79.88	135.72	**271.59**	104.72	102.75	105.35

Series	Mar	Apr	May	Jun	Jul	Aug	Ave
SE1W	3.31	2.68	3.74	2.90	3.35	3.42	3.39
SE1T	-3.08	3.47	10.48	17.40	18.35	**18.81**	6.44
SE1P	59.92	66.48	27.76	51.60	37.41	**23.80**	70.18
SE2W	3.11	**2.45**	3.32	3.07	2.74	2.71	2.94
SE2T	1.29	7.88	15.58	**21.07**	19.97	19.52	9.18
SE2P	56.92	66.48	27.83	50.10	37.41	**23.79**	70.19
SE3W	**3.87**	3.20	3.06	**2.50**	3.45	3.26	3.31
SE3T	3.19	9.75	16.90	**22.93**	21.03	20.19	11.01
SE3P	81.71	68.53	38.99	53.05	**37.27**	36.86	92.65
SE4W	5.18	4.75	5.22	3.83	5.64	4.61	4.91
SE4T	6.27	10.88	17.13	**22.27**	20.81	20.35	12.64
SE4P	92.86	73.87	73.42	103.37	**41.76**	49.56	105.35

Notes: Maximum and minimum monthly average observations are highlighted in black and blue, respectively. Monthly observations for SE3 are illustrated in Figure 3. “Ave” denotes the averages that are reported in Table 3.

***Table 5.* Monthly volatility observations for wind, temperature, and prices in the four zones.**

Series	Sep	Oct	Nov	Dec	Jan	Feb	Ave
SE1W	1.80	2.16	**2.48**	2.21	1.74	2.22	1.86
SE1T	2.21	2.42	**5.29**	3.56	3.88	4.23	9.25
SE1P	50.61	41.48	**114.23**	113.85	32.67	27.73	76.23
SE2W	1.68	1.68	**2.01**	1.50	1.56	1.91	1.60
SE2T	**1.44**	2.28	4.07	**4.44**	3.64	4.10	9.11
SE2P	50.49	42.20	**114.23**	113.82	32.67	27.73	76.31
SE3W	1.50	**2.24**	1.65	1.70	1.91	1.73	1.56
SE3T	**1.85**	2.51	**5.19**	4.08	2.68	2.39	8.68
SE3P	100.73	53.39	115.62	**152.91**	44.37	38.05	94.26
SE4W	**1.26**	1.76	1.66	2.29	**3.30**	2.42	2.35
SE4T	**1.68**	1.78	**4.63**	3.30	2.34	2.36	7.25
SE4P	100.74	56.11	112.97	**153.94**	53.40	47.47	91.90

Series	Mar	Apr	May	Jun	Jul	Aug	Ave
SE1W	1.63	**1.30**	1.57	1.60	1.50	1.63	1.86
SE1T	3.83	2.73	3.80	4.29	3.03	**1.72**	9.25
SE1P	24.17	29.11	33.30	34.33	20.59	**12.58**	76.23
SE2W	1.86	**1.26**	1.42	1.44	1.46	1.30	1.60
SE2T	3.33	4.02	4.39	3.98	2.12	1.95	9.11
SE2P	24.17	29.11	33.33	34.33	20.59	**12.58**	76.31
SE3W	1.63	1.35	**1.00**	1.07	1.15	1.09	1.56
SE3T	3.72	4.24	4.73	3.92	2.35	2.17	8.68
SE3P	36.94	31.42	28.28	33.05	**21.09**	34.76	94.26
SE4W	1.99	2.37	2.28	1.98	2.12	2.23	2.35
SE4T	2.66	2.78	3.73	2.20	2.23	3.01	7.25
SE4P	37.42	32.18	28.53	31.22	**25.03**	38.20	91.90

Notes: Maximum and minimum monthly average observations are highlighted in black and blue, respectively. Monthly observations for SE3 are illustrated in Figure 3. “Ave” denotes the averages that are reported in Table 3.

In Table 5, it is observed that December is the most (or very close to being the most) volatile month concerning prices. Additionally, the price series, in general, exhibit much higher volatility in Zone 3 and 4 compared to Zone 1 and 2. As a final observation, wind shows significantly higher volatility during the spring and summer months in Zone 4 compared to the other zones.

The summary statistics in Tables 4 and 5 indicate that both the mean and volatility (variances) for all series in all zones appear to vary over time, as already illustrated for Zone 3 in Figure 3. This has implications for model selection and is a key motivation for introducing the piecewise linear model in the previous Subsection 2.5.

The next set of summary statistics includes pairwise correlations between the price, temperature, and wind series in the four different zones, presented in Table 6.

Table 6. **The pairwise correlations of price, temperature, and wind in the four zones.**

	SE1P	SE1T	SE1W		SE2P	SE2T	SE2W
SE1P	1.00			SE2P	1.00		
SE1T	*-.42*	1.00		SE2T	*-.47*	1.00	
SE1W	*-.18*	.02	1.00	SE2W	*-.18*	.00	1.00
	SE3P	SE3T	SE3W		SE4P	SE4T	SE4W
SE3P	1.00			SE4P	1.00		
SE3T	***-.51***	1.00		SE4T	*-.45*	1.00	
SE3W	*-.26*	-.07	1.00	SE4W	***-.32***	*-.13*	1.00

Notes: Italics denote correlations that are significant at a 5% level. Italics and bold denote the minimum correlations observed.

Overall, the sign of the correlations in Table 6 is as expected, with higher temperature and more wind associated with lower prices. These negative signs are also anticipated to be reflected in our model estimation results for the impact of wind and temperature on prices. Furthermore, we observe that the correlation between temperature and prices is moderate and similar for all zones, ranging from -0.51 to -0.42. The correlations between wind and price are relatively small (in absolute values) but significant in Zones 1 and 2 (-0.18), and somewhat more pronounced in Zones 3 (-0.26) and 4 (-0.32). The correlations between temperature and wind are low and insignificant for all zones except in Zone 4. These low correlations imply that the estimated effects (reported in Section 4 below) of wind and temperature on electricity prices are not confounded by each other.

