Do households respond to Time-Of-Use tariffs? Evidence from Australia

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Abstract

We estimate the elasticity of substitution for households on Time-Of-Use (TOU) tariffs using a sample of 6,957 electricity bills from households in Victoria, Australia. Across the full sample we find the difference between peak and off-peak prices has little influence on the difference between peak and off-peak consumption and is not affected by access to rooftop photovoltaics. Households in the lowest socio-economic areas do not respond to differences in peak and off-peak prices. Our findings of the elasticity of substitution are remarkably similar to previous studies of TOU tariffs in the United States of America in the 1980s. This suggests retail market deregulation, the installation of smart meters, consumers' access to their consumption data and enduring policy support for TOU tariffs has not been rewarded with any measurable improvement in consumers' responsiveness to time-varying prices. While freedom to select TOU tariffs is valuable, these findings do not support the imposition of TOU tariffs as a default pricing policy.

Keywords: Time-Of-Use, load shifting, elasticity of substitution, electricity
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Declarations

Bruce Mountain and Amine Gassem are co-founders of a comparison website. The extraction and processing of electricity bill data used in this study was performed using data extraction and pricing software used by that website.

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Competing interests

The authors have no competing interests to declare.

Research data for this article

Individuals that provided their electricity bills to the Victorian Government's price comparison website were assured their personal information would be held and used in accordance with the Victorian Government's privacy policy. These records were provided to VEPC by the Victorian Government under a strict confidentiality agreement that prohibits the public release of source data contained in household bills.

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Highlights

- The ratio of peak to off-peak prices in TOU tariffs has little influence on the ratio of peak to off-peak electricity consumption.
- Whether a household installs rooftop photovoltaics does not affect responsiveness to peak and off-peak prices.
- Households in the lowest socio-economic areas do not respond to time-varying prices.
- Despite significant advancements since TOU tariffs were studied in the 1980's, the elasticity of substitution is little changed.
- This evidence does not support the imposition of TOU tariffs as default pricing policy.

1. Introduction

Time-Of-Use (TOU) electricity tariffs have consumption rates that vary by time of day and sometimes also by day of week and week of year. Electricity prices that reflect temporal variation in the cost of supply may reduce costs if consumers respond to time-varying prices by reducing their consumption when prices (and costs) are higher. For example, a more constant demand reduces the need to start and stop more expensive production to meet short-lived demand peaks. More constant demand improves the utilization of production and distribution infrastructure and so reduces average costs and defers or avoids capacity expansion. More constant electricity demand may also reduce greenhouse gas emissions although this depends on the greenhouse gas intensity of the production that would replace otherwise infrequently used peaking capacity. In these ways, a more constant demand can reduce investment and operating expenditure and thus help to ensure lower and less volatile electricity prices (Ericson, 2011; Gyamfi et al., 2013). In addition, in the context of increasing variable renewable electricity generation, demand that is better able to follow supply is increasingly valued (Nicholson et al., 2018). Finally TOU tariffs also offer private benefits to consumers by providing the opportunity to reduce their bills if they shift consumption from high priced periods to lower priced periods, although such shifts typically come at the expense of convenience and utility.

Do consumers respond to TOU tariffs and how is this affected by various factors? In this study, we use a sample of 6,957 household electricity bills obtained from consumers in Victoria, Australia, to assess whether there is a shift in consumption from peak to off-peak periods in response to the difference in peak and off-peak prices. The elasticity of substitution (the measure traditionally used to assess load shifting behavior under TOU tariffs) is estimated for the full sample and then separately for households that have installed rooftop photovoltaics (PV) and households that have separately metered (controlled) loads. We also break the sample into three socio-economic tiers (low, medium, high) based on the socio-economic ranking of the postcode of each household, to measure how the elasticity of substitution varies in these tiers.

We contribute to the literature in several ways. First, we use a large sample of actual household bills to assess the effectiveness of TOU tariffs in Victoria as measured by the elasticity of substitution. As far as we are aware such studies do not yet exist for TOU tariffs in Victoria.

Furthermore, globally there have been few such empirical studies since the 1980s and thus there is limited contemporary evidence on how responsiveness has changed following developments in market structure, technology and regulation. Second, by drawing on a large sample of household bills we analyze consumer responsiveness in a real market rather than the more commonly studied small pilots and experiments.

Our findings are relevant to policy makers in several ways. They help to inform the expectations of consumer responsiveness to prices that vary over the day. As explained, such responsiveness is increasingly valuable as variable renewable resources increasingly dominate supply. They also provide insights into the relative merits of opt-in versus opt-out policy for the selection of TOU tariffs. Finally, the results of this study provide insight into the extent to which consumers' responsiveness to TOU tariffs is affected by access to rooftop PV or controlled load.

