# Empirical Strategy

FIGURE, which shows household average daily electricity consumption over temperature and pre-and-post differences in the consumption, clearly demonstrates the motivation of this research project.\footnote{An important feature also stands out from the figure: the minimum household electricity consumption occurred at around 60 degrees of Fahrenheit. This phenomenon supports the setting of the reference temperature for calculating daily HDDs at the very level.} As illustrated in Panel A of the figure, household demand for electricity grew as the temperature decreased. In other words, in addition to temperature-insensitive electricity demand (i.e., for non-temperature-control uses), there was a sizeable demand for electricity for heating (i.e., for temperature-control use) in Irish households, which is highly responsive to temperature variations. In addition, Both panels in the figure collectively show three interesting points regarding the changes in household average daily demand for electricity after introducing the TOU prices: first, during the treatment period, households in the treatment group consumed less electricity over the entire temperature range, while those in the control group equally consumed on temperate days\footnote{In Panel A, non-treated households consumed more electricity during the baseline period, especially on days with higher heating need. The fact that the total HDDs during the baseline period were generally greater than those during the treatment period for a given temperature bin could explain the phenomenon.}; second, for a given temperature, the treated reduced their electricity consumption by a larger percentage; and third, the size of reduction in their electricity demand appears to depend heavily on temperature. Being motivated by those observations, I determine not only how much consumption changes, on average, in response to the time-varying tariffs but also how their impact varies across days with different temperatures in this research. In other words, the dynamic-pricing-causing effects on temperature- and non-temperature-control electricity uses are separately estimated to figure out the primary source of energy savings.

Instead of merely leaning on randomization, I employ a difference-in-differences (DID) approach to estimate the dynamic-price-inducing electricity savings. Because the CER experiment dataset primarily utilized in the following empirical analysis was generated from a carefully developed randomized controlled trial (RCT), in principle, the effect of the TOU tariffs on household electricity consumption can be measured simply through the difference in average usage between the two groups during the treatment period.\footnote{Because random assignment of participating households puts selection bias right, observed differences in electricity consumption between the control and treatment groups after introducing the TOU tariffs are only attributable to their differences in exposure to the time-varying electricity prices.} However, such a naive control/treatment difference is not valid here due to the non-trivial difference in electricity demand between the control and treatment groups during the baseline period. The poor balance in household demand for electricity during the benchmark period was the very reason the previous studies exploiting the same dataset also adopted the same identification strategy.

I include the temperature as an explanatory variable directly in my econometric models. In the previous papers using the identical dataset, fixed effects (FEs) were utilized to control for time-varying factors that influenced household electricity consumption. Since those studies focused on quantifying how households responded, on average, to the TOU price regimes newly introduced, adding such FEs to their models served their research purpose. In other words, they did not need to explicitly model the relationship between temperature and household electricity consumption to estimate the average treatment effects (ATEs). However, a primary interest of this research is to understand how electricity savings vary with the temperature after shifting to TOU prices. Therefore, more flexible controls rather than FEs, not sweeping out temperature variations across days, are required in my empirical analysis. For that reason, I extend the typical panel DID specification that contains three indicator variables by adding interaction terms between the indicator and temperature variables.\footnote{Under three identifying assumptions, applying the DID strategy to measure energy savings obtained from adopting the TOU prices makes sense. First, the parallel trend assumption is required for the DID estimator. Considering that the 30-minute interval meter reads for participating households were collected from a trial, the assumption means that the pre-treatment-period load profile for the treated households should be very similar to that for the non-treated households. FIGURE A showing average within-day load profiles for the two groups during the baseline period supports the plausibility of the parallel trend assumption. In addition, the electricity consumption profile for the control group illustrated in FIGURE B, which smoothly evolved over the entire experiment period although heavily fluctuated day to day, suggests its high reliability as a counterfactual under the assumption.

The second identifying assumption necessary for the plausibility of the identification strategy employed is the assumption of common temporal shocks. This assumption implies that a treatment-status-irrelevant unexpected event occurring at the same time as or following the deployment of the dynamic prices should have the same impact on both the control and treatment groups. Although the common shocks assumption cannot be tested directly, the similar trends in electricity demand profiles for the control and treatment groups shown in FIGURE B support the assumption required for the DID approach.

Third, the stable unit treatment value assumption (SUTVA) must hold too. The SUTVA requires that introducing TOU prices did not affect the electricity consumption of the untreated households. That is, the SUTVA allows no spillovers. During the recruitment process, the locational distribution of the participating households was aligned with that of the total Irish population to construct a representative sample of the national population. Because only a few thousand households scattered geospatially participated in the nationwide experiment, it is unlikely that the treated households influenced the households allocated to the control group. This again supports the SUTVA required under the DID identification strategy.} That is, I estimate the ATEs of the dynamic prices on household electricity demand by exploiting the within-household electricity consumption changes across not only periods but temperatures.\footnote{The attrition rate during the RCT was about 20%. The main reasons for participant attrition were changes in tenancy and supplier. Due to the imperfect compliance, the estimates must be interpreted as local average treatment effects (LATEs). However, according to CER (2011), attrition was unlikely to be associated with the RCT. Furthermore, the level of attrition varied only marginally across treatment status.}

# Average Responses to Time-of-Use Prices

**Half-Hourly Average Treatment Effects**

Utilizing a panel DID identification strategy, I first measure the impact of the TOU prices on 30-minute-interval household electricity consumption. To obtain the ATE for each half-hour interval, I estimate the following specification:

MODEL1

The term kWh is the electricity consumption by household $i$ on the day $t$ during the half-hourly time window $w$. The indicator variable Treatment and Post is equal to one only if household $i$ is in the treatment group and the day $t$ is in the treatment period, while the indicator variable Interval takes the value of one when the half-hourly interval is $w$. The terms alpha, gamma, and delta are household-by-half-hourly-interval, day-of-week-by-half-hourly-interval, and month-of-year fixed effects, respectively. In the specification, the point estimates of bw representing the ATE for each 30-minute interval $w$ are the parameters of interest. I cluster the standard errors at the household and the day of experiment levels to correct for serial correlation.

FIGURE summarizes the estimated ATEs in the form of a time profile. As also demonstrated in Prest (2019), the time profile shows dominant electricity savings during peak hours (i.e., from 5:00 p.m. to 7:00 p.m.). The result indicates that the TOU tariffs served their purpose to resolve the peak demand problem. In the following empirical analysis, I continually focus on household electricity demand responses to the time-varying prices during the peak rate period.

## Average Treatment Effects in the Peak Rate Period

It is worth estimating peak-rate-period ATEs relative to the control group to comprehend how the responsiveness of Irish households to TOU electricity pricing varied with the magnitude of price changes.\footnote{In this paper, the effects of four different information stimuli on household electricity consumption are not of interest. Pon (2017) studied the effects in detail using the same datasets.} To do so, I run the following regression for each of the four tariff groups:

MODEL2

TABLE summarizes the regression results.

The results demonstrated in TABLE indicate that the measured ATEs generally follow the law of demand: in general, the reduction in household demand for electricity during the peak rate period grows with the size of the price jump. Importantly, the results imply that household electricity savings from temperature-control use or ones from non-temperature-control uses depend on the amount of the tariff change in the peak rate period. Motivated by this implication, the relative responsiveness of the two distinct drivers of energy savings to the time-varying prices introduced is quantified below.

# Breakdown of Peak-Rate-Period Household Responses to Time-Of-Use Prices

## Breakdown of Household Responses in the Peak Period

## Peak-Rate-Period Household Responses as a Linear Function of Price Changes