In Table 7, pairwise correlations for the price and wind series in different zones are reported. In this table we see that all correlations are positive (and significant), close to one, indicating that prices in different zones co-move to a large extent. We observe high and low prices simultaneously in different zones. In Table 7, we observe that the wind in Zones 1 and 2 shows a moderate (significant) positive correlation. The strongest correlation between winds is in Zone 2 and 3. Wind in Zone 4 appears to be correlated only with the wind in Zone 3. Due to these correlations, we can expect to see some wind “cannibalism” among different zones, particularly between Zone 1 and Zone 2.

Table 7. **Pairwise correlations price and wind in the four zones.**

	SE1P	SE2P	SE3P	SE4P		SE1W	SE2W	SE3W	SE4W
SE1P	1.00				SE1W	1.00			
SE2P	*1.00*	1.00			SE2W	*.39*	1.00		
SE3P	*.90*	*.90*	1.00		SE3W	*.24*	*.50*	1.00	
SE4P	*.86*	.86	*.97*	1.00	SE4W	-.01	.14	*.30*	1.00

Note: Italics denote correlations that are significant at a 5% level.

4 Estimation Results and Statistical Analysis

4.1 ESTIMATION RESULTS FOR REFERENCE MODELS

Estimation results for all reference models are presented in Table 8. Starting with the results for the PDM, which serves as a reference for understanding how electricity prices are affected by wind and temperature at a "national" level, we observe a strong (significant) negative impact of wind. An increase in wind by one unit (i.e., an increase of 1 m/s) results in a decrease in electricity prices by 11.14 öre. Similarly, albeit with a less pronounced impact, a one-unit increase in temperature (i.e., an increase of 1 degree Celsius) causes prices to decrease by 4.03 öre. Moreover, the dummies exhibit the expected signs, indicating that electricity prices are 25.19 öre less expensive on weekends. When a nuclear power plant is temporarily shut down, prices increase by 68.42 öre. However, the explanatory power of the model is moderate, as evidenced by an adjusted R^2-value of 23%.

Turning next to the results for the RM1 and the RM2, we find that the estimated wind and temperature effects are negative (and significant) for all zones. Notably, wind has a much more negative impact on prices than temperature. Specifically, in Zones 1 and 2, we observe that the wind effects on prices range from -7.85 to -6.15, while the temperature effects range from -4.55 to -3.04. In combination, the effects of wind on prices are almost twice as large as those of temperature. Applying a similar analysis to Zones 3 and 4, we see that wind effects on prices are approximately 2.5 to 3 times as large as the temperature effects. For instance, in Zone 3 and for the RM2, we observe that temperature has an effect of -6.26 on prices, whereas wind has an effect of -14.58.

Due to the different scales of wind and temperature, analyzing standardized estimation results provides a more direct comparison of the relative importance of coefficients. Examining the standardized results in Table 8 (rows with β^s coefficients), it becomes evident that temperature now has a higher relative impact on prices than wind. To illustrate, using the results in Zone 1 for the RM2, if wind increases by one standard deviation (1.86 m/s; see Table 3), then the price decreases by β_1^s standard deviations or 12 öre (i.e., -0.16·76.23 = 12.20). If instead, temperature increases by one standard deviation (9.25 degrees; see Table 3), then the price decreases by β_2^s standard deviations or 30 öre (i.e., -0.39·76.23 = 29.73). Applying similar calculations for Zones 2, 3, and 4, we first conclude that a one standard deviation increase in wind (i.e., 1.60 m/s, 1.56 m/s, and 2.35 m/s, respectively; again see Table 3) implies that prices decrease by 11 öre (i.e., -0.14·76.31 = -10.68), 23 öre (i.e., -0.24·94.26 =- 22.62), and 27 öre (i.e., -0.29·91.90 = -26.65), respectively. If instead, a one standard deviation increase in temperature is considered (i.e., 9.11 degrees, 8.68 degrees, and 7.25 degrees, respectively; again, see Table 3), then prices decrease by 41 öre (i.e., -0.54·76.31 = -41.21), 54 öre (i.e., -0.57·94.26 =- 53.73), and 60 öre (i.e., -0.65·91.90 = -59.73), respectively.

As a note on the standardized results provided above, it is worth considering alternative standardization schemes. For instance, standardizing the price, wind, and temperature variables with respect to the winter months from November to March - presumed to be a period when temperature, influenced by electric heating and lighting, has the most significant impact on electricity demand - yields alternative effects, reported in Table 9 using the RM2.[10]

In Table 9, the newly estimated standardized effects for wind and temperature exhibit similar magnitudes. With this standardization scheme, we can conclude that wind and temperature have comparable effects on electricity prices for all zones. To illustrate using temperature, if temperature increases by one standard deviation, calculated over the winter months, the electricity price decreases by (refer to note 10 for numbers used in subsequent calculations) in Zones 1, 2, 3, and 4 by 15 öre (i.e., -0.15·99.78 = -14.97), 16 öre (i.e., -0.16·99.79 = -15.97), 28 öre (i.e., -0.24·115.64 = -27.75), and 32 öre (i.e., -0.28·114.08 = -31.94), respectively.

In terms of estimated weekend effects, the most pronounced impact is observed in Zone 4, with electricity prices being 34 öre less expensive on weekends. In Zones 1 and 2, electricity prices are (approximately) 20 öre less expensive on weekends, while in Zone 3, they are 26 öre less expensive.

Regarding the estimated proxy for bottlenecks, δ_3, based on RM1, we observe no significant estimated constraints in the network between Zone 1 and Zone 2. However, we do observe significant estimated bottleneck effects between Zone 2 and Zone 3, as well as between Zone 3 and Zone 4. Specifically, network constraints cause an excess supply in Zone 2 that cannot be distributed to Zone 3, leading to a reduction in prices in Zone 2 by 13.69 öre. Similarly, excess supply in Zone 3 that cannot be distributed to Zone 4 results in a reduction in prices in Zone 3 by 15.73 öre.

