***DOES TIME-OF-USE PRICING IMPACT RESIDENTIAL ENERGY EFFICIENCY AND SOLAR PANEL ADOPTION?***

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## Overview

Energy efficiency and solar energy are two measures promoted by policy makers to reduce residential energy consumption and the associated greenhouse gas emissions. However, the penetration of energy efficiency and solar energy is still relatively low. Many organizational, behavioral, and market factors have been analyzed in existing literature to explain the low adoption level (Gillingham et al., 2009; Davis, 2011). Yet, the impact of one particular factor (electricity rate structure) on energy efficiency investment and solar panel adoption is often overlooked (Novan and Smith, 2017). This paper compares the adoption of energy efficient appliances and solar panels between consumers on flat rates and those on Time-Of-Use (TOU) rates.

This study adds to three strands of literature. First, this study contributes to the strand of studies on energy efficiency gap by exploring whether rate design can contribute to the mitigation of energy efficiency gap and increases in the adoption of solar panels. Second, this study contributes further to studying the impact of TOU on energy consumption behaviors by examining whether TOU impacts energy technology adoption. Third, despite simulation or modeling on the interaction between rate design and solar panel adoption, there is a lack of empirical evidence for the impacts of rate design on the adoption of low-carbon technologies. We focus on energy efficient air conditioner units because air conditioner accounts for a half of the electricity use (Pérez-Lombard et al., 2008). An understanding of the impacts of TOU on energy efficient AC provides insights into the influences of TOU on other appliances. we also analyze the adoption of energy efficient room air conditioners because this could have good implications for policy-making, especially in the developing countries.

## Methods

We first build a theoretical model to show that TOU customers have larger incentives to adopt energy efficiency and solar panels. We construct a two-period model to illustrate consumers’ decision process. In period 1, a consumer makes a decision to 1) purchase energy efficient appliances (e.g., energy star air conditioner) or 2) adopt solar panels. In period 2, they decide on how much electricity to use after the decision in the first period. The theoretical model indicates that the cutoff points for the consumers to adopt solar panels or energy efficient appliances depends on the technology saving rate, the investment costs, and the relative magnitude of flat rate electricity price and the effective TOU price.

Then a probit model is employed to provide empirical evidence, using household-level data in Phoenix, Arizona from an appliance saturation survey of about 16,000 customers conducted by a major electric utility in 2014.

$y\_{i}=\left\{\begin{array}{c}1 if y\_{i}^{\*}>0\\0 otherwise\end{array}\right.$ (1)

$y\_{i}^{\*}=β\_{0}+β\_{1}\left(TOU\_{i}\right)+β\_{2}X\_{i}+ε\_{i}$ (2)

where *i* indicates individual household *i*; $y\_{i}$ is a binary dependent variable indicating the adoption of energy efficient air conditioner or solar panels. $y\_{i}^{\*}$ is the latent variable; TOU is equal to 1 if the household is on TOU pricing plans and is 0 if the household is on the flat rate. $ X$is a vector of control variables, including the demographics (age, households, income, etc.) and housing characteristics (square footage, ownership, stories, etc.). Although there are incentives for energy efficiency or solar panels, there is no variation for incentives because the utility provides same incentives to its consumers.

Since TOU is not mandatory, it is possible that some households are selected to enroll in TOU, meaning some consumers are more likely to enroll in TOU compared to others while these households are also more likely to adopt energy efficiency and solar panels. If these households have specific characteristics that are not observable to us, a potential self-selection bias exists. We address the concern of self-selection by applying a matching approach, i.e., propensity score matching and coarsened exact matching (Rubin, 1976; Iacus et al., 2011). For a customer that is on TOU rate, we find a control customer that is similar in terms of home and socio-economic characteristics and that is not on TOU rate.

We conduct three robustness checks to further analyze the adoption of energy efficient central air conditioner and solar panels between TOU and non-TOU consumers. First, we conduct a multinomial logit model to analyze combinations of technology choices. Second, we use an instrumental variable approach. We obtain predicted probabilities of enrolling in TOU using the probit model, and then the adoption of solar panels or energy efficiency is regressed on the predicted TOU using Ordinary Least Squares. The instrumental variables used is the share of customers on TOU in neighboring zip codes. Third, we run a bivariate probit model to examine the relationship between TOU enrollment and technology adoption. Machine learning approach is also adopted by using classification and regression trees (CART)-based propensity score model.

## Results

In sum, the empirical evidence shows that consumers in Arizona enrolled in TOU are about 0.9-1.4 percentage point or 28% on average more likely to install the solar panel, but there is no evidence that they are also more likely to adopt energy efficient air conditioning. The possible reason might be that while it is obvious that solar panels generate most electricity during peak hours (because the solar radiation is the strongest during afternoon hours which coincide with peak hours), it is not obvious to consumers whether energy efficiency saves the most electricity during peak hours.

The findings highlight that TOU could act as a cost-effective policy instrument to facilitate solar panel adoption, compared to other instruments with a similar magnitude of impacts such as direct rebates. The results have some policy implications for policymakers and utilities. First, utilities could provide more information regarding the benefit of TOU for solar adopters. Second, policies could be implemented to provide more information to consumers about times when energy savings occur. More studies are needed to show empirical evidence about the exact savings by hour of day for energy efficient appliances. Studies on the timing of energy savings also help with the understanding of the comparison between actual social savings and private savings (Boomhower and Davis, 2017).

TOU has a large potential to enhance social welfare. Firstly, TOU reduces the demand for electricity generated by fossil fuels and reduces the negative externalities such as pollutants and carbon emissions. Secondly, TOU aligns the social costs of energy consumption with the marginal prices, possibly increasing the market efficiency by reducing the deadweight loss. Thirdly, this study points out another approach through which TOU could enhance social welfare, which is promoting the adoption of energy technologies. By showing that TOU has a potential to increase the social welfare, our results add to the discussion of whether TOU should be mandated or voluntary for the residential sector***.***

## Conclusions

This paper compares investment decisions in energy efficient appliances and solar panels between consumers on flat rates (marginal electricity prices are constant throughout the day) and those on TOU rates. Empirical evidence suggests that TOU consumers are 28% more likely to install solar panels, but there is no empirical evidence that they are also more likely to adopt energy efficient AC. While TOU is found to enhance social welfare through aligning social costs with the private costs (Novan and Smith, 2017), this study shows that a TOU plan is a low-cost instrument to promote solar panel adoption and has almost the same magnitude of impact on promoting adoption as a rebate policy of $11,770, which adds to a new layer of potential benefit of adopting TOU pricing plan.

## References

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