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RESIDENTIAL DEMAND FOR ELECTRICITY IN NORWAY: ESTIMATING PRICE ELASTICITIES BY INSTRUMENTAL VARIABLE (IV) REGRESSION

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Acknowledgment

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Furthermore, I am grateful to Nord Pool AS and Montel for granting access to the data used in this study.

This research was conducted with Python and cross-validated using STATA. Should there be a need for it, the corresponding Python scripts can be provided to enable the replication of my study. However, sharing the dataset utilized in this study is subject to approval from Nord Pool AS and Montel and will be carried out in accordance with their guidelines and policies.

Abstract

This study employs the IV-GMM model to analyze panel data from the five price areas of Norway, estimating short-term spot price elasticities across hourly, daily, weekly, and monthly intervals from 2021 to 2023.

The results reveal varying degrees of responsiveness to price changes across different intervals and price areas, with NO1 and NO2 exhibiting higher elasticity compared to NO3, NO4, and NO5. The monthly spot price elasticity of residential electricity consumption is estimated between -0.08 to -0.01(or a weighted average of 0.022).

Additionally, monthly purchase price elasticities are calculated, considering the government compensation scheme introduced in December 2021 and including the averages of other components of purchase price such as grid rent and taxes. The estimates derived for the monthly purchase price elasticity range between -0.822 to -0.022 (or a weighted average of 0.227).

Overall, the study confirms the inelastic nature of household electricity demand in Norway, with implications for policy formulation and energy efficiency strategies. While the compensation scheme enhances household welfare and reduces price disparities, it also introduces minor economic inefficiencies.

The study underscores the importance of regional variations in demand responsiveness and highlights the need for precise estimations to inform policy decisions accurately. The limitation of the study lies in the approximation-based calculations, suggesting avenues for future research to incorporate actual purchase prices for a more nuanced analysis.

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1 Introduction

Over the last two decades, Norwegian households have enjoyed stable and relatively low electricity prices compared to other Organization for Economic Cooperation and Development (OECD) countries (IEA, 2020). However, in recent years, high prices have been recorded which significantly affect household incomes and electricity consumption of households. Not only did we see a surge in prices but also there has been substantial price variations between southern Norway and the northern part of the country as shown in Figure 1. With concerns arising over the potential financial strain on affected households, there have been discussions in Norway and Europe at large regarding proposals for new policies aimed at regulating wholesale electricity prices. However, command and control policies like implementing a price cap are contentious, as they carry the risk of disrupting balancing market mechanisms and jeopardizing supply security (Norwegian Competition Authority, 2022). These record-breaking electricity prices prompted the Norwegian government to launch an electricity support scheme to reduce the burden of high electricity prices for Norwegian households. This policy is only regarded as a short-term measure with concerns over its fiscal sustainability over a prolonged period of high electricity prices. Renowned economist at the Inland Norway University of Applied Sciences, Professor Ole Gunnar Austvik, therefore advocates for the adoption of a more pragmatic policy such as strict regulation of water levels of hydropower producers and export tariffs as a long-term solution to shield domestic consumers from soaring electricity prices, even if the latter entails a potential breach of The European Economic Area (EEA)Agreement[1].

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[1] https://www.inn.no/english/research/research-news/an-active-energy-policy-is-necessary-now/

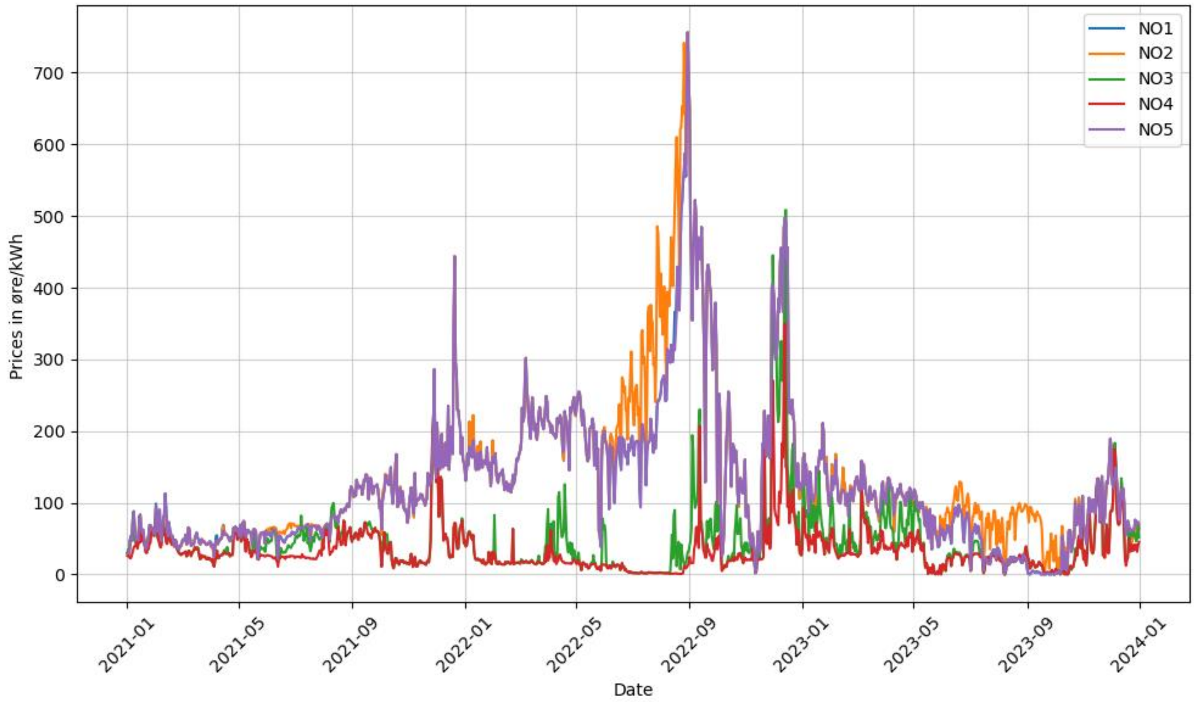

Figure 1: Average daily electricity spot price for price areas NO1 – NO5 in øre per kWh.

As seen in Figure 1, a record high electricity price was recorded in 2022 coupled with huge price variation between November 2021 and June 2023.

This situation has made it increasingly important for both policymakers and households to understand the dynamics of residential electricity demand. Understanding how demand responds to price shocks can offer valuable guidance for formulating optimal policies in the pursuit of a secure, affordable, and sustainable power supply, especially at this time the Norwegian population is expected to grow and urbanize to about 5.9 million in 2030 and further to 6.6 million by 2050 (NVE, 2018).

In academia, the concept of price elasticity of electricity demand is used to analyze the extent to which residential electricity consumers vary their electricity consumption when there are changes in electricity prices. This measures the percentage change in demand resulting from a percentage change in price. An elasticity of, for example, -0.5 implies that a 1% increase in price will result in a 0.5% fall in electricity demand other things being equal.

Several researchers have applied these estimates of elasticity globally to comprehend demand behaviour as well as to do additional tasks like predicting, policy analysis, and demand management.

Such estimates of elasticity are very important when planning pricing strategies because electricity costs should be appropriately set to reduce behavioural distortions and reflect their true costs. In this instance, where extremely high prices are recorded, current estimations of price elasticities for households in Norway would be much more valuable.

This study analyses the Norwegian household electricity demand response to high electricity spot prices. These shocks are directly associated with reduced precipitation levels in Southern Norway and elevated gas and coal prices in Europe (SSB, 2023c). These influencing factors, among others, contribute to the exogenous nature of the price increase. Hence, this is in line with Deaton's (2010) argument that ensuring the instrumental variable (IV) estimation's consistency requires the instrument to be orthogonal to the error term in the equation of interest. Consequently, I utilize the instrumental variable (IV) technique to estimate the spot price elasticity of hourly, daily, weekly, and monthly electricity demand for household consumers. The analysis covers the period from 2021 to 2023.

1.1 Significance and Objectives of the Study

Most previous studies in Norway were carried out during periods characterized by relatively low and stable electricity prices. In contrast, my research is conducted in a context where electricity prices in Norway have been notably high, particularly in the post-COVID era. The severity of the situation led the Norwegian government to implement an electricity support scheme aimed at easing the financial strain on households.

To the best of my knowledge, my research will be one of the first to investigate the economic impact of the government compensation scheme on household electricity demand in Norway. Also, compared to existing studies, this thesis uses more recent data that reflects the current demand behaviour of Norwegian households.

The main objectives of this research are:

1. *Estimate the spot price elasticity of electricity demand for the five price areas of Norway.*
2. *Compute an approximated monthly purchase price elasticity for the five price areas by taking into consideration the government compensation scheme*[2].
3. *Assess the economic implications of the government support scheme on market efficiency.*

In line with the objectives, the following research questions will be explored:

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[2] Note that the government compensation scheme is the same as the government support scheme and may be interchanged throughout the paper.

1. *What are the spot price elasticities of electricity demand in the five price areas of Norway? How do these elasticities vary across different regions?*
2. *How can the purchase price elasticities of electricity be approximated for the five price areas of Norway considering the government compensation scheme? What methodological approach can be used to incorporate the effects of this scheme into the elasticity calculations?*
3. *What are the economic implications of the government compensation scheme on market efficiency in the electricity sector of Norway? How does the scheme impact consumer behaviour and welfare, market pricing, and overall economic efficiency in the electricity market?*

1.2 Organization of the Study

The paper is organized into four main sections. Initially, in Chapter 2, I provide an overview of the Norwegian Electricity Market to set the research background. This is followed by a detailed literature review in Chapter 3, where I discuss the theoretical underpinnings and prior studies relevant to this research. Chapter 4 offers a description of the data used, including descriptive statistics. In Chapter 5, I introduce the analytical framework employed in the study. Chapter 6 details the findings from the IV-GMM regression model, presenting estimates of short-run spot price elasticities of electricity demand along with the algebraic derivation of approximated purchase price elasticities for each of the five price areas. Finally, Chapter 7 evaluates the implications of the government compensation scheme, compares the results of my estimates with previous literature, and discusses the validity of my study.

2 Overview of the Norwegian Electricity Market

This section covers the evolution of the Norwegian power market over the last four to five decades, the current structure and organization of the Norwegian power market, the production and consumption of electricity, the components of price contracts, and the price areas of Norway.

First, I briefly discuss how prices were determined before market deregulation. Next, I explain the 1991 deregulation and the new market-based price determination structure of Nord Pool. I then analyze the key attributes of the supply and demand sides of the Norwegian power market. Finally, I discuss the electricity price contracts available to residential consumers, justify my choice of price variable to be used, and then the price areas of Norway.

2.1 Price Determination before Deregulation

The Norwegian electricity market was regulated by political and government institutions for a long time. In 1971, Norwegian power producers founded a spot power exchange named Samkjøringen. However, the formalization of Samkjøringen dates to as early as 1931, marking the culmination of extensive years of collaboration and power exchange among various power plants. Preceding 1978/79, prices were determined by political institutions at various levels, intending to mirror the average cost of electricity production. Due to the low production costs in the hydropower industry, electricity prices remained notably low and stable. The supply side in most regions was predominantly controlled by a limited number of regional producers. In 1978/79, the average cost principle underwent a transition, but prices were still determined by government institutions. However, the prices were now tied to the cost of constructing new capacity. Over the ten years following 1978, the real price of electricity experienced an annual increase of approximately 3% (Bye and Hope, 2005).

Throughout the 1980s, multiple studies drew attention to the inefficiencies inherent in the existing system[3]. The primary objective behind the 1991 deregulation was to rectify these inefficiencies and more effectively manage the electricity and power sector of Norway.

2.2 The Deregulation of 1991

The deregulation of 1991 marked a significant and transformative shift in the electricity market. The authorities underwent a fundamental change in focus, shifting their primary objective to the establishment of an efficient electricity market. Competition was actively

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[3] See Bye and Strøm (2008) for a brief overview of these studies.

promoted, and prices were to be determined either on an exchange or through bilateral agreements between market participants. While government institutions retained ownership interests in electricity companies, these entities were required to function as private enterprises. Subsequently, many neighbouring countries (Sweden, Denmark, and Finland) also subscribed to this market.

2.3 Structure and Organization of the Power Exchange

Following the liberalization of the energy legislation in other Nordic countries, the Nord Pool spot power exchange, formerly known as Statnett Marked AS, was established in 1996. Nord Pool is the world's first power exchange and the world's first multinational power exchange where power could be traded across borders. Nord Pool plays a pivotal role in organizing a physical day-ahead market, intraday markets, regulating power services, and system services. The inception of forward market trades occurred in 1993. In 1996, Nord Pool orchestrated the merger of Norway and Sweden into a unified power market, followed by the inclusion of Finland and Denmark over the subsequent four years. Nord Pool is owned by Euronext (66%) and TSO Holding (34%) (Nord Pool).

In the discourse within the Norwegian media concerning the electricity market, the primary focus typically revolves around the day-ahead market at Nord Pool. This is a physical spot market where participants sell or buy energy for the next 24 hours in a closed auction. At 10:00 CET, the available capacities on interconnectors and within the grid are disclosed, allowing buyers and sellers until noon to submit their final bids to Nord Pool for the auction, covering delivery hours for the following day.

These submitted bids undergo matching with other bids in the pan-European market coupling process, known as the Single Day-Ahead Coupling (SDAC), facilitated by a common algorithm named Euphemia. During this matching process, a single price, referred to as the spot (wholesale) price, is established for each hour and each bidding zone, determined by the intersection of sell and buy price curves while considering network constraints. Typically, hourly clearing prices are announced to the market at 12:45 CET or later. After the price publication, individual results are communicated to each buyer and seller. The physical obligation to deliver or consume the purchased or sold energy is then initiated as Nord Pool nominates the trades to the imbalance settlement process applicable in each country (Nord Pool b). In intraday trading, wholesale prices adapt to the latest information on demand and supply (Nord Pool c).

Statnett assumes the role of the system operator (SO) and is responsible for building, operating, and maintaining the Norwegian power system. It is a state enterprise owned by the state at the Ministry of Oil and Energy. All bilateral deals must be reported to the SO. If the actual consumption or production deviates from predictions, or unforeseen line outages occur, the SO utilizes the clearing market at Nord Pool to rectify imbalances. Within this market, Statnett determines which entities will adjust their production or consumption to restore equilibrium, relying on pre-submitted price offers from physical producers and consumers. Major producers such as Statkraft might propose increasing their production by a GWh in a specific region at a specified cost if deemed necessary. Similarly, significant consumers may submit offers to decrease their consumption, provided they receive suitable compensation. The balanced market is thus relied upon to ensure production equals electricity consumption at every hour since electricity cannot be stored. When in balance, the Statnett system is at 50 Hz (Statnett, 2022).

2.4 Supply of Electricity

This section describes the generation or production of electricity in the Nordics that make up the Nord Pool production.

As indicated in section 2.3, the production of electricity at a given moment significantly shapes the market price of electricity. The implication is that the generation of electricity in neighbouring Nordic countries plays a crucial role in influencing the electricity market prices in Norway. Understanding these external factors is essential for grasping the dynamics of electricity pricing in Norway.

As seen in Figure 2, electricity production in Norway is highly dominated by hydropower. Hydropower accounts for most of the Norwegian power supply, and the resource base for production depends on the precipitation in a given year. This stands in stark contrast to the rest of Europe, where the security of supply primarily relies on thermal power plants with fuels available in energy markets. A distinctive aspect of the Norwegian hydropower system lies in its substantial storage capacity. Norway boasts half of Europe's reservoir storage capacity, and over 75% of its production capacity is flexible (Norway Reports, 2020). This flexibility allows for the swift and cost-effective adjustment of production, a crucial factor in maintaining a balance between production and consumption in the power system at all times.

The power supply in Norway had a total installed production capacity of 39,703 MW at the beginning of 2023. There are 1769 hydropower plants which generate about 88% of

Norwegian production capacity while 65 wind farms generate about 11% of the production capacity. The growing share of intermittent production technologies, such as wind and solar, makes it even more vital that there is flexibility available in the rest of the system. The share of wind in Norway's electricity system has increased tenfold in the last decade. In a normal year, the Norwegian power plants produce about 156 TWh.

In 2021, Norway set a new production record with a total power production of 157.1 TWh. However, in 2022, there were record low levels of water inflow to the reservoirs specifically Southern Norway, and the total power production was 146.1 TWh. Thus, production fluctuates based on inflow to the reservoir, reservoir level, and wind conditions. Later, I will discuss how these factors affect the supply and use them as instruments. It is worth noting that Norway has the highest share of electricity produced from renewable sources in Europe and the lowest emissions from the power sector (Energifaktanorge, 2023).

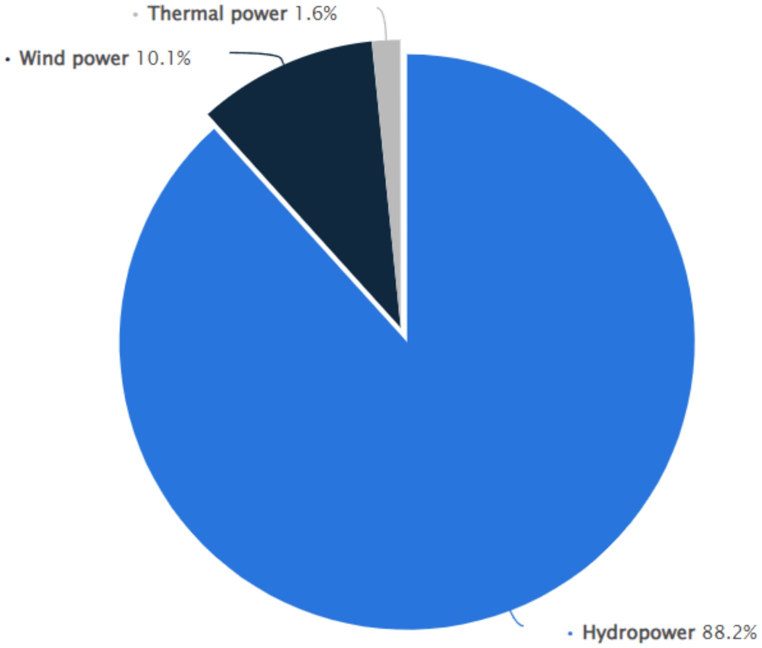

Figure 2: Distribution of electricity production in Norway, by source in 2023.

Source: SSB, 2023.

Electricity generation from other Nordic countries influences electricity prices in Norway through interconnectors and cross-border transmission into the grid. Sweden generates about 41% and 30% of its electricity from hydropower and nuclear power respectively. There has been a surge in electricity generated from wind power, about 19% and 5% from biofuels.

Sweden's electricity generation is almost independent of coal (0.4%) and oil (IEA, 2022).

More than half of Denmark's electricity generation comes from windmills. In 2022 wind power covered about 54% of the country's annual electricity production. Biofuels and coal generate about 17.9% and 12.7% respectively. Unlike Norway and Sweden, a fair share of electricity is generated with coal (IEA, 2022 b).

A third of the electricity generated in Finland is sourced from nuclear. Like Denmark, about 9% of electricity is produced from coal. Hydro, biofuels, and wind generate slightly more than half of Finland’s annual electricity (IEA, 2022 c).

Table 1: Electricity production in TWh from varying energy sources in the Nordic Area,2022.

Energy Source	Norway TWh	Sweden TWh	Denmark TWh	Finland TWh	Sum TWh	Share %
Hydropower	129.3	70.3		13.5	213.1	50
Wind power	14.8	33.1	18.9	12	78.8	18.5
Biofuels		9.4	6.3	11.9	27.6	6.5
Nuclear power		51.9		25.3	77.2	18.1
Coal	0.1	0.6	4.4	6.5	11.6	2.7
Waste	0.3	5.2	1.9	1.1	8.5	2
Solar PV	0.2	2	2.2	0.4	4.8	1.1
Natural gas	1	0.2	1	1	1	0.2
Oil		0.5	0.3	0.2	1	0.2
Others	0.4			0.2	0.6	0.14
Total Production	**146.1**	**173.2**	**35**	**72.1**	**426.4**	**100**

Source: IEA, 2022.

