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# Heterogeneity in demand responses to electricity spot prices *

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May 8, 2019
Preliminary version

**Abstract**

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**Keywords:** • • • •

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# 1 Introduction

The focus of this paper is how the hour-by-hour electricity consumption responds to hourly electricity prices for firms and households respectively. We use hourly observations since January 2016 on aggregated consumption for 52 of the local grid companies in Denmark.

To account for heterogeneity across the grid companies we estimate the price-elasticity both grid-by-grid and on aggregate while controlling for grid-level specific effects. The problems of endogeneity resulting from the simultaneity of demand and supply mechanics is handled by instrumenting the hourly price by both lagged prices and the prognosis for wind power production.

*SECTION ON OUR RESULTS*

is this precise?

Efficient and environmentally sustainable electricity provision implies that electricity production and thus electricity supply fluctuates according to weather conditions, namely wind speed and sunshine. This along with changes in the distribution of electricity implies that consumers are increasingly exposed to more volatile electricity prices. Heterogeneity and changes over time in demand responses can help predicting potential demand flexibility in the future as this is the main limit for further increasing the reliance on wind and solar power along with the infeasibility of electricity storage. From a policy point of view this can also reveal the potential for time-of-use tariffs which is often regarded as the best policy tool for incentivizing behavioural changes towards a more sustainable electricity consumption.

# 2 Literature review

Estimating price elasticities of electricity and has been an area of interest for economists for a long time and increasingly so. Deregulation of the electricity market made it important to measure how a broad spectre of consumers (residential, industrial and commercial) react to changing electricity prices.

The supply side is becoming even more volatile following the increased share of renewable energy driven by political goals and competitive establishment costs. In the case of a very inelastic electricity demand Wolak and Patrick (2001) outlines how an oligopolistic supply side can capitalize on intraday peaks in demand, however, firms that are able to have a more flexible energy use can face clear advantages in the market while on aggregate making it possible to further increase the share of renewables in the electricity supply.

Thus, it is of importance to conduct better empirical estimations of how consumers respond at a micro level - in particular because taxes often are used as a policy tool to incentivize a decreased consumption of power. In the following we highlight the key contributions in this area.

## 2.1 Modest price elasticity of demand

Patrick and Wolak (2001) were among the first to estimate the demand-side responses to electricity prices for intraday-markets. For firms in England and Wales they find the overall magnitude of the real-time price elasticity of electricity demand to be quite low, though significant. Similar results on an hour-to-hour basis are found for the Netherlands according to Lijesen (2007).

Regarding residential electricity demand most estimates of the demand response to price changes of electricity are in the range -2.01 to -0.004 in the short run and -2.25 to -0.04 in the long run as reported in Espey and Espey (2004), who does a meta analysis of 248 estimates in 36 non-time-of-day studies. With the median being -0.28 in the short run and -0.81 in the long run, elasticities tend to be bigger in the long run which is in accordance with economic reasoning since consumers better can better modify their capital stock in the long term. These estimates rely on a wide range of different empirical approaches.

## 2.2 Heterogeneous effects

Fan and Hyndman (2011) estimate yearly own-price elasticities for Southern Australia at the aggregated level using consumption on a half-hourly basis using a log-linear model. The authors find heterogeneous effects across quantiles, depending on how extreme the weather is.

Though only being able to use the average firm-level responses within each code of British Industrial Classification (BIC) Patrick and Wolak (2001) find a substantial heterogeneity across industries not only in terms of the magnitude of the own-price elasticity of electricity demand but also in the within-day patterns of cross-price elasticities.

## 2.3 Endogeneity problems

Estimating demands-side responses to shifting electricity prices is associated with potential problems of endogeneity as price and consumptions/production are simultaneous. That is, a higher expected demand can push up the overall prices and vice versa. An example of such a mechanism is that increasing demand-side competition can lead to imports of electricity from more expensive energy sources (Burke and Abayasekara, 2017) resulting in price increases. Therefore lagged prices are often included to avoid an omitted variable bias and to combat endogeneity (Lijesen, 2007), however, this inclusion creates a dynamic bias instead. This is , however, not likely to be as big of an issue in our estimation, because we only consider demand responses in the short run and the bias is likely to be bigger when estimating long term elasticities (Okajima and Okajima, 2013).

