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# Electricity Price and Demand Pattern Changes Due to Increases in Solar Generation in German Electricity Markets

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**ABSTRACT**

This article aims to explain the impacts of increases in solar generation in Germany on intra-day electricity price and demand patterns during the last decade. Electricity demand sensitivity to the changes in price patterns is also analyzed. It is concluded that there is a clear relationship between the amount of solar generation and daily peak price premiums over the average daily price. With increased solar generation, peak hour electricity price premiums are gradually decreasing. This relation is even more visible during the summer months, with higher amount of solar power produced. However, demand response analysis to the changes in price patterns has provided less conclusive results. While, between years 2007 and 2013, demand clearly adjusted relatively higher, with relatively lower peak prices, more recent periods haven't fully confirmed this trend. Some theories explaining the possible reasons for this fact are also presented in the article.

**Keywords:** Electricity Price, Renewable Generation, Demand Response
**JEL Classifications:** Q41, Q42

## 1. INTRODUCTION

Renewable generation is triggering electricity markets revolution particularly in the EU, as a leading region in development and application of sustainable sources of energy. However, higher shares of solar and wind power in electricity energy supply mix have significant impact on many aspects of electricity markets, with changing price and demand patterns being some of the most crucial ones. In a market environment with large amount of unpredictable renewable generation, issues of demand response also call for increased attention. If demand can help to adjust to fluctuating supply potential, EU goals regarding clean energy environment can be reached significantly easier.

Many researchers have analyzed the price elasticity of demand in the electricity sector as this issue is significantly related to the demand response problems. For the market operator, it is of crucial importance to understand how much demand adjustment can be expected with changes in electricity prices on different levels in different time horizons. Unfortunately, research of different publications on this issue provide very different results, ranging from conclusions that electricity demand is very inelastic on the level of approximately (−0.05) to quite elastic with price elasticity of demand on the levels of (−0.5) to (−1.5). Substantial differences in conclusions between various studies can be partially attributed to the fact that the problem of electricity demand elasticity can be approached in very different ways considering very short-term or very long-term time periods, various analysis methods, years analyzed, regions and power system designs. This paper aims to assess price elasticity of demand specifically related to increases in solar generation in Germany during the last decade. Thus, differences to studies with different scopes of objectives can be expected and justified. However, even very simple analysis of the market long-term data in Europe generally confirm the hypothesis that electricity demand is significantly inelastic in its nature as total consumption in different European countries has changed only negligibly with significant changes in electricity prices.

However, such simple analysis doesn't account for the fact, that consumers could have switched their consumption to the periods with lower prices.

In a study which analyzed many publications from various regions (Australian Energy Regulator, 2015) authors reached the conclusion that price elasticity of demand on the electricity markets generally ranges between (−0.1) and (−0.3) in the short run, however these numbers significantly increase if the long run periods are analyzed. In an older publication analyzing the effects that the market structure can have on elasticity of the demand for electricity (Kirschen et al., 2000) authors reached the conclusion that optimal coefficient for price elasticity of demand on the electricity markets in general is around (−0.1). Recent paper considering price elasticity in the US market (Burke and Abayasekara, 2017) differentiates between short term demand elasticity on the level of (−0.1) and long-term elasticity on the level of (−1). However, other study considering US electricity market (Borenstein, 2009) estimates the price elasticity of demand on the level between 0 and (−0.12) which is closer to the findings presented in this paper. Publication from the Central European region (Kiss and Kocsis, 2013) estimated electricity sector demand elasticity for both household and industrial consumers. Their findings show that while household demand elasticity is quite low on the level of (−0.089), the industry demand elasticity is much higher, on the level of (−0.397). In a study concentrating on household electricity demand in rural Nepal (Müller et al., 2018) authors calculated demand elasticity on the level of (−0.15) which is approximately in line with the previous paper. Therefore, most of the studies conducted on the issue of electricity sector demand elasticity reached a number close to (−0.1). However much higher numbers have been also calculated in certain cases. Some researchers have also analyzed the impact of energy prices on GDP and employment (Kentucky Department for Energy Development and Independence, 2011) with a conclusion that increase in energy prices by 10% would negatively impact GDP by approximately 0.15%. As renewables are at present the most expensive form of generation on the electricity markets, these numbers are also important to consider for the EU energy market regulators.