Table 1 shows that a large share of electricity generated in the Nordics is sourced from renewable sources mainly hydro and wind. As a result, there are seasonal effects on the supply side. Snow melting and rainfall create high inflow in the spring and over the summer relative to the winter when there is minimal inflow due to the freezing temperatures. The reservoir capacity, level, and inflow allow producers to transfer water from the high inflow periods of the spring and summer to the low inflow periods of the winter. Wind power is also intermittent and experiences high fluctuations in generation depending on the weather. It is important to mention that some thermal plants shut down in the summer months when there are no heating-degree days. Natural gas, oil, and coal make up a small percentage of electricity generated in the Nordic region, but increased prices of these technologies influence the pricing dynamics of Norway.

The main take-away is that even though the supply of electricity in Norway is dominated by hydropower, the import and export of electricity make other technologies such as natural gas and coal important in Norway as well. The price of coal, natural gas, and grid outages in other countries may cause shocks on the Norwegian supply side. Later on, I will test how the prices of natural gas and coal, carbon emission prices as well as reservoir level and inflow to reservoir influence electricity prices in Norway, and possibly use them as instruments.

2.5 Demand for Electricity

This section describes the sectoral consumption of energy in Norway. Subsequently, I will delve into a more detailed analysis of energy demand, specifically electricity demand associated with households.

2.5.1 Sectoral Energy Consumption[4].

Norway's total energy consumption in 2022 was 218 TWh. This represents a decrease of about 4% compared to that of 2021. That is a reduction of about 5.5 TWh less than in 2022.

The decrease is particularly noticeable in households, but energy consumption also decreased in industry and the service sector. This was largely observed in Southern Norway, where total electricity consumption decreased by more than 6.5 TWh. From Figure 3, Manufacturing and mining, and transport were the sectors that used the most energy in 2022, followed by households and others[5]. This pattern has not changed much since 1990 although total energy use has risen in this period. Residential energy demand decreased by about 10% in the same period.

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[4] Unless specified, all the information provided in this section is obtained from Statistics Norway, (SSB, 2022)

[5] Other include Commerce and Public Services, Agriculture and Fishing.

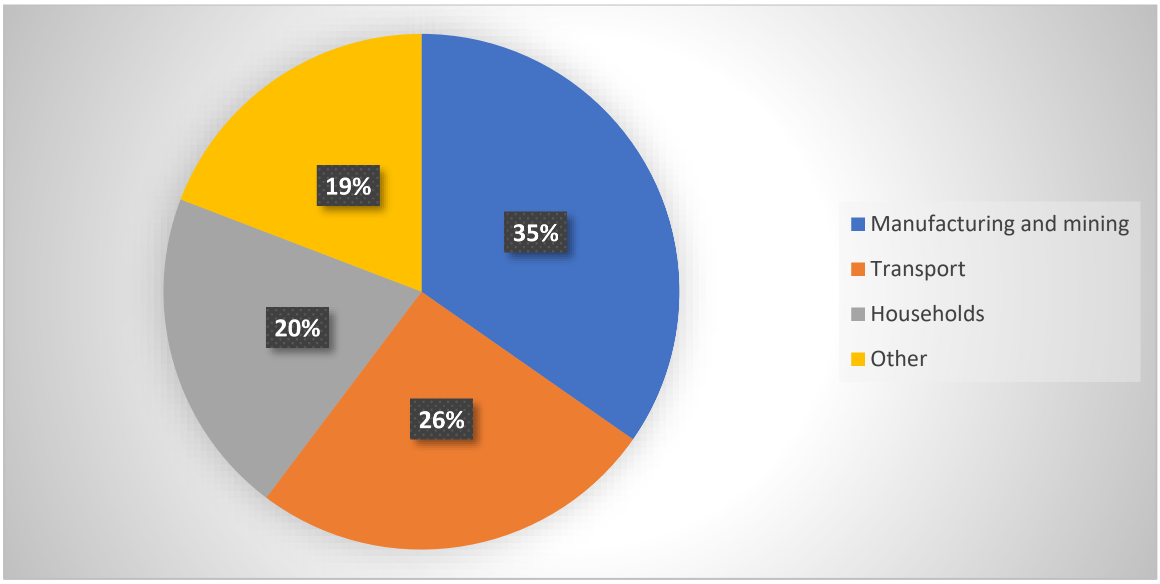

Figure 3: Energy consumption by sector in Norway, 2022. Source: SSB, 2022.

As seen in Figure 4, electricity is the primary energy source, with petroleum products following closely behind (energifaktanorge, 2020). The dominance of electricity is evident in manufacturing, households, and service industries. On the other hand, sectors related to transportation and machinery rely heavily on petroleum products. Although district heating and natural gas currently represent a relatively small portion of overall energy consumption, their usage has been on the rise in recent years. Notably, district heating has experienced increased adoption in service industries and households, while the utilization of gas has grown in manufacturing industries and the transportation sector. These alternative energy carriers are progressively supplanting fuel oil for heating and replacing coal, coke, and heavier petroleum products in various industrial processes.

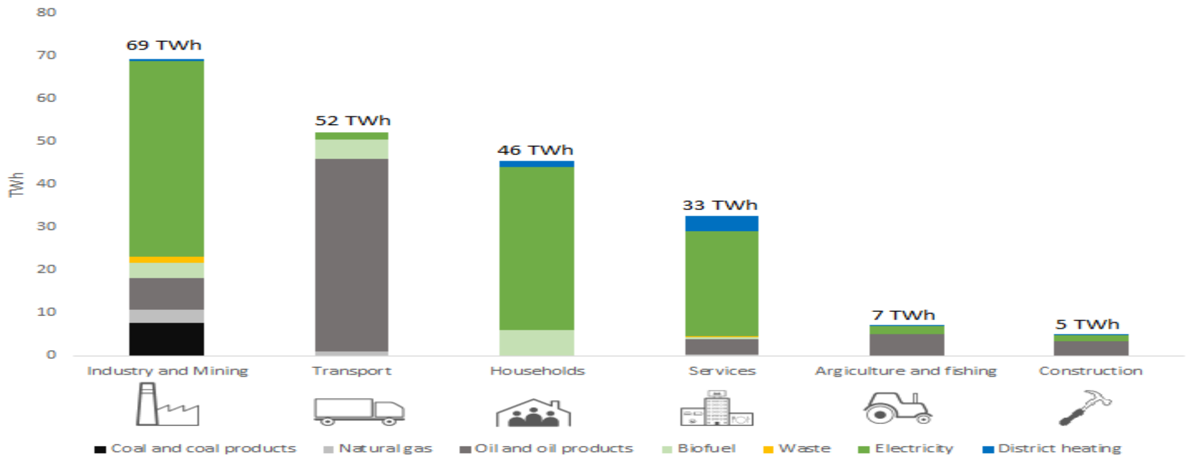

Figure 4: Final energy consumption in Norway split by energy carrier. Total in 2020: 211 TWh. Source: energifaktanorge, 2020.

2.5.2 Residential Electricity Consumption[6].

Electricity makes up the largest share of energy used by Norwegian households. Nesbakken (1999) asserts that electricity contributes over 70% of energy used by households. However, there are limited alternative energy sources available for substitution, especially during the cold winter period. According to the IEA (2021), approximately 83% of household energy consumption is attributed to electricity, with district heating and biofuels (primarily fuelwood) and waste comprising around 4% and 13%, respectively.

Following the outbreak of the pandemic in 2020, there was a surge in household electricity consumption, likely attributed to a higher number of individuals staying at home due to the implementation of infection prevention measures. During that period, a significant portion of the population had both homeschooling and home office setups. Household consumption in 2021 was similar to that of 2020 figures.

However, household electricity consumption in Norway decreased in 2022 compared to 2020 and 2021. The decline in household consumption is noticeable in the pricing areas of southern Norway, specifically in NO1, NO2, and NO5.

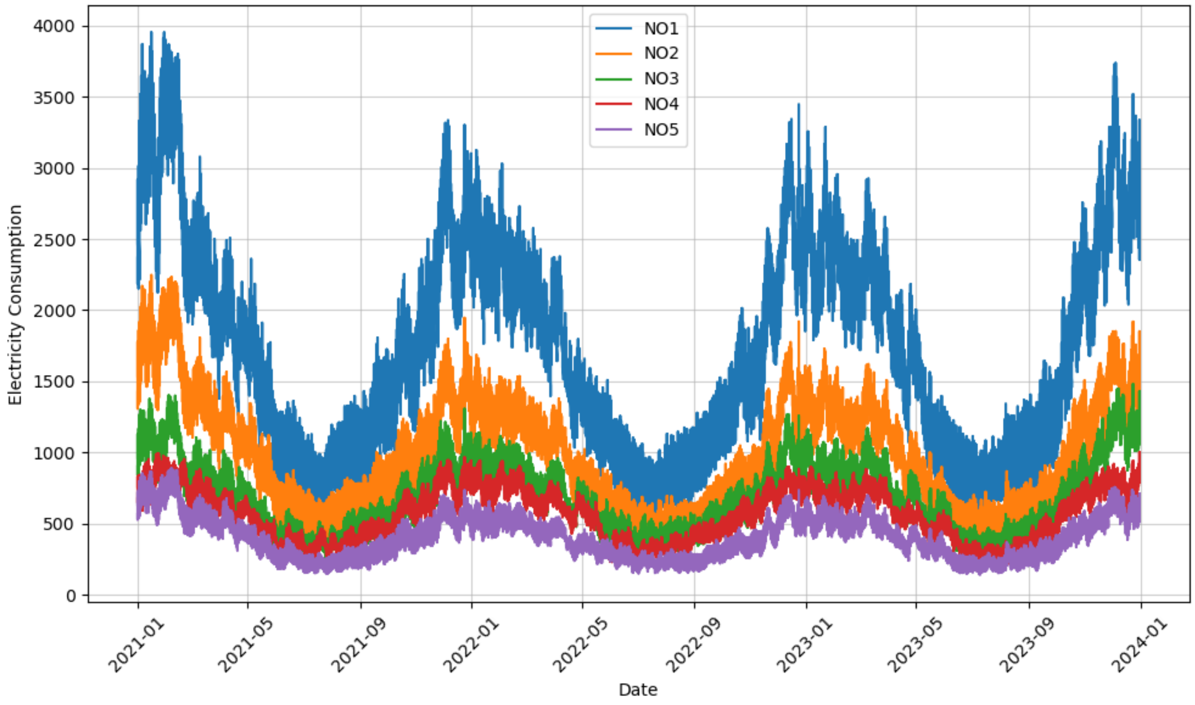

Figure 5: Hourly consumption for price areas NO1 – NO5 in volume per kWh.

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[6] Unless specified, all the information provided in this section is obtained from Statistics Norway, (SSB, 2021)

Figure 5 demonstrates that patterns of seasonality are evident in residential electricity consumption. During the dark and cold Norwegian winters, electricity usage, primarily for heating and lighting purposes, roughly doubles or triples. The winter season allows for more flexibility, given that most households have wood technologies.

2.6 Price Zones and Price Contracts

This section describes the price areas of Norway and also the various price contracts available to household consumers to choose from. I then explain the choice of price contract that is adopted for my analysis.

2.6.1 Price Zones

The 1990s saw the deregulation of the power markets, which increased national energy markets' integration and resulted in the creation of the modern, interconnected European power network. As a result, Norway's electricity exchange with its neighbours has increased over time. The goal of this integration process has been to balance supply surpluses and deficits across borders, maximize the efficiency of power-producing capacity, and maintain the stability of national power networks (The Norwegian Government, 2016).

Nord Pool determines area prices subject to grid congestion. These prices establish an equilibrium between purchase and sales bids from participants in various bidding zones across the Nordic region. As seen in Figure 6, Norway has had five bidding zones in recent years, but the existence of bidding zones doesn't automatically result in different area prices. When the Nordic power grid faces no capacity constraints, area prices are uniform throughout the region (i.e. including Sweden, Denmark, and Finland), aligning with the system price.

The differences in prices stem from areas experiencing power surpluses while others face a deficit. In areas with a power deficit, electricity must be imported, whereas in areas with a surplus export power. Grid congestion arises when the grid lacks the capacity to facilitate necessary power imports and exports. Consequently, area prices are higher in regions with a power deficit compared to those with a surplus. This price difference prompts power flows from low-price areas to high-price areas, effectively enhancing the power supply where demand is most critical.

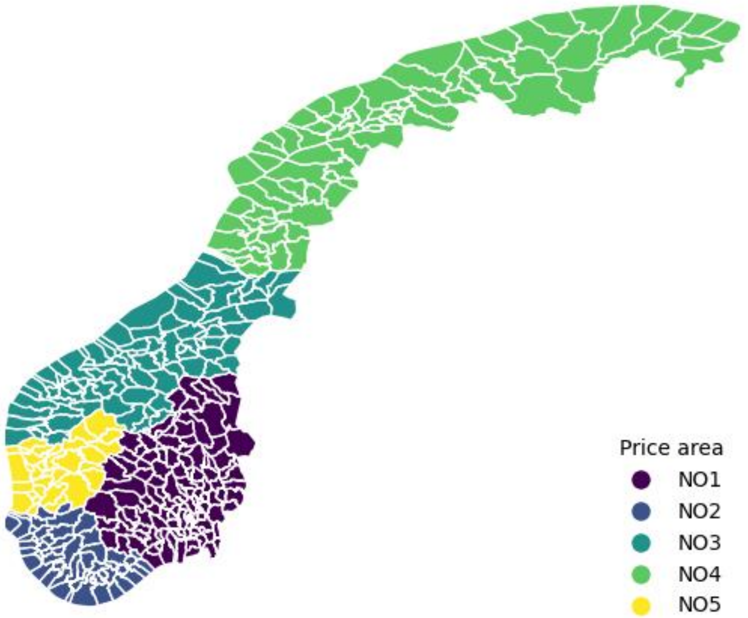

Figure 6: Map showing price areas (zones) of the Norwegian electricity market.

Source: Statnett, 2022.

2.6.2 Price Contracts

Norwegian households have a range of electricity price contract options to consider, broadly falling into fixed price contracts, spot price contracts, and variable price contracts. Among the fixed price contracts are the new one-year or shorter-term contracts, priced at 36.9 øre/kWh, the extended duration contracts with a cost of 48.2 øre/kWh, and the older fixed-price contracts available at 51.6 øre/kWh (SSB, 2023c). Some electricity providers have recently halted the introduction of new fixed-price contracts, citing uncertainties about future electricity prices. The remaining fixed-price contracts accessible to households are contingent on their specific spot price area assignments. Currently, only around 3.3% of Norwegian households opt for fixed price contracts.

Approximately 4.2% of households have opted for variable price contracts, which, during the third quarter of 2023, marked the highest-cost electricity contracts for households. Under the variable price contract, the price you pay for electricity varies in accordance with electricity market spot price changes. Those with variable contracts paid an average of 109.8 øre per kWh consumed, excluding taxes and grid rent—almost three times higher than the average price for spot price contracts (SSB, 2023c). Electricity suppliers must inform consumers about any impending price changes at least two weeks prior, indicating that the price remains fixed for fourteen days.

The prevalent contract choice among Norwegian households is the spot price contract, as shown by Figure 7. Statistics released by Norway's National Bureau for Statistics indicate that approximately 92% of all household electricity contracts were linked to the spot price in the third quarter of 2023 (SSB, 2023b). As outlined in section 2.3, the spot market price is established through the interplay of demand and supply for electricity among participants in the Nordic Power exchange for the following day. The pricing and volume are influenced by various market factors, with transactions occurring between different bidding zones. In addition to the spot market price, the customers pay a mark-up price.

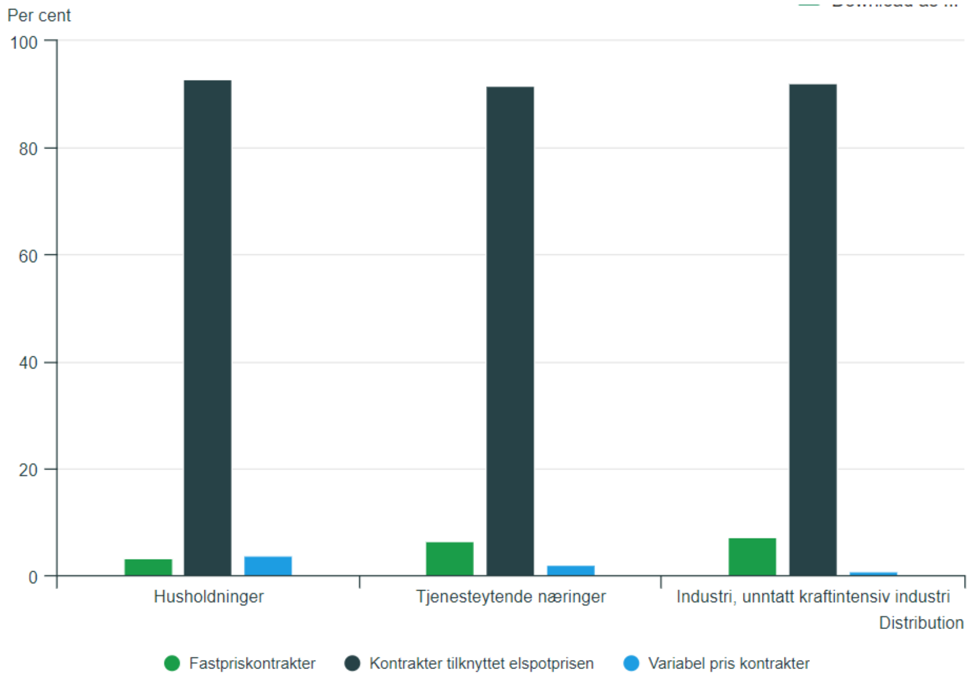

Figure 7: Distribution of price contract types for the third quarter of 2023.

Source: SSB, 2023b.

From 2000 onward, the electricity costs for Norwegian households have progressively relied more on concurrent spot prices (SSB, 2015). Other components to electricity bills such as grid rent to the local network operators, taxes, and fees have fairly been constant as seen in Figure 8. Even though the spot price is not the only component of the price household consumers pay for electricity (purchase price), it is the main source for purchase price variation.

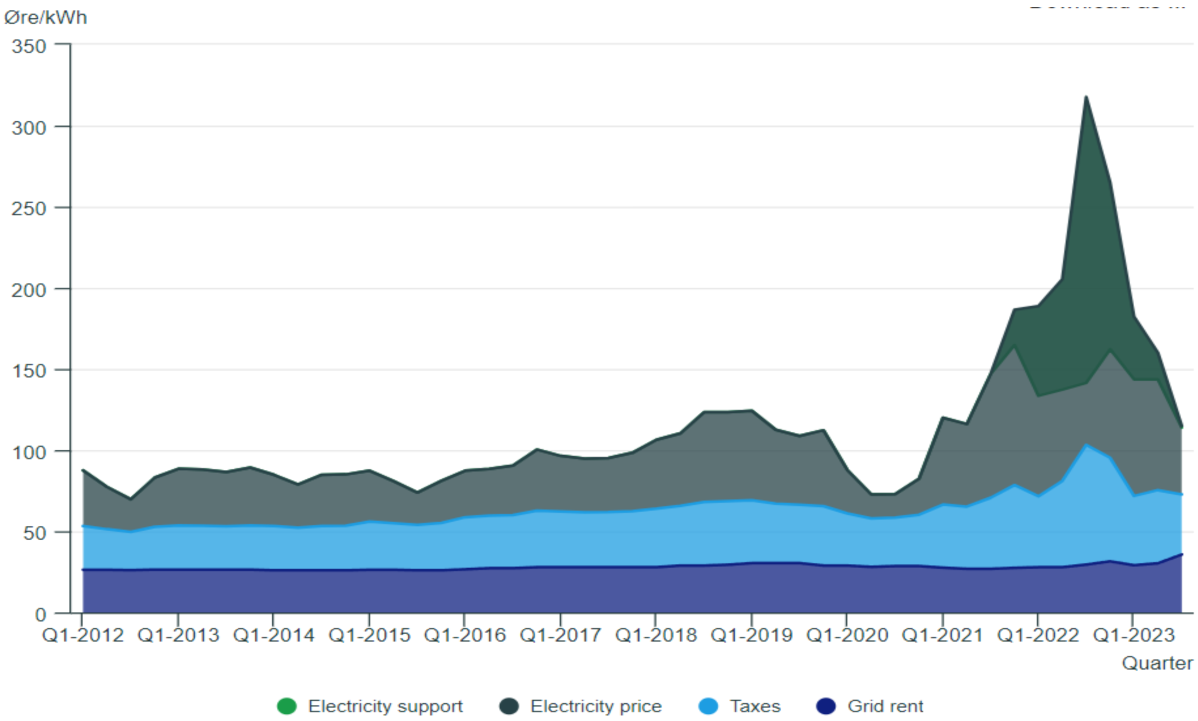

Figure 8: Electricity prices, grid rent, and taxes for households in Øre/kWh.

