3 Empirical Analysis and Results

3.1 Household Average Responses to Time-Of-Use Electricity Pricing

3.1.1 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 Average Treatment Eﬀect (ATE) for each half-hour interval, I estimate the following speciﬁcation:

kWhitw = βw1[Treatment & Post]it + αiw + γtw + δm + %itw (1)

The term kW hitw is the electricity consumption by household i on the day t during the half-hourly time window w. The indicator variable 1[Treatment & Post]it is equal to 1 only if household i is in the treatment group and the day t is in the treatment period. The terms αiw, γtw, and δm are household-by-half-hourly-interval, day-of-sample-by-half-hourly-time-window, and month-of-year ﬁxed eﬀects, respectively. In the speciﬁcation, the point estimates of βw, 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 6 summarizes the estimated ATEs in the form of a time proﬁle. As already demonstrated in Prest (2020), peak hours (i.e., from 5:00 p.m. to 7:00 p.m.), during which the ineﬃciency of a ﬁxed ﬂat rate tariﬀ is greatly intensiﬁed, show dominant electricity savings. The ﬁgure also demonstrates reductions in household electricity consumption not only in most of the meter readings prior to the peak rate period but also in three successive meter readings right after the period, even though the reductions, with two exceptions, are not statistically signiﬁcant. The insigniﬁcant reductions in household electricity consumption are interesting because TOU prices in oﬀ-peak hours (i.e., prices in the night and day rate periods) were lower than the ﬂat rate in the baseline period. The counterintuitive changes might indicate that households preemptively adjusted their consumption behavior to avoid the incident of paying higher prices. In other words, the peak-hour price increases under the TOU program were likely to cause some spillover eﬀects in the hours leading up to and following the peak rate period. To explore whether households responded to the TOU program outside of the peak rate period as well or not, in the following empirical analysis, I will also pay attention to the oﬀ-peak hours, particularly the hours surrounding the peak rate period.

3.1.2 Hourly Average Treatment Eﬀects in and near the Peak Rate Period

Estimating by-tariﬀ-group ATEs in and near the peak rate period allows understanding how the relationship between the degree of change in household electricity consumption and the magnitude of a peak-demand-hour price increase evolves in and near the peak rate period.[[1]](#footnote-1) To do so, I run the following regression for each of the four tariﬀ groups:

kWhith = βp1[Treatment & Post]it + αiw + γtw + δm + %ith (2)

Excepting the dependent variable and the parameter of interest, the econometric model above is the same as (1). Speciﬁcally, the response variable kW hith, which means the electricity consumption by household i on the day t during the hour of the day h, is utilized due to its better accessibility in interpretation. The point estimates of βp indicate the ATE for each of the three intervals included in rate period p. Table 4 summarizes the regression results.

The measured ATEs for the peak rate period re-conﬁrm the ﬁnding provided in Prest (2020).[[2]](#footnote-2) The table clearly shows that within-household aggregate demand for electricity during the peak rate period declined, with a signiﬁcance level of 0.01, due to the deployment of TOU pricing. However, based on the point estimates for the four tariﬀ groups, it is unclear whether an incremental change in peak-rate-period price increase induces a statistically meaningful additional change in household electricity consumption or not.

To quantify how residential consumers responded to the TOU program in oﬀ-peak hours close to the peak rate period, I also estimate ATEs in periods of two hours before and after the peak rate period (i.e., in pre-and post-peak periods). Interestingly, the table also demonstrates that in the pre- and post-peak periods, the implementation of the TOU tariﬀ structures resulted in reductions in household electricity consumption, which are statistically diﬀerent from zero, even though TOU prices were lower than the ﬂat rate of 14.1 cents per kWh.[[3]](#footnote-3) The reductions in both periods surrounding the peak hours suggest that the impact of the price increases in the peak rate period overtook the impact of the price drops in each oﬀ-peak period. Therefore, in the following empirical analysis, I will focus on linking household electricity consumption in the pre- and post-peak periods with the price increases in the peak rate period, instead of the price decreases in those oﬀ-peak periods.

