The results from my empirical analysis clearly indicate that under Time-Of-Use (TOU) electricity pricing, residential electricity consumption is governed by various factors, such as the timing of consuming electricity in a day, daily Heating Degree Days (HDDs), and the magnitude of a price increase in the peak rate period. In other words, within-household electricity consumption behavior shows multidimensional dynamics over the three drivers. Based on my empirical findings, I will discuss the dynamics in detail in the following sections. Furthermore, I will also discuss its policy implications.

# Multidimensional Dynamics of Household Electricity Consumption

## Household Consumption Behavior in and near the Peak Rate Period

Examining participating households' electricity consumption, following a time sequence from the pre-peak to the post-peak period, facilitates a complete understanding of how they adapted to the TOU tariff structures in the CER experiment. Intuitively, residential consumers can respond to a peak TOU price by conserving their electricity consumption during peaks, leading to an overall reduction in their demand for electricity. Instead of reducing their electricity consumption, they can shift it to off-peak hours so as not to be subject to the peak rate as much as possible. In this case, the level of their net electricity consumption is maintained. Of course, those two ways of responding to time-varying price structures can co-occur. Because those two ways reshape load curves not only in the peak rate period but also in the hours surrounding that period, it will be natural to examine the impact of the TOU program on household electricity consumption from a time-moving perspective in order to grasp the whole dynamics of households' behavioral changes. In the following paragraphs, I will provide interpretations of the changes in households' consumption behavior, which are observed in my empirical analysis.

Regarding residential electricity demand for non-temperature-control uses, the leading reaction of the treated households to the TOU tariffs was to reduce their consumption in and near the peak rate period. According to my regression results summarized in Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period}, in the peak period, the reduction in non-temperature-control-related electricity consumption increased as the magnitude of a peak-rate-period price change under the TOU program grew. Non-temperature-control-driven electricity consumption for the pre- and post-peak periods showed an opposite variation---i.e., the reduction originating from households' non-for-heating consumption diminished as the degree of a price increase in the peak rate period became larger. In the case of Tariff Group A, although there was almost zero price variation relative to the flat rate (i.e., only 0.1 cents per kWh) in the pre- and post-peak periods, the amount of the diminution in non-temperature-control-related electricity consumption for that group was nearly the same in all three periods. Meanwhile, despite more sizable price decreases, the remaining tariff groups also conserved their consumption for non-temperature-control uses in both surrounding periods. In sum, the price increases in the peak rate period caused a spillover effect in those pre- and post-peak periods: a reduction in electricity consumption for non-temperature-control uses. In other words, with respect to non-temperature-control-driven electricity consumption, the households assigned to the treatment group responded to the TOU program, on the whole, via not load-shifting but load-shedding. Interestingly, the total non-temperature-control-relevant reduction in and near the peak rate period, which is depicted in the fourth column of the first row in the figure, did not vary with the level of a peak-hour price increase.

With respect to temperature-control-related household electricity consumption, Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period} depicts that the treated households' primary response to the TOU program was also load-shedding. The program caused a reduction in for-heating electricity use during the peak rate period, especially around typical values of daily HDDs during winter in Ireland\footnote{See Figure \ref{Figure:Distribution-of-Heating-Degree-Days-during-the-Experiment-Period}.}---interestingly, the smaller the magnitude of a peak-demand-hour price increase, the larger the induced reduction in temperature-control-related consumption in the peak period. That is, the reduction violated the law of demand. A possible explanation for this phenomenon will be discussed later. As described in Figure \ref{Figure:Time-Of-Use-Pricing-Structures}, there were price drops in the hours surrounding the peak rate period. Furthermore, for marginal electricity consumption, because the tariff group that paid the highest price in the peak rate period (i.e., Tariff Group D) paid the lowest price in the surrounding hours, the households in that group were more incentivized to relocate their peak-hour electricity consumption to off-peak hours. Therefore, the reduction in electricity consumption for heating in the pre-peak period, which occurred only on days with heavy heating needs, cannot be explained as a consequence of a price decrease or load-shifting. In other words, regarding temperature-control-driven household electricity consumption, in addition to the peak rate period, price signals did not function well in the pre-peak period. In the post-peak period, although high daily HDDs incurred additional electricity consumption for heating after introducing TOU tariffs, which also cannot be justified by price signals for the same reasons as in the pre-peak period, its amount was generally not large enough to fully offset, for given heating needs in a day, the reductions in the preceding periods.

Measuring the induced consumption reduction of households in Tariff Group D relative to Tariff Group A validates the load-shedding interpretation. Suppose that for the treated residential consumers, load-shifting is a primary countermeasure against the TOU program. Then the residential consumers in Tariff Group D, compared to those in Tariff Group A, had more incentive to reallocate a portion of their peak-hour electricity consumption to off-peak hours because they faced a much larger price increase in the peak rate period as well as a much larger price decrease in the pre- and post-peak periods. So, compared to those in Tariff Group A, the households in Tariff Group D should consume more electricity in both periods surrounding the peak rate period, while their electricity consumption should be less in the peak rate period. However, Figure \ref{Figure:Relative-Comparison-of-Tariff-Group-D-to-Tariff-Group-A}, which shows point estimates obtained by setting Tariff Groups A and D as the control and treatment groups, respectively, exhibits only a little hint of load-shifting only in the post-peak period, though the reduction in non-temperature-control-driven household electricity consumption was evident. That is, load-shifting did not play a role in reshaping households' load profiles in and near the peak rate period.

From Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period}, examining the curves of aggregate change in temperature-control-associated electricity consumption for three consecutive periods simultaneously, but taking account of their time sequence, suggests a significant implication of the effectiveness of the TOU prices in the peak rate period. According to the figure, as the degree of peak-hour price escalation increased, the temperature-control-related consumption reduction in the pre-peak period expanded, while those in the peak period decreased gradually. Altogether, it is likely that a larger pre-adjustment leads to a smaller reduction in electricity demand for heating during peak-demand hours, which in turn seems to result in limited additional consumption during the following post-peak period. Compared to the case that a household does not reduce for-heating electricity consumption during the pre-peak period, consuming more for-heating electricity during peak hours seems necessary to prevent indoor temperatures from falling too much or persisting at a low level when the household significantly reduces its temperature-control-driven consumption during the pre-peak period.\footnote{This interpretation is in line with the concept ``discomfort'' in \cite{Smart-Thermoststs-Automation-and-Time-Varying-Prices\_Blonz-et-al\_2021}. See Section 3.4 in the paper.} In addition, the household will have less incentive to increase its electricity consumption for heating during post-peak hours since its room temperatures will be higher than if it were to considerably reduce its electricity consumption for heating during peak hours. In light of the fact that TOU tariffs are intended to conserve electricity consumption during peak-demand hours, it is reasonable to conclude that a lower reduction in peak hours due to a too large pre-adjustment results in a deterioration in the performance of the TOU tariffs.

## Household Consumption Behavior over Daily Heating Degree Days

My empirical results obviously illustrate that the effectiveness of TOU tariffs, as measured by the amount of an induced reduction in household electricity consumption, nonlinearly varies with daily HDDs. As discussed, the alteration in electricity consumption caused by the deployment of TOU electricity pricing consists of two elements: the change in non-temperature-control-driven electricity consumption and that in temperature-control-driven electricity consumption. By definition, the change originating from non-temperature-control-related electricity consumption is independent of ever-changing weather conditions, including daily HDDs. Hence, the nonlinearity in the effectiveness of the TOU tariff structures, as illustrated in Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period}, is utterly attributable to the other type of electricity consumption, that for heating.

The nonlinear relationship between the amount of change in temperature-control-associated electricity consumption and daily HDDs indicates an interesting characteristic of TOU pricing: the day-varying effect of TOU pricing on residential electricity consumption. Daily HDDs, one of the critical determinants of temperature-control-relevant electricity consumption, fluctuate day by day. Therefore, it is intuitive that in response to daily changing household heating needs, the TOU-price-induced change in electricity consumption for heating also alters every day.

The day-varying effectiveness of TOU electricity pricing suggests a significant implication in connection with Real-Time Pricing (RTP), a more granular time-varying electricity tariff structure.\footnote{\cite{Household-Responses-to-Time-Varying-Electricity-Prices\_Harding-and-Sexton\_2017} provides a detailed description of various kinds of time-varying electricity tariff structures.} Contrary to TOU pricing, rates typically change hourly under RTP. So compared to TOU pricing, RTP has an advantage in reflecting generation costs contemporaneously. In other words, RTP imposes a higher price in the situation that electricity demand is high, followed by high generation costs, to curb household electricity consumption. Economists, therefore, prefer RTP to TOU pricing.

Because of the reduction in temperature-control-driven electricity consumption that covaries with daily HDDs, TOU electricity pricing can somewhat emulate the favorable feature of RTP on relatively warm winter days in Ireland---roughly speaking, on days when the value of daily HDDs is below ten. As evidently illustrated in Figure \ref{Figure:Average-Daily-Electricity-Consumption}, households' heating needs drive the demand for electricity in Irish households. So, a more significant diminution in household electricity consumption is required on cold winter days to relieve the burden on the power grid. According to Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period}, for example, for the households in Tariff Group A, the reduction in heating-associated electricity consumption in the peak rate period on warm winter days (i.e., on days when the value of daily HDDs fell between zero and ten), whose amount was more than half of the aggregated reduction in household electricity consumption under the TOU program at its maximum, expanded as households' heating needs became larger. This empirical finding means that TOU electricity pricing induces a larger reduction in household electricity consumption during peak hours as generation costs rise due to higher electricity demand, even though there were only within-day price variations under the price scheme. Consequently, in that case, the additional gains obtained by switching to RTP might not be as substantial as economists have expected. The excellent feature of TOU electricity pricing, however, gradually disappeared as daily HDDs grew above the value of ten, even though a more considerable reduction in household electricity consumption is required to ease the burden on the power grid.