Also an unobserved factor can influence both prices and demand.

Bönte et al. (2015) were able to use wind speed as an instrument for the spot market price, however, the effectiveness of this strategy might be isolated to Germany due to their feed-in-tariff for Renewable Energy Sources that is designed to directly affect the price. Likewise, Graf and Wozabal (2013) tried using emissions right and prices for primary energy as instruments but to limited success. For the US Burke and Abayasekara (2017) use the state level share of coal and hydro as an instrument for yearly prices as they have generally been the two cheaper source of electricity.

## 2.4 Estimation methods

When data is limited to total electricity demand it is common to apply a two stage least square (2SLS) regression and either include a time trend (Lijesen, 2007) or estimate the elasticity year-by-year (Bönte et al., 2015).

For more dis-aggregated data different methods can be utilized. Unobserved heterogeneity must be accounted for, usually by including unit-specific fixed-effects. On household level data one option is to use Seemingly Unrelated Regression Equations (SUR/SURE) (Vesterberg et al., 2014).

# 3 Economic theory

## 3.1 The electricity market

In order to understand how the price of electricity is formed it is necessary understand how the nature of the supply side, demand side and the workings of the electricity market. The electricity market differs from the majority of other markets because demand and supply must synchronize completely at all times. Storing electricity is possible, but at best highly inefficient and thus too costly to implement practically. Instead supply must be at least as great as demand at all times if blackouts are to be avoided. Historically this has been ensured through the production of a surplus of electricity. This is, however, costly and associated with a negative externality due to carbon dioxide emissions from power plants.

The electricity market consists of both the physical infrastructure required for electricity generation and transport while it on the other hand is also a well-organized market.

There are several ways to organize the market. In the European Union most of the decisions related to the organization of the energy market happen at supra-national level. In recent years the electricity market has undergone great changes following the Third Energy Package. The package aims at improving the functioning of the energy market by ensuring more competition and transparency through unbundling of suppliers from operators, greater independence of regulators, more cross-border cooperation and better transparency in retail markets. [1]. This has increased the number of actors on the electricity market that now comprises producers, distributors, TSO, DSO, balance responsible. Actors on the market This improve conditions for the consumers while also has perspective of climate. decarbonize "Clean Energy for all Europeans" package.

In recent years the electricity market has undergone many changes to induce competition and reduce surplus production and thus "unnecessary" carbon dioxide emissions. The

[1] https://ec.europa.eu/energy/en/topics/markets-and-consumers/market-legislation

move towards more market liberalization still recognizes that that the distribution net constitutes a natural monopoly. In many countries including Denmark the firm in charge maintaining and building the grid is still state-controlled while the remaining market operators are private. Competition is then ensured by letting thirds parties get access to the electric grids in a transparent way. This is only one of several ways to organize a market which has been adopted by the EU, that furthermore wants to promote a single energy market. This single market implies linking the electrical grids throughout Europe such that the electricity price is the same across all of Europe. As of now Nord Pool has already combined 13 markets; the Nordic countries, the Baltic countries, Germany, Austria, France, Belgium, the Netherlands and the UK, now constitute a single electricity market. The price still varies across countries due to limited cross border transfer capacity. For instance electricity consumers in Denmark also face different prices depending on what side of The great Belt they are situated. [2]

Firms and residential households enter the energy market differently. They face different prices that are formed in different ways. This is described further below.

### 3.1.1 The retail market

The retial market is comprised by the suppliers and the consumers. The group of consumers consists of both small firms and residential consumers. In the retail-market the suppliers act as intermediaries between the power generators and the consumers. The suppliers then enter the wholesale market (described below) on behalf of the retail consumers and buy electricity from the generators. The consumers are then offered a contract that typically implies that the retail consumers face a single fixed price.