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

3.2.1 Breakdown of Household Responses in and near the Peak Rate Period

Figure 4 indicates the limitations of focusing on aggregate electricity consumption, as many studies have been doing. The ﬁgure clearly shows that aggregate household electricity consumption increases as the weather becomes colder in Ireland. Intuitively, the negative correlation between them can be mainly attributable to for-heating electricity consumption, which strongly depends on outdoor temperatures. It is a fact that aggregate residential electricity consumption also includes another type of electricity consumption: electricity consumption that is irrelevant to temperature variations, such as consumption for lighting. Those two broad categories of electricity consumption could react diﬀerently to TOU electricity pricing. Electricity consumption for heating can be transferred to a diﬀerent time of the day (e.g., from 6 p.m. to 4 p.m. to avoid a higher unit price under the TOU tariﬀ structures). On the other hand, electricity consumption for lighting is time sensitive. Due to the diﬀerence in the costs of relocating or changing electricity consumption, it is possible that the two channels of household electricity consumption respond to TOU electricity pricing in diﬀerent ways. Therefore, using aggregate electricity consumption to examine households’ responses to the time-varying price scheme enables me to access only the aggregated response.

Considering the discussion above, I decompose household electricity consumption into two broad categories—non-temperature-control-driven and temperature-control-driven electricity consumption—and examine how each category of electricity consumption responds to the introduction of the TOU tariﬀ structures. The temperature- control-related electricity consumption here means using electricity to satisfy home heating needs (e.g., to warm up space or water). So, the use of electricity for heating strictly depends on each day’s weather conditions, especially temperatures. Naturally, the non-temperature-control-associated electricity consumption makes up the rest.

I exploit daily Heating Degree Days (HDDs), which imply overall heating needs on a given day, to isolate the temperature-control-driven consumption from aggregate household electricity consumption. Because only aggregate metering data is available from the CER experiment dataset, there is no clue allowing me to classify household electricity consumption into two distinct categories in the dataset. To address this challenge, I presume that the portion of household electricity consumption that ﬂuctuates according to daily HDDs is temperature- control-driven electricity consumption. Therefore, the electricity consumption for temperature-control use is additional consumption that appears only on days with non-zero daily HDDs due to household heating needs.

To break down household responses to the TOU program around the peak rate period, I exploit the following DID-style spline regression model:

Diagram, text

Description automatically generated

Like (2), the dependent variable kW hith 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 1[Treatment]i has the value of 1 if household i is assigned to the treatment group; the second indicator variable 1[Post]t equals 1 when the day t is in the treatment period; the last indicator variable 1[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, HDDt means the daily heating degree days on the day t. And HDD∗t , which is required to introduce nonlinearity in HDD-associated response to TOU pricing, is mathematically deﬁned as follows:

HDD∗t = (HDDt − Knot) × 1[HDDt > Knot], (4)

where Knot is a reference value at which the slope of the predicted line starts to change. For Knot, I utilize the value of ten in the following regression analysis because the median values of daily HDDs in the baseline and treatment periods are ten. The terms αiw, γdw, and δmw 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 (3) are β9, β10, and β11. The three coeﬃcients show how much electricity consumption the households assigned to the treatment group changed after implementing the TOU program compared to those in the control group. To be speciﬁc, β9 demonstrates the change in residential electricity consumption for non-temperature-control use. Both β10 and β11 collectively represent the change in the amount of electricity consumed to meet household heating needs at given daily HDDs.

Using the point estimates of the three coeﬃcients of interest provided in Table 5, I graphically summarize the predicted change in each of the two channels of electricity consumption in Figure 7. Regarding the change in electricity consumption for non-temperature-control use, the table and ﬁgure clearly show that the treated households signiﬁcantly reduced their consumption when they were subject to peak-hour prices (i.e., in the peak rate period). Their non-temperature-control-driven electricity consumption also decreased in the pre- and post-peak periods, albeit noisy and relatively smaller in magnitude than the peak-hour changes.

The change in temperature-control-associated electricity consumption occurred as well in all three periods of two hours, but its evolving pattern over daily HDDs was quite diﬀerent in each period. Speciﬁcally, the impact of TOU pricing on residential electricity consumption for heating was U-shaped in the peak rate period, while it was salient only when daily HDDs were suﬃciently large in the two periods surrounding the peak rate period. In other words, from the ﬁgure, it is evident that the change originating from temperature-control-related electricity consumption was a nonlinear function of daily HDDs in all three periods.