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[10] The standard deviations for Price, Wind, and Temperature in the different zones are: 99.78 öre (SE1), 99.79 öre (SE2), 115.64 öre (SE3), and 114.08 öre (SE4); 2.08 m/s (SE1), 1.77 m/s (SE2), 1.73 m/s (SE3), and 2.48 m/s (SE4); and 4.47° (SE1), 4.58° (SE2), 4.41° (SE3), and 3.91° (SE4).

Table 8. **Estimation results for the reference models.**

	Sweden	**SE1**		**SE2**	
	PDM	RM1	RM2	RM1	RM2
$cons$	167.27 (***)	112.54 (***)	212.60 (***)	127.71 (***)	208.59 (***)
β_1	-11.14 (***)	-6.15 (***)	-6.36 (***)	-7.65 (***)	-6.74 (***)
β_1^s		-0.15 (***)	-0.16 (***)	-0.16 (***)	-0.14 (***)
β_2	-4.03 (***)	-3.04 (**)	-3.25 (***)	-3.54 (***)	-4.55 (***)
β_2^s		-0.37 (**)	-0.39 (***)	-0.42 (***)	-0.54 (***)
δ_1	-25.19 (***)	-19.49 (***)	-19.43 (***)	-19.15 (***)	-18.90 (***)
δ_2	68.42 (***)	55.22 (***)	28.51 (**)	46.08 (***)	21.80 (*)
δ_3		7.66	-7.57	-13.69 (*)	-3.33
θ_1			-88.10 (***)		-68.19 (***)
θ_2			-106.12 (***)		-83.99 (***)
θ_3			-63.41 (***)		-42.75 (***)
θ_4			-117.11 (***)		-112.64 (***)
θ_5			-138.68 (***)		-123.49 (***)
θ_6			-146.07 (***)		-124.85 (***)
θ_7			-115.13 (***)		-87.71 (***)
θ_8			-112.00 (***)		-82.62 (***)
θ_9			-80.01 (***)		-35.46
θ_{10}			-88.01 (***)		-55.79 (**)
θ_{11}			-102.84 (***)		-74.30 (***)
N^*	1394	345	334	345	334
F	0.00	0.00	0.00	0.00	0.00
$\bar{R}^2$	0.23	0.05	0.48	0.28	0.49
$\hat{\sigma}_\epsilon$		54.97	55.00	64.84	54.60

***Table 8 (continued).* Estimation results for the reference models.**

	SE3		**SE4**	
	RM1	RM2	RM1	RM2
$cons.$	205.46 (***)	298.79 (***)	252.35 (***)	343.52 (***)
β_1	-17.38 (***)	-14.58 (***)	-14.39 (***)	-11.21 (***)
β_1^s	-0.29 (***)	-0.24 (***)	-0.37 (***)	-0.29 (***)
β_2	-4.92 (***)	-6.26 (***)	-5.50 (***)	-8.22 (***)
β_2^s	-0.45 (***)	-0.57 (***)	-0.43 (***)	-0.65 (***)
δ_1	-26.23 (***)	-25.84 (***)	-37.51 (***)	-34.50 (***)
δ_2	96.24 (***)	70.23 (***)	73.41 (***)	48.77 (***)
δ_3	-15.73 (*)	7.71		
θ_1		-72.92		-64.14
θ_2		-82.12 (***)		-86.31 (***)
θ_3		-68.37 (***)		-62.65 (***)
θ_4		-128.52 (***)		-112.24 (***)
θ_5		-6.15 (***)		-124.68 (***)
θ_6		-144.52 (***)		-143.17 (***)
θ_7		149.82 (***)		-121.98 (***)
θ_8		-123.33 (***)		-61.87 (***)
θ_9		-102.65 (***)		-5.02
θ_{10}		-55.88 (**)		-56.39 (**)
θ_{11}		-85.91 (***)		-69.25 (***)
N^*	345	334	345	334
F	0.00	0.00	0.00	0.00
$\bar{R}^2$	0.41	0.65	0.17	0.63
$\hat{\sigma}_\epsilon$	72.41	55.1	58.62	55.78

Notes: β_1^s and β_2^s denote standardized regression coefficients. '***', '**', and '*' in parentheses designate significance at a 1%, 5%, and 10% level, respectively. N^*denotes the effective sample size. *F* abbreviates significance testing of the model (joint significance testing of the variables included), and *p*-values for this test are reported. $\bar{R}^2$ abbreviates the adjusted coefficient of determination. $\hat{\sigma}_\epsilon$ denotes the estimate of σ_ϵ, and corresponds also to a root mean square error estimate.

***Table 9.* Standardized effects relative to Winter conditions for wind and temperature.**

	SE1	SE2	SE3	SE4
β_1^{ms}	-0.13 (***)	-0.12 (***)	-0.22 (***)	-0.24 (***)
β_2^{ms}	-0.15 (***)	-0.16 (***)	-0.24 (***)	-0.28 (***)

Notes: β_1^{ms} and β_2^{ms} denote standardized regression coefficients where the standardization is based on the winter months from November to March. '***' in parentheses designates significance at a 1% level.

With regards to differences in estimation results between RM1 and RM2, the estimates on wind (β_1), temperature (β_2), and weekend effects (δ_1) are "similar" and comparable. Concerning the effects of a nuclear plant being temporarily shut down (δ_2), we observe that estimates by RM2 are substantially lower for all zones than the ones by RM1. Regarding TFE (i.e., monthly dummies), most of them are significantly estimated for all months, and as such, they are deemed critical in capturing monthly effects that we are not controlling for in RM1.

Lastly, a marked difference in adjusted R^2-values between RM1 and RM2 is observed, with RM2 providing a substantially better model fit. For instance, in Zone 4, the adjusted R^2-value for RM2 is 63%, whereas it is only 17% for RM1. As final comments on the estimated reference models, we conclude that the RM2 model, in many aspects, is the most adequate reference model for describing electricity prices, and it has the best predictive power (highest adjusted R^2-values).