In this article, the impact of increases in solar generation in Germany on average daily electricity price and demand patterns are analyzed. The period of 2007–2017 is chosen for the analysis as solar generation in Germany during this time has increased from 0.3% of total consumption in 2007 to 6.6% in 2017. Strength of relationship between electricity prices and demand is also assessed. As Germany is a reference market for the whole Central Europe, results of this research are important also for other markets in the region. It was established (Krizanic and Oplotnik, 2013) that a change in electric power prices in Germany by 1% causes the adaptation in electricity prices of smaller countries in the region by 0.6% in the short run and 0.8% in the long run.

## 2. RENEWABLE GENERATION IN GERMANY

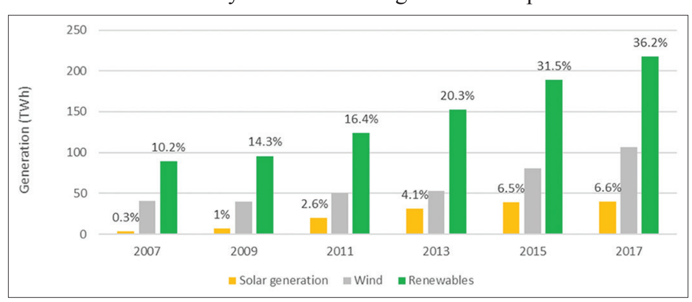
The Council of the EU defined a framework for the future of renewable energy in 2014, specifically aiming to achieve at least 27% renewable energy of final energy demand by 2030 (Serim and Oran, 2017). Renewable targets for all the EU member countries have also been established. Particularly Germany as a leader in renewable revolution in the EU has shown very substantial increases in generation from different sustainable sources during the last decade. The situation is summarized in Figure 1.

Data show that Germany managed to increase its renewable generation from 10.2% of total consumption in 2007 to 36.2% in 2017. Solar generation, which is central to the analysis presented in this paper, increased from 0.3% of total consumption in 2007 to 6.6% in 2017. Such rapid changes have affected German electricity market substantially from various perspectives. The crucial factor with solar generation that must be dealt with is that solar energy is not available during all hours of the day. Therefore, it significantly affects supply during midday hours, particularly in summer, while not being available during night hours at all. As supply increases during some periods but not the others, price profile on the market would be expected to change. The related analysis is performed in the next sections of this work.

## 3. DAILY PRICE PATTERNS ANALYSIS

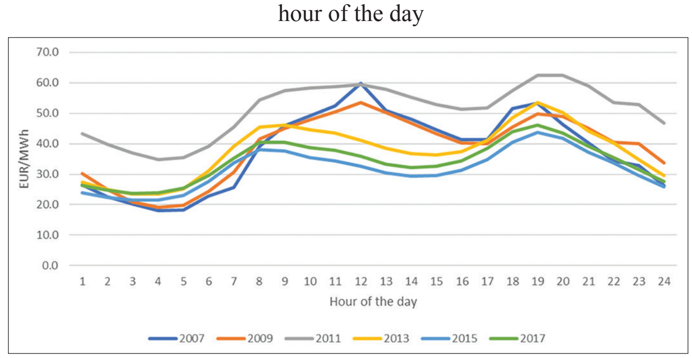
In this part the average prices for every hour of the day are analyzed for different years. Traditionally, in the electricity markets, the highest prices of the day were observed around noon. However, with solar capacities gradually coming online, this pattern has been affected. The issue is summarized in Figure 2, which shows average exchange prices for every hour of the day in Germany during 2007–2017 period. While in 2007 and 2009, noon hours

**Figure 1:** Generation from solar, wind and total renewable generation in Germany with % of total gross consumption




Data source: German federal ministry for economic affairs and energy

**Figure 2:** Daily average price profile on German electricty market by hour of the day




Data source: Energinet.dk

registered the highest prices of the day, the pattern has already changed if looking at the more recent periods. Chart shows that in 2015 and 2017, the midday electricity prices on the German market were already lower compared to morning and evening prices.