The speciﬁcation (3) is also utilized to examine, for the peak rate period, the relationship between the degree of a price increase in that period and the change in electricity consumption. The by-tariﬀ-group estimates of the coeﬃcients of interest are also presented in Table 5. As shown in the table, on the whole, the reduction stemming from electricity demand for non-temperature-control use tends to be proportional to the size of price growth in peak hours, even though the point estimate for Tariﬀ Group C is an exception. Therefore, the marginally diminishing eﬀects of TOU pricing, discussed in Prest (2020), seem not to be championed by my point estimates. And the two estimates associated with temperature-control-driven electricity consumption (i.e., βˆ10 and βˆ11) are statistically signiﬁcant only for the case of the smallest price increase (i.e., only for Tariﬀ Group A).

Altogether, those results imply two interesting points. First, as expected, the two distinct types of electricity consumption showed widely diﬀerent responses to TOU prices in all three periods of two hours. Second, the measured reductions in non-temperature-control-related electricity consumption seem highly sensitive to the magnitude of a price increase in the peak rate period. Inspired by those implications, I formulate the resulting variations in household electricity consumption as a linear function of the magnitude of a rate change in peak-demand hours in the following section.

3.2.2 Household Responses as a Linear Function of Price Changes

To fully understand how residential consumers adjust their consumption behavior as a set of reactions to the price changes under the TOU program, it is necessary to explicitly examine, for each of the three periods (i.e., the pre-peak, peak, and post-peak periods), the relationship between the size of a price increase in the peak rate period and the changes in the two distinct categories of household electricity consumption. For that reason, I quantitatively determine the relationship by utilizing the following econometric model:

Text

Description automatically generated

The model is the same with (3) except for interaction terms between treatment-status-relevant indicator variables (i.e., 1[Treatment]i and 1[Treatment & Post]it) and ∆PCi, where ∆PCi 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 TOU tariﬀs on household electricity consumption as a linear function of the degree of a peak-demand-hour price change.

The estimates of the six coeﬃcients of interest (i.e., from β12 to β17) presented in Table 6 are summarized graphically in Figure 8. And this ﬁgure, showing the estimated treatment eﬀects for the two consumption channels and the sum of the treatment eﬀects in each of the three intervals, re-conﬁrms the ﬁnding of peak-rate-period price increases’ diminishing returns in Prest (2020).

In the peak rate period, the reduction in non-temperature-control-associated electricity consumption increased as the magnitude of a peak-hour price increase grew. On the contrary, at given daily HDDs, the reduction in temperature-control-related electricity consumption weakly moved towards zero as the size of a peak-demand-hour tariﬀ escalation increased. As well illustrated in the ﬁgure, for a given value of daily HDDs, the diﬀerences in treatment eﬀect across the level of price growth are seemingly dampened when the estimated treatment eﬀects from two distinct categories of electricity consumption are aggregated due to the opposite response to peak-hour price increases in the two consumption categories. Indeed, this empirical result is consistent with the ﬁnding discussed in the paper that a higher price results in a larger diminution in electricity demand, while additional gains diminish in the peak interval.

The opposite order of by-rate-change treatment eﬀects for given daily HDDs in two diﬀerent types of electricity consumption also holds in the pre-peak interval, although in a contrary manner. The interval shows a more signiﬁcant reduction in non-temperature-control-driven electricity consumption for a more minor change in peak-hour price. By contrast, the diminution in non-temperature-control-related electricity consumption exhibits an inverse relationship with the peak-rate-period price change. For the same reason as in the peak interval, the aggregate treatment eﬀects of the TOU tariﬀs described in the last row of Figure 8 are seemingly less sensitive to the peak-hour prices. Note that regarding electricity consumption for heating during the pre-peak interval, TOU pricing played a role only when household heating needs were suﬃciently high.

Irish residential consumers adjusted their electricity consumption behavior during the post-peak period as well. As in the pre-peak period, consumption changes stemming from non-temperature-control-related electricity use increased as the size of a peak-demand-hour rate change diminished. The TOU-price-induced change in temperature-control-driven electricity consumption evolved over daily HDDs somewhat complicatedly. Though depending on the magnitude of a peak-hour price increase, TOU tariﬀs reduced household electricity consumption for heating on Ireland’s typical winter days in that period. Interestingly, the CER TOU program provoked additional heating-related consumption during the post-peak period on extremely cold days in Ireland. In addition, as the level of peak-demand-hour price alteration grew, the proﬁle of measured treatment eﬀect for temperature-control-associated consumption moved downward. Consequently, a higher price increase in the peak rate period resulted in a more signiﬁcant reduction in electricity consumption for heating when heating demands were lower, while a smaller addition to electricity consumption for heating on cold winter days.