The remainder of the paper proceeds as follows: Section 2 discusses literature relevant to this study; Section 3 describes the data and presents a preliminary analysis of the data; Section 4 is the econometric analysis and is followed with a discussion of the findings in Section 5 and conclusions in Section 6.

2. Relevant literature

Studies of consumers' responsiveness to TOU tariffs use a variety of measures including own-price elasticity of demand, cross-price elasticity, the elasticity of substitution and reductions in load during peak hours. Own-price elasticity of demand measures how demand changes in response to a change in price, but doesn't measure how consumption in one period is influenced by the price in the other period. Cross-price elasticity measures how consumption in one period is influenced by the price of electricity in the other period and can be used to identify whether goods are compliments or substitutes. Although this measure captures how demand in one period is influenced by price in the other period, it does not measure how the difference between peak and off-peak prices affects the difference between peak and off-peak consumption. Elasticity of substitution measures how consumption in peak and off-peak hours is affected by differences between peak and off-peak prices. Since we are interested in measuring the extent to which consumers shift load from peak to off-peak hours in response to differences between peak and off-peak prices the elasticity of substitution is the appropriate measure and so our literature review focusses on this.

Empirical literature relevant to our study starts with Caves and Christensen (1980b). They study changes in the relative amounts of electricity used in peak versus off-peak periods as measured in a TOU tariff experiment in Wisconsin in 1976 and 1977.[1] They estimate that the elasticity of substitution declines as the length of the price blocks increases, meaning that consumers respond less when price blocks are longer (the elasticity of substitution falls from 0.139 to 0.113 to 0.103 when the price blocks increases from 6 hours (9am-12pm; 1pm-4pm) to 9 hours (8am-5pm) to 12 hours (8am-8pm), respectively). The average elasticity of substitution is 0.117 across all price blocks. Further, responsiveness is positively related to major appliances, but they find no causal relationship between peak/off-peak usage and family size or education. They also classify their sample according to low, medium and high usage and find households that use more electricity are not necessarily more responsive to time-of-use price differences.

In a second study of the Wisconsin TOU pricing experiment (July to August 1977), Caves and Christensen (1980a) relax the assumption of constant elasticity of substitution[2] between peak and off-peak periods and estimate the elasticity of substitution to similarly vary between 0.09 to 0.17, close to the results of their first study. In a third study of the Wisconsin data from 1976 to 1980, Caves et al. (1987) similarly relax the assumption of constant elasticity of substitution, as well as take account of major appliances (air conditioning, electrical hot water) and household size (number of residents), and estimate that the elasticity of substitution over the day ranges from 0 to 0.233 for a typical household.

The various studies by Caves and Christensen estimate the elasticity of substitution under TOU pricing with a two good model (peak and off-peak weekdays). In contrast, Parks and Weitzel

[1] The Wisconsin pricing experiment trialled time-of-use tariffs for 600 households. There were 6 different cohorts, that had prices in peak versus off-peak periods that ranged from 1:1, 2:1, 4:1 and 8:1) and in which period periods that were in blocks 6, 9 and 12 hour peak periods). The 1:1 cohort was the control group. The method assumes constant elasticity of substitution rates from hours in the peak period to hours in the off-peak period.

[2] Constant Elasticity of Substitution (CES) imposes the restriction that two goods are perfect substitutes. The Leontief utility function allows for multiple goods as well as complementarity between goods (thus relaxing the assumption of perfect substitutability in the CES function). The CES offers the advantage of simplicity and is preferred where there are only two time periods. Which measure is most appropriate can also depend on the magnitude of the true elasticity being modelled (Caves & Christensen, 1980). However, (Caves, Christensen, & Herriges, 1987) show that differences in the estimates generated from these two specifications is not substantial.

(1984) consider a four good model (off-peak night and weekend, shoulder day, peak morning and afternoon, shoulder evening) and estimate the elasticity of substitution to vary between 0.085 and 0.240. Although these results are not directly comparable to Caves and Christensen owing to methodological differences, they are notably similar in magnitude.

Several subsequent TOU pricing experiments have also been undertaken in California with similar results to the Wisconsin pilot program. For instance, Charles River Associates (2006) estimate the price elasticity of substitution to vary between 0.04 to 0.13 (for peak to off-peak price ratios of between 3 and 6) for a Californian state-wide pricing experiment (Gyamfi et al., 2013). Caves et al. (1984) test whether the elasticity of substitution estimated across 5 experimental USA studies are statistically equal. The studies were conducted between 1977 and 1980, with price block durations between 3 and 12 hours, and peak to off-peak prices of between 6:1 and 16:1. The pooled estimated elasticity of substitution is 0.136 and 0.102 for summer and winter, respectively. Caves et al. (1989) similarly estimate the elasticity of substitution for a Californian voluntary TOU experiment to be slightly higher at 0.18 when differences in demographics and appliances are accounted for. It is notable that despite differences in location, pilot program design, sample data and methodology, these studies report remarkably similar estimates of the elasticity of substitution.