The residential electricity consumers have historically not been treated as 'genuine demanders' (Kirschen, 2003). Instead of facing the actual cost of electricity they instead sign contracts where a distributor acts as a middleman that trades electricity in the market on behalf of its customers, but they receive a premium for undertaking the market risk. The distributors and the consumers then undergo contracts where the price of electricity is typically fixed for up to a year. This insulates the retail consumers from the spot price that better reflects the cost of electricity production at a given point in time. This "distance" to the actual price of electricity is exacerbated even more by the tariffs on electricity that the residential consumers face. The electricity tariffs are particularly high in Denmark where they make up around 68 percent of the price paid for electricity. [3]

It is, however, worth noting that the way residential customers are settled is likely to change in the future as smart meters are adopted more widely. For instance Denmark has decided to enrol smart meters to all consumers by 2020 in the Energy Agreement from

[2] https://www.nordpoolgroup.com/the-power-market/Integrated-Europe/

[3] https://www.dr.dk/nyheder/penge/skatter-og-afgifter-aeder-din-elregning-0

2013. In Denmark several grid companies have already rolled out the smart meters which allows for more flexible settlement such that demand can respond to different prices.

### 3.1.2 The wholesale market

Large scale electricity consumers [4] enter into the wholesale market for electricity. Here electricity is bought and sold in different markets depending on how well in advance before the actual time of delivery the electricity is traded. Electricity is thus traded via

**Long term contracts** Electricity bought and sold further ahead of time than the day before consumption can be agreed upon by undergoing long term contracts or from trades in the forward market. In the forward market futures, forwards, Electricity Price Area Differentials (EPADs) and put and call options are traded. The products are traded either bilaterally or as stocks at NASDAQ OMX Commodities and serves as a way to reduce risks by ensuring a fixed price or insurance against realized price differentials. The value of the futures (and forwards) shifts based on the reference price that is the official nordic day-ahead price.

**The day-ahead market (The spot-market)** The day-ahead market is where the majority of electricity is traded either for specific hours or blocks thereof. The price is determined in an auction where all bids and asks are aggregated to form the hourly supply and demand - while the market clearing price is determined by where they intersect subject to the capacity constraints in the market. All the actors in the market (generators, distributors and wholesale clients) pay or receive the same price within a price region. Distributional bottlenecks between regions entails price differences within the market. This price, also referred to as the spot price, thus reflects how much power producers believe they can supply which in turn depends on weather prognoses, expected plant shutdowns etc. but also how much consumers (retail and wholesale) are expected to consume given the physical constraints of the electric grid. It should be noted that Nord Pool Spot have both lower and upper price caps outside of which bids are reduced by a fixed percentage rate.

**The intra-day market** The day-ahead market closes at 12 pm the preceding day but from 2 pm and up until an hour before time of delivery trade can occur on the intra-day market where. Here electricity is sold in blocks, hours and 15 minute intervals. Similar to the spot-market this is operated by Nord Pool. The quantities traded in the intra-day market is much smaller than the day-ahead market but this is likely to change as a larger share of the production capacity is constituted by renewables.

**The balancing market** If gaps between supply and demand reamin after the closing of the intra-day market they must be balanced by the responsible system operator. Each of the actors in the market rarely live completely up to their obligations for instance

[4] In Denmark this entail firms that consume more than 100.000 kWh a year, to whom hourly settlement is obligatory

more or less wind power can be produced or firms may consume unforeseeable large amounts of electricity. This necessitates that the responsible Transmission System Operator (TSO), Energinet[5] in Denmark, balances during the delivery period.

## 3.2 Production of electricity

Electricity is supplied by different kinds of power plants that each has their own advantages in terms of when they can produce and how fast they reach an efficient production level. In most of Europe the most common types of power include lignite, coal, gas, nuclear, solar, wind and hydro, ranged from the more emission intense to the least. The marginal cost of electricity from renewable sources are far because almost no (costly) inputs are needed, but these typically require certain weather conditions outside the control of the supplier. Coal and lignite power plants have higher costs running and have to be running for a while to reach efficient production, but do not rely on external parameters. These are typically used as a part of the base-load and are typically used as part of the base-load. The available production capacities and weather conditions thus shape the supply curve.