Another question related to predictive power is which of the two variables, wind, and temperature, contributes the most to the overall predictive power of the model. By answering this question, we will also address our second empirical question stated in the introduction. Instead of examining this question for all models that we are estimating, we simplify the analysis by only using wind and temperature as variables to explain prices in a simple regression model. Then we simply calculate a Relative Predictive Importance Measure (RPI) to answer the question. In such a regression analysis, we find that temperature contributes by (i.e., the RPIs) 85%, 88%, 79%, and 67% to the adjusted R^2-values for Zone 1, 2, 3, and 4, respectively, and consequently contributes wind by 15%, 12%, 21%, and 33%, respectively. Evidently, temperature explains most of the overall variation in electricity prices, but we observe that wind is more than two times as influential in Zone 4 as in Zone 1.

4.2 TESTING FOR STRUCTURAL BREAKS

To formally test for a linear relationship between prices and wind and temperature, we apply a Chow test.[11] This test examines whether the series are subject to so-called structural changes or structural breaks. It tests the null hypothesis of parameter constancy (i.e., a linear relationship or no structural breaks) against the alternative hypothesis of parameter non-constancy (i.e., a nonlinear relationship or structural breaks). In our case, we choose to base the Chow test on RM2, and the outcomes are reported in Table 10.

Table 10. **Testing for structural breaks in the relationship between prices and wind and temperature.**

	SE1 RM2	SE2 RM2	SE3 RM2	SE4 RM2
Chow *F*-test	0.001	0.002	0.000	0.001

Notes: p-values for the Chow *F*-test are reported. The break date for conducting the Chow test is set at December 1 for all series.

According to the results in Table 10, we observe a strong rejection of the null hypothesis of parameter constancy. As a robustness check, we explored alternative break dates other than December 1, and once again, we were able to reject the null hypothesis of linearity. These additional findings suggest that the relationship between the variables is prone to multiple structural breaks.

We also individually tested the wind, temperature, and wind series for structural breaks, again using the Chow test (results not reported here). In all zones, we found that each series is subject to structural breaks in the mean and/or in the volatility. This finding corroborates the visual observations in Figure 3 and the summary statistics in Tables 4 and 5.

4.3 ESTIMATION RESULTS FOR THE PIECEWISE LINEAR MODEL

The outcomes of the Chow test in the previous section indicate that a linear relationship between prices and wind and temperature breaks down in all four zones. Several parametric modeling options are available that can account for (multiple) structural breaks in model parameters. In this study, we attempt to address this issue by utilizing the PWLM, as described in Subsection 2.4. This assumes that the series and the relationship between the series are, at least approximately, stationary, and linear, respectively, on monthly segments of the data. A potential concern with this approach is the resulting small sample sizes (about 30 observations). However, even

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[11] See footnote 4 for a reference to the Chow test.

though the number of parameters to estimate is six per segment of data, we still expect to retain some efficiency properties of the estimates.

The estimation results for the wind and temperature effects by the PWLM are reported in Table 11. In Table 11, we observe that temperature has a significant impact on prices from November to April or May for all zones (more cold months, as expected), and also in August for Zones 1 and 2.

Turning next to the impact of wind, we find that there is no significant impact of wind on prices from November to March in Zone 1, and from November to February in Zone 2, and from December to January in Zone 3. Wind has a significant impact on prices for all months in Zone 4.

For Zones 3 and 4, we note that wind has a significant effect on prices in September and October, and June, July, and August when temperature does not.

Focusing on standardized estimation results, we see that in January to April in Zone 3, when both wind and temperature are significant, temperature has a stronger impact on prices. For the other zones, there are mixed findings about the strongest effects of wind and temperature on prices.

Lastly, by studying the adjusted R^2-values, we can see in more detail which months wind and temperature are capable of better predicting prices. For instance, in March, we observe high adjusted R^2-values for all zones ranging from 61% (in Zone 1) to 72% (in Zone 2), whereas October is more challenging, and the adjusted R^2-values range from 24% to 56%. Average adjusted R^2-values ($\overline{\bar{R}^2}$) over all months are moderate and range from 44% (Zone 1) to 53% (Zone 3).

Table 11. Estimation results for the piecewise linear models.