Other relevant findings relate to the effect of major appliances, technology, home ownership and the duration of price blocks on responsiveness. Caves and Christensen (1980b) find the elasticity of substitution is significantly different for households owning none or five major appliances (dishwasher, electric water heater, electricity ranges, air conditions and clothes dryers). Faruqui and Sergici (2010) find that the reduction in peak demand under TOU tariffs increased from 4% to 6% when combined with enabling technologies. Bartusch and Alvehag (2014) find greater responsiveness to price differences in summer than winter periods and responsiveness is lower in rental compared to owner occupied residences. Caves et al. (1984) find that the duration of the price block does not influence significantly the elasticity of substitution once differences in appliances, household occupancy and seasonality is accounted for. On the other hand Ham et al. (1997) find greater responsiveness when peak periods are short (approximately 5 hours) but that when the peak period is longer (and the price difference is smaller) they observe no significant reduction in electricity consumption. Similarly, Faruqui and Sergici (2010) find shorter (one hour) peak price blocks generate reductions in peak demand four times as large as TOU tariffs with a much longer peak block.

3. Data and Preliminary analysis

3.1 Data

Our data is obtained from 6,957 household electricity bills for households on TOU tariffs, as these are defined in Victoria. These bills were part of a larger sample of 47,114 bills that were voluntarily uploaded to the Victorian Government's price comparison website (https://compare.energy.vic.gov.au/) over the period from July 2018 to December 2018.[3] 15% of the households in our full sample have TOU tariffs, compared 13% of households in the population of households in the state of Victoria (Mountain and Burns, 2020). TOU tariffs in Victoria have consumption rates (cents per kWh) that are different for electricity consumed in peak (7am to 11pm weekdays) and off-peak (all other hours). In addition to time-variant consumption rates, consumers on TOU tariffs also pay a daily charge (cents per day). This daily charge accounts for around 30% of the median annual bill for households in Victoria (Carbon and Energy Markets, 2017).[4]

Of the 6,957 households on TOU tariffs, 455 (6%) also have separately metered controlled loads. Controlled load refers to separately metered and switched loads (typically electric hot water or underfloor heating). Controlled loads are typically charged at a lower rate than the main loads that operate during off-peak hours (e.g. overnight) and the controlled load rate does not vary by time of day. In our sample 3,914 homes have rooftop PV. This is 56% of the 6,957 households in our sample. By comparison, in Victoria 16% of households have access to rooftop PV and only 13% have TOU tariffs (Carbon and Energy Markets, 2017; Climate Council, 2018). Households with rooftop PV are far more likely to be on a TOU tariff since in many cases they were automatically placed on these tariffs by their network service providers when they installed rooftop PV, and their retailers subsequently reflected this in their retail supply contracts.

In our analysis we segment our data to account for the socio-economic status of the postcode in which each house is located. Postcode level socio-economic decile data is obtained from the

[3] For further details on the data extraction, processing and measurement methods applied to individual household bills, please refer to Mountain and Burns (2020).

[4] Calculated based on an estimate median annual bill of $1,388 and median annual network charge of $415 for Victorian retail electricity customers.

Australian Bureau of Statistics Census of Population and Housing (Australian Bureau of Statistics, 2011). The decile varies from 1 to 10 (1 is the most disadvantaged). We organize the declines into three tiers as follows: “high” = deciles 7 to 10, “middle” = deciles 4 to 6 and “low” = deciles 1 to 3. In our sample, 55% of households on TOU tariffs are in high socio-economic status post codes, 30% in the middle and 15% in the low socio-economic post codes. Although comparative data on the socio-economic distribution of all households on TOU tariffs in Victoria is not known, the distribution in our sample is similar to the distribution of the population (46%, 35% and 20% of Victorian households are in the high, medium and low socio-economic tiers, respectively).

We also account for the possible effect of rooftop PV electricity that is consumed on the premises and/or exported to the grid. Households with rooftop PV consume part of the electricity generated from their PV system, and any remainder is fed into the electricity grid. Since data for the amount of rooftop solar PV produced and consumed by a household (which is needed to measure solar PV that is self-consumed) is not directly reported on household bills, we estimate solar that is self-consumed using the methodology described in Mountain et al. (2020).

Two possible sources of bias might arise in our sample. First it might be suggested that households that uploaded their bills to the Government’s price comparison website are more engaged than households in the population (and by implication more responsive to TOU prices than households in the population). Mountain and Burns (2020) examine whether consumers who had uploaded their bills were likely to be more engaged than the population and concluded that this was likely. Second it might be suggested that TOU consumers self-select and so the measurement of responsiveness is biased (i.e. consumers who can easily shift load would select TOU tariffs and may not shift much more load even in response to larger price differences). However in Victoria the majority of consumers on TOU tariffs did not explicitly select such tariffs, but were instead automatically placed on such tariffs following the installation of rooftop PV.

