# How aggregate electricity demand responds to hourly wholesale price fluctuations

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## Overview

Electricity is a peculiar good in that it must be supplied at the very moment of consumption. Reflecting this physical requirement, wholesale electricity markets clear at hourly or even sub-hourly intervals. The corresponding prices fluctuate widely within a day, regularly reaching multiples of their average and even turning negative occasionally. This study investigates the response of aggregate, nationwide electricity demand to these price fluctuations, given that only some consumers are exposed to time-varying wholesale prices. There are many studies on the demand response to more persistent price changes and of distinct consumer groups, but studies on the price elasticity of aggregate demand at short time scales have remained inconclusive to date.

Meanwhile, robust estimates of the aggregate high-frequency demand elasticity are critical for many analyses of electricity systems and markets. First, the aggregate demand response substitutes for generation capacity at a given level of security of supply (Bushnell, 2005; Hogan, 2005). Therefore, it is a key input parameter to regularly conducted resource adequacy studies (e.g., ENTSO-E, 2022; NERC, 2022). Second, the aggregate demand response limits the incentive to exercise market power (Borenstein et al., 1999; Albadi and El-Saadany, 2007). Third, the degree to which demand is responding to prices drives policy decisions, such as the current assessments of the spatial granularity of European electricity markets (ACER, 2020; Ofgem, 2022). Notably, government-mandated capacity mechanisms are often justified by a lack of demand response (Cramton et al., 2013). Finally, the aggregate demand response helps in integrating wind and solar energy to enable long-term decarbonization scenarios, avoid curtailment, and substitute other, most costly flexibility options such as fossil power plants or energy storage (Roscoe and Ault, 2010; Ruhnau, 2022).

## Methods

First, we develop a theoretical framework for the causal identification of demand response, using wind energy as an instrument. To do so, we discuss in-depth discussion of how prices impact load, given the institutional context of the German and European electricity market. Second, we conduct a broad range of sensitivity analyses and robustness checks to show the soundness of using wind energy as an instrument and define the bounds of the estimates of price elasticity. Importantly, we perform a long list of tests and analyses concerning challenges to the exogeneity of the instrument, including alternative and additional instruments. Third, we use multiple model specifications, including a purely linear specification (as in Knaut and Paulus, 2016), a log-linear specification, and specifications with nonparametric elements. This matters because there are many reasons to expect nonlinear relationships in power markets. The models are estimated using a 2-stage least squares (2SLS) and a 2-stage generalized additive models (2SGAM). This allows us to study the shape of the demand curve. Fourth, we study the heterogeneity of demand response across time, including the time of the day, day of the week, and season of the year, as well as across different regions, and compared the spatial heterogeneity to the uneven distribution of industrial load across Germany. Finally, we update and extend the scope of previous analyses to five years from 2015 to 2019. This is important for ascertaining the robustness of the analysis and accounting for time trends.

## Results

We estimate that a 1 €/MWh increase in the price in the wholesale markets causes the aggregate electricity demand in Germany to decline by 67–80 MW (linear estimates) or 0.12–0.14% (log-linear estimates). At the average price and demand, these estimates correspond to a price elasticity of demand of about −0.05. Comparing situations with high and low wind energy (5–95$^{th}$ percentile), we estimate that prices vary by 26 €/MWh, and the corresponding demand response is about 2 GW, or 4% of average demand. Our estimates are robust across years or seasons. We find a strongly nonlinear demand curve during night and a quite linear curve during daytime hours. Our estimates of the regional distribution of demand response match with the regional distribution of energy-intensive industry in Germany, consistent with the fact that it is mostly industrial consumers who are exposed to wholesale electricity price variations. The results are statistically significant and remarkably robust across a broad range of model specifications, estimators, time periods, alternative instruments, and other sensitivity analyses.

## Conclusions

Our estimates show that, even if only a fraction of (industrial) consumers are exposed to wholesale price variations at very short intervals, their demand response is substantial enough to help in the decarbonization of the electricity sector. The ongoing energy transition heavily relies on variable wind and solar energy, but their further expansion is impeded by the fact that they are not always available when electricity is needed. On the other hand, there may be times when renewables are abundant and curtailed. However, our estimate for price elasticity implies that in Germany about an increase (decrease) in aggregate demand during periods of high (low) wind generation and low (high) electricity prices reduces the need for expensive battery storage (and fossil-fueled back-up power plants) by up to 8%.

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