In summary, under TOU electricity pricing, the degree of a price change in peak-demand hours, not just its existence, still matters to residential consumers’ electricity consumption. The empirical results above suggest that the opposite directional changes in the two channels of electricity consumption make Irish households appear insensitive to the time-varying price structure. In other words, their high sensitivity to TOU prices is revealed only when their electricity consumption is disaggregated. 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 increase in the peak rate period.

4 Dynamics of Household Electricity Consumption under Time-Of-

Use Electricity Pricing

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.

4.1 Multidimensional Dynamics of Household Electricity Consumption

4.1.1 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 8, 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 8 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[[4]](#footnote-4)—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 1, 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 9, 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 8, 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.[[5]](#footnote-5) 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.

4.1.2 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 8, 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.[[6]](#footnote-6) 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 4, 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 8, 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.

4.2 Policy Implications

4.2.1 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 10 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 kW h. After that point, every time daily HDDs rise by ﬁve, the degree of peak-demand-hour price change increases by six cents per kW h. 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.

4.2.2 Home Automation Technologies

As noted in Section 4.1.1, 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 8, 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.[[7]](#footnote-7) 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.[[8]](#footnote-8)

5 Conclusion

The primary aim of various types of time-varying electricity pricing is to reshape load curves, especially around the peak-demand hours. Under the dynamic pricing of electricity, prices—more precisely, price variations—,which reﬂect instantaneous generation costs, are utilized to incentivize consumers to change their consumption behavior. Therefore, their responsiveness to the price changes in the tariﬀ structures determines whether the time-varying electricity prices, including TOU pricing, will work as intended. In this paper, I quantify how sensitively households adjust their electricity consumption in response to TOU prices in and near the peak rate period. The results from my empirical analysis reveal two interesting points: household electricity consumption, consisting of two categories of electricity use—non-temperature-control-driven and temperature-control-driven consumption—, 1) sensitively responded to the magnitude of the price change in the peak rate period, and 2) also depended on daily heating degree days as well as the point electricity was consumed in time for a given rate change. In other words, my empirical analysis discloses the multidimensional dynamics of households’ responses to the TOU tariﬀs.

Those ﬁndings provide important policy implications for TOU electricity pricing. First, along with residential consumers’ high price sensitivity, the nonlinearity in their responses to daily heating needs proposes an alternative pricing scheme: TOU pricing with additional ﬂexibility induced by synchronizing the magnitude of the peak-demand-hour price jump with daily heating degree days. Second, taking a close look at the relationship between the size of the peak-hour price increase and the changes in electricity consumption for temperature-control uses in chronological order emphasizes the importance of adopting home automation technologies, like Programmable Communicating Thermostats (PCTs), to improve the performance of TOU pricing.

My empirical ﬁndings and the policy implications derived from them ultimately indicate that an integrated understanding of the multidimensional dynamics of households’ responses to TOU electricity pricing is required to make the price structure function with its full potential as a demand management tool. Furthermore, even for stakeholders in the electricity market, such as power generators, investors, regulators, and policymakers, comprehending how electricity consumption reacts to the time-varying pricing is critical because consumers’ behavioral changes are an important piece of information in their decision makings.

1. 23In 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. [↑](#footnote-ref-1)
2. See Figure 6 in Prest (2020). [↑](#footnote-ref-2)
3. Even insigniﬁcant point estimates (i.e., point estimates for Tariﬀ Groups C and D in the pre-peak interval and Tariﬀ Group C in the post-peak interval) have negative values. [↑](#footnote-ref-3)
4. 27See Figure 3. [↑](#footnote-ref-4)
5. This interpretation is in line with the concept “discomfort” in Blonz et al. (2021). See Section 3.4 in the paper. [↑](#footnote-ref-5)
6. Harding and Sexton (2017) provides a detailed description of various kinds of time-varying electricity tariﬀ structures. [↑](#footnote-ref-6)
7. 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 (Johnson and Goldstein, 2003; Abadie and Gay, 2006), car insurance (Johnson et al., 1993), and participation in retirement savings plans (Samuelson and Zeckhauser, 1988; Madrian and Shea, 2001; Choi et al., 2019). [↑](#footnote-ref-7)
8. 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 https://www.seai.ie/grants/research-funding/. [↑](#footnote-ref-8)