We also checked for the possibility of self-selection bias by studying consumption in a sample of 2,152 households for which half-hourly electricity consumption data for 2018 is available.[5] The sample covered 1,368 households on tariffs that do not have time-variant consumption rates (also known as "flat" tariffs) and 159 households on TOU tariffs (without solar PV or controlled loads). The median ratio of peak to off-peak consumption (1.19) is exactly the same for those households on flat tariffs, and those on TOU tariffs. In other words, consumers on TOU tariffs typically do not consume more in peak hours than compared to off-peak hours than consumers on flat tariffs. From this, and evidence that TOU tariffs are typically not an active choice for most consumers, we think self-selection bias is unlikely. Indeed identical median peak/off-peak consumption ratios for households on flat and TOU tariffs is an indicator that perhaps consumers on TOU tariffs do not respond to price differences. This is the focus of the rest of our analysis.

3.2 Preliminary analysis

Figure 1 plots the ratio of peak to off-peak prices against the ratio of peak to off-peak usage for the 6,957 households on TOU tariffs.[6] It is clear from this scatter that a wide range of peak and off-peak price combinations are offered and used. It is also clear from the dispersion in the scatter plot that there is no obvious relationship between relative prices and relative consumption. The same observation applies even if we restrict the data to households with TOU tariffs and controlled load or households with TOU tariffs and rooftop PV or if we segment the data into the three socio-economic tiers.[7]

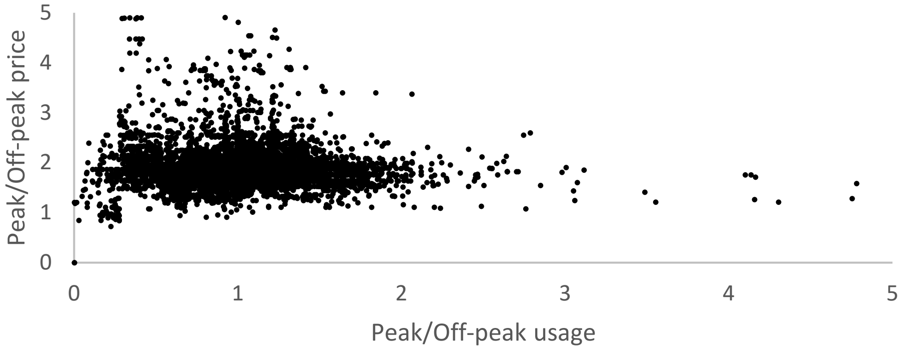

Figure 1. Scatter plot of peak/off-peak usage and peak/off-peak price

[5] These data were provided to us by The Centre for New Energy Technologies (https://c4net.com.au/). They covered households located in the areas of supply of two of Victoria's five distributors.
[6] We excluded outliers where the ratio of peak/off-peak price or usage exceeds 5:1.
[7] These scatter plots are available from the authors upon request.

Table 1 reports the median peak/off-peak usage, the median peak/off-peak price and median annual grid volume purchased, for the full sample of households on TOU tariffs, by TOU tariff type and by socio-economic tier. Measured over the full sample, households on TOU tariffs consume almost as much electricity in the peak period as they do in the off-peak period. Households with TOU tariffs and controlled loads use relatively more in peak periods because their controlled load consumption occurs in the off-peak period at night (and so the residual amount of their consumption in the TOU off-peak period is lower). Conversely households with TOU tariffs and rooftop PV purchase a little less electricity from the grid in the peak period because the PV electricity produced and consumed on the premises occurs during the day time (i.e. the peak period for weekdays which are five out of seven days per week).

	Tariff type			Socio-economic status		
	All households on two-rate tariffs (n=6957)	All households on two-rate tariffs with controlled load (n=455)	All households on two-rate tariffs with PV (n=3914)	All households on two-rate tariffs, low socio-economic status (n=1037)	All households on two-rate tariffs, middle socio-economic status (n=2096)	All households on two-rate tariffs, high socio-economic status (n=3824)
Median Peak/Off-peak usage	0.99	1.16	0.94	0.97	0.94	1.02
Median Peak/Off-peak price	1.83	1.75	1.85	1.86	1.84	1.82
Median annual grid purchases (kWh)	4,096	4,300	3,772	4,358	4,165	4,002

Table 1. Descriptive statistics for sample and sub cohorts

As expected, median annual grid electricity purchases are noticeably lower for households with PV. Median household consumption is higher for households with controlled load and those living in low socio-economic status postcodes. The latter result is unexpected and may reflect higher occupancy rates and less energy efficient households.

