# Breakdown of Household Responses to Time-Of-Use Electricity Pricing

## Breakdown of Household Responses around the Peak Rate Period

I decompose TOU-tariff-causing reductions in household electricity consumption around the peak rate period into two parts to determine the share of electricity savings stemming from two distinct sources: savings from non-temperature-control and temperature-control electricity uses. Here, the non-temperature-control-related electricity savings mean the reductions in electricity demand that are stably achievable regardless of each day's weather conditions, especially temperatures. That is, the savings associated with non-temperature-control electricity uses do not vary across days. On the contrary, the latter savings strictly depend on daily HDDs, which fluctuate daily. Specifically, temperature-control-associated electricity savings are additional savings that appear only on days with non-zero daily HDDs due to for-heating electricity consumption in households. Isolating the impact of the TOU prices on household electricity demand for temperature-control uses from the total reductions in electricity demand enables us to know how differently the TOU tariff structures function from day to day, whose implications will be discussed later.

To break down household responses to the TOU program around the peak rate period, I exploit the following DID-style spline regression model\footnote{Table XYZ shows point estimates that are from a nonparametric model. The U-shaped ATEs across daily HDDs substantiate the use of the DID-style spline regression model in \cite{Eq:Model-Specification\_Breakdown-of-Hourly-Average-Treatment-Effect}.}:

[MODEL-3]

Like (\ref{Eq:Model-Specification\_Hourly-Average-Treatment-Effects}), the dependent variable $kWh\_{ith}$ is the electricity consumption by household $i$ on the day $t$ during the hour of the day $h$. There are three indicator variables in the model: the first indicator variable $\mathbb{1}[\text{Treatment}]\_{i}$ has the value of 1 if household $i$ is assigned to the treatment group; the second indicator variable $\mathbb{1}[\text{Post}]\_{t}$ equals 1 when the day $t$ is in the treatment period; the last indicator variable $\mathbb{1}[\text{Treatment \& Post}]\_{it}$ is equal to 1 only for treatment households in the treatment period. The model also includes interaction terms between HDD-relevant terms and those indicator variables. In the econometric model, $HDD\_{t}$ means the daily heating degree days on the day $t$. And $HDD\_{t}^{\*}$ is required to introduce nonlinearity in HDD-associated response to TOU pricing.\footnote{Mathematically, $HDD\_{t}^{\*}$ is defined as follows:

\begin{equation}

HDD\_{t}^{\*} \ = \ (HDD\_{t} - Knot) \ \times \ \mathbb{1}[HDD\_{t} > Knot],

\end{equation}

where $Knot$ is a reference value at which the slope of the predicted line starts to change.

} The terms $\alpha\_{iw}$, $\gamma\_{dw}$, and $\delta\_{mw}$ are household-by-half-hourly-time-window, day-of-week-by-half-hourly-time-window and month-of-year-by-half-hourly-time-window fixed effects, respectively.

The primary coefficients of interest in (\ref{Eq:Model-Specification\_Breakdown-of-Hourly-Average-Treatment-Effect}) are $\beta\_{9}$, $\beta\_{10}$, and $\beta\_{11}$. The three coefficients show how much electricity consumption the households assigned to the treatment group reduced after deploying the TOU program compared to those in the control group. To be specific, $\beta\_{9}$ demonstrates the decrease in residential electricity consumption for non-for-heating uses. Both $\beta\_{10}$ and $\beta\_{11}$ collectively mean the reductions in electricity consumed to satisfy household heating needs at given daily HDDs.

[FIGURE]

Using the point estimates of the three coefficients of interest provided in Table \ref{Table:Breakdown-of-Average-Treatment-Effects-in-the-Peak-Rate-Period}, I graphically summarize the predicted reductions from each of the two sources of electricity savings in Figure \ref{Figure:Breakdown-of-Hourly-ATEs-in-the-Peak-Rate-Period}. Regarding the savings in electricity consumption for non-temperature-control uses, which are independent of weather conditions, the figure clearly shows that the treated households significantly reduced their consumption when they were subject to peak-hour prices. Their non-for-heating electricity consumption also decreased in both pre- and post-peak intervals, albeit relatively smaller in magnitude. The changes in temperature-control-use-associated electricity consumption occurred as well in all three intervals, but its evolving pattern over daily HDDs was quite different in each interval. Specifically, the impact of TOU pricing on residential electricity consumption for heating is U-shaped in the peak rate period, while it is salient only when daily HDDs are sufficiently large in the two off-peak intervals. In other words, from the figure, it is evident that the savings originating from for-heating-purpose household electricity consumption are a nonlinear function of daily HDDs in all three intervals.