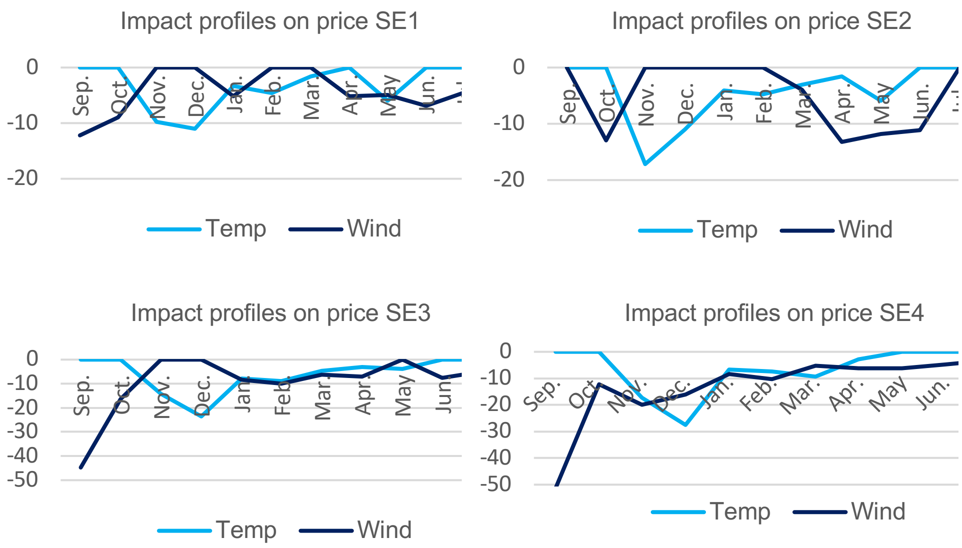
		Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	β
SE1								
	$\beta_{1\tau}$	-12.20	-9.00	-	-	-5.13	-	-6.15
	$\beta_{1\tau}^{s}$	-0.43	-0.47	-	-	-0.27	-	-0.15
	$\beta_{2\tau}$	-	-	-9.78	-11.01	-3.36	-4.55	-3.04
	$\beta_{2\tau}^{s}$	-	-	-0.45	-0.29	-0.40	-0.69	-0.37
$\overline{\bar{R}^2} =$ 0.44	$\bar{R}^2$	0.25	0.24	0.24	0.17	0.41	0.60	
SE2								
	$\beta_{1\tau}$	-	-12.93	-	-	-	-	-7.65
	$\beta_{1\tau}^{s}$	-	-0.52	-	-	-	-	-0.16
	$\beta_{2\tau}$	-	-	- 17.16	-11.05	-4.13	-4.81	-3.54
	$\beta_{2\tau}^{s}$	-	-	-0.61	-0.37	-0.46	-0.71	-0.42
$\overline{\bar{R}^2} =$ 0.45	$\bar{R}^2$	0.24	0.25	0.37	0.21	0.40	0.61	
SE3								
	$\beta_{1\tau}$	-44.75	-16.37	-	-	-8.31	-9.94	-17.38
	$\beta_{1\tau}^{s}$	-0.67	-0.66	-	-	-0.38	-0.45	-0.29
	$\beta_{2\tau}$	-	-	- 14.27	-.13.56	-7.74	-8.81	-4.92
	$\beta_{2\tau}^{s}$	-	-	-0.64	-0.63	-0.45	-0.55	-0.45
$\overline{\bar{R}^2} =$ 0.53	$\bar{R}^2$	0.52	0.56	0.57	0.57	0.69	0.61	
SE4	$\beta_{1\tau}$	-51.34	-12.33	- 19.96	-16.09	-8.41	-10.22	-14.39
	$\beta_{1\tau}^{s}$	-0.64	-0.39	-0.29	-0.24	-0.52	-0.52	-0.37
	$\beta_{2\tau}$	-	-	- 17.23	-27.52	-6.76	-7.46	-5.50
	$\beta_{2\tau}^{s}$	-	-	-0.71	-0.59	-0.30	-0.37	-0.43
$\overline{\bar{R}^2} =$ 0.52	$\bar{R}^2$	0.50	0.26	0.57	0.65	0.70	0.66	

Table 11 (continued). Estimation results for the piecewise linear models.

		Mar.	Apr.	May	Jun.	Jul.	Aug.	β
SE1								
	$\beta_{1\tau}$	-	-5.14	-4.88	-6.84	-4.44	-1.06	-6.15
	$\beta^s_{1\tau}$	-	-0.23	-0.23	-0.32	-0.32	-0.14	-0.15
	$\beta_{2\tau}$	-1.58	-	-5.96	-	-	-4.42	-3.04
	$\beta^s_{2\tau}$	-0.25	-	-0.68	-	-	-0.60	-0.37
$\overline{\bar{R}^2} =$ 0.44	$\bar{R}^2$	0.61	0.27	0.61	0.74	0.32	0.79	
SE2								
	$\beta_{1\tau}$	-3.99	-13.22	-	-11.11	-	-4.87	-7.65
	$\beta^s_{1\tau}$	-0.31	-0.57	11.77	-0.46	-	-0.50	-0.16
				-0.50				
	$\beta_{2\tau}$	-3.09	-1.62	-5.86	-	-	-1.31	-3.54
	$\beta^s_{2\tau}$	-0.42	-0.22	-0.77	-	-	-0.20	-0.42
$\overline{\bar{R}^2} =$ 0.45	$\bar{R}^2$	0.72	0.48	0.60	0.60	0.24	0.65	
SE3								
	$\beta_{1\tau}$	-6.35	-6.96	-	-7.65	-4.90	-13.83	-17.38
	$\beta^s_{1\tau}$	-0.28	-0.30	-	-0.25	-0.27	-0.43	-0.29
	$\beta_{2\tau}$	-4.76	-2.94	-3.84	-	-	-	-4.92
	$\beta^s_{2\tau}$	-0.48	-0.33	-0.64	-	-	-	-0.45
$\overline{\bar{R}^2} =$ 0.53	$\bar{R}^2$	0.65	0.36	0.47	0.41	0.35	0.58	
SE4	$\beta_{1\tau}$	-5.12	-6.12	-6.30	-4.66	-3.21	-7.64	-14.39
	$\beta^s_{1\tau}$	-0.27	-0.45	-0.50	-0.29	-0.27	-0.44	-0.37
	$\beta_{2\tau}$	-9.29	-2.89	-	-	-	-	-5.50
	$\beta^s_{2\tau}$	-0.66	-0.25	-	-	-	-	-0.43
$\overline{\bar{R}^2} =$ 0.52	$\bar{R}^2$	0.69	0.47	0.25	0.54	0.34	0.56	

Notes: Only estimates that are significant at a (one-sided) 10% significance level are reported. The significant estimates in this table are also plotted in Figures 5 and 6. $\overline{\bar{R}^2}$ denotes the average $\bar{R}^2$-value for all 12 months. In the column with the β heading, corresponding β_1 and β_2 estimates from the RM1 in Table 8 are reported as reference estimates.