Table 2 presents the correlation of the ratio of peak to off-peak usage with the other variables.

				Socio-economic status		
Variable	All households on two-rate tariffs (n=6957)	All households on two-rate tariffs with solar (n=3914)	All households on two-rate tariffs with controlled load (n=455)	Low socio-economic status (n=1037)	Middle socio-economic status (n=2096)	High socio-economic status (n=3824)
Volume of rooftop PV self-consumed	-0.01	-0.01	-0.11	-0.05 (n=580)	-0.07 (n=1262)	0.00 (n=2078)
Peak/Off-peak price	-0.04	-0.04	0.11	-0.06	-0.06	-0.05
Controlled load volume	0.08	0.06 (n=65)	0.08	0.10 (n=84)	-0.02 (n=95)	0.05 (n=328)
Socio-economic decile	0.02	0.08	0.01	0.03	0.03	0.00
Annual grid purchases	-0.01	-0.07	0.01	-0.01	-0.09	0.00

Table 2. Correlation between peak/off-peak usage and other variables

The data in Table 2 confirms our expectation of weak correlation between relative usage (i.e. the ratio of grid supplied electricity consumed in peak versus off-peak periods) and relative price (i.e. the ratio of peak to off-peak price), annual grid purchases and rooftop PV that is self-consumed for the reasons discussed above.

There is a weak but positive association between socio-economic decile and relative usage. In other words, households living in more affluent areas tend to have higher relative usage. Perhaps wealthier households are less sensitive to relative prices. Controlled load and relative usage are also weakly positively correlated. Again, this is expected because households that use a separately metered controlled load for water and under-floor heating use less electricity in the off-peak period.

Descriptive statistics and measures of correlation shed some light on the association between peak/off-peak consumption and other relevant variables but do not establish evidence on the magnitude and direction of causal relations, if any. We therefore proceed to estimate a multivariate econometric model in the following section.

4. Econometric analysis

4.1 Methodology

The review of relevant literature earlier found that the elasticity of substitution is traditionally used to measure how consumption in peak and off-peak periods changes in response to two-rate time variant tariffs. The elasticity of substitution is defined as:

$$\boldsymbol{E_{sub}} = \frac{\%\Delta\left(\frac{\boldsymbol{Q_P}}{\boldsymbol{Q_{OP}}}\right)}{\%\Delta\left(\frac{\boldsymbol{P_P}}{\boldsymbol{P_{OP}}}\right)}$$

[1]

where: Q_p is usage in peak period,

Q_{Op} is usage in off-peak period,

P_p is peak price, and

P_{Op} is off-peak price.

Alternatively, the elasticity of substitution can be expressed as:

$$E_S = \frac{d\ln(Q_p/Q_{Op})}{d\ln(P_p/P_{Op})}$$

[2]

To estimate the elasticity of substitution, we estimate the following multivariate model:

$$\ln(Q_{i,p}/Q_{i,Op}) = \alpha + \beta\ln(P_{i,P}/P_{i,OP}) + \gamma Z_i + \varepsilon_i$$

[3]

where: Z_i is a vector of potential additional explanatory variables, and

i refers to the individual consumer.

We ascertain the vector of potential additional explanatory variables, Z_i, using the Likelihood ratio redundant variable test. The vector, Z_i, comprises the following variables: socio-economic decile, (log) annual grid purchases, (log) volume of solar PV consumed and produced on the premises and the (log) volume of controlled load consumed on the premises (if any).

We test the hypothesis that households respond to time-varying prices by testing the statistical significance, sign and magnitude of the estimated coefficient β (where $\beta = \frac{d\ln(Q_p/Q_{Op})}{d\ln(P_p/P_{Op})}$). If $\beta = 0$, the household does not respond to time-varying prices. If -1< β < 0, the household is weakly responsive. Finally, if β < -1, the household is responsive.

We apply this methodology to six separate cohorts of our sample. These are all households on TOU tariffs, households with PV, households with controlled load and households segmented by low, middle and high socio-economic status. We then compare the estimated coefficient β's to assess how relative usage is influenced by the peak/off-peak price, PV, controlled load and socio-economic status.

4.2 Results

We ascertain the vector of potential additional explanatory variables, Z_i, using the Likelihood ratio redundant variable test (Table 3).[8] The controlled load variable fails the redundant variable test and is therefore excluded from the specification of the multivariate model. We also exclude annual grid purchases because it is very strongly correlated (0.76) with PV self-consumed and so introduces multi-collinearity into the estimation results.

	Likelihood ratio	Probability
(log) peak / off-peak price	8.84***	0.003
(log) PV self-consumed	30.67***	0.000
Decile	31.13***	0.000
(log) Controlled load usage	0.08	0.774

Notes: The null hypothesis of the likelihood ratio redundant variable test is the variable of interest is redundant.