For each supplier it is optimal (at least in the short term) to ask for the marginal cost of producing electricity at a given point in time. This implies that the supply curve and thus the order in which generators are dispatched reflects the merit order. If the weather conditions are right electricity from renewable sources are dispatched first and then hard coal and lignite plants. If the share of renewables in the productional capacity is large the supply curve is shifted to the right. The marginal costs of electricity production from carbonizing plants are even higher in the EU where the supplier has to buy emission quotas such that renewable and low-emission power production is prioritized.

All receive the same price such that low cost production rewarded. Convergence of prices would be obtained if the interconnection capacity is sufficient.

In the case where the demand for electricity is particularly high i.e. at a peak costs (financial and external) very high are also very high and mainly high-emission. Demand peak => higher prices that are sufficiently high to cover costs of higher cost production units when answering to spikes in demand.

Cost of capacity is charged as a flat transmission grid fee to all consumers.

*Negative prices. Renewables and must-run capacities may in combination produce a greater supply of power than what is demanded in which case the price turns negative. This reflects that there a cost associated to running the plant that producers will want to cover to any extent possible even if this means a. For our analysis we aim at estimating the implicit own-price elasticity of demand by assuming the individual firms takes the spot price as given and plans its hourly electricity use accordingly.

[5] https://en.energinet.dk

## 3.3 Theory of demand-side response to electricity prices

The market of electricity itself differs from most other markets as described above. This complexity of the market and its price formation the price is even higher because the nature of the demand for electricity is of indirect character. Electricity demand, for retail and wholesale consumers alike, is shaped by the demand for the use of other appliances that require electricity to function. This indirectness implies that even less information on costs is available to the consumer which makes responding difficult. In order to calculate the price of using an appliance knowledge of both electricity prices and how much each device uses is required. This implies that many consumers have to rely on behavioral rules when deciding how much energy to consume cf. (Kirschen, 2003).

$$\ln e_{i,t} = \beta_0 + \beta_1 \ln E_{i,t-1} + \beta_2 P_{it} \tag{3.1}$$

In terms of demand of electricity there is an important distinction to make between residential and wholesale electricity consumers. They differ in how flexible they are and how they pay for electricity such that different elasticities are to be expected. But it is common for both types of consumers that electricity is hard to replace. There are no close substitutes which in suggests that demand should be quite inelastic. Furthermore moves toward a society that in general is more electrified may also lower the own-price elasticity of electricity demand. For wholesale consumers electricity typically constitute a greater share of all costs as compared to residential consumers. Because of this wholesale consumers face an hourly price which even though it requires monitoring allows firms to better reduce their consumption when prices are high. Firms are also mostly exempt from paying tariffs on their electricity.
On the other hand firms are also subject to more restrictions in regards to when they operate as this is typically in business hours depending, of course, on the nature of the firm i.e. what industry it is in. Similarly firms are often required to deliver a product or a service subject to a contract which does not allow firms to postpone production for too long.

The residential consumers on the other hand. Two obvious limitations to the flexibility of demand is that demand responses require knowledge of prices and that one can assume taking action in order to reduce demand at a certain hour carries a fixed cost of e.g. $5 which makes is optimal for small consumers to ignore spot market except at extreme prices or when time-of-use (TOU) tariffs are introduced (Wolak, 2011).

This all adds up to a weak elasticity. Another aspect has to do with how electricity is regarded as a good. (Kirschen, 2003) points to the fact that electricity is regarded as a good that is indispensable and essential to quality of life. It has always been marketed as easily accessible in terms of usage and availability although this may not genuinely be the case. In addition all consumption of electricity is indirect and consumption happens through the usage of other goods such as electrical appliances, entertainment etc. Distinction between some consumption that is foregone - lightning, listening to music, the radio etc. while other is postponed (dryer, washing machine etc.)

It is likely to get easier to smooth load profiles in the future as smart meters become more common, but as of now they are not rolled out yet. This is a necessity for interruptable contracts.

