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

Exploring participating households' electricity consumption, following a time sequence surrounding the peak rate period, facilitates comprehending how they adapted to the deployment of TOU electricity pricing more completely. 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 the time-varying price structure can co-occur. Because those two ways of reacting to the time-varying tariff scheme reshape load curves around the peak rate period, it is natural to examine the TOU-tariff-inducing electricity savings as a whole from a time-moving perspective in order to grasp the dynamics of households' behavioral changes. In the following paragraphs, interpretations of the changes in households' consumption behavior relevant to each of the two broad categories of electricity use are followed by policy implications drawn from them in the subsequent sections.

Regarding residential electricity demand for non-temperature-control use, the leading reaction of the treated households to the TOU tariffs was to reduce their heating-irrelevant consumption around the peak rate period. According to my empirical analysis, as the magnitude of the peak-hour price changes under the TOU program grew, the savings from the not-for-heating electricity use increased, while it diminished in the pre- and post-peak intervals. 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 before- and after-peak intervals, the amount of electricity savings for that group was nearly the same in all three intervals. Meanwhile, despite the price decreases, the remaining tariff groups (maintained or) conserved their consumption in both intervals. In sum, the price changes in the peak rate period caused a spillover effect in those pre- and post-peak intervals: reductions in electricity consumption for non-temperature-control uses. In other words, with respect to non-temperature-control-driven electricity consumption, the households allocated to the treatment group responded to the TOU program, on the whole, via not load-shifting but load-shedding.

With respect to temperature-control-use-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 savings in for-heating electricity use during the peak rate period, especially around moderate values of daily HDDs. In the pre-peak interval, heating-associated electricity savings only occurred on days with low temperatures. In the post-peak interval, although high daily HDDs incurred additional electricity consumption after introducing TOU tariffs, which might be a consequence of load-shifting or rate decline, its amount was not large enough to offset, for given heating needs in a day, the savings in the preceding intervals.

Measuring the electricity savings of the households in Tariff Group D relative to Tariff Group A validates the load-shedding interpretations. 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 electricity consumption to off-peak hours because they faced a much larger price increase in the peak rate period. So in both near-peak intervals, the savings for Tariff Group D must be significantly smaller than those for Tariff Group A. 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, does not demonstrate a meaningful difference between them in the two intervals. That is, load-shifting did not play a role in reshaping households' load profiles in and near the peak rate period.

Going through the curves of the predicted savings related to temperature-control electricity use for the three intervals simultaneously but by taking account of their time sequence suggests a significant implication of the effectiveness of the TOU prices in the peak rate period. According to Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period}, as the magnitude of the peak-hour price escalations increased, the temperature-control-related electricity savings in the pre-peak interval expanded, while those in the peak rate period decreased gradually. Collectively, it is likely that a larger pre-adjustment leads to smaller reductions in electricity demand for heating during peaks, which in turn results in limited additional consumption in the post-peak interval. Considering that the TOU tariffs are intended to conserve electricity consumption during the peak rate period, it is inferable that fewer savings caused by too large pre-adjustment deteriorate the performance of the TOU tariffs.

## Household Consumption Behavior over Daily Heating Degree Days

My empirical results obviously illustrate that the effectiveness of the TOU tariffs, as measured by the amount of the induced electricity savings, nonlinearly varies with daily HDDs. As discussed, the total electricity savings caused by the deployment of TOU pricing consists of two elements: the savings from electricity consumption for non-temperature-control use and those from electricity consumption for temperature-control use. By definition, the savings originating from non-for-heating electricity consumption are independent of daily HDDs. Hence, the nonlinearity in the effectiveness of the TOU structures is utterly attributable to the other type of electricity consumption, that for heating which Figure \ref{Figure:Treatment-Effects-as-a-Linear-Function-of-Price-Changes-in-the-Peak-Rate-Period} confirms.

The nonlinear relationship between the amount of TOU-price-causing electricity savings and daily HDDs indicates an interesting characteristic of the tariff structure: the day-varying effects 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 total amount of TOU-price-inducing electricity savings also alters every day.

The day-varying effectiveness of TOU electricity pricing suggests an implication in connection with Real-Time Pricing (RTP), a type of 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. Economists, therefore, prefer RTP to TOU pricing. But because TOU-tariff-inducing electricity savings covariate with daily HDDs, TOU electricity pricing can somewhat emulate the favorable feature of RTP, especially on days with moderate temperatures. For example, on typical winter days in Ireland, Tariff Group A's heating-associated electricity savings in the peak rate period were more than half of the total savings under the TOU program. In other words, the time-varying rate structure already induced substantial reductions in electricity consumption according to across-day variations in generation costs, even though there were only within-day price variations under the price structure. Consequently, in that case, the additional gains obtained by switching to RTP might not be significant as economists have expected.

# Policy Implications

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

The U-shaped curve of temperature-control-use-associated electricity savings in the peak rate period is not a desirable feature of TOU pricing. The fundamental intention of the time-varying tariff scheme is to reshape load profiles, especially in the peak-demand period, to avoid excessive investment in power generation capacity. So a higher amount of savings in electricity consumption for heating on freezing days (i.e., on days in which the grid is most burdened) serves the purpose of the price scheme. In light of that, the U-shaped evolving pattern of the savings over daily HDDs is unattractive because on days with high heating needs, the price structure induces even less savings 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., fewer electricity savings on days with very low temperatures). My empirical findings illustrate two important relationships between TOU-tariff-inducing electricity savings and the price variations in the peak-demand hours. First, the savings from electricity consumption for non-temperature-control use become larger as the size of price escalation during peak hours increases. Second, raising the magnitude of price change in the peak rate period somewhat inhibits heating-related electricity savings from disappearing even at a high level of daily HDDs. Those two points collectively imply that scaling up the size of rate changes in the peak rate period as daily HDDs escalate allows for achieving more considerable TOU-price-inducing aggregate savings in residential electricity consumption.

Figure \ref{Figure:Additional-Savings-from-an-Alternative-Electricity-Pricing-Scheme} depicts additional electricity savings under an alternative pricing scheme. In the pricing scheme, the peak-demand-hour price jumps as household heating needs become serious. Specifically, under the alternative pricing demonstrated in the figure, every time daily HDDs rise by 5, the size of rate change in the peak rate period, which is evenly 6 cents per $kWh$ before the daily HDDs where typical TOU pricing becomes ineffective, increases by 6 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, the alternative price scheme can induce additional savings in household electricity consumption, which are highlighted by using three different colors in the figure.

## 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 consumption behavior for temperature-control electricity use during the pre-peak hours seem to result in fewer savings in the following period (i.e., the peak rate period). 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 savings at given daily HDDs between the lowest and the highest peak-hour rate changes, therefore, might be understood as potentially attainable savings 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 use of electricity are highly likely to contribute to minimizing the behavioral changes before 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 benefits obtained 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. And detailed information about Home Energy Grants is available at \url{https://www.seai.ie/grants/research-funding/}.}

Confining the impact of TOU prices on household electricity consumption for temperature-control use to the peak rate period by exploiting an automation technology provides more than realizing the potential electricity savings in the period. As discussed in Section 4.1.2, TOU electricity pricing can induce substantially larger electricity savings on days when the temperatures are more extreme and the demand on the grid is higher, even though the rates under the tariff structure do not vary across days. Because an automated system for heating controls causes additional savings in electricity consumption for temperature-control use during peaks, especially on typical winter days in Ireland, the savings are comparable to those from more granular types of dynamic price schemes.