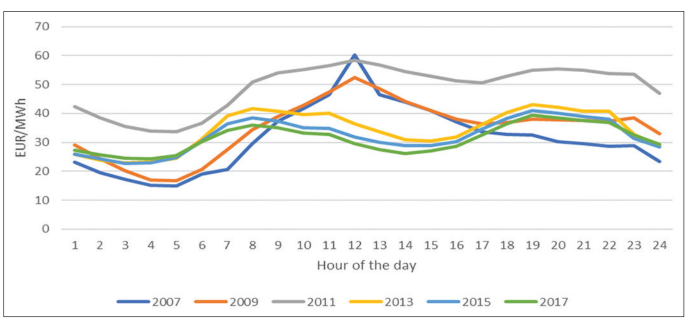
Figure 3 summarizes the same issue for summer months only. This chart is presented as solar generation is higher in summer, so the impact of new solar capacities on power prices should be even stronger during this period. This is exactly what is shown in the Figure 3. The daily price profile in 2007 and 2009 is completely different compared to price profiles in 2015 and 2017. In 2007 and 2009 the off-peak prices were visibly lower compared to years 2015 and 2017, however, this was compensated by significantly higher prices during the day, particularly around 12 o'clock.

The issues outlined in the charts are analyzed more specifically in Tables 1 and 2 using the relative price concept, where the prices during midday hours are compared to average prices of the whole 24 h period. Premium of 11–14 h and 9–16 h periods are calculated separately in EUR/MWh and percentage terms.

It is shown that the relative price premium of midday hours has decreased steadily from around 30% to 40% in 2007 to almost 0 in 2015. There is no significant difference between 2015 and 2017 patterns, which is not surprising as advance in solar energy has almost stopped in Germany since 2015. Table 2 summarizes the same data for summer months only and it is visible that the differences between the years analyzed are somewhat higher, which is also in line with the hypothesis presented in this paper.

Based on this analysis it is concluded that increasing solar electricity supply in Germany has completely changed the average daily price profile. In the next section, the impact of changes in electricity prices on electricity demand daily profile is analyzed.

**Figure 3:** Daily average price profile on German market by hour of the day (June, July, August only)




Data source: Energinet.dk

## 4. DEMAND RESPONSE ANALYSIS TO CHANGES IN ELECTRICITY PRICES

Analysis presented in this part concentrates on the changes in daily demand patterns in comparison to changes in average daily price curve between the years analyzed. Average load for every hour of the day is taken as a measure of demand at every point.

The average intraday load pattern for different years is presented in Figure 4. While the patterns don't seem to show too much valuable information on the first glance, a couple of interesting observations can still be made. Years 2009 and 2013 show very similar patterns for most hours, however, load around noon hours was higher in 2013 than 2009. This could be attributed to demand response of consumers as noon prices were relatively lower in 2013 compared to 2009. Similarly, it is shown that average load was visibly lower in Germany in 2011 compared to 2007. However, during noon hours 2011 load was comparable to 2007. Relatively higher noon load in 2011 compared to 2007 can also be attributed to changing price profile, as noon prices were relatively lower in 2011 compared to 2007. Thus, there is some logics in load curves presented in Figure 4.

Figure 5 summarizes load patterns for June, July and August months only. With higher differences in price profile between years during summer months, more significant spread between load curves during noon hours would also be expected. While comparison between years 2009 and 2013 confirms this hypothesis, it is questionable if these expectations hold true for other years shown.

The patterns shown in charts are further analyzed more specifically using relative load concept as presented in Table 3. This table summarizes relative increases in demand during the hours most affected by the solar generation. It shows how much higher the load was during midday hours as compared to the average load of the day in different years. Cases of 11–14 h and 9–16 h are analyzed separately. Table shows that the difference between noon hours load and the average load of the day was gradually increasing between years 2007 and 2013. However, this increase didn't materialize for years 2015 and 2017.

Table 4 provides the same data for summer months only. While it shows that the difference in load between midday hours compared to the average is higher for summer months, the changes between different years are very similar in Tables 3 and 4.