Figure 5. **The estimated time-varying effects that wind and temperature have on electricity prices.**

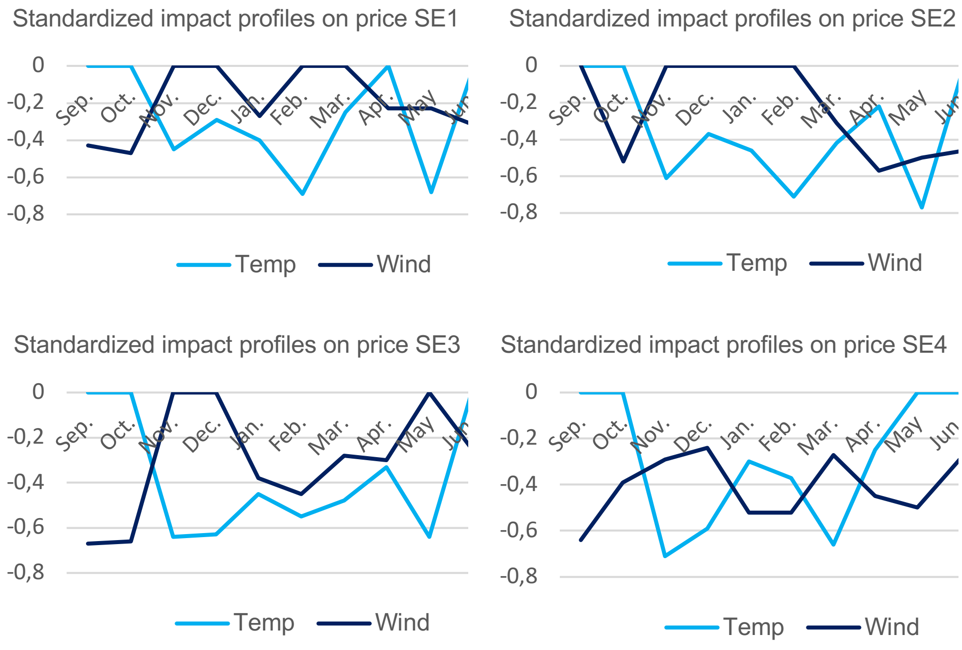

Impact profiles on price SE1

Impact profiles on price SE2

Impact profiles on price SE3

Impact profiles on price SE4

Figure 6. **The standardized estimated time-varying effects that wind and temperature have on electricity prices.**


Standardized impact profiles on price SE1

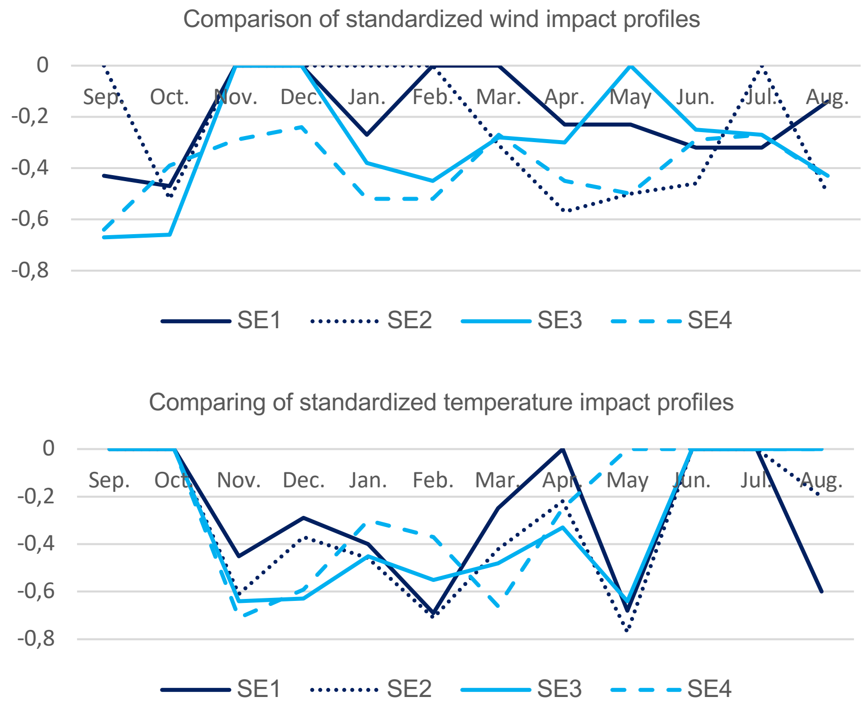
Standardized impact profiles on price SE2

Standardized impact profiles on price SE3

Standardized impact profiles on price SE4

To gain an overview of the results in Table 10, the monthly impacts that wind and temperature have on prices are depicted as “impact profiles” in Figures 5 and 6. In addition, the comparison of wind and temperature “impact profiles” on prices are shown in Figure 7.

***Figure 7.* Comparison of standardized wind and temperature impact profiles for the different zones.**



4.4 ESTIMATION RESULTS FOR THE DYNAMIC MODEL

Estimation results for the DM are presented in Table 12. If we focus on standardized marginal effects of wind and temperature on prices, we notice first that wind now has a stronger impact than temperature for all zones. The estimates for wind range from -0.64 (in Zone 4) to -0.44 (in Zone 2). The estimates for temperature range from -0.50 (in Zone 4) to -0.37 (in Zone 1).

Providing more details about the marginal effects on prices for the different zones, we first note for Zone 1 that if wind increases by one standard deviation (1.86 m/s), then prices decrease by 36 öre (i.e., -0.47·76.23 = -35.83). If, instead, temperature increases by one standard deviation (9.25 degrees), then prices decrease by 28 öre (i.e., -0.37·76.23 = -28.20). Analyzing corresponding effects for Zone 2, we find that if wind increases by one standard deviation (1.60 m/s), then prices decrease by 34 öre (i.e., -0.44·76.31 = -33.57). If, instead, temperature increases by one standard deviation (9.11 degrees), then prices also decrease by 34 öre (i.e., -0.44·76.31 = -33.57). Analogously, for Zone 3, if wind increases by one standard deviation (1.56 m/s), then prices decrease by 55 öre (i.e., -0.58·94.26 = -

54.67). If, instead, temperature increases by one standard deviation (8.68 degrees), then prices decrease by 44 öre (i.e., -0.47·94.26 = -44.30). Lastly, for Zone 4, if wind increases by one standard deviation (2.35 m/s), then prices decrease by 59 öre (-0.64·91.90 = -58.82), whereas if temperature increases by one standard deviation (7.25 degrees), then prices decrease by 46 öre (-0.50·91.90 = -45.95).