The specification (\ref{Eq:Model-Specification\_Breakdown-of-Hourly-Average-Treatment-Effect}) is also utilized to examine, during the peak rate period, the relationship between the degree of price increases and the electricity savings. The by-tariff-group estimates of the coefficients of interest are presented in Table \ref{Table:Breakdown-of-Average-Treatment-Effects-in-the-Peak-Rate-Period}. As shown in the table, on the whole, the savings from electricity demand for non-temperature-control uses tend to be proportional to the size of price risings in peak hours. Moreover, the marginally diminishing effects of TOU pricing, discussed in \cite{Peaking-Interest:How-Awareness-Drives-the-Effectiveness-of-Time-of-Use-Electricity-Pricing\_Prest\_2020}, seem not to be championed by my point estimates. And the two estimates associated with temperature-control-use-related electricity savings (i.e., $\hat{\beta}\_{10}$ and $\hat{\beta}\_{11}$) are statistically significant only for the case of the smallest price increase (i.e., only for the Tariff Group A). Jointly, those findings imply two points. First, household reaction to the TOU prices in peak hours differs in non-temperature- and temperature-control uses. Second, the savings from non-for-heating electricity consumption do not behave as expected from the previous study. Inspired by those implications, I formulate the resulting variations in household electricity consumption as a linear function of the magnitude of rate changes in the peak-demand hours in the following section.

[TABLE-XYZ]

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

To fully understand how residential consumers adjust their electricity consumption behavior as a set of reactions to the price changes in and near the peak rate period under the TOU price structures, it is necessary to examine the relationship between the size of price increases in the period and the electricity savings from each of the two distinct sources for different points in time where electricity is consumed. For that reason, I quantitatively determine the relationship by utilizing the following econometric model:

[MODEL].

The model is the same with (XYZ) except for interaction terms between treatment-status-relevant indicator variables (i.e., $\mathds{1}[\text{Treatment}]\_{i}$ and $\mathds{1}[\text{Treatment \& Post}]\_{it}$) and $\Delta RC\_{i}$, where $\Delta RC\_{i}$ is the difference between the peak-hour prices in the treatment period and the flat rate in the baseline period. The coefficients of those interaction terms capture the impacts of deploying the TOU tariffs on household electricity consumption as a linear function of the amount of peak-demand-hour price changes.

The estimates of the six coefficients of interest (i.e., from $\beta\_{12}$ to $\beta\_{17}$) presented in Table XYZ are summarized graphically in Figure XYZ. And this figure, showing estimated treatment effects and predicted electricity savings for each of the three intervals, re-confirms the finding of price insensitivity in \cite{Peaking-Interest:How-Awareness-Drives-the-Effectiveness-of-Time-of-Use-Electricity-Pricing\_Prest\_2020}. In the peak rate period, the non-for-heating-associated electricity savings were directly proportional to the rate changes in the period. On the contrary, at a given daily HDDs, the for-heating-related electricity savings, having HDD-varying U-shaped profile, were inversely proportional to the magnitude of peak-demand-hour tariff changes. As shown in the figure clearly, the differences in the predicted electricity savings over the degree of price changes are apparent when the savings stemming from the two distinct sources are examined individually. The differences, however, are seemingly dampened when the electricity savings are aggregated due to the opposite correlations. Indeed, this empirical result is consistent with the finding discussed in the previous work that households were unusually insensitive to the size of the price changes in the peak rate period.

The opposite order in estimated treatment effects between the two sources of electricity savings also holds in the two-hour-length pre-peak interval, although in a contrary manner. The interval shows directly proportional savings from electricity consumption for temperature-control uses to changes in the peak rate. By contrast, the variations in non-temperature-control-related electricity consumption caused by TOU prices exhibit an inverse relationship with the price changes in the peak rate period. For the same reason, the aggregated treatment effects of the TOU tariffs are seemingly less sensitive to prices. Note that regarding the electricity consumption for heating, the TOU tariffs played a role only when temperatures were sufficiently low.

Residential consumers adjust their electricity consumption behavior during the two-hour-length post-peak period as well. As in the pre-peak interval, the savings stemming from non-for-heating-associated electricity consumption were inversely proportional to the price jumps in the peak rate period. In the case of electricity consumption for heating, the TOU program provoked additional consumption in that interval, especially on freezing days. The amount of the added for-heating-relevant household electricity consumption increased as the price variations in the peak-hour interval diminished. Therefore, the resulting treatment effects (i.e., the aggregated treatment effects) also agree with the finding of price insensitivity in the previous paper.

In summary, under TOU pricing, the level of price changes, not merely its existence, still matters to residential consumers. The empirical results above suggest that the opposite order in estimated treatment effects between non-temperature- and temperature-control uses of electricity makes Irish households appear to violate the law of demand. In other words, due to the opposite order, their high sensitivity to the TOU prices is revealed only when household electricity consumption is disaggregated to the two distinct sources of electricity savings. Together with the empirical findings in previous sections, the results imply that three simultaneously interacting factors govern the dynamics of residential electricity consumption under TOU pricing: the timing when electricity is consumed, daily HDDs, and the magnitude of price increases in the peak rate period.