Source: SSB, 2023b.

In summary, this suggests that fluctuations in spot prices are immediately mirrored in the costs that the majority of households incur for their electricity consumption. Given the higher prevalence of Norwegian households opting for the spot price and the significant impact of spot prices on purchase price fluctuations, I employ this price as my endogenous variable in my analysis.

2.7 Electricity Support Scheme

In response to the exceptionally high electricity prices, the Norwegian government implemented a policy in December 2021 aimed at temporarily assisting households with their electricity expenses, known as the *Strømstøtteordningen*. Under this initiative, households receive compensation for the portion of the average monthly spot price paid that exceeds a cap of 70 øre per kWh for all consumption up to 5000 kWh per month (including VAT). For December 2021, the support covered 55% of the excess-cap expenditure, and from January 2022 to August 2023, the coverage rate was increased to 80%.

Conversely, during the third quarter of 2023, electricity spot prices witnessed a sharp decline. The average household electricity price, exclusive of taxes, grid rent, and electricity support, stood at 42.2 øre/kWh on average (SSB, 2023b). This represents an 80% decrease compared to the third quarter of 2022 when Norway faced record-high electricity prices amid the energy crisis in Europe. This informed the government to alter the support scheme from a monthly to an hourly spot price basis. The state therefore compensated for a share of the additional expenses in the hours where the area price is above 73 øre/kWh, instead of the 70 øre/kWh used previously. Also, the coverage rate was changed from 80% to 90% (NVE, 2023). It is worth mentioning that the average deduction for electricity support for households in the third quarter was a mere 1 øre/kWh, a significant drop from the 16.5 øre/kWh recorded in the previous quarter. The highest amount of electricity support disbursed to households occurred in the third quarter of 2021, with average support totalling 176.1 øre/kWh. The substantial decrease in electricity support in 2023 is attributed to a significant fall in the electricity market price, plummeting below 70 øre/kWh across all price areas except South-West Norway (NO5) in the third quarter (SSB, 2023b).

This policy of compensating households inevitably weakens the demand response typically linked to elevated electricity prices. Average household data for the year 2022 indicates that a significant portion of the impact of the spot price shock was mitigated by the support scheme, despite average purchase prices still rising by 32% compared to the previous five years (SSB 2023c).

Consequently, I categorize the spot price variable based on the compensation scheme. The period without compensation extends from January 1, 2021, to November 30, 2021, while the period with compensation or government support spans from December 1, 2021, to December 31, 2023. This categorization will be relied upon when estimating the purchase price elasticity of demand and discussing the economic implications of the scheme.

3 Literature Review

In this section, the pertinent literature both within Norway and internationally are explored. Initially, I discuss international studies, which extensively employ the Generalized Method of Moments (GMM) estimation techniques to address static and dynamic models, along with the ongoing discourse regarding marginal versus average prices. Following this, the discussion shifts to literature specifically conducted in Norway and finishes by discussing literature on energy (electricity) consumption subsidies.

3.1 GMM, Static vs Dynamic, Marginal vs Average Prices

Various scholars have employed the Generalized Method of Moments (GMM) to estimate both short-run and long-run price elasticities, especially when dealing with demand specification concerns.

The choice of demand specification has been a major source of controversy in recent studies. Different researchers have adopted different approaches from static to dynamic models for electricity demand. Unlike static models of demand, dynamic models incorporate past consumption and decisions to forecast future demand, recognizing the temporal interdependence in consumption choices. Espey and Espey (2004) find dynamic models to estimate smaller values for price elasticities than static models.

A potential issue with dynamic models is the possibility of a correlation between lagged dependent (consumption) variables and the error term. Alberini and Filippini (2011) state that the lagged consumption term on the right-hand side of the demand equation is endogenous, resulting in potentially inconsistent estimates of the long-run price elasticity of demand. Hence a partial adjustment model, which is more robust against dynamic panel bias and measurement errors is often adopted (Liu, 2004; Csereklyei, 2020; Cialani and Mortazavi, 2018).

Liu (2004) estimates the price and income elasticities of several energy goods in OECD countries from 1978 to 1999 by applying the one-step GMM estimation method suggested by Arellano and Bond (1991) to a panel data set, specifying energy demand by a simple partial adjustment model. He finds that the estimates yielded lower values for price elasticities compared to the results from earlier studies.

Cialani and Mortazavi (2018) employ panel data for 29 European countries from 1995 to 2015, to estimate price elasticities for residential and industrial electricity demand using both

GMM and ML (maximum likelihood) approaches. They find electricity demand in both sectors to be highly price and income-inelastic in the short run.

Csereklyei (2020) employs both instrumental variable models using the between estimator, as well as dynamic panel models to examine the short- and long-run price and income elasticities of residential and industrial electricity demand in the European Union between 1996 and 2016. She finds results similar to that of Cialani and Mortazavi (2018).

While economists contend that consumers should react to marginal prices, as these prices accurately reflect the real costs of their consumption decisions, there is an ongoing debate about whether consumers actually respond to marginal prices or average prices (Espey and Espey 2004; Alberini and Filippini, 2011; Bohi, 2011; Krishnamurthya and Kriströmb, 2013; Fell et al., 2014).

Using a national-level demand estimation from publicly available expenditure data and utility-level consumption data in the U.S., Fell et al. (2014) used GMM to estimate a price elasticity near -1 for household electricity demand in the U.S., suggesting that consumers are more likely to respond to average prices.

Krishnamurthya and Kriströmb (2013) use data for annual consumption of electricity and sample-derived average electricity price to estimate price and income elasticity for 11 OECD countries. They find evidence for non-price related factors to significantly affect energy demand strong price responsiveness, with elasticities varying between −0.27 and −1.

Espey and Espey (2004) find that short-run price elasticity estimates derived from marginal prices tend to be lower than those obtained when average prices are used as the regressor.

Bohi (2011), after reviewing various studies, concludes that marginal prices are generally more effective when compared to average prices, especially considering the inconsistent findings on whether average prices provide a suitable alternative.

Nonetheless, Alberini and Filippini (2011) posit that average prices are frequently used because they are often the only prices available to households since block marginal prices are not available. Alberini and Filippini (2011) cited Shin (1985), who initially highlighted the issue in the economic debate, stating that households respond to the average price because it is easily calculated from the electricity bill, rather than actual block marginal price, which is costly to determine. There is still the need for further research to provide additional insights into the issue.

3.2 Research on Residential Electricity Demand in Norway

Following the deregulation in 1991, numerous researchers have explored the Norwegian electricity markets. These studies exhibit variations in methodology and differences in the periods under examination. Consequently, it is intriguing to compare these findings and analyze how the methodological and temporal disparities contribute to divergent results.

Nesbakken (1999) and Halvorsen and Larsen (2000) explored the relationship between the stock of heating or household appliances and energy consumption.

Nesbakken (1999) examines the connection between the choice of heating equipment and residential energy consumption, with a particular focus on the income and energy price variables. Stability over time is assessed by applying the model to microdata for the years 1993 to 1995. Utilizing data from the annual consumer expenditure survey between 1976 and 1993, Halvorsen and Larsen (2000) delve into the factors contributing to the growth in Norwegian residential electricity demand during this period. Roughly half of the growth is attributed to an increase in the number of households, while the remainder is linked to a rise in average consumption per household. The elevated average consumption is linked to a surge in households owning electric appliances like dryers and dishwashers, an uptick in real disposable household income, and an expansion in the floor space of dwellings.

While many previous studies in and outside of Norway use purchase prices or consumer expenditure survey data for estimating elasticities, Johnsen (2001), and Bye and Hansen (2008) are among the few that base their research on electricity spot prices. In their 2008 study, Bye and Hansen (2008) examine the impact of Nord Pool's electricity spot prices on the aggregate demand for electricity in Norway and Sweden over both short- and long-term periods. Employing a simultaneous supply and demand model approach and utilizing data from 2000 to 2004, they discovered that price elasticities are lower during nights and weekends compared to days and midweeks. The direct spot price elasticity is generally zero during the summer and −0.02 in the winter, measured as a weighted average over the week. These estimates also remain fairly robust when considering demand responses to different lags.

Leveraging weekly data from 1994 to 1995, with 1996 data as a post-sample examination, Johnsen (2001) effectively captures the variations in electricity generation, demand, and price, especially influenced by unexpected inflow, snow conditions, and temperatures. He observes that 90 percent of the observed variation in the first difference for electricity demand can be explained by factors such as price, temperature, and day length.

Hofmann and Lindberg (2019) investigated how the electricity demand in the main Norwegian metropolitan area of Oslo responds to variable electricity prices and if it contributes to lower peak demand for electricity. They applied a general linear model to estimate the short-term price elasticity from a historical data set, and their results show that no price elasticity exists on the coldest days, and on days with the highest peak demand for electricity. Price elasticity was however significant in some other periods, with estimates between -0.011 and -0.075.

3.3 Electricity Consumption Subsidies

There is no universally accepted definition of subsidies, owing to the varied forms in which products and services can be subsidized. However, the Global Subsidies Initiative (GSI) defines a subsidy as any form of preferential treatment granted to consumers or producers by a government (Kitson et al., 2011). Thus, the government compensation scheme is a form of preferential treatment provided to household electricity consumers by the government since the industrial sector was excluded. This support may distort market efficiency (Charap et al., 2013; Burke and Kurniawati, 2017; Pineau and Rafizadeh, 2020). Energy consumption subsidies commonly occur through price controls or are typically greater in countries where the energy sector is state-owned[7]. Hence, there is limited literature on energy consumption subsidies in the liberalized markets of Europe. It is worth noting that Norway implemented the policy as a temporary measure.

Charap et al. (2013) analyze a panel of cross-country data to assess the implications of energy subsidy reform. They find that short-term gains from subsidy reform are likely to be much smaller suggesting the need for either a gradual approach to subsidy reform or for more generous safety nets in the short term. They estimate a long-term price elasticity of energy demand between -0.3 and -0.5, which suggests that countries can reap significant long-term benefits from the reform of energy subsidies.

A study by Burke and Kurniawati (2017) in Indonesia from 1992 to 2015 revealed that subsidy reductions since 2013 had induced savings in annual electricity use of around 7% relative to the no-reform counterfactual as of 2015. They suggest that eliminating the remaining subsidies could further enhance the efficiency of electricity usage and free up resources for other critical areas, such as infrastructure investment.

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[7] For more information, see https://www.iisd.org/gsi/.

Pineau and Rafizadeh (2020) investigate the welfare loss created by subsidies in the global electricity markets employing data from 2016 on electricity consumption by country.

They found that electricity subsidies were the largest component of the total global energy subsidies, with an estimated 128 billion USD out of 287 billion USD. The total annual deadweight loss worldwide and the environmental costs of electricity consumption in 2016 were 12.4 billion USD and at least 652.8 billion USD respectively, making up about 700 billion USD in total annual costs in the global electricity markets.

With limited research on electricity consumption subsidies among EU and OECD countries, the Norwegian government support scheme provides researchers with the opportunity to assess the economic and environmental implications of subsidies.

Table 2: Summary of Author’s Literature Review.

Study	**Sample**	**Study Period**	**Product**	**Price Elasticity**
Alberini and Filippini (2011)	48 states of the USA	1995-2007	Electricity	Short-term: From -0.08 to -0.15 Long-term: From -0.45 to -0.75
Burke and Abayasekara (2018)	48 states of the USA	2003-2015	Electricity	Short-term: -0.01 Long-term: close to -1
Bye and Hansen (2008)	Norwegian and Swedish electricity market	2000-2004	Electricity	Summer: 0 Winter: -0.02
Charap et al (2013)	66 Countries	2002–2010	Fuels	Long-term: From -0.3 to -0.5
Cialani and Mortazavi (2018)	29 European countries	1995–2015	Electricity	Short-term: From -0.041 to -0.044 Long-term: From -0.189 to -0.302
Cssereklyei (2020)	European Union	1996-2016	Electricity	Short-term: From -0.07 to -0.08 Long-term: From -0.53 to -0.56
Fell, H., et al. (2014)	US Household	2006-2008		Long-term: close to -1
Halvorsen and Larsen (2000)	Norwegian Household	1975-1994	Electricity	From -0.4 to -0.8

Johnsen (2001)	Norwegian electricity market	1994-1995	Electricity	Long-term: From -0.05 to -0.35
Nesbakken (1999)	Norwegian Household	1993-1995	Fuels, Electricity	Short-term: -0.53

4 Data and Descriptive Statistics

This section discusses the assortment of data necessary for analysis, and their sources and elucidates the rationale behind the selection of variables to be included.

I gathered secondary historical data from diverse sources, encompassing electricity prices and household consumption across the five distinct price areas of Norway, as well as recorded city temperatures corresponding to each price area. Additionally, I obtained data on reservoir filling levels, inflow rates to reservoirs, carbon spot prices, gas prices, and coal prices. The dataset consists of time series data for each price area, with hourly observations spanning from January 1, 2021, to December 31, 2023, totalling 26,280 observations after compiling them into a single data file.

This dataset is comprehensive, containing observations for all variables across the different price areas. For the analysis of household price elasticity of electricity demand, I will employ an instrumental variable (IV) regression approach, so I have categorized potential variables into four groups based on IV characteristics. A brief discussion of the economic rationale for their potential influence is included. The dependent variable, also known as the response variable or outcome variable, is the variable that is being studied and measured. Endogenous variables are those likely to affect both the supply and demand of electricity simultaneously. Instrumental variables exclusively influence supply and are uncorrelated with the demand side. Exogenous explanatory (control) variables serve as control variables that only impact the demand side (see details in Appendix 1).

4.1 Dependent Variable

4.1.1 Household Electricity Consumption.

Aggregate electricity consumption data is retrieved from *Elhub*[8] which is a subsidiary of *Statnett* the System Operator (SO) Of the Norwegian Power System. The consumption data is organized based on the price area, and consumer groups following the Standard Industrial Classification (SIC 2007)[9]. The study specifically focuses on the variable labelled "Husholdning" (residential housing). Consumption volumes are quantified in kilowatts and are reported for each hour (kWh).

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[8] https://elhub.no/data/apnedata/#consumption_per_group_mba_hour

[9] Details of classification can be found here: https://www.ssb.no/en/klass/klassifikasjoner/6/koder.

Table 3: Average hourly electricity consumption, NO1-NO5 in volume per kWh.

Year	NO1	NO2	NO3	NO4	NO5
2021	1830902 (804453.8)	1069678 (440787.9)	692055.4 (264785.9)	578629 (189037.7)	429695.5 (169572.3)
2022	1581510 (643941.9)	898275.8 (332729.4)	657352.2 (214426.4)	557142.7 (176246.4)	376023.2 (126814.3)
2023	1731502.4 (724345.6)	972258 (365031.6)	704244.5 (268851.6)	562617.3 (183685.8)	399898.7 (141453)

Table 3 presents a summary of average hourly electricity consumption by households along with their corresponding standard deviations in parentheses for the years considered. Notably, household electricity consumption witnessed a decline across all price areas in 2022, with particularly noteworthy decreases observed in NO1 and NO2.

Household electricity demand fell by 14%, 16%, and 13% in the southern price areas of NO1, NO2 and NO5 respectively while the decline in the northern price areas of NO3 and NO4 were 5% and 4% respectively.

4.2 Endogenous Variable

4.2.1 Electricity Price

Electricity prices provide long-term investment signals and play an important part in the short-term balancing of supply, demand, and transmission. Electricity price data is downloaded from the Nord Pool[10] exchange ftp-server which contains hourly observations of the electricity spot price for each price area in Norway, measured in euros per megawatt hour (€/ MWh). I converted the spot prices into Norwegian currency using historical exchange rate data published by Norges Bank (Norges Bank, 2024).

Table 3 presents data summarizing the average hourly spot prices (in øre per kWh) and their corresponding standard deviations for two distinct periods: *the period without compensation* (January 1, 2021 to November 30, 2021) and *the period with compensation* (December 1, 2021 to December 31, 2023).

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[10] ftp://nordpool.com.

Table 4: Average hourly electricity consumption in NO1-NO5 in øre per kWh during periods of *no compensation* and *compensation*.

Peroid	NO1	NO2	NO3	NO4	NO5
No compensation *01.01.2021-30.11.21*	74.981 (36.46)	75.499 (35.58)	45.091 (28.66)	37.537 (27.44)	74.902 (36.16)
Compensation *01.12.2021-31.12.23*	150.817 (119.01)	167.968 (128.78)	47.077 (60.36)	32.734 (40.54)	150.583 (118.27)

As observed in Table 4, the average hourly spot prices in the Southern price areas have demonstrably risen and exhibited greater volatility compared to spot prices in the Northern price areas during both periods without compensation and with compensation. The elevated average prices in the southern price areas during the *period* of *no compensation* can be attributed to the divergence of electricity prices in those areas from the northern price areas starting from early August 2021 even before the government support was introduced.

4.3 Exogenous Explanatory (Control) Variable

4.3.1 Temperature Data.

Nesbakken (1999), Johnsen (2001), and Bye and Hansen (2008) assert that temperature is the most important driving force influencing electricity demand. Electricity is primarily used by households for heating purposes in Norway. As a result, low outdoor temperatures increase the electricity consumption in households for a comfortable indoor temperature, and thus the demand for heating services. I retrieved the temperature data from the weather stations of selected cities in each price area from the Norwegian Centre for Climate Services[11]. Specifically, I obtained the mean daily temperatures for Hovin, Kjevik, Trondheim–Voll, Tromsø, and Bergen – Florida for NO1, NO2, NO3, NO4, and NO5 respectively. The temperature is recorded in degrees Celsius (°C). The daily mean temperatures are converted to heating degrees days (HDD) by subtracting the daily mean temperatures from a base temperature of 17 degrees Celsius. Norwegian households barely use electricity for cooling purposes so daily mean temperatures that exceeded 17 degrees Celsius were set to zero. That is, there are no cooling degree days (CDD). The heating degrees days variables for each city

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[11] https://seklima.met.no

were converted to an hourly time resolution, and the observation was extended to cover all hours within the day by forward filling.

The selection of weather stations was based on their proximity to city centres, their size, and population. The chosen weather stations - Hovin, Kjevik, Trondheim–Voll, Tromsø, and Bergen – Florida - are situated near the city centres of Oslo, Kristiansand, Trondheim, Tromsø, and Bergen respectively. This proximity ensures that they can adequately capture any potential variations in electricity consumption resulting from temperature changes.