Table 12. **Estimation results for the dynamic model.**

	SE1	SE2	SE3	SE4
	DM	DM	DM	DM
$cons.$	27.52 $^{(***)}$	31.02 $^{(***)}$	55.11 $^{(***)}$	74.07 $^{(***)}$
β_1	-2.99 $^{(***)}$	-3.54 $^{(***)}$	-6.37 $^{(***)}$	-5.33 $^{(***)}$
β_1^*	-19.33	-22.12	-33.53	-24.22
β_1^s	-0.07 $^{(***)}$	-0.07 $^{(***)}$	-0.11 $^{(***)}$	-0.14 $^{(***)}$
β_1^{s*}	-0.47	-0.44	-0.58	-0.64
β_2	-0.48 $^{(**)}$	-0.61 $^{(***)}$	-1.04 $^{(***)}$	-1.35 $^{(***)}$
β_2^*	-3.20	-3.81	-5.47	-6.14
β_2^s	-0.06 $^{(**)}$	-0.07 $^{(***)}$	-0.09 $^{(***)}$	-0.11 $^{(***)}$
β_2^{s*}	-0.37	-0.44	-0.47	-0.50
δ_1	-14.06 $^{(***)}$	-14.14 $^{(***)}$	-21.26 $^{(***)}$	-27.78 $^{(***)}$
δ_2	1.58	-0.76	12.52	8.18
ρ	0.85 $^{(***)}$	0.84 $^{(***)}$	0.81 $^{(***)}$	0.78 $^{(***)}$
N^*	343	343	343	343
F	0.00	0.00	0.00	0.00
$\bar{R}^2$	0.81	0.80	0.83	0.81
$\hat{\sigma}_\epsilon$	33.67	33.68	39.12	40.61

Notes: There are no estimates (δ_3) for the network constraints dummy variable $NR_{(ij)t}$ because such effects are now confounded with the lagged price variable. β_1^* (β_1^{s*}) and β_2^*(β_2^{s*}) denote (standardized) marginal effects for wind and temperature respectively.

In final remarks, the DM yields a number of important findings. First, lagged prices have a stronger predictive power on prices than wind and temperature (contributing the most to the adjusted R^2-values; results not shown here). Second, once we control for this price level, wind has a substantially larger impact on prices than temperature except for Zone 2. Third, because the DM model explains about 80% of the variation in prices, it emerges as the strongest contender for predictive purposes among all models considered in this project.

5 Summary of Estimation Results and Concluding Remarks

5.1 SUMMARY RESULTS AT A NATIONAL LEVEL

In this report, we have shown that, at a national (aggregate) level:

- The wind effect decreases electricity prices by 11 öre.
- The temperature effects decrease electricity prices by 4 öre.
- Weekend effects decrease electricity prices by 25 öre.
- A supply shortage of electricity, such as when a nuclear power plant is temporarily shutdown, increases prices by 68 öre.

5.2 SUMMARY RESULTS FOR THE DIFFERENT ZONES

There are a few important findings concerning the different zones and models used. To assess and summarize our findings regarding our first empirical question, we will use a simple measure to compare two wind and temperature estimates, namely a Relative Driver Importance (RDI) measure, calculated as:

$$RDI_i = \frac{|\beta_i|}{|\beta_1| + |\beta_2|}, \quad i = 1,2,$$

and where β_1 and β_2 are generic notations for the impact of wind and temperature, respectively.

5.2.1 Summary results for the second reference model

The RDI based on the RM2 - the reference model with the highest adjusted R^2-values, as well as wind and temperature effects on electricity prices, is summarized in Table 13.

Table 13. **RDI and price effects wind and temperature based on the RM2.**

	RDI Wind (β_1)	RDI Temp. (β_2)	Price effect Wind	Price effect Temp.	RDI Wind (β_1^s)	RDI Temp. (β_2^s)	Price effect Wind	Price effect Temp.
SE1	66%	34%	-6.36	-3.25	29%	71%	-12.20	-29.73
SE2	60%	40%	-6.74	-4.55	21%	79%	-10.68	-41.21
SE3	70%	30%	-14.58	-6.26	30%	70%	-22.62	-53.73
SE4	58%	42%	-11.21	-8.22	31%	69%	-26.65	-59.73

By the RM2, we also reported estimates for TFE (monthly dummies; see Table 8 for details). They give important, yet crude, information about (monthly) factors not controlled for by wind and temperature when modelling prices. Moreover, dummy variable effects for the four zones are summarized as:

- Zone 1: Weekend effects decrease electricity prices by 19 öre. A temporary nuclear power plant shutdown increases prices by 29 öre. Proxy for bottleneck effects is not significant.

- Zone 2: Weekends effects decrease electricity prices by 19 öre. A temporary nuclear power plant shutdown increases prices by 22 öre. Proxy for bottleneck effects decrease prices with 14 öre.

- Zone 3: Weekend effects decrease electricity prices by 26 öre. A temporary nuclear power plant shutdown increases prices by 70 öre. Proxy for bottleneck effects decreases prices by 16 öre.

- Zone 4: Weekend effects decrease electricity prices by 34 öre. A temporary nuclear power plant shutdown increases prices by 49 öre. No proxy for bottleneck effects is estimated.

With respect to the predictive performance of the RM2, we see that the adjusted R^2-values are reasonably high, and about 50% to 65% of the variations in the electricity price series are explained.

In Table 14, the relative predictive importance (RPI) of wind and temperature on electricity prices is summarized for the different zones (see Subsection 4.1 for details). The RPIs in this table make it evident that temperature has the best predictive power in all zones for electricity prices.