This does not allow price spikes to form which may not be a good thing because they highlight what state the market is in - so it is unclear to the producers.

Something about tariffs. They are large may overshadow any price fluctuations and thus make it more difficult for residential consumers to adjust their consumption.

(Kirschen, 2003)

# 4 Data and variables

We have scraped most of our data from various web sources in respect of the terms of use. The descriptive statistics for the main variables are shown in Table 2 below.

For the regressions we log-transform electricity consumption, the number of electricity meters, and the electricity spot price. Before taking the natural logarithm the variables are censored with 1 as the lower bound whereby we loose some information as the spot price is negative for a few instances due to exceed wind power production.

## 4.1 Grid-level consumption

The Danish Transmission System Operator (TSO), Energinet provides public access to hourly aggregated consumption data[6] since January 2016 for each of the 52 grid companies grouped by hourly-settled consumption, flex settled consumption, and residual consumption. This allows us to distinguish between wholesale and retail consumption. Hourly-settled consumption consists of all firms with an annual electricity consumption of at least 100,000 kWh. Flex-settled consumption was introduced in January 2018 such that households and small firms can also have their electricity consumption settled flexibly according to hour-by-hour prices. Though installation of smart meters to enable flex-settling is only being introduced gradually, this allows a portion of residential consumers and small firms to respond to price changes at an hourly rather than a quarterly basis. The residual consumption is the remaining retail electricity consumption for which flex-settling is not used, thus, including all households and small firms till December 1 2017 and a majority throughout 2018 as well.

For each grid we include the number of metering points[7] by each of the three consumer categories. This data is monthly by the 1$^{\text{st}}$ of the month. For studies on state-level data it is likewise common to control for size (Burke and Abayasekara, 2017).

[6] Scraped from energidataservice.dk/en/dataset/consumptionpergridarea using their transparent API via SQL statements.

[7] Received from Energinet after request.

**Figure 1:** Electricity consumption by hour (business days)

## 4.2 Spot market prices and wind power prognosis

We include the hour-by-hour spot market price on the day-ahead-market for the price region DK1 or DK2 depending on where the grid company is located (see section 3.1).

**Figure 2:** Time series for spot price and total consumption (business days)

An important factor for the spot price on the day-ahead-market is the hour-by-hour wind power prognosis[8] for the following day.

**Figure 3:** Wind power prognosis and spot price by hour (business days)

**Table 1:** Correlation matrix for consumption, spot price, and wind power prognosis

## 4.3 Time-of-use tariff

From December 2017 grid companies have been allowed to introduce time-of-use (TOU) tariffs for retail consumption in order to send signals that can direct the more flexible tasks away from the peak hours around dinnertime. Thus, two of the bigger grid companies have already introduced TOU tariffs for the peak-hours 5-7 PM (from here written as hours 17-19) for the months October-March in which electricity consumption is also higher due to the lack of daylight. While NRGI initially only runs an experiment for a smaller group of flex-settled consumers Radius is introducing a full-scale TOU tariff scheme while exchanging the old prepayment meters with smart meters for the 600,000 retail customers in the Copenhagen metropolitan area.[9]

The variable for the TOU tariff represents the share of retail customers in Radius exposed to the tariff. As seen in Figure 4 and Table 2 below the increasing share ends near 60 pct. in December 2018.

**Figure 4:** Time series for retail consumption and no. meters in Radius

## 4.4 Weather data

The outside temperature is relevant to the extent that electrical heaters or air conditioning is used (Lijesen, 2007; Vesterberg et al., 2014). As the electricity consumption ceteris paribus is expected to be higher for both low-end and high-end temperatures, $temperature^2$

[8] 'Elspot prices' and 'Wind power prognosis' by price region and year is updated daily after 2PM by Nord Pool and downloadable at nordpoolgroup.com/historical-market-data

[9] See ing.dk/artikel/nu-loebes-fleksible-elforbrug-omsider-gang-209251 (Danish).

is included as well.[10]

Lighting is used more in the absence of daylight. Therefore, an indicator for daytime is included such that $daytime = 1$ for hours between sunrise and sunset and e.g. $daytime = 0.25$ for $hour = 7$ if sunrise was a quarter past 7.[11]

Taking advantage of the dense size of Denmark, temperature and daytime are not scraped by the location of each of the 52 grid companies which often cross municipality-borders but for the two most populace municipalities and applied to all grids within that price region.[12]

## 4.5 Time variables

Year dummies as well as a time trend indicating the number of days since January 1 2016 are included to account for economic growth (increase), technological progress (decrease) (Lijesen, 2007), or compositional changes that can affect electricity consumption other than the number of meters.