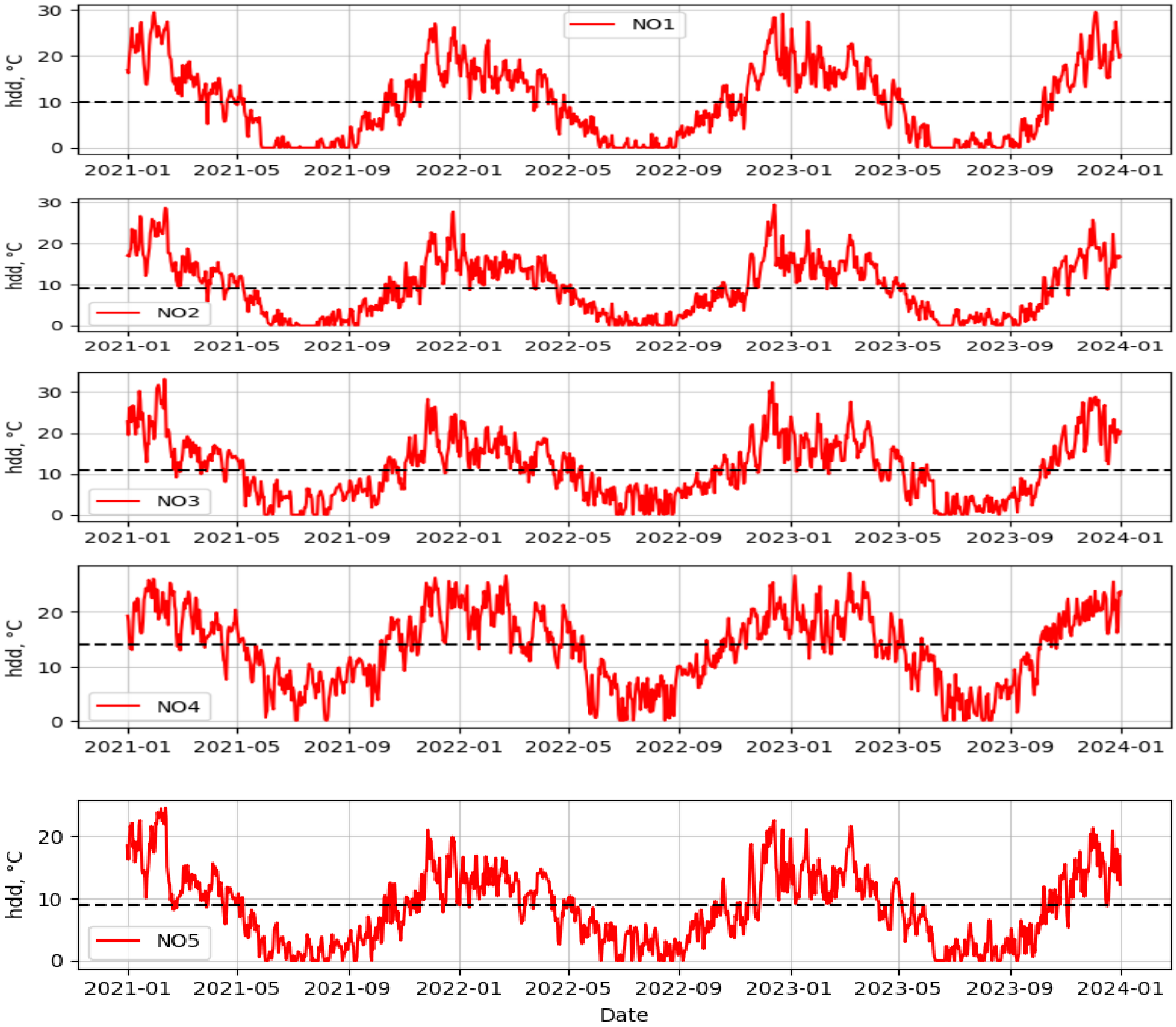

Figure 9: Temperature in heating degree days for NO1-NO5. Temperature mirrors the household electricity consumption.

4.4 Instrumental Variables

4.4.1 Reservoir Levels.

In a nation like Norway, which is heavily reliant on hydropower, the reservoir filling holds paramount importance in maintaining stable and cost-effective electricity prices. Reservoir levels play a pivotal role for power producers, influencing decisions on water valuation, electricity generation, and acting as a key indicator of electricity availability. Hydropower producers seek to maximize the net present value of their reservoir filling, underlining its significance in electricity production. I use data sourced from Norway's Directorate of Water Resources and Energy (NVE)[12] as an instrument for the spot price variable. Deviation from the historical median reservoir level for the past twenty years is employed since it is likely to be exogenous. These reservoir levels are observed weekly, typically at 24:00 on Sunday evenings, or through the nearest available measurement within 48 hours (NVE, 2019). I adjusted the frequency of reservoir filling to hourly observations and used linear interpolation to fill in missing data for hours with corresponding reservoir content from the respective week. The reservoir capacity remained stable over the sample period and is approximately 87.3 TWh.

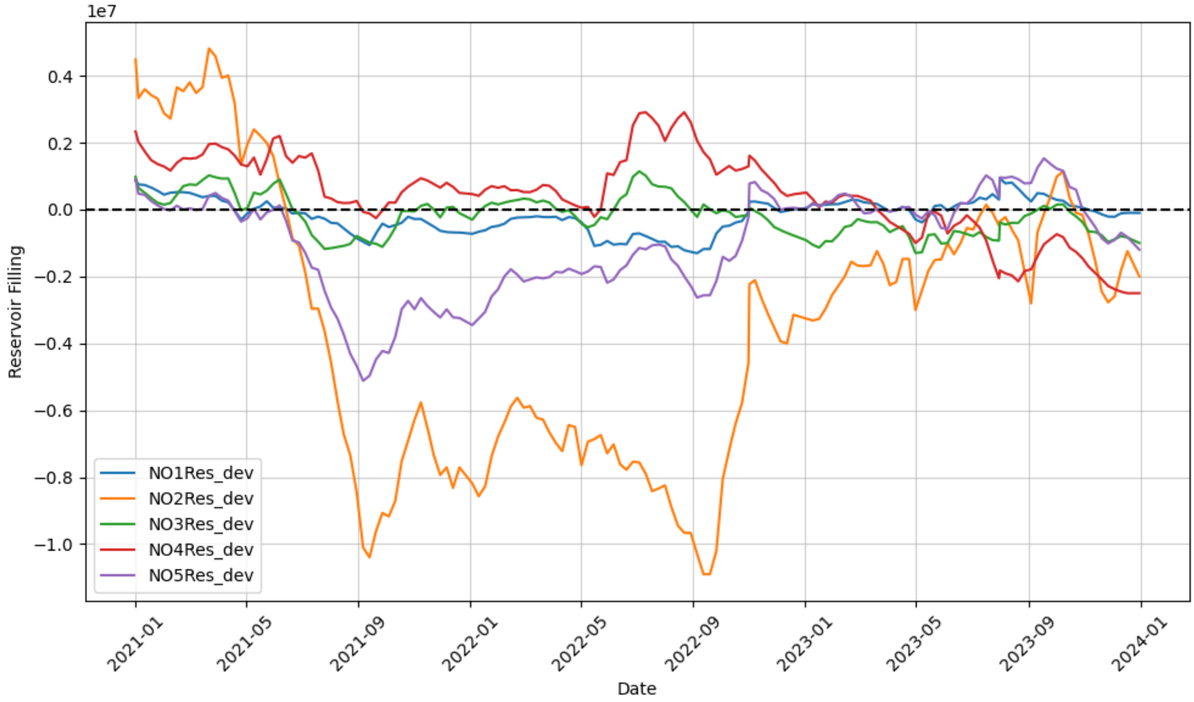

Figure 10: Deviation from median reservoir filling for NO1-NO5. The decline in water reservoir levels in southern Norway is evident from the third quarter of 2021 to the third quarter of 2022.

4.4.2 Inflow to Reservoirs.

Inflow refers to the amount of energy in the water that flows to reservoirs and power plants during the week. The water inflow into hydro dams is expected to be entirely independent of electricity demand, as it is dictated by natural factors like the level of precipitation and

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[12] https://www.nve.no/energi/analyser-og-statistikk/hydrologiske-data-til-kraftsituasjonsrapporten/

melting snow. It is therefore exogenous. Deviations from median reservoir inflow are adopted to adjust for seasonal patterns. NVE records inflow to the reservoir every week, on Sundays just like the reservoir filling. Like the reservoir filling, I modified the frequency of inflows to the reservoir to hourly observations and utilized linear interpolation to complete missing data for hours based on the corresponding inflows from the respective week.

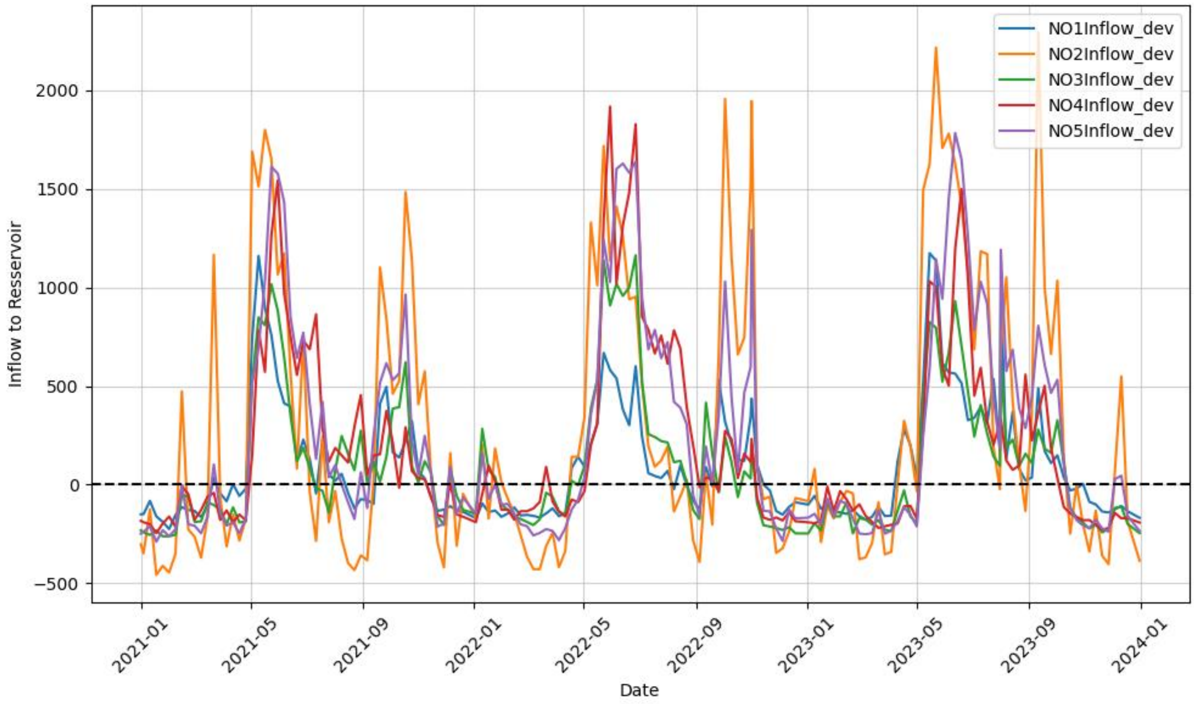

Figure 11: Deviation from median inflows to reservoir for NO1-NO5. The low levels of inflow in southern Norway especially NO2 due to low precipitation are observed from the third quarter of 2021 to the third quarter of 2022. However, inflows increased sharply from the last quarter of 2022.

4.4.3 Spot price of natural gas, coal prices, and carbon emissions price in Europe.

The TTF day-ahead price of natural gas traded on the Title Transfer Facility (TTF) in Amsterdam, Netherlands, the price of carbon allowances in the European Union Emission Trading System (EU ETS), and the vector of future contract prices of coal are all obtained from Montel[13]. Although a very small share of electricity is sourced from gas (1%) and coal (0.1%) in Norway, the prices of these technologies in Europe influence the spot price of electricity as explained in section 2.4. I therefore assume that the price of coal and natural gas

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[13] https://app.montelnews.com/Exchanges/GFI/gfi.aspx?247

are only shifting the supply side and that coal and natural gas prices are therefore for any practical purposes a proper instrument. An increase in the price of coal will increase the marginal costs of electricity in coal-fired thermal plants and gas plants, and thus increase the price of electricity in the Nord Pool area.

Missing values were identified for all three variables on weekends and holidays after extracting the daily closing price from Montel. To address this issue, I employed the Last Observation Carried Forward (LOCF) method, where missing values were replaced with the nearest prior closing prices. This method was deemed appropriate since the market was closed on these days, resulting in no official closing prices. To align with the dataset, I adjusted the frequency of the three variables to hourly observations, and all hours of the day were filled with the corresponding closing price of the day.

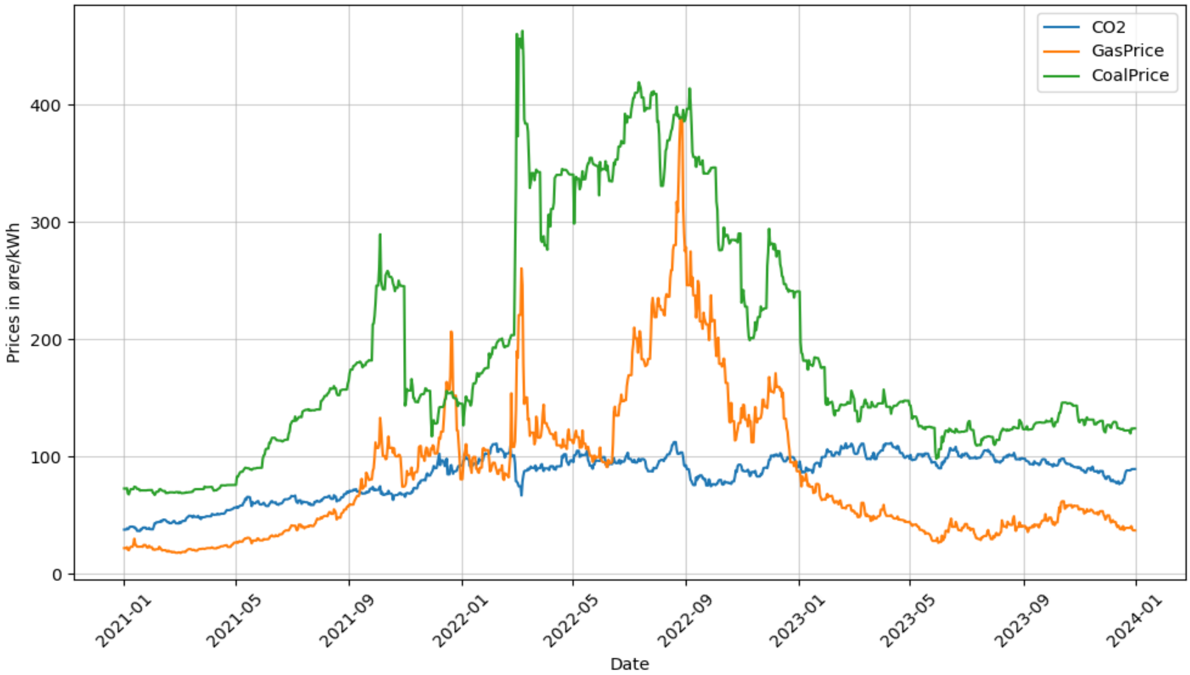

Figure 12: Price of carbon emission allowance, coal and gas prices. All three prices experienced a hike from the last quarter of 2021.

5 Analytical Framework

This section focuses on constructing a model to estimate the price elasticities of electricity demand for Norwegian households, using the IV-GMM approach.

I begin the estimation of the price elasticity of electricity demand by employing the conventional demand equation. Equation (1) illustrates the standard demand model wherein electricity consumption data is regressed against contemporaneous spot market prices. Four distinct time specifications, represented by t, are utilized: hourly prices, daily averages, as well as weekly and monthly averages. While the spot price data inherently includes hourly and daily averages, weekly and monthly averages are derived through aggregation. Separate regressions are conducted for residential housing within each price area, denoted by i.

$$Cons_{it} = \beta_0 Spotprice_{it}{}^{\beta_1} \tag{1}$$

$Cons_{it}$ is the household electricity consumption, β_0 is the intercept, and $Spotprice_{it}$ is the electricity spot price. The parameter of interest, β_1 represents the variation in electricity consumption that is explained by a change in the spot price variable.

Taking natural logs of both sides of equation (1) to obtain:

$$ln\ Cons_{it} = \beta_0 + \beta_1 ln\ Spotprice_{it} \tag{2}$$

Simplifying, adding a temperature variable measured in heating degree days hdd_{it}, and error term ε_{it} to capture the statistical noise, the equation can be rewritten as:

$$ln\ Cons_{it} = \beta_0 + \beta_1 ln\ Spotprice_{it} + \beta_2 hdd_{it} + \varepsilon_{it} \tag{3}$$

Econometrically, there is a preference for variables that follow a conditional normal distribution. Log-transformed variables exhibit a distribution that aligns more closely with the normal distribution than non-transformed variables. As a result, log-transformed variables tend to conform more extensively to the assumptions underlying econometric analyses. Additionally, it facilitates the interpretation of the coefficient of $Spotprice_{it}$ explanatory variable by expressing it in proportionate terms. Thus, the estimates for

β_1 represents the percentage change in household electricity consumption following a one percentage change in the spot price as explained in section 1.

The natural logarithm applies only to values greater than zero. In the context of spot market price data in the electricity market, this presents a pertinent issue as hourly spot prices may occasionally fall below zero. In such instances, negative values were substituted with 0.1 to address this concern.

However, estimating equation (3) by OLS will not yield consistent estimates of the parameter, β_1. Wright (1920) demonstrated that regressing quantity on price does not estimate a demand curve; rather, it estimates a combination of both the supply and demand curves. This is because theoretically, price is determined through the interaction between both demand and supply. The regressor of price is correlated with the disturbance term resulting in simultaneous causality bias.

This can be crosschecked by formulating a simple inverse supply equation:

$$ln\ Spotprice_{it} = \alpha_0 + \alpha_1 ln\ Cons_{it} + \alpha_2 hdd_{it} + \Sigma\ ln\alpha_{n,it}\ K_{n,it} + v_{it} \qquad (4)$$

The K variables, $\Sigma\ ln\alpha_{n,it}\ K_{n,it}$, are exogenous variables that exclusively influence supply and not demand. Consequently, both equations are identified. Examining the reduced form of this two-equation system reveals an evident correlation between $ln\ Spotprice_{it}$ and the disturbance term, ε_{it} in equation (3). The correlation between $ln\ Spotprice_{it}$ and the disturbance term, ε_{it} becomes apparent when considering a scenario where the disturbance term, ε_{it} in equation (3) is positive. A positive disturbance term, ε_{it} leads to an increase in $ln\ Cons_{it}$. However, this increase in $ln\ Cons_{it}$ influences the price through equation (4). Assuming that the coefficient of $ln\ Spotprice_{it}$, α_1 in equation (4) is positive, an increase in $ln\ Cons_{it}$ will result in an increase in price, $ln\ Spotprice_{it}$. Consequently, if the disturbance term, ε_{it} is positive, $ln\ Cons_{it}$ and $ln\ Spotprice_{it}$ will be positively correlated. This violates the least squares assumptions, and as a result, an ordinary least squares (OLS) regression will yield inconsistent results. Hence, it is imperative to address this issue of simultaneity or endogeneity bias.

5.1 Instrumental Variable Estimation

Instrumental variable estimation is often used to deal with the challenges associated with simultaneous causality bias.

Instrumental variable estimation uses an additional instrument(s) say, variable K in equation (5) to isolate the part of the endogenous price that is uncorrelated with the error term ε_{it}.

Regressing the spot price of electricity, $ln\ Spotprice_{it}$ on all exogenous variables and instruments could be expressed in the form of equation (5).

$$ln\ Spotprice_{it} = \alpha_0 + \alpha_2 hdd_{it} + \Sigma\ ln\alpha_{n,it}\ K_{n,it} + v_{it} \qquad (5)$$

In equation (5), the electricity price, $ln\ Spotprice_{it}$, is determined by exogenous supply-side variables $\Sigma\ ln\alpha_{n,it}\ K_{n,it}$. The K variables or instruments that are employed include deviations from median inflow to reservoirs, deviation from median reservoir levels, the price of coal, the spot price of natural gas in Europe, and the EU carbon emission allowances. The reasoning behind the adoption of these instruments was explained in section 4.4.

The purpose of estimating a price equation as represented by equation (5), is to identify the influence of supply-side variables on the electricity price, $ln\ Spotprice_{it}$. Subsequently, these identified variables can serve as instruments in the instrumental variable estimation if they pass the tests to be discussed below.

Formally, instrumental variable estimation decomposes the price variable into two components: one that may exhibit correlation with the regression disturbance term, v_{it}, and another that is uncorrelated with v_{it}. The second stage utilizes the uncorrelated variable to estimate the demand-side price coefficient, β_1.

Wooldridge (2016) explains that for parameters β_0 and β_1 to be consistent and unbiased estimates, the instrumental variables, $\Sigma\ ln\alpha_{n,it}\ K_{n,it}$ must satisfy two conditions:

1. They must be exogenous. That is, the instrumental variables, $\Sigma\ ln\alpha_{n,it}\ K_{n,it}$ should have no partial effect on $ln\ Cons_{it}$ after controlling for the endogenous variable, $ln\ Spotprice_{it}$ in equation (3). Hence the covariance between the set of instruments, $\Sigma\ ln\alpha_{n,it}\ K_{n,it}$ and the error term, ε_{it} should be uncorrelated.

   i.e. Cov ($\Sigma\ ln\alpha_{n,it}\ K_{n,it}$, ε_{it}) = 0.