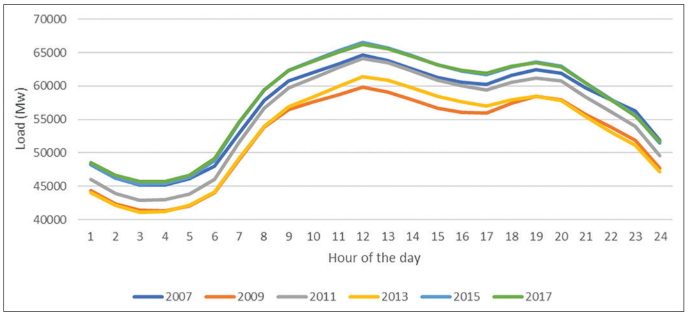
**Table 1: Electricity prices during peak hours with premium compared to average hours**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| Peak price between 9 h and 16 h (EUR/MWh) | 52.8 | 50.3 | 57.8 | 40.0 | 31.6 | 34.7 |
| Peak price between 11 h and 14 h (EUR/MWh) | 49.0 | 47.2 | 56.4 | 40.5 | 32.5 | 35.7 |
| Average spot price for the year | 38.0 | 38.9 | 51.1 | 37.8 | 31.6 | 34.2 |
| Premium of 11–14 h peak price (EUR/MWh) | 14.8 | 11.4 | 6.7 | 2.2 | 0.0 | 0.5 |
| Premium of 9–16 h peak price (EUR/MWh | 11.0 | 8.3 | 5.3 | 2.7 | 0.9 | 1.5 |
| Premium of 11–14 h peak price (EUR/MWh) (%) | 39.0 | 29.5 | 13.1 | 5.9 | −0.1 | 1.5 |
| Premium of 9–16 h peak price (EUR/MWh) (%) | 29.0 | 21.5 | 10.3 | 7.2 | 2.8 | 4.4 |

**Table 2: Electricity prices during peak hours with premium compared to average hours (June, July and August months only)**

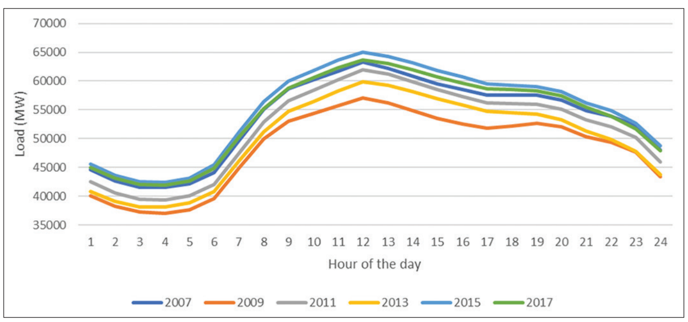
| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| Peak price between 9 h and 16 h (EUR/MWh) | 49.4 | 48.2 | 56.5 | 35.3 | 31.4 | 29.0 |
| Peak price between 11 h and 14 h (EUR/MWh) | 44.3 | 44.2 | 55.0 | 35.5 | 32.1 | 30.0 |
| Average spot price for the year | 31.4 | 35.0 | 49.1 | 34.2 | 32.3 | 31.3 |
| Premium of 11–14 h peak price (EUR/MWh) | 18.0 | 13.2 | 7.4 | 1.1 | −0.9 | −2.3 |
| Premium of 9–16 h peak price (EUR/MWh | 12.9 | 9.2 | 5.9 | 1.3 | −0.2 | −1.3 |
| Premium of 11–14 h peak price (EUR/MWh) (%) | 57.2 | 37.9 | 15.2 | 3.1 | −2.6 | −7.4 |
| Premium of 9–16 h peak price (EUR/MWh) (%) | 41.0 | 26.4 | 12.1 | 3.7 | −0.5 | −4.2 |

**Figure 4:** Daily average load profile on German electricty market by hour of the day




Data source: Entsoe.eu

**Figure 5:** Daily average load profile on German market by hour of the day (June, July, August only)




Data source: Entsoe.eu

Load pattern developments are further compared with the price pattern changes presented in the previous part of this paper. Table 5 shows comparison between the average 11–14 h price premium and relative load increase for the same hours in different years. Between years 2007 and 2013 the drop in price premiums and increase in load spread is visible. Price premiums decreased by 33.1% during the period and load spread increased by 2.2%, thus related price elasticity of demand calculated on this basis shows (−0.066). If years 2015 and 2017 are accounted for, calculated elasticity further drops, however there was no significant change in price premiums between years 2013 and 2017 so price elasticity for these years is difficult to establish.