Danish bank holidays as well as a few other common holidays with lower wholesale electricity consumption[13] are taken into account in order to do sample split regressions for business days and non-business days, the latter including holidays and weekends.

**Table 2:** Descriptive statistics

| | mean | sd | min | p50 | max |
|---|---|---|---|---|---|
| Wholesale electricity use | 34694.1 | 84721.53 | 63.157 | 5928.1 | 757557.1 |
| Household electricity use | 29160.88 | 75328.71 | 141.67 | 5833.974 | 906396.4 |
| Number of wholesale meters | 930.5284 | 2482.449 | 7 | 140.5 | 17674 |
| Number of retail meters | 57736.69 | 150765 | 858 | 14371 | 1006061 |
| - of which flex-settled | 4150.065 | 37655.51 | 0 | 0 | 596267 |
| - of which residual | 53586.63 | 136813.6 | 855 | 14357 | 998864 |
| Electricity spot price | 253.0939 | 108.095 | -398.61 | 235 | 1898.9 |
| Wind power prognosis same region | 1069.817 | 911.7859 | 0 | 787 | 3973 |
| Wind power prognosis other region | 482.2171 | 568.4732 | 0 | 313 | 3973 |
| Price region DK1 | .8269231 | .3783139 | 0 | 1 | 1 |
| Share time-of-use tariff | .0001431 | .0081221 | 0 | 0 | .5926748 |
| Temperature | 9.101392 | 6.918248 | -11.9 | 8.7 | 31.4 |
| Daytime | .5135293 | .4857424 | 0 | .6666667 | 1 |
| Time trend | 547.4559 | 316.4119 | 0 | 547 | 1095 |
| Holiday (not in a weekend) | .0437643 | .2045702 | 0 | 0 | 1 |
| Observations | 1367600 | | | | |

[10] Scraped via iterative lookups in the records of the Danish Meteorological Institute at dmi.dk/vejrarkiv/

[11] Sunrise and sunset are scraped for each date in the sample via iterative lookups at soltider.dk

[12] Temperature is for the municipalities of Aarhus and Copenhagen respectively while sunrise and sunset are for the City Hall Square in each of the two cites.

[13] January 2 (the day after New Year's Day), May 1 (International Workers' Day), Friday after Ascension Day, June 5 (Constitution Day), last Friday before Christmas, and the days between Christmas and New Year's. All holidays according to kalendersiden.dk

# 5 Empirical strategy

## 5.1 Baseline model

Our baseline model is a Random Effects (RE) model to be estimated using feasible Generalized Least Squares (fGLS). Electricity consumption $e$ for grid company $i$ at time $t$ (date by hour) is given by:

$$\begin{aligned} \ln e_{it} = \varepsilon \ln \hat{p}_{rt} + \delta \ln n_{im} + \boldsymbol{w}_{rt}^{'} \lambda + \gamma \ days \\ + \eta_{year} + \eta_{week} + \eta_{month} \cdot \eta_{hour} + \eta_{day} \cdot \eta_{hour} + \psi_i + u_{it} \end{aligned} \tag{5.1}$$

Where $p$ is the electricity spot price in price region $r$ at time $t$, $n$ is the number of meters at the beginning of the month $m$, $\boldsymbol{w}$ is a vector of weather variables for the given price region $r$ at time $t$. Time variables include the time trend $days$. The $\eta$'s' represent dummies for each year and each ISO week number, as well as dummies for hour of the day interacted with each month and each day of the week respectively. $\psi_i$ is the grid-specific time-invariant constant term that is treated as random and $u_{it}$ is the idiosyncratic error term.