2. They must be relevant. That is, they should either be positively or negatively, correlated with the endogenous $ln\ Spotprice_{it}$ variable. Thus, the covariance between the set of instruments, $\Sigma\ ln\alpha_{n,it}\ K_{n,it}$ and the endogenous variable, $ln\ Spotprice_{it}$ should be correlated.

   i.e. Cov ($\Sigma\ ln\alpha_{n,it}\ K_{n,it}$, $ln\ Spotprice_{it}$) ≠ 0.

   The exogeneity principle which was the premise for the classification of instrumental variables earlier cannot be tested according to Wooldridge (2016). The relevance principle however can be tested and will be discussed and presented in the results section after estimating the model.

5.2 The IV-GMM

The Instrumental Variables Generalized Method of Moments (IV-GMM) is a statistical technique used for estimating parameters in econometric models, particularly when dealing with endogeneity or simultaneity issues. IV-GMM extends the standard Generalized Method of Moments (GMM) approach by incorporating instrumental variables to address endogeneity problems. It is more robust to violations of the homoscedasticity and normality assumptions that are required for two-stage least square (2SLS) estimation. It also offers greater efficiency and consistency in estimating parameters, especially in the presence of endogeneity.

IV-GMM typically involves a two-stage estimation process that uses instrumental variables, $\Sigma\, ln\alpha_{n,it}\; K_{n,it}$ to isolate the variation in the endogenous variable, $ln\; Spotprice_{it}$ that is uncorrelated with the error term, ε_{it}. The first stage equation is given by equation (5). That is, $ln\; Spotprice_{it}$ is regressed on the set of instrumental variables, $\Sigma\, ln\alpha_{n,it}\; K_{n,it}$, and temperature variable, hdd_{it}.

In the second stage, the model is estimated using the generalized method of moments (GMM) by adding the estimated value of $ln\; Spotprice_{it},$ say $ln\; Spotprice_{it\_}fitted$ to the structural model equation (3) to estimate the price elasticity of electricity demand. The second stage equation is expressed in equation (6).

$$ln\; Cons_{it} = \beta_0 + \beta_1 ln\; Spotprice_{it\_}\, fitted + \beta_2 hdd_{it} + \varepsilon_{it} \qquad (6)$$

6 Results

This section demonstrates the relevance and validity of the instruments used, details the findings regarding the short-run spot price elasticity of electricity demand among Norwegian households across the five price areas, and concludes with the calculation of monthly purchase price elasticities for the five designated price areas.

6.1 Evidence of relevance and validity of instruments

As detailed in section 5.1, I assess the relevance and validity of the instruments utilized in my analysis.

To begin, the test for weak or strong instruments yields a p-value of zero and a substantial F-statistic surpassing the commonly accepted rule of thumb of 20 across all price areas. This outcome indicates that the null hypothesis of weak instruments should be firmly rejected.

Again, the Wooldridge-Hausman-Wu test for endogeneity or instrument relevance also gives a p-value of zero for all price areas, hence the null hypothesis of exogeneity of the price variable, $ln\ Spotprice_{it}$ should be rejected.

The Sargan J-test for overidentification restrictions yields a p-value of 1.0 for all price areas, which is greater than the significance level of 0.05. Hence, we fail to reject the null hypothesis indicating that there is evidence to suggest that the instrumental variables, $\Sigma\ ln\alpha_{n,it}\ K_{n,it},$ are invalid or that the model is misspecified due to over-identification restrictions. Thus, the results of the Sargan J-test suggest that the instrumental variables used in the regression model are valid and that the model is correctly specified in terms of its instruments (see details of tests in Appendix 2).

Adding to the endogeneity test, I examined the correlation between the endogenous spot price, $ln\ Spotprice_{it}$ and the set of instruments, $\Sigma\ ln\alpha_{n,it}\ K_{n,it},$ using the Pearson correlation coefficient (Pearson's r). In all cases, the p-values were approximately zero indicating that the observed correlations are statistically significant. The correlation between spot price and coal price (Pearson's r = 0.716) and spot price and gas price (Pearson's r = 0.838) exhibited a very strong positive linear relationship while the correlation between the spot price and carbon emission price (Pearson's r = 0.328) shows a moderate positive linear relationship.

On the other hand, the correlation between spot price and reservoir filling (Pearson's r = -0.309) and the correlation between spot price and inflow to reservoir (Pearson's r = -0.182) show a moderate and weak negative linear relationship respectively.

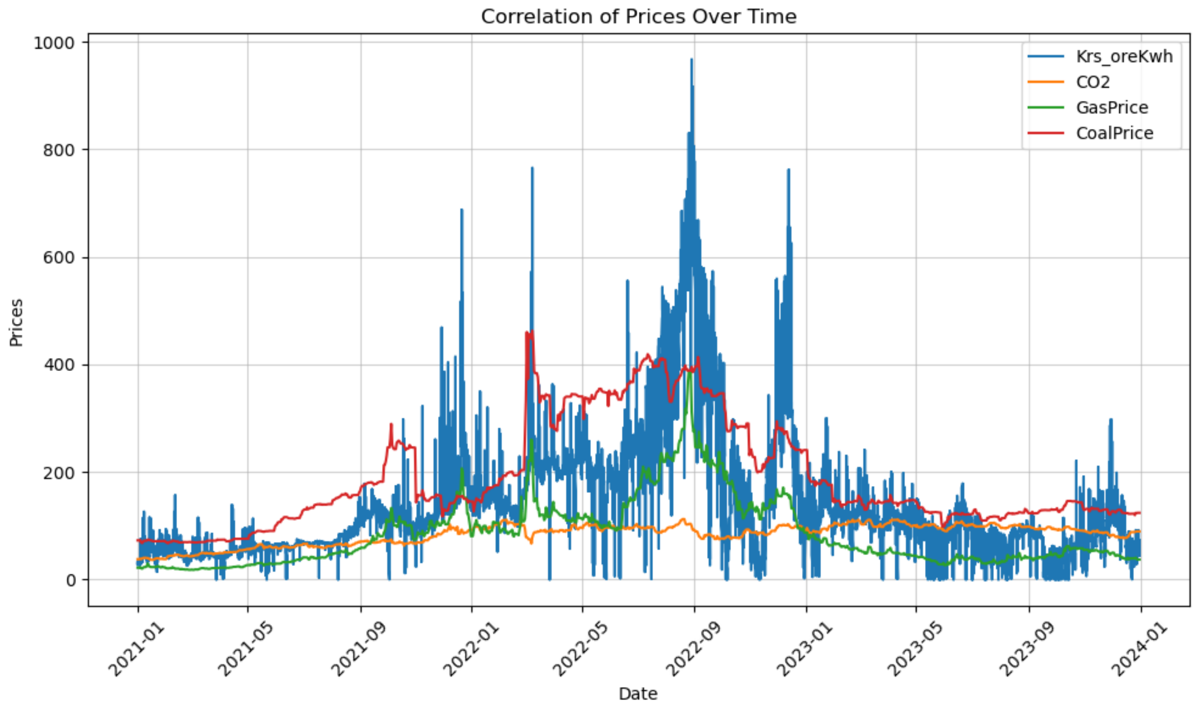

Figure 13: Observed correlation between electricity spot price, price of carbon emission allowance, coal price, and gas price. The trend of the graph indicates a strong positive relationship between electricity spot price[14], coal price, and gas price.

In summary, the results of these tests strongly indicate that the instruments are relevant, and the model is correctly specified. This underscores the reliability of the estimates and the overall validity of the conclusions drawn from the statistical analysis.

6.2 Price Elasticity Estimates for the IV-GMM Regression Model

The results of the model estimation are presented in Table 7. Most of the parameter estimates for the price areas are statistically significant and the coefficients generally have the expected signs. In particular, the coefficients for spot price variable, $ln\ Spotprice_{it}$ are negative except NO4 which has a positive coefficient while those for temperature variable, hdd_{it} are positive, as predicted by economic theory.

Table 5: Results of Estimations of spot price elasticity of electricity demand by Norwegian households per price area (NO1-NO5).

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[14] Electricity spot price for NO2 is shown in the graph.

PRICE AREA	HOURLY	DAILY	WEEKLY	MONTHLY
$\mathbf{NO1}\boldsymbol{ln\ Spotprice}_{\square}$	-0.0364***	-0.0317***	-0.0284***	-0.0216***
	(0.0010)	(0.0023)	(0.0045)	(0.00117)
$\mathbf{NO1\_}\boldsymbol{hdd}_{\square}$	0.0359***	0.0359***	0.0419***	0.0527***
	(0.0003)	(0.0007)	(0.0019)	(0.0033)
$\mathbf{NO2}\boldsymbol{ln\ Spotprice}_{\square}$	-0.0868***	-0.0898***	-0.0818***	-0.0745***
	(0.0015)	(0.0039)	(0.0075)	(0.0109)
$\mathbf{NO2\_}\boldsymbol{hdd}_{\square}$	0.0351***	0.0359***	0.0443***	0.0475***
	(0.0003)	(0.0010)	(0.0024)	(0.0033)
$\mathbf{NO3}\boldsymbol{ln\ Spotprice}_{\square}$	-0.0124***	-0.0096***	-0.0109**	-0.0128***
	(0.0015)	(0.0032)	(0.0119)	(0.0022)
$\mathbf{NO3\_}\boldsymbol{hdd}_{\square}$	0.0291***	0.0295***	0.0337***	0.0368 ***
	(0.0002)	(0.0006)	(0.0013)	(0.0014)
$\mathbf{NO4}\boldsymbol{ln\ Spotprice}_{\square}$	0.0256***	0.0229***	0.0170**	0.0112
	(0.0014)	(0.0042)	(0.0128)	(0.0090)
$\mathbf{NO4\_}\boldsymbol{hdd}_{\square}$	0.0270***	0.0270***	0.0336***	0.0368***
	(0.0002)	(0.0007)	(0.0015)	(0.0057)
$\mathbf{NO5}\boldsymbol{ln\ Spotprice}_{\square}$	-0.0230***	-0.0180***	-0.0164***	-0.0163***
	(0.0009)	(0.0021)	(0.0039)	(0.0044)
$\mathbf{NO5\_}\boldsymbol{hdd}_{\square}$	0.0348***	0.0351***	0.0426***	0.0549***
	(0.0003)	(0.0008)	(0.0024)	(0.0046)

The main values are the price elasticity and temperature estimates. The corresponding robust standard errors are given in parentheses. *** Significance at the 1% level ** Significance at the 5% level * Significance at the 10% level.

Table 5 presents the results of the estimation from my model. The results show that in the southern price areas of NO1, NO2, and NO5, there is a significant negative relationship between electricity spot price and household electricity demand across all time intervals, indicating that as spot prices increase, household demand decreases. This relationship is strongest in NO2, followed by NO1 and NO5. For instance, the coefficient of hourly price elasticity for NO2 suggests that a 1% increase in the spot price of electricity will, ceteris paribus, result in an approximately 0.09% decline in household electricity demand. For the northern price areas, NO3 exhibits a significant negative relationship for the hourly, daily, weekly, and monthly estimates, while NO4 shows a significant positive relationship with price at all the time intervals except the monthly estimate.

The coefficients associated with the temperature variable, hdd_{it}., which signifies the demand for electricity for heating purposes, exhibits the anticipated sign, and are statistically significant across all estimates. The elasticity estimates derived from hdd_{it} for both hourly and daily intervals range from 0.027 to 0.036, while for weekly estimates, they vary from 0.03 to 0.04, and for monthly estimates, they range from 0.04 to 0.06.

The positive coefficients imply that as the number of heating degree days increases, there is a corresponding rise in the demand for electricity among Norwegian households, primarily driven by heating needs. for instance, the coefficient of 0.036 implies that for a 1% increase in heating degree days, households' consumption of electricity for heating purposes increases by 0.036%. The relatively modest impact of hdd_{it} could be attributed to other energy sources, such as fuelwood, being more commonly utilized for heating purposes, particularly during the colder winter months.

The hourly price elasticity throughout the analysis period spans from -0.087 to 0.026, while the daily price elasticity ranges from -0.09 to 0.023. Similarly, the weekly price elasticity varies from -0.08 to 0.02, and the monthly price elasticity ranges from -0.08 to -0.01 (see details in Appendices 3, 4,5, and 6 for hourly, daily, weekly, and monthly estimates respectively).

6.3 Computing the Purchase Price Elasticities.

Previous studies investigating the price elasticity of electricity demand have typically focused on the purchase price rather than the spot market price of electricity. Therefore, in order to make meaningful comparisons and evaluate the compensation scheme, it is essential to calculate the purchase price elasticities for Norwegian households. While the variability in spot prices is indeed significant, it does not directly reflect one-to-one to the changes in the purchase price for Norwegian households. If this were the case, households would essentially be compensated for consuming electricity during periods of negative hourly spot prices. As outlined in section 2.6.2, the variable contract price contract adjusts in response to changes in spot prices, whereas other utility contracts maintain a fixed rate. Thus, to estimate the purchase price elasticity of electricity demand for Norwegian households, I employ a simplified version of the total purchase price for a variable contract, as described by equation (7).

$$\begin{aligned} Purchase\ price\ (in\ øre\ per\ kWh) \\ &= (spot\ price^{15} + grid\ rent + electricity\ levy \\ &+ Enova\ levy) + (0.25 \text{ x } Total) \end{aligned} \tag{7}$$

As depicted in equation (7) above, apart from the spot price, consumers also incur expenses for grid rent, the Enova levy, and an electricity levy, with 25% VAT applied to the total. These levies and rents are assessed per kilowatt-hour (kWh) of consumption.

During the period preceding the compensation scheme, specifically, from the first quarter to the fourth quarter of 2021, Norwegian households paid an average of 27.2 øre per kWh for the grid fee, 27.1 øre per kWh for the electricity levy, and 1 øre per kWh for the Enova levy (SSB, 2023d).

Table 6: Purchase price before the introduction of the compensation scheme for price areas, NO1-NO5.

Price Area	Mean Spot Price	Grid rent	Electricity Levy	ENOVA	25% VAT	Purchase Price
NO1	75	27.2	27.1	1	32.6	162.9
NO2	76	27.2	27.1	1	32.8	164.1
NO3	45	27.2	27.1	1	25.1	125.4
NO4	38	27.2	27.1	1	23.3	116.6
NO5	75	27.2	27.1	1	32.6	162.9

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[15] Mean spot prices for the period of *no compensation* as presented in Table 3.

Table 6 illustrates the electricity purchase prices expended by Norwegian households prior to the implementation of the compensation scheme. NO2 exhibits the highest purchase price at 164.1 øre per kWh, trailed closely by both NO1 and NO5, each registering a purchase price of 162.9 øre per kWh. NO3 reports a purchase price of 125.4 øre per kWh, while NO4 records the lowest purchase price at 116.6 øre per kWh.

To determine the purchase price during the period of the compensation scheme, it's essential to consider the government support (Strømstøtte) provided to Norwegian households. As outlined in section 2.7, this scheme encompassed the excess electricity spot price above the cap of 70 øre per kWh for households consuming up to 5000 kWh of electricity per month. Initially, the scheme had a coverage of 55% in December 2021, which was then increased to 80% from January 2022 to August 2023. However, in September 2023, it was further adjusted to 90%, and the cap was raised to 73 øre per kWh for hourly prices, deviating from the previous average monthly price. Households received reimbursements equivalent to 55%, 80%, and 90% of the variance between the actual spot price and the cap, inclusive of VAT, depending on the specified time frames.

To simplify calculations, I adopt the 80% coverage for the monthly average of electricity spot price above the cap of 70 øre per kWh. This decision is based on the fact that this coverage was applied for the majority of the compensation period. I further assume that no household consumed more than the 5000kWh threshold in a month. The purchase price formula, incorporating government support (Gov), is then represented by equation (8).

$$
\begin{aligned}
&Purchase\ price\ (in\ øre\ per\ kWh) \\
&\qquad = (spot\ price^{16} + grid\ rent + electricity\ levy \\
&\qquad + Enova\ levy) + (0.25 \text{ x } Total) - Gov
\end{aligned}
\tag{8}
$$

Government Support, Gov is given by equation (9) below.

$$
\begin{aligned}
&Gov \\
&= 0.8 \text{ x } (mean\ monthly\ spot\ price\ in\ øre\ per\ kWh - 70\ øre\ per\ kWh) \\
&+ (\ 0.25 \text{ x } Total\ )
\end{aligned}
$$

---

[16] Mean spot prices for period of *compensation* as presented in Table 3.

(9)

Throughout the period of the compensation scheme, spanning from the fourth quarter of 2021 to the fourth quarter of 2023, Norwegian households incurred an average cost of 30.5 øre per kWh for the grid fee, 24.6 øre per kWh for the electricity levy, and 1 øre per kWh for the Enova levy (SSB, 2023d).

Table 7: Purchase price during the compensation period for price areas, NO1-NO5.

Price Area	**Mean Spot Price**	**Grid Rent**	**Electricity Levy**	**ENOVA**	**25% VAT**	**Total**	**Gov Support**	**Purchase Price**
NO1	151	30.5	24.6	1	51.8	258.9	81	177.9
NO2	168	30.5	24.6	1	56	280.1	98	182.1
NO3	47	30.5	24.6	1	25.8	128.9	-	128.9
NO4	33	30.5	24.6	1	22.3	111.4	-	111.4
NO5	151	30.5	24.6	1	51.8	258.9	81	177.9

Table 7 presents the purchase prices paid by households during the compensation period. Similar to the period before compensation, NO2 demonstrates the highest purchase price at 182.1 øre per kWh, closely followed by both NO1 and NO5, each recording a purchase price of 177.9 øre per kWh. NO3 reports a purchase price of 128.9 øre per kWh, while NO4 has the lowest purchase price at 111.4 øre per kWh.

Given the mean spot prices of 47 øre per kWh and 33 øre per kWh for NO3 and NO4 respectively, falling below the cap of 70 øre per kWh, it is assumed that the government support is zero for these two price areas. Across both periods, it is evident that the market was coupled for the two southern price areas of NO1 and NO5.

With the estimated monthly spot price elasticity of electricity demand for the various price areas, I derive the proportionate change in electricity consumption for each price area using equation (10).

$$\%\Delta\ in\ demand = monthly\ Spot\ PED \text{ x } \frac{compensation\ spot\ price - no\ compensation\ spot\ price}{no\ compensation\ spot\ price} \text{ x } 100 \tag{10}$$

Similarly, I compute the proportionate change in purchase price between the compensation period and the period without compensation using equation (11).

$$\%\Delta\ in\ purchase\ price = \frac{compensation\ purchase\ price - no\ compensation\ purchase\ price}{no\ compensation\ purchase\ price} \text{ x } 100 \tag{11}$$

Dividing equation (10) by equation (11) to obtain the purchase price elasticity of electricity demand.

$$Monthly\ Purchase\ price\ elasticity\ of\ demand = \frac{\%\Delta\ in\ demand}{\%\Delta\ in\ purchase\ price} \tag{12}$$

Table 8: Monthly purchase price elasticity of electricity demand for price areas, NO1-NO5.

Price Area	**%∆ in demand**	**%∆ in Purchase Price**	**Monthly Purchase price elasticity**
NO1	-2.19	9.21	-0.238
NO2	-9.02	10.97	-0.822
NO3	-0.06	2.79	-0.022
NO4	-0.15	-4.46	0.034
NO5	-1.65	9.21	-0.179

Table 8 illustrates the proportional changes in electricity demand, proportional changes in the purchase price, and the corresponding monthly purchase price elasticities across all price areas in Norway. Notably, NO2 experienced the most significant increase in purchase price at 10.97%, resulting in a corresponding decline in electricity consumption by 9.02%. Similarly, both NO1 and NO5 saw a purchase price increase of 9.21%, yet experienced decreases in demand by 2.19% and 1.65% respectively. NO3 witnessed a purchase price increase of 2.79%, with a marginal decline in demand by only 0.06%. Conversely, NO4 demonstrated a decrease in purchase price by 4.46%, but with a minor decrease in electricity demand by 0.15%.