Table 3. Redundant variable test results

[8] This vector comprises the following variables: socio-economic decile, solar (net) usage and controlled load.

Based on these results, we estimate the following multivariate model to explain (log) relative peak to off-peak usage:

$$\boldsymbol{ln}\frac{\boldsymbol{Q_{i,P}}}{\boldsymbol{Q_{i,OP}}} = \boldsymbol{\alpha} + \boldsymbol{\beta}\textbf{ln}(\boldsymbol{P_{i,P}}/\boldsymbol{P_{i,OP}}) + \boldsymbol{\gamma_1 lnSolar_i} + \boldsymbol{\gamma_2 Decile_i} + \boldsymbol{\varepsilon_i}$$

[4]

where: Q_p and Q_{Op} are grid purchases in peak and off-peak period, respectively

P_p and P_{Op} is peak and off-peak price, respectively

lnSolar is (log) solar self-consumed, and

Decile is the socio-economic decile (takes values 1 to 10).

Table 4 presents the estimation results of equation [4] for each of the six cohorts. There is a statistically significant shift in consumption from peak times to off-peak times in response to the difference in peak and off-peak prices when measured across the full sample. However, the response is weak: a 1 % increase in peak prices relative to off-peak prices only results in a 0.2% shift in consumption from peak times to off-peak times. This means that if the median peak to off-peak price ratio doubled from 1.83 to 3.76, the ratio of peak to off-peak consumption would fall by only 14%. However, consumers in the low socio-economic cohort or those that have controlled loads do not respond to the ratio of peak to off-peak prices. However, a doubling of the (median) peak to off-peak price ratio would bring about a 19% and 11% fall in relative usage in the medium and high socio-economic cohorts, respectively.

Access to rooftop PV does not affect the responsiveness of households to the difference in peak and off-peak prices, compared to those households without rooftop PV. However, the amount of rooftop PV that is produced and consumed on the premises affects the amount of electricity purchased from the grid by that household during the peak and off-peak times. The impact is the highest for the low socio-economic cohort - a 1% increase in rooftop PV consumed on the premises reduces the relative consumption in peak and off-peak periods by 0.12% - and is lowest for the highest socio-economic cohort.

Socio-economic status has a positive but very weak relationship to relative usage for all households: a one tier increase in socio-economic decile brings about a 0.2% increase in peak/off-peak usage. If socio-economic status is a proxy for income, this result suggests that income is weakly but positively related to peak/off-peak usage (and electricity is a normal good).

All models provide a poor fit of the data (as is often the case with cross sectional data), however, this does not necessarily undermine the robustness of the coefficient estimates. The scatter plot of peak/off-peak prices and usage (Figure 1) combined with the low correlation results (Table 2) suggest that relative usage may suffer from statistical randomness (that is, no recognisable patterns or trends) making it implausible to construct a theoretically sound model that also provides a good fit of the data.

	Tariff type			Socio-economic status		
	All households on two-rate tariffs (n=6957)	All households on two-rate tariffs with solar (n=3914)	All households on two-rate tariffs with controlled load (n=455)	All households on two-rate tariffs, low socio-economic status (n=1037)	All households on two-rate tariffs, middle socio-economic status (n=2096)	All households on two-rate tariffs, high socio-economic status (n=3824)
α	0.54*** (0.123)	0.58*** (0.118)	0.26 (0.997)	0.98*** (0.313)	0.47* (0.256)	0.43** (0.181)
$ln\frac{P_P}{P_{OP}}$	-0.20*** (0.066)	-0.20*** (0.064)	0.48 (0.522)	-0.25 (0.169)	-0.27** (0.131)	-0.16* (0.086)
lnSolar	-0.08*** (0.014)	-0.08*** (0.014)	-0.07 (0.103)	-0.12*** (0.036)	-0.08*** (0.027)	-0.07*** (0.019)
Decile	0.02*** (0.003)	0.02*** (0.003)	0.00 (0.020)	0.01 (0.025)	0.03 (0.017)	0.02* (0.010)
$\overline{R^2}$	0.017	0.019	-0.020	0.019	0.009	0.009

Note: An ***, ** and * indicates statistical significance at the 1, 5 and 10 per cent level of significance, respectively. Standard errors are in parenthesis.

Table 4. Equation [4] estimation results

5. Discussion

Our study finds that across the full sample of 6,957 households on TOU tariffs, a 1% increase in prices in the peak period prices relative to prices in the off-peak period results in a 0.2% shift in consumption from peak hours to off-peak hours. In the conventional definition of the elasticity of substitution, this qualifies as inelastic or very weak responsiveness.