We use a log-log specification for electricity consumption, the spot price, and the number of meters as it allows us to model demand responses across grid areas of different size. Furthermore, log-log is the more standard specification which allows for a more direct comparison to the results in other studies (Burke and Abayasekara, 2017). Other attractive properties include that the estimation provides the elasticity directly and does not predict non-positive electricity consumption, furthermore, the specification reduces the impact of outliers and are found to reduce systematic patterns in the estimated residuals (Burke and Abayasekara, 2017).

The specification is first estimated for each hour of the days to identify peak-hours, off-peak, and the shoulder-period.

## 5.2 Instrumenting for prices

To circumvent the simultaneity problem described in section 2.3 we consider using lagged prices or wind-power production as price instruments. The latter makes sense as the marginal cost of production is close to zero, such that a high expected wind-power production will increase the overall supply capacity and drive down the prices. As an overproduction of wind power will lead to transmission to neighboring bidding areas, the wind-power production prognosis for the other bidding area in Denmark is also included as an instrument.

## 5.3 Effect of Time-of-use tariff

Since 2018 flex-settled consumers in the Copenhagen metropolitan area are charged a time-of-use (TOU) tariff for the hours 17-19. To estimate this effect the baseline specification (5.1) is estimated for the hours 17-19 solely for the grid company Radius using 2SLS, thus, without the grid-area random effect $\psi_i$ but including a term for the effect of the TOU tariff:

$$\beta \frac{nf_{month}}{nr_{month}} \tau_{year,month} \tag{5.2}$$

Where $nf$ is the number of flex-settled meters by month, $nr$ is the total number of meters for retail customers, and $\tau$ is a dummy for being in January-March or October-December in 2018. To isolate the effect of the TOU tariff we need to assume that residual consumers do not react on the tariff, on the contrary their consumption is assumed to follow the same hour-by-day, hour-by-month, and week patterns as the previous years and the effect of year dummies and the time trend to be evenly distributed across the year.

As Figure 4 shows, a weakness is that the monthly records for the number of flex-settled meters provides a lack which can result in an upward bias of $\hat{\beta}$.

### 5.4 Random Effects estimation

*Why Random Effects estimation is more efficient for the present data than both Least Squares Dummy Variables (LSDV) estimation, Fixed Effects (FE) estimation, Generalized Methods of Moments (GMM).*

### 5.5 Tests for endogeneity and overidentifying restrictions

### 5.6 Robustness checks

The robustness of the elasticity for wholesale electricity demand in the peak-hours 12-15 is tested by splitting the sample by region, year, and month respectively to look for heterogeneous effects. Furthermore, we run do the estimation for each grid area and for the mean of each price region using 2SLS. As the FE estimates are identical, however less efficient, we also try to weight the estimates by the number of wholesale meters in each grid.

Tests of the robustness of the effect of the TOU tariff is less straight forward. We try including the dummy constructed for Radius in estimation of retail electricity demand in different grids.

## 6 Results and discussion

### 6.1 Results for wholesale

For the peak-hours 12-15 on business days wholesale of electricity is estimated to decrease with 5.5 pct. when the spot price doubles, other things equal (Table 3).

**Table 3:** log wholesale electricity consumption (REIV)

| | (1) Peak: 11-15<br>b/se | (2) Off-peak: 00-04<br>b/se | (3) Shoulder<br>b/se | (4) Non-business days<br>b/se |
|---|---|---|---|---|
| log spot price | -0.05395*** | -0.02602*** | -0.03519*** | -0.01843** |
| | (0.01526) | (0.00803) | (0.01347) | (0.00869) |
| log wholesale meters | 0.77368*** | 0.77700*** | 0.76910*** | 0.78972*** |
| | (0.19452) | (0.21942) | (0.21198) | (0.22659) |
| Temperature | -0.00374*** | -0.00188*** | -0.00282*** | -0.00475*** |
| | (0.00072) | (0.00058) | (0.00041) | (0.00068) |
| Temperature squared | 0.00016*** | 0.00019*** | 0.00015*** | 0.00021*** |
| | (0.00003) | (0.00004) | (0.00002) | (0.00003) |
| Daytime | | | -0.03280*** | -0.02832*** |
| | | | (0.00855) | (0.00712) |
| Time variables | Yes | Yes | Yes | Yes |
| Observations | 191,100 | 191,100 | 685,256 | 450,320 |

Cluster robust standard errors are in parentheses. * p<0.10, ** p<0.05, *** p<0.01.
Log spot price is instrumented for by wind power prognosis for the same and the other region.