The derived monthly purchase price elasticities are as follows: -0.238 for NO1, -0.822 for NO2, -0.022 for NO3, 0.034 for NO4, and -0.179 for NO5. (see details of calculations in Appendixes 7, 8, and 9).

7 Discussion

This section starts by examining the implications of the government compensation scheme. Following this, I compare the findings from my estimates to those in the existing literature and conclude by evaluating the validity of my study.

7.1 Implication of the Government Support Scheme

This section discusses the implication of the government support scheme on consumer welfare and market equilibrium.

Generally, energy (electricity) subsidies have both economic and environmental implications usually bordering on market efficiency, equity, and sustainability concerns.

1. Efficiency: In general, subsidies tend to encourage wasteful consumption of the good or service that is subsidized. This not only implies an inefficient use of resources in the economy but also, in the case of energy subsidies, may increase pollution and the emission of greenhouse gases. By distorting market incentives, subsidies may encourage overuse or misallocation of resources, ultimately hindering the economy's overall productivity and sustainability.

2. Equity: Energy subsidies are often indiscriminate and disproportionately favour wealthier segments of the population over lower-income groups. This socioeconomic disparity in subsidy distribution can exacerbate existing inequalities by providing greater financial relief to those who are already more affluent. Consequently, the regressive nature of energy subsidies not only fails to effectively alleviate energy costs for those who need it most but also widens the gap between socio-economic classes, perpetuating inequality within society.

3. Sustainability Concerns. The substantial scale of energy subsidies raises apprehensions about fiscal sustainability across numerous nations, particularly amid periods of elevated energy costs. As governments grapple with the financial implications of sustaining these subsidies, there's a growing realization of their potential to strain public finances and impede long-term economic stability. The persistent reliance on subsidies to mitigate energy expenses underscores broader challenges in balancing budgetary constraints with the imperative of ensuring affordable energy access for citizens.

I begin the analysis by drawing on the classification of my spot price variable into two periods, namely, the period of *no compensation* and the period of *compensation* in section 4.1.2 and the approximated monthly purchase prices calculated in section 6.3 for the two periods. The NO2 price area will be the central focus for evaluating efficiency and consumer welfare following the introduction of the subsidies.

Figure 14 serves to illustrate the distortions of the market equilibrium created by the government support scheme with the help of a linear demand function, DD. For the sake of simplicity, I assume a perfectly elastic supply as this is a short-run analysis. $COMP_{NO}$ represents the electricity supply in the period of *no compensation* with a monthly average selling price of 164.1 øre per kWh and quantity, Q_{NO}. In the period of *compensation*, the monthly average electricity price rises to 280.1 øre per kWh shown by the supply curve, $COMP_{WO}$. That is, without government support, households would have paid an average monthly purchase price of electricity of 280.1 øre per kWh with quantity demand, Q_{WO}.

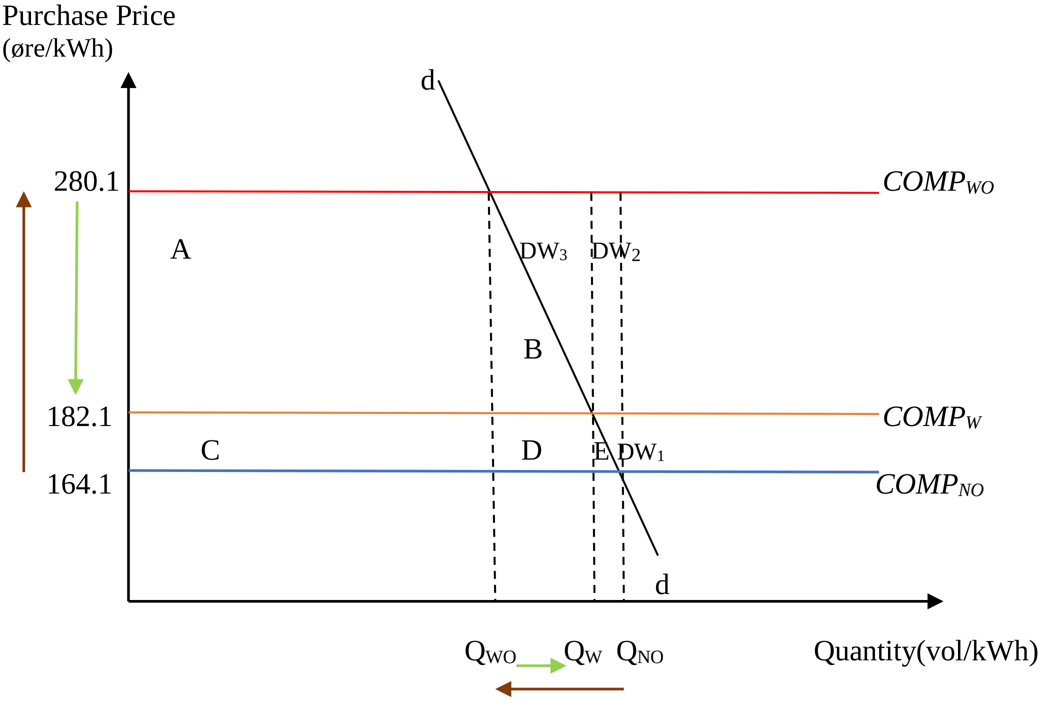

Figure 14: Cost and Deadweight Loss from the government support scheme.

Source: Author’s Illustration.

The government had the option of compensating consumers to leave them just as well-off before the price shock by compensating households by the whole difference between the prices in the two periods (i.e. 280.1 – 164.1 = 116). The rectangle formed by the areas A, B, C, D, E, DW_1, DW_2, and DW_3 constitutes the total subsidy that the government would have given to household consumers in this scenario. Notice that the consumer surplus is the areas A, B, C and D, and the total deadweight loss[17] from this subsidy is the sum of DW_1, DW_2, and DW_3 —that is, the area in which willingness to pay by consumers (given by the height of the demand curve) is below the opportunity cost (280.1 øre per kWh).

Conversely, the government actually compensated only when the monthly average electricity price exceeded the cap of 70 øre per kWh per month. The subsidized price in this case is 182.1 øre per kWh with quantity, Q_W represented on the supply curve, $COMP_W$. The rectangle formed by the areas A, B, and DW_3 constitutes the total subsidy that the government actually paid to household consumers. Hence the deadweight loss reduces only to DW_3.

If the government did not introduce the compensation scheme (i.e. price remains at 280.1 øre per kWh), it would save areas A, B, and DW_3, but the welfare of household consumers declines greatly because they are now consuming less of the good (i.e. from Q_{NO} to Q_{WO}) and paying 116 øre per kWh more.

With the compensation scheme in place, the government rebates back areas A, B, and DW_3 to household consumers with A and B representing the consumer surplus. Notice that areas C, D, and E are the loss in consumer surplus as a result of the scheme. This results in a small decline in consumption from Q_{NO} to Q_W while households pay relatively less purchase price per month. The market distortion arising from the compensation scheme is therefore minimal compared to the welfare gains to Norwegian households. The energy savings resulting from the scheme represent the difference from Q_{NO} to Q_W although this could have been larger in the absence of the scheme (i.e. $Q_{WO} - Q_{NO}$).

In addition, the compensation scheme bridged the wide variation in electricity purchase prices across different price areas as shown in Table 6. For instance, the difference in the monthly average purchase price between NO2 and NO4 was narrowed down to approximately 70 øre per kWh. Without the compensation scheme, the difference would have been a staggering 168.7 øre per kWh. Such a scenario would undoubtedly have had profound implications for the proportion of household income allocated to electricity expenses, especially the households of the southern price areas, diminishing their overall welfare. Hence, the compensation scheme proves crucial in addressing both the short-term

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[17] The size of the deadweight loss is relatively small because of the inelastic price elasticity.

repercussions of high electricity prices and the significant disparities in prices between southern and northern price areas.

There are however concerns over the long-term sustainability of government support scheme in the event of prolonged high electricity prices especially in this period of uncertainty regarding natural gas prices in Europe.

7.2 Comparison with Previous Research

Most research on spot price elasticity of demand in Norway utilizes aggregated data across all five price areas of the country and spans various sectors of the economy. To facilitate easy comparison of my results with previous studies, I have computed the overall price elasticity for Norway by using the population of the largest municipalities in each price area as weights. Specifically, I used Oslo, Kristiansand, Trondheim, Tromsø, and Bergen to represent NO1, NO2, NO3, NO4, and NO5 respectively. The population figures for 2023 are 709,037 for Oslo, 115,569 for Kristiansand, 212,660 for Trondheim, 77,992 for Tromsø, and 289,330 for Bergen (SSB, 2023e). The overall monthly spot price elasticity was calculated as -0.022, and the monthly purchase price elasticity as -0.227 (see details of calculations in appendices 10 and 11).

These findings align with prior research conducted in Norway, as documented by scholars such as Johnson (2001), Bye and Hansen (2008), Halvorsen and Larsen (2000), and Hofman and Lindberg (2019). This consistency underscores the established conclusion that electricity demand in Norway is relatively inelastic.

Several factors contribute to the observed trends, including the lack of widely available alternatives for heating, which leads to high switching costs, historically low and stable electricity prices that have shaped consumption habits, and the impact of welfare state interventions. Espey and Espey (2004) posit that variations in elasticity estimates can be attributed to differences in demand specifications, characteristics of the data, and the timing and geographic location of the study. Consequently, it is not unexpected that the absolute price elasticity in Norway is relatively low in comparison to other countries.

7.3 Discussion of Validity

This section addresses the validity of my findings, beginning with an examination of internal validity, specifically focusing on omitted variable bias. The primary challenge in achieving internal validity stems from the absence of reliable data at the necessary frequency, resulting in the exclusion of several variables from my models. Additionally, I will explore the implications for external validity.

7.3.1 Internal validity

7.3.1.1 Fuelwood

Wood remains a significant heating source for Norwegian households. While in many European cities, wood burning for heat primarily occurs in rural and suburban areas, Norwegian cities, particularly Oslo and neighbouring Akershus, have a high prevalence of wood burning, with 62% of dwellings utilizing this method (López-Aparicio et al., 2017). Fuelwood constitutes approximately 12% of total household energy consumption during the study period (SSB, 2021). However, obtaining reliable data on fuelwood at the required frequency proved challenging. Simen Gjølsjø, a Senior Advisor at NIBIO Division of Wood Technology, noted a lack of comprehensive statistics for the required analysis. Nonetheless, he confirmed a significant increase in fuelwood prices post-COVID. Gjølsjø mentioned that birch, the most common wood species, saw a substantial price rise, from approximately 300 NOK per m^3 + VAT in 2020 to around 800 NOK + VAT presently. Similarly, the cost of a 40-liter bag of firewood nearly doubled from 50 NOK to 100 NOK during winter periods. This surge in fuelwood prices may be linked to increased consumption as households seek alternatives to costly electricity, especially during winter. Additionally, some households may opt for personal wood chopping without monetary transactions.

Nonetheless, the estimate provided by Statistics Norway indicates only 12% of fuelwood consumption by Norwegian households is relatively modest compared to overall electricity consumption. Consequently, the absence of a wood price variable is unlikely to significantly impact the quality of my estimate. If wood proves to be a crucial factor, the price elasticity estimate may be positively biased, given that the substitution from electricity to wood-based heating appears primarily triggered by high electricity prices.

7.3.1.2 Snow data

Snow data holds significance for understanding the intertemporal behavior of hydropower producers in maximizing the water in their reservoirs. Extensive snow accumulation in Norwegian mountains throughout the long winter months leads to substantial inflows when the snow melts in spring. If this knowledge is integrated into electricity pricing, current prices are expected to decrease due to reduced opportunity costs associated with water usage. However, this impact is anticipated to be minimal in my model, as it is partially captured by the inflow variable already included. Therefore, it does not pose a significant concern as an omitted variable.

7.3.1.3 North Sea Link and NordLink Cables

North Sea Link is a joint venture between Norwegian Transmission Operator Statnett and the National Grid of Britain. Commissioned in 2021, the 720-kilometre subsea interconnector is the longest in the world and connects Norway to Great Britain.

Also, in 2021, the NordLink project, with a capacity of 1400 MW, was developed by Statnett in cooperation with grid company TenneT and investment bank KfW in Germany. The 500-kilometer subsea cable connects the Norwegian and German electricity markets for the first time.

The commencement of operations of these two cables coincided with the period of my study. While these cables were established to enhance the security of electricity supplies for both countries, there has been widespread speculation that they might contribute to the high electricity prices observed in Norway. Many Norwegians hold the belief that these interconnectors are responsible for importing high prices into the country. However, data provided by Statistics Norway indicates that the elevated electricity prices stem primarily from the high prices of natural gas and coal in Europe, as well as the diminished levels of reservoirs in Southern Norway due to low precipitation (SSB, 2023c). Therefore, electricity exports along these cables may have only an insignificant effect on my results from being omitted from my model.

7.3.2 External Validity

The external validity of my findings depends on the extent to which institutional, geographical, and time settings differ in future studies that analyze demand responses.

7.3.2.1 Compensation Scheme for High Electricity Prices

Although Norway experienced very high electricity prices during the period of study similar to other European countries, the compensation scheme introduced by the government contributed to a smaller response in electricity demand to these high price shocks. In contrast, for countries where households have comparably smaller confidence in their government to help them through negative economic shocks, a similar price increase may induce more risk-aversive behaviour and higher precautionary energy savings, hence, a larger demand response.

7.3.2.2 Type of heating used and the Sources of heating fuel

In Figure 4, the cyclical fluctuations in electricity demand are depicted, peaking during winter months when electricity consumption for residential housing increases by 2 to 3 times. This cyclical pattern is primarily driven by the demand for electric heating. As detailed in section 2.5.2, approximately 83% of energy consumption in Norwegian households is derived from electricity. This high reliance on electricity, coupled with limited substitutes, distinguishes Norway from other countries.

For instance, in Germany, 44% of residential energy consumption comes from gas, with electricity accounting for 22%. In the Netherlands, 73% of heating energy is gas-based, while in France, households rely on a mix of gas (30%) and electricity (37%) (IEA, 2022). These countries exhibit a greater degree of substitutability in household energy consumption compared to Norway.

Conducting a similar study on a comparable price shock in countries with less reliance on electric heating and greater substitution options may yield different price elasticity estimates. Despite the correlation between electricity and gas prices to some extent, the unique energy consumption patterns in each country can significantly influence elasticity outcomes. Even if another region shares Norway's reliance on electric heating, geographical factors such as altitude, proximity to sea currents, and latitudes, along with temperature variations, can alter heating demand profiles. These geographical nuances further contribute to the divergence in price elasticity estimates across regions.

8 Conclusion

In this study, employing the IV-GMM model and analyzing panel data specific to the five price areas of Norway, I have conducted estimations of short-term spot price elasticities across hourly, daily, weekly, and monthly intervals, covering the period from 2021 to 2023.

The hourly, weekly, and daily spot price elasticity estimates range between -0.01 to 0.03 while the monthly spot price elasticity ranges between -0.08 to -0.01 for the five price areas. However, the degree of responsiveness to price changes varies particularly between the southern price areas of NO1 and NO2 compared to the other price areas (i.e. NO3, NO4, and NO5) for the hourly, daily, weekly, and monthly spot price elasticity estimates. NO1 and NO2 tend to be relatively more elastic than the other price areas.

Additionally, I used the monthly spot price elasticities to calculate the monthly purchase price elasticities of -0.238, -0.822, -0.02, and -0.179 for NO1, NO2, NO3, and NO5 respectively. That is the monthly purchase price elasticity ranges between -0.822 to -0.022. These purchase price elasticity estimates accounted for the government compensation scheme introduced in December 2021 to cushion households against high electricity prices.

To facilitate a comparison of my findings with earlier research conducted within the country, I calculated the overall monthly spot price and monthly purchase price elasticities, which are 0.022 and 0.227 respectively. The results of both the price area-specific and the overall price elasticity estimates confirm the inelastic nature of household electricity demand in Norway, as documented in previous studies.

I also explore the economic implications of the compensation scheme and find that it significantly enhanced the welfare of Norwegian households while reducing price disparities between the southern and northern price areas. Despite these benefits, the scheme introduced a minor loss in economic efficiency, primarily attributable to the inelastic nature of household electricity demand. Nevertheless, the environmental impact of increased electricity consumption is negligible, given that electricity in Norway is predominantly generated through hydroelectric power.

These results underscore the importance of considering regional variations in electricity demand responsiveness when formulating policy measures aimed at managing electricity pricing and consumption. Moreover, the derived purchase price elasticities offer valuable insights into consumer behaviour and preferences, which can inform policymakers in designing effective strategies to promote energy efficiency and affordability.

The limitation of the study lies in the reliance on approximations in the calculations of the monthly purchase price elasticity estimates. Future research that incorporates actual purchase prices paid by Norwegian households would offer a more precise analysis of the compensation scheme's impact. This enhanced approach could delve deeper into understanding how variations in actual purchase prices influence household electricity consumption behaviour and, consequently, shed more light on the effectiveness of the compensation scheme in shaping consumer decisions.

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APPENDIX

Appendix 1: Description of variables in the model estimation

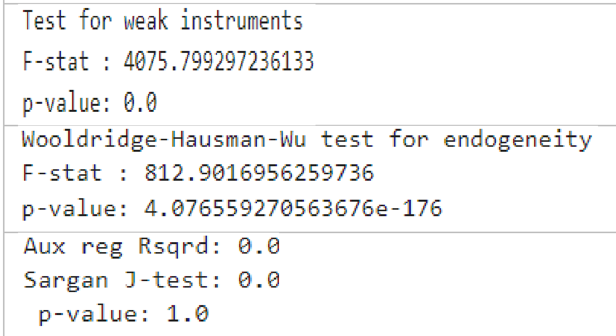
Price area	**Dependent (Consumption) Variable (log)**	**Endogenous (Spot price) Variable (log)**	**Exogenous (Temperature) Variable**	**IV1 (Reservoir)**	**IV2 (Inflow)**
NO1	LOsl_volKwh	LOsl_oreKwh	Osl_HDD	NO1Res_dev	NO1Inflow_dev
NO2	LKrs_volKwh	LKrs_oreKwh	Krs_HDD	NO2Res_dev	NO2Inflow_dev
NO3	LTrh_volKwh	LTrh_oreKwh	Trh_HDD	NO3Res_dev	NO3Inflow_dev
NO4	LTro_volKwh	LTro_oreKwh	Tro_HDD	NO4Res_dev	NO4Inflow_dev
NO5	LBer_volKwh	LBer_oreKwh	Ber_HDD	NO5Res_dev	NO5Inflow_dev

LCO2, LGasPrice, and LCoalPrice represent the log-transformed instrumental variables of carbon emission price, natural gas price, and coal price respectively, and they are the same for all price areas.

Monthly dummies are included with December as a baseline or reference month.