Similar analysis considering 9–16 h of the day shows decrease in price premiums between years 2007 and 2013 on the level of 21.8% and load spread increase by 1.9% during the same period. This results in price elasticity of demand on the level of (–0.087), with significantly lower numbers if years 2015 and 2017 are also considered.

Similar analysis of summer months presented in Tables 6 and 7 shows much more significant drops in price premiums between different years, however similar response in demand to previous two tables. Therefore, calculated elasticity of demand from this tables is significantly lower, on the levels of (−0.033) and (−0.04) respectively.

Similarly to Tables 5 and 8, even much lower elasticity is registered if years 2015 and 2017 are accounted for. Thus, demand elasticity calculated based on the price pattern changes due to increase in solar generation show values on the low end compared to other researches available on this issue. However, there are a couple of important factors which significantly lower the calculated demand to price sensitivity in the analysis presented:

- Calculated sensitivity of demand to price in this paper considers wholesale electricity prices on the exchanges and ignores other charges paid by the customers. Real electricity prices paid by the consumer are significantly higher as wholesale electricity prices constitute only about 40% of the total electricity bill. Other charges related particularly to transmission and distribution of electricity don't fluctuate in time, so percentage changes in electricity prices calculated in this article are about 2.5 lower from the consumer perspective. If all the other charges are considered, calculated elasticity of demand would have been about 2.5 times higher than presented.
- Only certain part of consumers deal with the hourly electricity prices and are able to optimize their consumption accordingly. Majority of consumers don't deal with the prices on the hourly level and for this reason their elasticity of demand derived from the hourly data is lowered by this factor. Calculated elasticity results would have been probably higher if all the domestic and industry consumers paid prices based on the hourly spot electricity price.

On the other hand, if 2015 and 2017 years were considered, calculated elasticities would have been much lower. However, there are two relevant factors regarding data from years 2015 and 2017 that need to be addressed:

- Price patterns between 2013 and 2017 changed only marginally compared to previous years, therefore impact of prices on demand is difficult to calculate from such small changes.
- 2015 and 2017 prices in Germany have shown the lowest prices on electricity exchanges in history, with averages on the level of 30 EUR/MWh. With such low prices it might happen that incentives of consumers to react to price changes decrease, resulting in dropping price elasticity of demand values. Furthermore, with lower exchange prices, their weight in

**Table 3: Electricity load during peak hours with premium compared to average hours**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| Load 11–14 h average (MW) | 49.4 | 48.2 | 56.5 | 35.3 | 31.4 | 29.0 |
| Load 9–16 h average (MW | 44.3 | 44.2 | 55.0 | 35.5 | 32.1 | 30.0 |
| Load all hours (MW) | 31.4 | 35.0 | 49.1 | 34.2 | 32.3 | 31.3 |
| 11–14 h load increase (MW) | 6891 | 6389 | 7785 | 7593 | 7798 | 7573 |
| 9–16 h load increase (MW) | 5670 | 5312 | 6442 | 6268 | 6505 | 6349 |
| 11–14 h load increase (%) | 12.2 | 12.2 | 14.1 | 14.4 | 13.5 | 13.1 |
| 9–16 h load increase (%) | 10.0 | 10.1 | 11.6 | 11.9 | 11.3 | 11.0 |