## 6.2 Results for households and small companies

For the grid company Radius operating in the Copenhagen metropolitan area flex-settled customers (households and small companies) are charged a Time-of-Use (TOU) tariff of 0.835 DKK (0.112 EUR) for the hours 17-19 from October-March as opposed to 0.3236 DKK otherwise (0.043 EUR). The estimated effect of this tariff is found to be a decrease in electricity demand of 1.9 pct. However, on business days the smaller effect of 1.4 pct. is only statistically significant at the 10% level while the decrease is 4.4 pct. on non-business days. Table 4 shows pooled 2SLS estimates of electricity consumption for households and small companies in Radius for the hours 17, 18, and 19. The estimation results also show a small elasticity for the hourly spot price which is instrumented for by wind power prognosis for DK2 and DK1. This is despite that for two of the three years none of the consumers pay the spot market price rather than a quarterly average.

**Table 4:** log retail electricity consumption in Radius, hours 17-19 (2SLS)

| | (1) All days<br>b/se | (2) Business days<br>b/se | (3) Non-business days<br>b/se |
|---|---|---|---|
| log spot price | -0.01597** | -0.02624*** | -0.00515 |
| | (0.00734) | (0.00803) | (0.01823) |
| Share time-of-use tariff | -0.01907** | -0.01382* | -0.04444*** |
| | (0.00796) | (0.00800) | (0.01553) |
| log retail meters | -0.92839 | -1.31922 | -0.29035 |
| | (0.85359) | (0.92132) | (1.53637) |
| Temperature | -0.00332*** | -0.00405*** | -0.00395*** |
| | (0.00058) | (0.00073) | (0.00133) |
| Temperature squared | 0.00002 | 0.00004 | -0.00000 |
| | (0.00002) | (0.00003) | (0.00005) |
| Daytime | -0.04708*** | -0.04502*** | -0.02614 |
| | (0.01018) | (0.01084) | (0.01884) |
| Time variables | Yes | Yes | Yes |
| Observations | 3,288 | 2,205 | 1,083 |

Robust standard errors are in parentheses. * p<0.10, ** p<0.05, *** p<0.01.
Log spot price is instrumented for by wind power prognosis for the same and the other region.

## 6.3 The validity of instruments

Test for endogeneity (Appendix **??**) and overidentifying restrictions (Appendix **??**).

## 6.4 Heterogeneity and robustness

Heterogeneous effects

**Figure 5:** Wholesale elasticity by hour

**Figure 6:** Wholesale peak-elasticity by log grid size

## 6.5 Discussion

## 6.6 Possible extensions

One possible extension could be to include grid-specific effects other than the random constant term. This is feasible yet cumbersome. The motivation being that one can expect a exists great variation between companies in terms of size, distribution of customers (residential and commercial), industry-intensity. Both at a certain point in time and regarding the time patterns. In our estimation results the time trend does not carry much explanatory power given the other controls, however, this can be due to effects of different direction for different grids covering different areas of the country.

A very tractable extension would be to use micro data which would allow to control for compositional changes in the presence of heterogeneous consumers.

# 7 Conclusion

We estimate statistically significant own-price elasticities of demand for wholesale consumers and a statistically significant effect of the time-of-use (TOU) tariff in the grid company Radius. However, the economic magnitude of the quite modest is debatable.

Literature in this field is quite large but there is still substantial room for improvement, especially within the field of estimating hour-by-hour responses at the micro-level to capture heterogeneity in this aspect.

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