***Table 14.* RPI based on the "RM1."**

	β_1 (Wind)	β_2 (Temp.)
SE1	15%	85%
SE2	13%	88%
SE3	21%	79%
SE4	33%	67%

5.2.2 Summary results for the dynamic model

The RDI based on the DM - the model with the overall highest adjusted R^2-values, as well as wind and temperature effects on electricity prices, is summarized in Table 15.

Table 15. **RDI and price effects wind and temperature based on the DM.**

	RDI Wind (β_1)	RDI Temp. (β_2)	Price effect Wind	Price effect Temp.	RDI Wind (β_1^s)	RDI Temp. (β_2^s)	Price effect Wind	Price effect Temp.
SE1	86%	14%	-19.33	-3.20	56%	44%	-35.83	-28.20
SE2	85%	15%	-22.12	-3.81	50%	50%	-33.57	-33.57
SE3	86%	14%	-33.53	-5.47	55%	45%	-54.67	-44.30
SE4	80%	20%	-24.22	-6.14	56%	44%	-58.82	-45.95

Moreover, with respect to the estimates of dummy variables, we note that both the effects of nuclear power plant shutdown and bottleneck effects are absorbed (not being significantly estimated) in the lagged price variable. Hence, the only significantly estimated dummy variable is the one for weekend effects, as summarized for zones:

- Weekend effects in Zone 1, 2, 3, and 4 decrease electricity prices by 14 öre, 14 öre, 21 öre, and 28 öre, respectively.

Lastly, with respect to the predictive performance of the DM, we see that the adjusted R^2-values are high, and about 80% of the variations in the electricity price series are explained. This makes the model suitable for predictive purposes.

5.2.3 Summary results for the piecewise linear model

Summary results for the PWLM are shown in Table 11, with an overview of estimation results in Figures 5, 6, and 7. Quantitative monthly effects that wind and temperature have on electricity prices can be directly read from these figures and answers our last empirical question. Some notable qualitative findings are:

- There are months where wind and/or temperature do not have any significant impact. One exception is Zone 4, where wind has a significant impact on prices for all months.

- Temperature has a significant impact on prices from November to April or May for all zones, and also in August for Zone 1 and Zone 2.

- Wind has no significant impact on prices from November to March in Zone 1, from November to February in Zone 2, and from December to January in Zone 3.

- For Zone 3 and Zone 4, we note that wind has a significant effect on prices in September and October, and June, July, and August when temperature does not.

Lastly, the adjusted R^2-values are moderate, and the PWLM explains about 44% to 53% of the variations in the electricity price series. This model provides valuable information about how wind and temperature affect electricity prices on a monthly basis, and assumptions on stationarity and linearity are less likely to be violated, resulting in more accurate results. A caveat, though, is the relatively small number of time series observations used for estimation.

5.3 CONCLUDING REMARKS

In this project, we have examined the role that wind and temperature have in influencing Swedish electricity prices over the period from August 2022 to September 2023. The specific empirical questions that we have addressed are as follows: What effects do wind and temperature conditions exert on Swedish electricity prices? How significant are wind and temperature in predicting electricity prices? And what monthly effects do wind and temperature conditions manifest on Swedish electricity prices?

To explore these questions, several linear reference models have been employed to gain a better understanding of the role that wind and temperature serve in predicting electricity prices. Through formal testing, we also demonstrated that the time series of interest are not only subject to multiple breaks individually but also in their relationships. This implies that all linear models used are, at best, crude approximations to a time-varying behavior. As a simple remedy for these caveats, we also estimated a piecewise linear model. As the last candidate model, which has strong support from the data despite being linear, we employed a dynamic model where lagged prices are included as an explanatory variable.

Regarding our empirical questions and findings, we observed that, generally, wind has a greater driving importance in both a linear reference model and the dynamic model compared to temperature for all zones. If we consider standardized estimates, temperature exhibits stronger driving importance in a linear reference model, while in the dynamic model, wind remains the most crucial driver. It is important to note that these conclusions depend on the fact that wind supply constitutes "only" 20% of the total supply. Regarding the second empirical question, temperature has a significantly higher RPI than wind. When lagged prices are also incorporated, as in our dynamic model, it becomes the variable with the highest RPI. Our last empirical question is effectively addressed by the so-called wind and temperature impact profiles, where the monthly effects of wind and temperature on prices are presented.

Taking the predictive power of our models together, all models except the dynamic one explain about 50% of the variation in electricity prices. The dynamic model explains about 80%. The moderate predictive performance of the static models does not come as a surprise (admittedly, as several potentially important variables are omitted). In fact, wind and temperature reasonably account for variations in electricity prices.

It would be interesting to study the same empirical questions raised above using data over a much longer time period, starting from when wind power was introduced as a power source (around 1990). With such data, it would be possible to assess the gradual impact that wind has had over time on electricity prices. We also suggest that factors beyond wind and temperature influence electricity prices, such as unaccounted nuclear and hydroelectric data. German wind conditions notably impact Swedish prices, especially in Zone 4. Future studies should incorporate this data for a more comprehensive analysis. Moreover, while various time series models are employed, additional models like time-varying mean and conditional heteroscedasticity models could provide more insights, though they require longer time series. Multivariate models could also be beneficial, simultaneously considering factors from Sweden and neighboring countries, given their interconnected electricity price markets. This approach would raise new empirical questions for exploration. Hopefully, this can be the scope for further research.

WIND AND ELECTRICITY PRICES IN SWEDEN – A STATISTICAL ANALYSIS

The Swedish electricity prices have long shown a strong seasonal dependence, with high prices during winter months and low prices during summer months. With the significant expansion of wind power expected to take place in the coming decades, electricity prices are anticipated to become more volatile due to variations in wind conditions. This new pattern is expected to become more pronounced as the share of wind power in electricity production increases.

In this report, we investigate the impact of wind and temperature on electricity prices in the four zones SE1, SE2, SE3, and SE4 during the 2022–23 season using various time series models. Although electricity prices still exhibit a strong seasonal dependence, we observe overall that wind has a greater influence on electricity prices than temperature. This is despite the fact that wind power currently accounts for "only" 20% of the supply.

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