**Table 4: Electricity load during peak hours with premium compared to average hours (June, July and August months only)**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| Load 11–14 h avg. (MW) | 62034 | 55971 | 60827 | 58914 | 64032 | 62776 |
| Load 9–16 h avg. (MW) | 60633 | 54960 | 59269 | 57469 | 62565 | 61358 |
| Load all hours (MW) | 53559 | 48420 | 51834 | 50112 | 54992 | 54091 |
| 11–14 h load increase (MW) | 8475 | 7551 | 8993 | 8802 | 9040 | 8685 |
| 9–16 h load increase (MW) | 7074 | 6540 | 7435 | 7357 | 7573 | 7267 |
| 11–14 h load increase (%) | 15.8 | 15.6 | 17.3 | 17.6 | 16.4 | 16.1 |
| 9–16 h load increase (%) | 13.2 | 13.5 | 14.3 | 14.7 | 13.8 | 13.4 |

**Table 5: Comparison of premiums in prices and loads during 11–14 h of the day compared to average prices/loads**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| % premium in price for 11–14 h | 39.0 | 29.5 | 13.1 | 5.9 | −0.1 | 1.5 |
| % increase in load for 11–14 h | 12.2 | 12.2 | 14.1 | 14.4 | 13.5 | 13.1 |

**Table 6: Comparison of premiums in prices and loads during 11–14 h of the day compared to average prices/loads (June, July, August months only)**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| % premium in price for 11–14 h | 57.2 | 37.9 | 15.2 | 3.1 | −2.6 | −7.4 |
| % increase in load for 11–14 h | 15.8 | 15.6 | 17.3 | 17.6 | 16.4 | 16.1 |

**Table 7: Comparison of premiums in prices and loads during 9–16 h of the day compared to average prices/loads (June, July, August months only)**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| % premium in price for 11–14 h | 41.0 | 26.4 | 12.1 | 3.7 | −0.5 | −4.2 |
| % increase in load for 11–14 h | 13.2 | 13.5 | 14.3 | 14.7 | 13.8 | 13.4 |

**Table 8: Comparison of premiums in prices and loads during 9–16 h of the day compared to average prices/loads**

| Price premium | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 |
|---|---|---|---|---|---|---|
| % premium in price for 11–14 h | 29.0 | 21.5 | 10.3 | 7.2 | 2.8 | 4.4 |
| % increase in load for 11–14 h | 10.0 | 10.1 | 11.6 | 11.9 | 11.3 | 11.0 |

total electricity bill decreases substantially, marginalizing the relevance of exchange prices from the consumer perspective. Therefore, calculated elasticities consider average exchange prices on the level of 40 EUR/MWh, with a significant potential for elasticities to decrease if prices drop significantly below this level.

Thus, analysis presented in this paper can be understood particularly as an analysis of changes in price and demand patterns in Germany due to solar generation increases. Demand elasticities presented in this paper consider specific conditions outlined and can't be understood generally. Real elasticity of demand of the consumers who are affected by hourly prices can be reasonably expected to be much higher than the numbers shown, however it is very hard to calculate the exact numbers with present market conditions. Generally, conclusions of most of the other studies with calculated price elasticities of demand in the electricity sector on the level between (−0.1) and (−0.3) are confirmed by the the findings presented in this paper.

## 5. CONCLUSIONS

This article aimed to analyze impact of increased solar generation in Germany during the last decade on average daily price pattern and daily load distribution throughout a day. It was shown that price patterns have changed substantially in Germany during the last decade as peak noon prices ceased to occur on the market and prices during noon hours has became lower compared to morning and evening prices. This impact is even stronger during the summer months, with the highest amount of solar generation.

Impact of changes in average daily price curve on demand distribution however is somewhat muted and less conclusive. Demand in the electricity industry is inelastic in its nature so significant changes in load patterns wouldn't be expected. However, load has shown certain response to price changes as spreads between noon hours load and average 24 hours load has increased during the last decade. Results shown are quite conclusive for the period between years 2007 and 2013 as noon load has been increasing relatively to the average gradually during this period. However, 2015 and 2017 data haven't fully confirmed this trend. The hypothesis outlined in this regard is, that this was caused by the significant electricity price drop during the more recent years. With exchange prices below certain level, consumers don't get enough incentive to move their consumption to hours with even lower prices. Therefore, when calculating price elasticity of demand, it is important to consider also average electricity price level. When electricity prices decrease, price elasticity of demand seems to be also going down.

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