# Policy Implications

## Time-Of-Use Pricing with Additional Dynamics over Daily Heating Degree Days

The U-shaped curve of peak-demand-hour reduction in temperature-control-related electricity consumption is not a desirable feature of TOU electricity pricing. The fundamental intention of the time-varying tariff scheme is to reshape load profiles, especially in the peak rate period, in order to avoid excessive investment in power generation capacity. So a higher amount of reduction in electricity consumption for heating on freezing days (i.e., on days when the power grid is most burdened) serves the purpose of the price scheme. In light of that, the U-shaped evolving pattern over daily HDDs is unattractive because on days with high heating needs, TOU electricity pricing induces even less reduction in for-heating-relevant household electricity consumption.

An alternative electricity pricing scheme, a TOU-like tariff structure with additional flexibility in price variations across daily HDDs, could address the disadvantage of typical TOU pricing revealed from my analysis (i.e., less effectiveness on days with very low temperatures). My empirical findings illustrate two important points with respect to the relationship between TOU-tariff-induced changes in household electricity consumption and price increases during the peak rate period. First, the reduction stemming from non-temperature-control-associated electricity consumption becomes larger as the magnitude of a price escalation in the peak period increases. Second, the gains obtained by marginally raising the peak-hour electricity price (i.e., an additional reduction in non-temperature-control-relevant electricity consumption) exceed the losses from such a marginal increase (i.e., a fewer reduction in temperature-control-driven electricity consumption). Those two points collectively imply that scaling up the size of a rate change in the peak rate period as daily HDDs rise enables achieving a more considerable TOU-price-induced aggregate reduction in residential electricity consumption.

Figure \ref{Figure:Additional-Savings-from-an-Alternative-Electricity-Pricing-Scheme} depicts an alternative price scheme and additional gains from it. Under the price scheme proposed in the figure, the peak-demand-hour price jumps as household heating needs become serious. To be specific, prior to the value of daily HDDs that typical TOU pricing becomes ineffective, the magnitude of peak-rate-period price change is evenly 6 cents per $kWh$. After that point, every time daily HDDs rise by five, the degree of peak-demand-hour price change increases by six cents per $kWh$. As illustrated in the figure, compared to the case in which the size of peak-hour price growth is fixed at 6 cents for all values of daily HDDs, the alternative price scheme can induce a more significant reduction in household electricity consumption according to increasing household heating needs by synchronizing price increases in the peak rate period with daily HDDs. In other words, the weakness of typical TOU pricing is alleviated under the new price structure. Moreover, this proposed price structure is better than the typical TOU tariff structure with a higher fixed peak-demand-hour price. For example, Tariff Group D reduces household electricity consumption as much as the alternative price scheme on extremely cold days. However, compared to Tariff Group D, households under the proposed price structure can consume more electricity on warm days when the power grid is ready for higher demand.

## Home Automation Technologies

As noted in Section \ref{Sub-subsection:Household-Consumption-Behavior-in-and-near-the-Peak-Rate-Period}, under the TOU program, households' adjustments to their behavior for temperature-control-driven electricity consumption during the pre-peak hours seem to determine the degree of a reduction in that use of electricity during the following period (i.e., during the peak rate period) in lieu of price signals. In Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period}, the gap in the temperature-control-related treatment effect at given daily HDDs between the lowest and the highest peak-hour rate changes, therefore, might be understood as potentially attainable gains when the pre-adjustments are suppressed. This explanation motivates the necessity of adopting home automation technologies, like Programmable Communicating Thermostats (PCTs), to restrict such adjustments only to the peak rate period. Considering the fact that households generally set a target temperature instead of micromanaging their heating devices according to ever-changing outdoor temperatures, PCTs with recommended default settings for temperature-control-associated use of electricity are highly likely to contribute to minimizing their behavioral changes prior to the peak rate period.\footnote{\cite{Default-Effects-and-Follow-on-Behavior\_Evidence-from-an-Electricity-Pricing-Program\_Fowlie-et-al\_2021} examines default effects in a randomized controlled trial, in which the participants assigned to the control group defaulted into a residential electricity pricing program. Default effects have been studied in a range of settings, such as organ donation \citep{Medicine\_Do-Defaults-Save-Lives\_Johnson-and-Goldstein\_2003, The-Impact-of-Presumed-Consent-Legislation-on-Cadaveric-Organ-Donoation\_Abadie-and-Gay\_2006}, car insurance \citep{Framing-Probability-Distortions-and-Insurance-Decisions\_Johnson-et-al\_1993}, and participation in retirement savings plans \citep{Status-Quo-Bias-in-Decision-Making\_Samuelson-and-Zeckhauser\_1988, The-Power-of-Suggestion\_Madrian-and-Shea\_2001, For-Better-or-For-Worse\_Choi-et-al\_2019}.} Moreover, the additional gains realized by utilizing the automated instruments provide legitimacy for the ongoing SEAI-offering Home Energy Grants, in which heating controls are an essential part.\footnote{Sustainable Energy Authority of Ireland (SEAI) is Ireland's national sustainable energy authority whose goal is to promote and assist the development of sustainable energy in Ireland. Detailed information about Home Energy Grants is available at \url{https://www.seai.ie/grants/research-funding/}.}