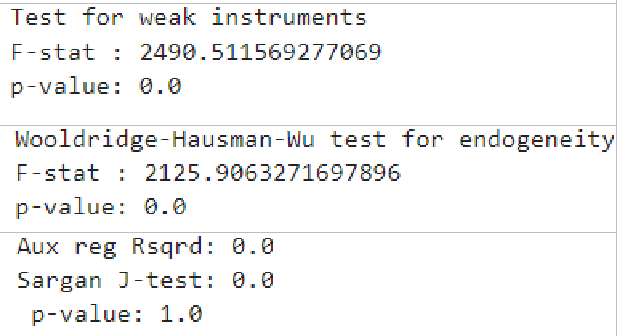
Appendix 2: Results of tests for weak/strong instrument, endogeneity, and overidentification restrictions

NO1



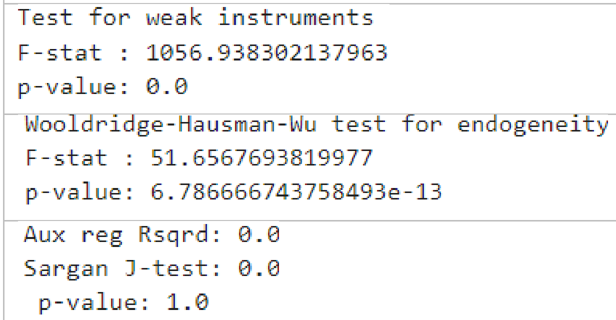
```
Test for weak instruments
F-stat : 4075.799297236133
p-value: 0.0
Wooldridge-Hausman-Wu test for endogeneity
F-stat : 812.9016956259736
p-value: 4.076559270563676e-176
Aux reg Rsqrd: 0.0
Sargan J-test: 0.0
 p-value: 1.0
```

NO2



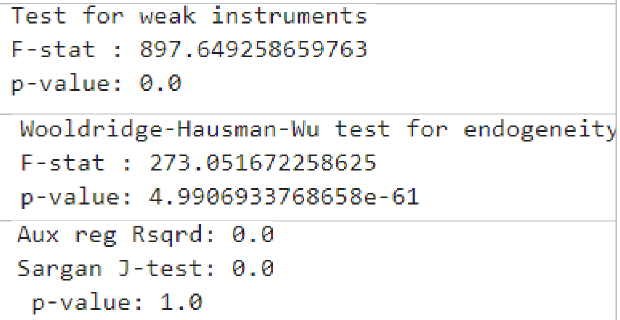
```
Test for weak instruments
F-stat : 2490.511569277069
p-value: 0.0
Wooldridge-Hausman-Wu test for endogeneity
F-stat : 2125.9063271697896
p-value: 0.0
Aux reg Rsqrd: 0.0
Sargan J-test: 0.0
 p-value: 1.0
```

NO3



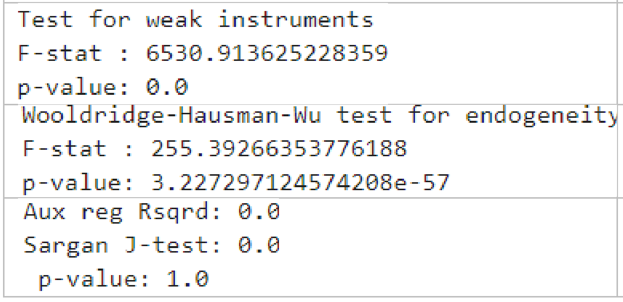
```
Test for weak instruments
F-stat : 1056.938302137963
p-value: 0.0
Wooldridge-Hausman-Wu test for endogeneity
F-stat : 51.6567693819977
p-value: 6.786666743758493e-13
Aux reg Rsqrd: 0.0
Sargan J-test: 0.0
 p-value: 1.0
```

N04



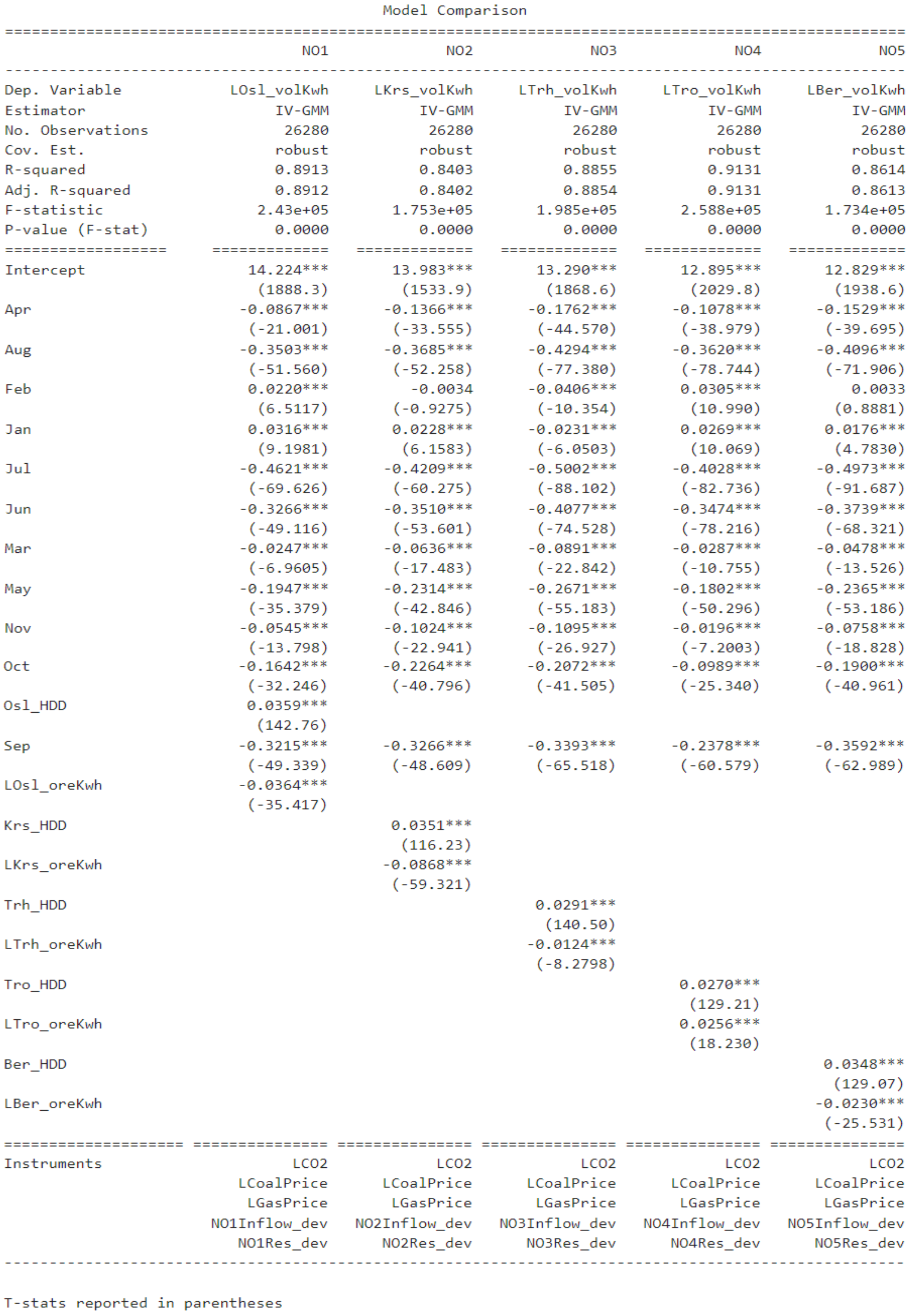
```
Test for weak instruments
F-stat : 897.649258659763
p-value: 0.0
Wooldridge-Hausman-Wu test for endogeneity
F-stat : 273.051672258625
p-value: 4.9906933768658e-61
Aux reg Rsqrd: 0.0
Sargan J-test: 0.0
 p-value: 1.0
```

NO5



```
Test for weak instruments
F-stat : 6530.913625228359
p-value: 0.0
Wooldridge-Hausman-Wu test for endogeneity
F-stat : 255.39266353776188
p-value: 3.227297124574208e-57
Aux reg Rsqrd: 0.0
Sargan J-test: 0.0
 p-value: 1.0
```

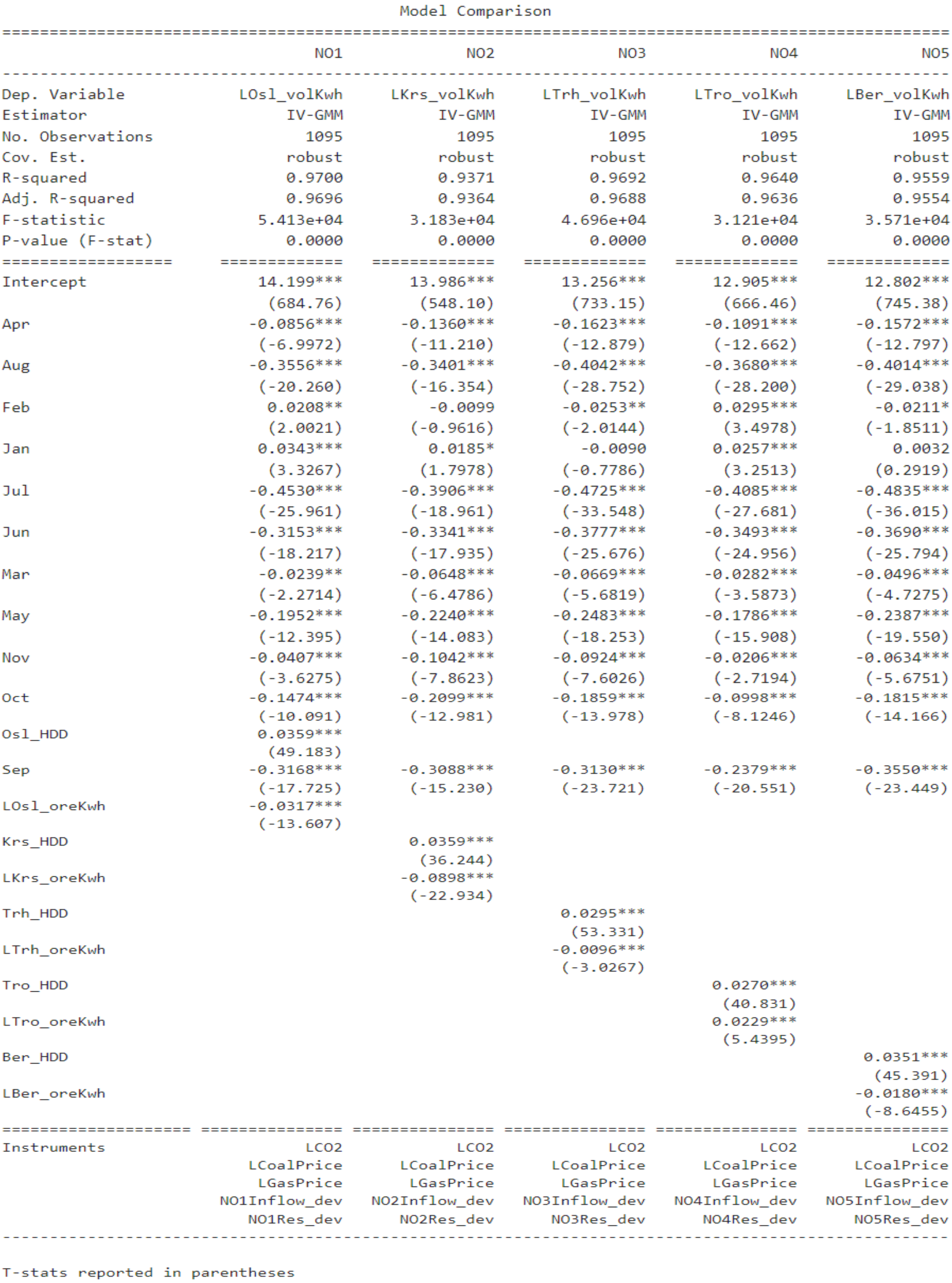
Appendix 3: Hourly spot price elasticity estimates



```
                                          Model Comparison
====================================================================================================
                                 NO1             NO2             NO3             NO4             NO5
----------------------------------------------------------------------------------------------------
Dep. Variable            LOsl_volKwh     LKrs_volKwh     LTrh_volKwh     LTro_volKwh     LBer_volKwh
Estimator                     IV-GMM          IV-GMM          IV-GMM          IV-GMM          IV-GMM
No. Observations               26280           26280           26280           26280           26280
Cov. Est.                     robust          robust          robust          robust          robust
R-squared                     0.8913          0.8403          0.8855          0.9131          0.8614
Adj. R-squared                0.8912          0.8402          0.8854          0.9131          0.8613
F-statistic                 2.43e+05       1.753e+05       1.985e+05       2.588e+05       1.734e+05
P-value (F-stat)              0.0000          0.0000          0.0000          0.0000          0.0000
==================     =============   =============   =============   =============   =============
Intercept                  14.224***       13.983***       13.290***       12.895***       12.829***
                            (1888.3)        (1533.9)        (1868.6)        (2029.8)        (1938.6)
Apr                       -0.0867***      -0.1366***      -0.1762***      -0.1078***      -0.1529***
                           (-21.001)       (-33.555)       (-44.570)       (-38.979)       (-39.695)
Aug                       -0.3503***      -0.3685***      -0.4294***      -0.3620***      -0.4096***
                           (-51.560)       (-52.258)       (-77.380)       (-78.744)       (-71.906)
Feb                        0.0220***         -0.0034      -0.0406***       0.0305***          0.0033
                            (6.5117)       (-0.9275)       (-10.354)        (10.990)        (0.8881)
Jan                        0.0316***       0.0228***      -0.0231***       0.0269***       0.0176***
                            (9.1981)        (6.1583)       (-6.0503)        (10.069)        (4.7830)
Jul                       -0.4621***      -0.4209***      -0.5002***      -0.4028***      -0.4973***
                           (-69.626)       (-60.275)       (-88.102)       (-82.736)       (-91.687)
Jun                       -0.3266***      -0.3510***      -0.4077***      -0.3474***      -0.3739***
                           (-49.116)       (-53.601)       (-74.528)       (-78.216)       (-68.321)
Mar                       -0.0247***      -0.0636***      -0.0891***      -0.0287***      -0.0478***
                           (-6.9605)       (-17.483)       (-22.842)       (-10.755)       (-13.526)
May                       -0.1947***      -0.2314***      -0.2671***      -0.1802***      -0.2365***
                           (-35.379)       (-42.846)       (-55.183)       (-50.296)       (-53.186)
Nov                       -0.0545***      -0.1024***      -0.1095***      -0.0196***      -0.0758***
                           (-13.798)       (-22.941)       (-26.927)       (-7.2003)       (-18.828)
Oct                       -0.1642***      -0.2264***      -0.2072***      -0.0989***      -0.1900***
                           (-32.246)       (-40.796)       (-41.505)       (-25.340)       (-40.961)
Osl_HDD                    0.0359***
                            (142.76)
Sep                       -0.3215***      -0.3266***      -0.3393***      -0.2378***      -0.3592***
                           (-49.339)       (-48.609)       (-65.518)       (-60.579)       (-62.989)
LOsl_oreKwh               -0.0364***
                           (-35.417)
Krs_HDD                                    0.0351***
                                            (116.23)
LKrs_oreKwh                               -0.0868***
                                           (-59.321)
Trh_HDD                                                    0.0291***
                                                            (140.50)
LTrh_oreKwh                                               -0.0124***
                                                           (-8.2798)
Tro_HDD                                                                    0.0270***
                                                                            (129.21)
LTro_oreKwh                                                                0.0256***
                                                                            (18.230)
Ber_HDD                                                                                    0.0348***
                                                                                            (129.07)
LBer_oreKwh                                                                               -0.0230***
                                                                                           (-25.531)
==================== =============== =============== =============== =============== ===============
Instruments                     LCO2            LCO2            LCO2            LCO2            LCO2
                          LCoalPrice      LCoalPrice      LCoalPrice      LCoalPrice      LCoalPrice
                           LGasPrice       LGasPrice       LGasPrice       LGasPrice       LGasPrice
                       NO1Inflow_dev   NO2Inflow_dev   NO3Inflow_dev   NO4Inflow_dev   NO5Inflow_dev
                          NO1Res_dev      NO2Res_dev      NO3Res_dev      NO4Res_dev      NO5Res_dev
----------------------------------------------------------------------------------------------------

T-stats reported in parentheses
```

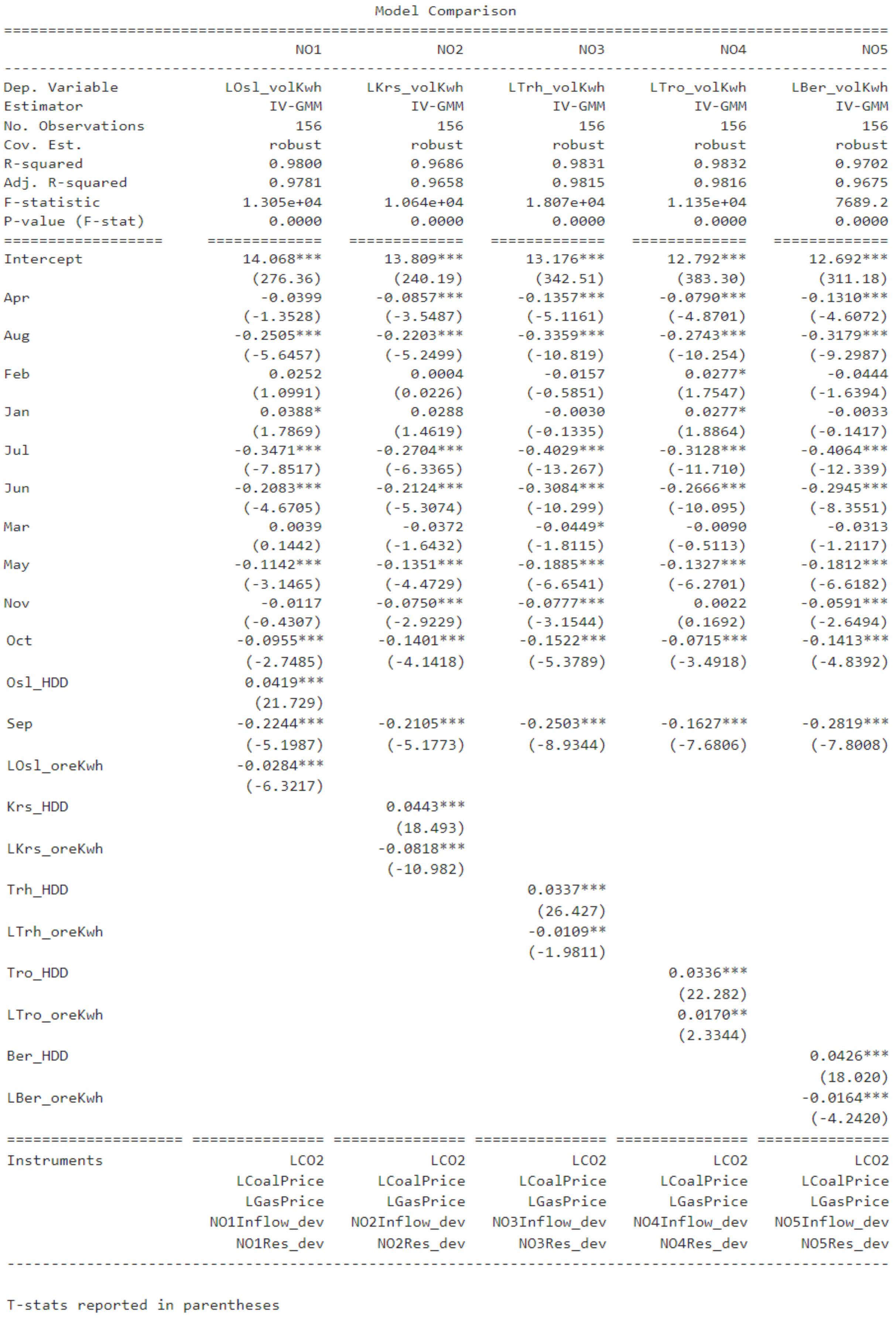
Appendix 4: Daily spot price elasticity estimates.



```
                                        Model Comparison
===================================================================================================
                                NO1             NO2             NO3             NO4             NO5
---------------------------------------------------------------------------------------------------
Dep. Variable           LOsl_volKwh     LKrs_volKwh     LTrh_volKwh     LTro_volKwh     LBer_volKwh
Estimator                    IV-GMM          IV-GMM          IV-GMM          IV-GMM          IV-GMM
No. Observations               1095            1095            1095            1095            1095
Cov. Est.                    robust          robust          robust          robust          robust
R-squared                    0.9700          0.9371          0.9692          0.9640          0.9559
Adj. R-squared               0.9696          0.9364          0.9688          0.9636          0.9554
F-statistic               5.413e+04       3.183e+04       4.696e+04       3.121e+04       3.571e+04
P-value (F-stat)             0.0000          0.0000          0.0000          0.0000          0.0000
==================    =============   =============   =============   =============   =============
Intercept                 14.199***       13.986***       13.256***       12.905***       12.802***
                           (684.76)        (548.10)        (733.15)        (666.46)        (745.38)
Apr                     -0.0856***      -0.1360***      -0.1623***      -0.1091***      -0.1572***
                          (-6.9972)       (-11.210)       (-12.879)       (-12.662)       (-12.797)
Aug                     -0.3556***      -0.3401***      -0.4042***      -0.3680***      -0.4014***
                          (-20.260)       (-16.354)       (-28.752)       (-28.200)       (-29.038)
Feb                       0.0208**         -0.0099       -0.0253**       0.0295***        -0.0211*
                           (2.0021)       (-0.9616)       (-2.0144)        (3.4978)       (-1.8511)
Jan                      0.0343***         0.0185*         -0.0090       0.0257***          0.0032
                           (3.3267)        (1.7978)       (-0.7786)        (3.2513)        (0.2919)
Jul                     -0.4530***      -0.3906***      -0.4725***      -0.4085***      -0.4835***
                          (-25.961)       (-18.961)       (-33.548)       (-27.681)       (-36.015)
Jun                     -0.3153***      -0.3341***      -0.3777***      -0.3493***      -0.3690***
                          (-18.217)       (-17.935)       (-25.676)       (-24.956)       (-25.794)
Mar                      -0.0239**      -0.0648***      -0.0669***      -0.0282***      -0.0496***
                          (-2.2714)       (-6.4786)       (-5.6819)       (-3.5873)       (-4.7275)
May                     -0.1952***      -0.2240***      -0.2483***      -0.1786***      -0.2387***
                          (-12.395)       (-14.083)       (-18.253)       (-15.908)       (-19.550)
Nov                     -0.0407***      -0.1042***      -0.0924***      -0.0206***      -0.0634***
                          (-3.6275)       (-7.8623)       (-7.6026)       (-2.7194)       (-5.6751)
Oct                     -0.1474***      -0.2099***      -0.1859***      -0.0998***      -0.1815***
                          (-10.091)       (-12.981)       (-13.978)       (-8.1246)       (-14.166)
Osl_HDD                  0.0359***
                           (49.183)
Sep                     -0.3168***      -0.3088***      -0.3130***      -0.2379***      -0.3550***
                          (-17.725)       (-15.230)       (-23.721)       (-20.551)       (-23.449)
LOsl_oreKwh             -0.0317***
                          (-13.607)
Krs_HDD                                  0.0359***
                                          (36.244)
LKrs_oreKwh                             -0.0898***
                                          (-22.934)
Trh_HDD                                                  0.0295***
                                                          (53.331)
LTrh_oreKwh                                             -0.0096***
                                                          (-3.0267)
Tro_HDD                                                                  0.0270***
                                                                          (40.831)
LTro_oreKwh                                                              0.0229***
                                                                          (5.4395)
Ber_HDD                                                                                  0.0351***
                                                                                          (45.391)
LBer_oreKwh                                                                             -0.0180***
                                                                                          (-8.6455)
==================== =============== =============== =============== =============== ===============
Instruments                    LCO2            LCO2            LCO2            LCO2            LCO2
                         LCoalPrice      LCoalPrice      LCoalPrice      LCoalPrice      LCoalPrice
                          LGasPrice       LGasPrice       LGasPrice       LGasPrice       LGasPrice
                       NO1Inflow_dev   NO2Inflow_dev   NO3Inflow_dev   NO4Inflow_dev   NO5Inflow_dev
                         NO1Res_dev      NO2Res_dev      NO3Res_dev      NO4Res_dev      NO5Res_dev
---------------------------------------------------------------------------------------------------

T-stats reported in parentheses
```