Segmenting our sample uncovers further results, some of which were expected, others unexpected and others of which we had no prior expectation. It was not obvious *a priori* whether the elasticity of substitution would be affected by the installation of rooftop PV. The uncertainty arises from incentives on households to use their own rooftop PV production to substitute for grid-supplied electricity. On the one hand households with rooftop PV that do not receive a premium feed-in tariff (about 69% of all consumers with solar PV and TOU tariffs in our sample) have an incentive to use as much of their rooftop PV production as possible since the marginal cost of production is zero while the avoided cost of grid supplied electricity is at least 30 cents per kWh and the foregone income from otherwise selling the PV produced electricity is typically around 11 cents per kWh. The opposite incentive applies to the 31% of households with rooftop PV, access to TOU tariffs and a government-mandated premium feed-in tariff. This is because the premium feed-in tariff of 60 cents per kWh and in addition whatever feed-in rate those consumers' retailers offer, far exceeds the typical cost of grid supplied electricity. Households on premium feed-in tariffs therefore have an incentive to export as much of their rooftop production as possible, by shifting their consumption into the off-peak periods. Our finding that the elasticity of substitution for households with rooftop PV is exactly the same for those without rooftop PV suggests that the installation of rooftop PV does not affect the extent to which households alter their consumption in response to time variant rates, when compared to households without rooftop PV.

We did not expect to find that households in the low socio-economic tier do not respond to TOU tariffs. It may be that households in the low socio-economic tier have less efficient appliances and lower rates of employment and hence spend more time at home and thus suffer greater inconvenience by shifting load from peak to off-peak hours, than consumers in higher socio-economic cohorts, as suggested by European Energy Agency (2013), Gyamfi et al. (2013) and Simmons and Rowlands (2010). Further research might confirm this finding or suggest more plausible alternatives.

While the literature focusses on behavioral factors, tariff design and technology to explain responsiveness in TOU tariffs, it is striking that our estimate of responsiveness (between zero and 0.20) is so close to the estimates in the last major study of responsiveness in TOU tariffs – see Caves and Christenson – of zero to 0.24. Those studies measured responsiveness of TOU tariff experiments applied to households supplied by monopolies in Wisconsin and six other U.S. states in the 1970s. Our Australian study reflects outcomes in a market that was deregulated almost 20 years ago, where retailers are free to set peak and off-peak prices, where consumption is metered half-hourly by remotely read “smart meters”, where competing suppliers have long offered close to real-time consumption data to consumers on easy to use hand-held devices, where technology to automatically control household electricity devices is widely available and inexpensive and where policy and regulation has long enthusiastically supported TOU tariffs.

The low elasticity of substitution under TOU tariffs reported in this and previous other studies raises the question of how might TOU tariffs be made more effective in encouraging consumers to shift load away from peak periods? Some of the behavioral literature – see for example Aldabas and Gstrein, 2015; Frederiks et al., 2015 - suggest that consumers make decisions that do not always reflect an understanding of their own best interests. Yoon et al. (2014) points to the important role of technology and others (see Frey and Jegen, 2001; Schulz, 2016; Stern et al., 1993) focus on both economic and environmental factors as motivations to shift load. Tariff design is also important. As dicussed earlier consumers may be expected to suffer a greater loss of utility if they are required to defer consumption for longer periods although previous studies of this reach different conclusions. Nevertheless it seems plausible to suggest that the long duration of the peak price block that applies to TOU tariffs in Victoria may partly explain the low responsiveness we find.

Our findings raise the important policy question of whether TOU tariffs be imposed as the default (as suggested by Schneider and Sunstein, 2017) even though TOU tariffs are generally ineffective in encouraging consumers to shift load from peak to off-peak hours and there is no certainty of improving responsiveness. The main argument for default (opt-out) TOU tariffs is that time-varying tariffs attempt to better reflect time-varying costs, than simpler pricing such as flat rate tariffs. Thus, at least in principle, they reduce cross subsidies that arise when under-charging for electricity when it costs more to supply and over-charging when it costs less. There is also some evidence that consumers on TOU tariffs achieve higher savings when they switch to cheaper retail offers - see Mountain and Burns (2020) - and in this sense the greater complexity of TOU tariffs is not undermining consumers ability to engage effectively in retail markets. The main counter-arguments, arising from the evidence in this study, are that TOU tariffs are not generally effective in encouraging consumers to shift load, and it seems that this has not improved since the responsiveness of such tariffs was first rigorously assessed in the 1980s. Furthermore, the finding of no statistically significant responsiveness for lower socio-economic consumers suggests that TOU tariffs are likely to be regressive. Taken together, the case for mandating TOU tariffs as the default pricing structure does not seem to be compelling. Nevertheless, consumers may value the opportunity to reduce their bills by shifting consumption to cheaper periods, and this is also likely to provide shared benefits for the reasons set out in the introduction. On this basis, freedom to choose a TOU tariff (i.e. the choice to opt-in rather than forced to opt-out) would seem to be the preferable approach.

