The results from my empirical analysis clearly indicate that under Time-Of-Use (TOU) electricity pricing, residential electricity consumption is driven by various factors, such as the timing when electricity is consumed, daily HDDs, and the magnitude of price increases in the peak rate period. In other words, within-household electricity consumption behavior shows multidimensional dynamics. Based on my empirical findings, I will discuss the dynamics in detail in the following sections. Furthermore, I will also discuss the policy implications suggested by it.

# Multidimensional Dynamics of Household Electricity Consumption

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

Exploring participating households' electricity consumption, according to a time sequence around the peak rate period, facilitates comprehending how they adapted to the deployment of TOU electricity pricing precisely. 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 choose to shift it to off-peak hours in order not to be subject to the peak rate as much as possible. In this case, the level of their net electricity consumption is maintained. Because those two ways of reacting to the time-varying tariff scheme reshape load curves around the peak rate period, it is required to examine the TOU-tariff-inducing electricity savings, as a whole, in and near the period in order to grasp households' behavioral changes.

Regarding residential electricity demand for non-temperature-control uses, the leading reaction of the households allocated to the treatment group to the TOU tariffs was to reduce their heating-irrelevant consumption around the peak rate period. As discussed, to the magnitude of the peak-hour price changes under the TOU program, the not-for-heating electricity savings were directly proportional in the peak rate period while inversely proportional 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 in 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 increases, the remaining tariff groups (maintained or) conserved their consumption in both pre- and post-peak 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, the households allocated to the treatment group responded to the TOU program, on the whole, not through load-shifting but load-shedding.

With respect to temperature-control-use-related household electricity consumption, Figure XYZ illustrates 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 occurred even though on days with low temperatures only. 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 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-relevant interpretation. Let's suppose that for the treated, load-shifting is a primary countermeasure against the TOU program. Then 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 before- and after-peak intervals, the savings for Tariff Group D must be significantly smaller than those for Tariff Group A. However, Figure XYZ, 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. That is, load-shifting did not play a role in reshaping households' load profiles.

The over-HDD load profiles from pre- to post-peak intervals suggest a significant implication of the effectiveness of the TOU prices in the peak rate period. As shown in Figure XYZ, on days with high heating needs, savings from for-heating-associated electricity consumption during the pre-peak hours were directly proportional to the price increases in the peak rate period. On the contrary, the savings decreased according to the price increases during the peak rate period. Collectively, it is likely that large pre-adjustment leads to small reductions in electricity demand for heating during peaks, which in turn results in limited additional consumption during the post-peak hours. Considering that the TOU tariffs are intended to conserve electricity consumption during the peak rate period, less savings from too large pre-adjustment deteriorates the performance of the TOU tariffs.

## Household Consumption Behavior over Daily Heating Degree Days

My empirical results obviously show that the effectiveness of the TOU tariffs, as measured by the magnitude 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 uses and those from electricity consumption for temperature-control uses. 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 source of electricity savings, electricity consumption for heating.

The nonlinear relationship between the amount of TOU-price-causing electricity savings and daily HDDs suggests an interesting characteristic of the tariff structure: the day-varying effects of TOU pricing on residential electricity consumption. Daily HDDs, which are one of the critical determinants of for-heating-relevant saving, vary day by day. Therefore, it is natural that in proportion 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 interesting 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 extreme temperatures. For example, on typical winter days in Ireland, Tariff Group A's heating-associated electricity savings in the peak rate period is almost half of the total savings under the TOU program. In other words, the time-varying rate structure already induces substantial reductions in electricity consumption according to real-time generation costs, even though there were only within-day price variations. 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 with flexibility in daily HDDs, alongside within-day rate variations, could address the disadvantage of typical TOU pricing, less electricity savings on days with very low temperatures. My empirical findings illustrate two important dynamics in peak-hour electricity savings. First, the savings from electricity consumption for non-temperature-control uses are directly proportional to the size of price increases in that period. Second, raising the magnitude of price changes in the peak rate period 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 savings in residential electricity consumption.

Figure XYZ proposes an even more dynamic TOU price structure. ...

## Home Automation Technologies

The behavioral adjustment during the pre-peak hours to temperature-control use of electricity seems to result in less savings in the peak rate period. As noted in Section XYZ, the gap in the savings from electricity consumption for temperature-control uses at a given daily HDDs between saving curves of the lowest and the highest rate changes in the peak rate period illustrates attainable savings potentially. And the potential savings could be realized by minimizing households' pre-adjustment in the pre-peak interval. In other words, technologies that confine such behavioral changes regarding electricity consumption to the peak-demand hours may improve the effectiveness of TOU electricity pricing in the peak rate period.