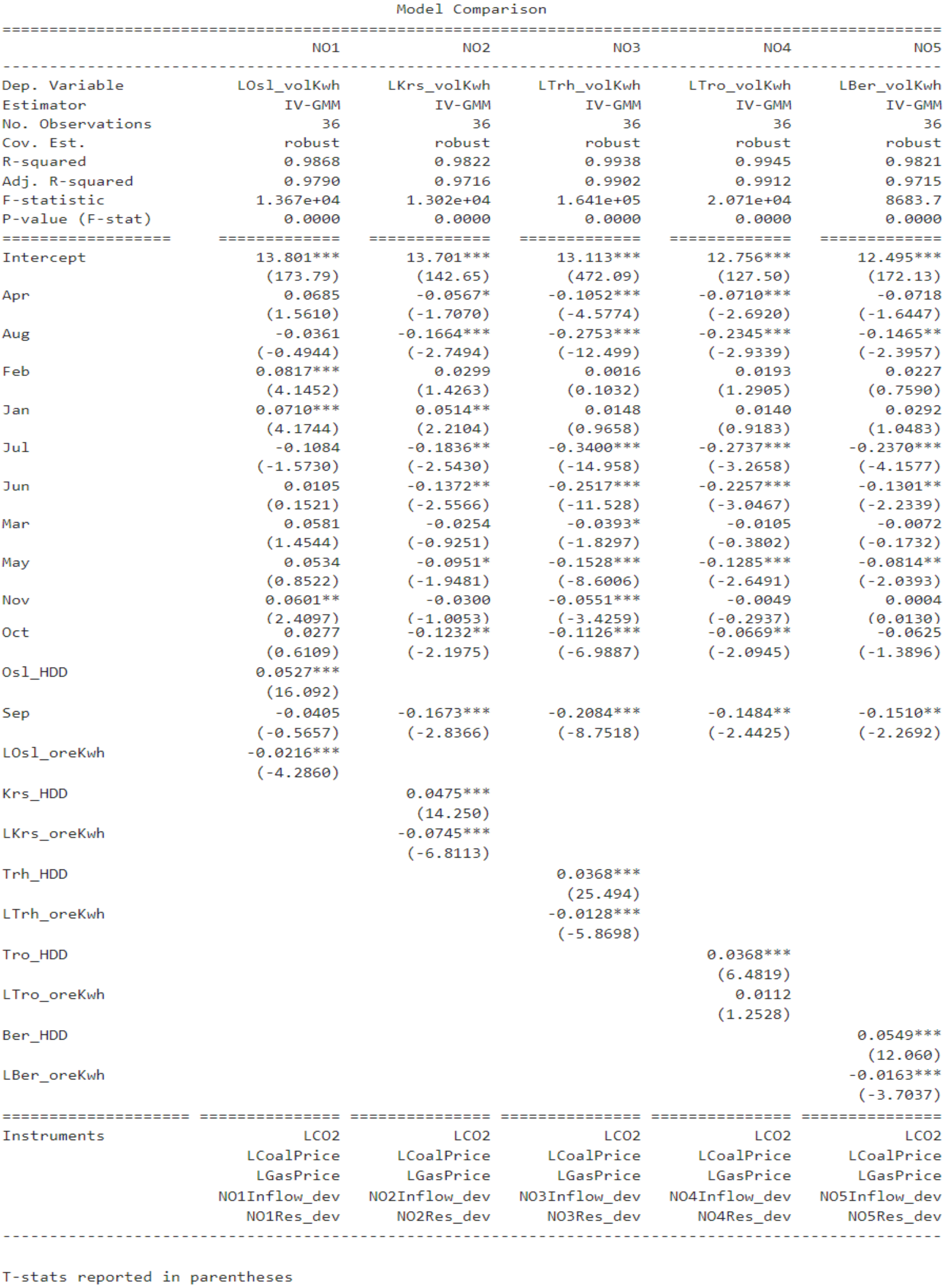
Appendix 5: Weekly spot price elasticity estimates.



```
                                      Model Comparison
=============================================================================================
                              NO1            NO2            NO3            NO4            NO5
---------------------------------------------------------------------------------------------
Dep. Variable         LOsl_volKwh    LKrs_volKwh    LTrh_volKwh    LTro_volKwh    LBer_volKwh
Estimator                  IV-GMM         IV-GMM         IV-GMM         IV-GMM         IV-GMM
No. Observations              156            156            156            156            156
Cov. Est.                  robust         robust         robust         robust         robust
R-squared                  0.9800         0.9686         0.9831         0.9832         0.9702
Adj. R-squared             0.9781         0.9658         0.9815         0.9816         0.9675
F-statistic             1.305e+04      1.064e+04      1.807e+04      1.135e+04         7689.2
P-value (F-stat)           0.0000         0.0000         0.0000         0.0000         0.0000
==================  =============  =============  =============  =============  =============
Intercept               14.068***      13.809***      13.176***      12.792***      12.692***
                         (276.36)       (240.19)       (342.51)       (383.30)       (311.18)
Apr                       -0.0399     -0.0857***     -0.1357***     -0.0790***     -0.1310***
                        (-1.3528)      (-3.5487)      (-5.1161)      (-4.8701)      (-4.6072)
Aug                    -0.2505***     -0.2203***     -0.3359***     -0.2743***     -0.3179***
                        (-5.6457)      (-5.2499)      (-10.819)      (-10.254)      (-9.2987)
Feb                        0.0252         0.0004        -0.0157        0.0277*        -0.0444
                         (1.0991)       (0.0226)      (-0.5851)       (1.7547)      (-1.6394)
Jan                       0.0388*         0.0288        -0.0030        0.0277*        -0.0033
                         (1.7869)       (1.4619)      (-0.1335)       (1.8864)      (-0.1417)
Jul                    -0.3471***     -0.2704***     -0.4029***     -0.3128***     -0.4064***
                        (-7.8517)      (-6.3365)      (-13.267)      (-11.710)      (-12.339)
Jun                    -0.2083***     -0.2124***     -0.3084***     -0.2666***     -0.2945***
                        (-4.6705)      (-5.3074)      (-10.299)      (-10.095)      (-8.3551)
Mar                        0.0039        -0.0372       -0.0449*        -0.0090        -0.0313
                         (0.1442)      (-1.6432)      (-1.8115)      (-0.5113)      (-1.2117)
May                    -0.1142***     -0.1351***     -0.1885***     -0.1327***     -0.1812***
                        (-3.1465)      (-4.4729)      (-6.6541)      (-6.2701)      (-6.6182)
Nov                       -0.0117     -0.0750***     -0.0777***         0.0022     -0.0591***
                        (-0.4307)      (-2.9229)      (-3.1544)       (0.1692)      (-2.6494)
Oct                    -0.0955***     -0.1401***     -0.1522***     -0.0715***     -0.1413***
                        (-2.7485)      (-4.1418)      (-5.3789)      (-3.4918)      (-4.8392)
Osl_HDD                 0.0419***
                         (21.729)
Sep                    -0.2244***     -0.2105***     -0.2503***     -0.1627***     -0.2819***
                        (-5.1987)      (-5.1773)      (-8.9344)      (-7.6806)      (-7.8008)
LOsl_oreKwh            -0.0284***
                        (-6.3217)
Krs_HDD                                0.0443***
                                        (18.493)
LKrs_oreKwh                           -0.0818***
                                       (-10.982)
Trh_HDD                                               0.0337***
                                                       (26.427)
LTrh_oreKwh                                           -0.0109**
                                                      (-1.9811)
Tro_HDD                                                              0.0336***
                                                                      (22.282)
LTro_oreKwh                                                           0.0170**
                                                                      (2.3344)
Ber_HDD                                                                               0.0426***
                                                                                       (18.020)
LBer_oreKwh                                                                          -0.0164***
                                                                                      (-4.2420)
==================== ============== ============== ============== ============== ==============
Instruments                  LCO2           LCO2           LCO2           LCO2           LCO2
                       LCoalPrice     LCoalPrice     LCoalPrice     LCoalPrice     LCoalPrice
                        LGasPrice      LGasPrice      LGasPrice      LGasPrice      LGasPrice
                    NO1Inflow_dev  NO2Inflow_dev  NO3Inflow_dev  NO4Inflow_dev  NO5Inflow_dev
                       NO1Res_dev     NO2Res_dev     NO3Res_dev     NO4Res_dev     NO5Res_dev
---------------------------------------------------------------------------------------------

T-stats reported in parentheses
```

Appendix 6: Monthly spot price elasticity estimates



```
                                          Model Comparison
====================================================================================================
                                 NO1             NO2             NO3             NO4             NO5
----------------------------------------------------------------------------------------------------
Dep. Variable            LOsl_volKwh     LKrs_volKwh     LTrh_volKwh     LTro_volKwh     LBer_volKwh
Estimator                     IV-GMM          IV-GMM          IV-GMM          IV-GMM          IV-GMM
No. Observations                  36              36              36              36              36
Cov. Est.                     robust          robust          robust          robust          robust
R-squared                     0.9868          0.9822          0.9938          0.9945          0.9821
Adj. R-squared                0.9790          0.9716          0.9902          0.9912          0.9715
F-statistic                1.367e+04       1.302e+04       1.641e+05       2.071e+04          8683.7
P-value (F-stat)              0.0000          0.0000          0.0000          0.0000          0.0000
==================     =============   =============   =============   =============   =============
Intercept                  13.801***       13.701***       13.113***       12.756***       12.495***
                            (173.79)        (142.65)        (472.09)        (127.50)        (172.13)
Apr                           0.0685        -0.0567*      -0.1052***      -0.0710***         -0.0718
                            (1.5610)       (-1.7070)       (-4.5774)       (-2.6920)       (-1.6447)
Aug                          -0.0361      -0.1664***      -0.2753***      -0.2345***       -0.1465**
                           (-0.4944)       (-2.7494)       (-12.499)       (-2.9339)       (-2.3957)
Feb                        0.0817***          0.0299          0.0016          0.0193          0.0227
                            (4.1452)        (1.4263)        (0.1032)        (1.2905)        (0.7590)
Jan                        0.0710***        0.0514**          0.0148          0.0140          0.0292
                            (4.1744)        (2.2104)        (0.9658)        (0.9183)        (1.0483)
Jul                          -0.1084       -0.1836**      -0.3400***      -0.2737***      -0.2370***
                           (-1.5730)       (-2.5430)       (-14.958)       (-3.2658)       (-4.1577)
Jun                           0.0105       -0.1372**      -0.2517***      -0.2257***       -0.1301**
                            (0.1521)       (-2.5566)       (-11.528)       (-3.0467)       (-2.2339)
Mar                           0.0581         -0.0254        -0.0393*         -0.0105         -0.0072
                            (1.4544)       (-0.9251)       (-1.8297)       (-0.3802)       (-0.1732)
May                           0.0534        -0.0951*      -0.1528***      -0.1285***       -0.0814**
                            (0.8522)       (-1.9481)       (-8.6006)       (-2.6491)       (-2.0393)
Nov                         0.0601**         -0.0300      -0.0551***         -0.0049          0.0004
                            (2.4097)       (-1.0053)       (-3.4259)       (-0.2937)        (0.0130)
Oct                           0.0277       -0.1232**      -0.1126***       -0.0669**         -0.0625
                            (0.6109)       (-2.1975)       (-6.9887)       (-2.0945)       (-1.3896)
Osl_HDD                    0.0527***
                            (16.092)
Sep                          -0.0405      -0.1673***      -0.2084***       -0.1484**       -0.1510**
                           (-0.5657)       (-2.8366)       (-8.7518)       (-2.4425)       (-2.2692)
LOsl_oreKwh               -0.0216***
                           (-4.2860)
Krs_HDD                                    0.0475***
                                            (14.250)
LKrs_oreKwh                               -0.0745***
                                           (-6.8113)
Trh_HDD                                                    0.0368***
                                                            (25.494)
LTrh_oreKwh                                               -0.0128***
                                                           (-5.8698)
Tro_HDD                                                                    0.0368***
                                                                            (6.4819)
LTro_oreKwh                                                                   0.0112
                                                                            (1.2528)
Ber_HDD                                                                                    0.0549***
                                                                                            (12.060)
LBer_oreKwh                                                                               -0.0163***
                                                                                           (-3.7037)
==================== =============== =============== =============== =============== ===============
Instruments                     LCO2            LCO2            LCO2            LCO2            LCO2
                          LCoalPrice      LCoalPrice      LCoalPrice      LCoalPrice      LCoalPrice
                           LGasPrice       LGasPrice       LGasPrice       LGasPrice       LGasPrice
                       NO1Inflow_dev   NO2Inflow_dev   NO3Inflow_dev   NO4Inflow_dev   NO5Inflow_dev
                          NO1Res_dev      NO2Res_dev      NO3Res_dev      NO4Res_dev      NO5Res_dev
----------------------------------------------------------------------------------------------------

T-stats reported in parentheses
```

Appendix 7: Percentage change in household electricity consumption

$$\%\Delta\ in\ demand$$
$$= monthly\ PED \text{ x } \frac{compensation\ spot\ price - no\ compensation\ spot\ price}{no\ compensation\ spot\ price} \text{ x } 100$$

NO1=> $= -0.0216 \text{ x } \frac{150-75}{75} \text{ x } 100 = -2.19\%$

NO2=> $= -0.0745 \text{ x } \frac{168-76}{76} \text{ x } 100 = -9.02\%$

NO3=> $= -0.0128 \text{ x } \frac{47-45}{45} \text{ x } 100 = -0.06\%$

NO4=> $= 0.0112 \text{ x } \frac{33-38}{38} \text{ x } 100 = -0.15\%$

NO5=> $= -0.0163 \text{ x } \frac{151-75}{75} \text{ x } 100 = -1.65\%$

Appendix 8: Percentage change in purchase price of electricity

$$\%\Delta\ in\ purchase\ price$$
$$= \frac{compensation\ purchase\ price - no\ compensation\ purchase\ price}{no\ compensation\ purchase\ price} \text{ x } 100$$

NO1=> $= \frac{177.9-162.9}{162.9} \text{ x } 100 = 9.21\%$

NO2=> $= \frac{182.1-164.1}{164.1} \text{ x } 100 = 10.97\%$

NO3=> $= \frac{128.9-125.4}{125.4} \text{ x } 100 = 2.79\%$

NO4=> $= \frac{111.4-116.6}{116.6} \text{ x } 100 = -4.46\%$

NO5=> $= \frac{177.9-162.9}{162.9} \text{ x } 100 = 9.21\%$

Appendix 9: purchase price elasticity of electricity demand.

$$Purchase\ price\ elasticity\ of\ demand = \frac{\%\Delta\ in\ demand}{\%\Delta\ in\ purchase\ price}$$

NO1=> $= \frac{-2.19}{9.21} = -0.238$

NO2=> $= \frac{-9.02}{10.9} = -0.822$

NO3=> $= \frac{-0.06}{2.79} = -0.022$

NO4=> $= \frac{-0.15}{-4.46.} = 0.034$

NO5=> $= \frac{-1.65}{9.21} = -0.179$

Appendix 10: Calculation of overall monthly spot price elasticity of demand

$$Weighted\ Monthly\ spot\ price\ elasticity = \text{monthly elasticity} \times \frac{Population\ of\ Muncipality}{Total\ Population}$$

NO1=> $= -0.0216 \times \frac{709037}{1404588} = -0.011$

NO2=> $= -0.0745 \times \frac{115569}{1404588} = -0.006$

NO3=> $= -0.0128 \times \frac{212660}{1404588} = -0.002$

NO4=> $= 0.0112 \times \frac{77992}{1404588} = 0.001$

NO5=> $= -0.0163 \times \frac{289330}{1404588} = -0.003$

$$Overall\ monthly\ spot\ price\ elasticity\ of\ demand^{18} = \sum_{n=1}^{5}(Weighted\ price\ elasticity\ NO1 - NO5)$$

---

[18] NO4 is excluded because the monthly price elasticity coefficient is not statistically different from zero.

$$= (-0.011) + (-0.006) \; + (-0.002) + (-0.003) = \; \mathbf{-0.022}$$

Appendix 11: Calculation of overall monthly purchase price elasticity of demand

$$Weighted\ Monthly\ purchase\ price\ elasticity$$
$$= \text{ monthly elasticity } \times \frac{Population\ of\ Muncipality}{Total\ Population}$$

NO1=> $= -0.238 \; \times \frac{709037}{1404588} = \; -0.120$

NO2=> $= -0.822 \; \times \frac{115569}{1404588} = \; -0.067$

NO3=> $= -0.022 \times \frac{212660}{1404588} = \; -0.003$

NO4=> $= 0.034 \times \frac{77992}{1404588} = \; 0.002$

NO5=> $= -0.179 \; \times \frac{289330}{1404588} = \; -0.037$

$$Overall\ monthly\ purchase\ price\ elasticity\ of\ demand$$[19]

$$= \sum_{n=1}^{5} (Weighted\ price\ elasticity\ NO1 - NO5)$$
$$= (-0.120) + (-0.067) \; + (-0.003) + (-0.037) = \; \mathbf{-0.227}$$

---

[19] NO4 is excluded because the monthly price elasticity coefficient is not statistically different from zero.

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