6. Conclusions

TOU tariffs promise private benefits (lower bills for consumers who shift to hours when consumption rates are lower) and shared benefits (lower and less volatile prices). Also, flexible demand is becoming increasingly valuable as variable renewable electricity generation expands. Our study of the elasticity substitution in 6,957 households on TOU tariffs in Victoria seeks to determine the extent to which consumers have responded to time varying consumption rates. Our findings suggest that Victorian households respond weakly to time varying rates and households in the lowest socio-economic areas do not respond at all. Despite significant advancements since TOU tariffs were studied rigorously in the 1980s, this Victorian study suggests these tariffs remain ineffective in encouraging households to shift load from peak to off-peak periods and may be regressive for the poorest consumers. A policy to allow consumers the choice to opt-in to such tariffs would therefore be preferable to a policy that forces them to opt out.

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References

Aldabas, M., Gstrein, M., 2015. Changing Energy Consumption Behaviour : Individuals ' Responsibility and Government Role. J. Electron. Sci. Technol. 13, 343–347.

Australian Bureau of Statistics, 2011. Census of Population and Housing: Socio-Economic Indexes for Areas (SEIFA), Australia, 2011 [WWW Document]. URL https://www.abs.gov.au/AUSSTATS/abs@.nsf/allprimarymainfeatures/8C5F5BB699A0921CCA258259000BA619?opendocument

Bartusch, C., Alvehag, K., 2014. Further exploring the potential of residential demand response programs in electricity distribution. Appl. Energy 125, 39–59. https://doi.org/10.1016/j.apenergy.2014.03.054

Carbon and Energy Markets, 2017. The retail electricity market for households and small businesses in Victoria Analysis of offers and bills.

Caves, D., Christensen, L., 1980a. Econometric analysis of residential time-of-use electricity pricing experiments. J. Econom. 14, 287–306.

Caves, D., Christensen, L.R., 1980b. Residential Substitution of Off-peak for Peak Electricity Usage under Time-of-Use Pricing. Energy J. 1, 85–142. https://doi.org/10.5547/issn0195-6574-ej-vol1-no2-4

Caves, D., Christensen, L.R., Herriges, J.A., 1987. The Neoclassical Model of Consumer Demand with Identically Priced Commodities: An Application to Time-of-Use Electricity Pricing. RAND J. Econ. 18, 564. https://doi.org/10.2307/2555642

Caves, D., Christensen, L.R., Herriges, J.A., 1984. Consistency of residential customer response in time-of-use electricity pricing experiments. J. Econom. 26, 179–203.

Caves, D., Herriges, J., Kuester, K., 1989. Load Shifting Under Voluntary Residential Time-of-Use Rates. Energy J. 10, 83–99.

Climate Council, 2018. POWERING PROGRESS : State Renewable Energy Race.

Ericson, T., 2011. Households' self-selection of dynamic electricity tariffs. Appl. Energy 88, 2541–2547. https://doi.org/10.1016/j.apenergy.2011.01.024

Eurpean Energy Agency, 2013. Achieving energy efficiency through behaviour change: what does it take?

Faruqui, A., Sergici, S., 2010. Household response to dynamic pricing of electricity: A survey of 15 experiments. J. Regul. Econ. 38, 193–225. https://doi.org/10.1007/s11149-010-9127-y

Frederiks, E.R., Stenner, K., Hobman, E. V, 2015. Household energy use : Applying behavioural economics to understand consumer decision-making and behaviour.

Renewableand Sustain. Energy Rev. 41, 1385–1394. https://doi.org/10.1016/j.rser.2014.09.026

Frey, B.S., Jegen, R., 2001. Motivation crowding theory. J. Econ. Surv. 15, 589–611. https://doi.org/10.1111/1467-6419.00150

Gyamfi, S., Krumdieck, S., Urmee, T., 2013. Residential peak electricity demand response - Highlights of some behavioural issues. Renew. Sustain. Energy Rev. 25, 71–77. https://doi.org/10.1016/j.rser.2013.04.006

Ham, J., Mountain, D., Chan, L., 1997. Time-of-Use Prices and Electricity Demand : Allowing for Selection Bias in Experimental Data. RAND J. Econ. 28, S113–S141.

Mountain, B., Burns, K., 2020. Loyalty taxes and search costs in retail electricity markets: have we got it wrong?

Mountain, B., Gassem, A., Burns, K., Percy, S., 2020. A model for the estimation of residential rooftop PV capacity. https://doi.org/10.26196/5ebca99c43e1a

Mountain, B., Rizio, S., 2019. Do households in Victoria get a better deal by switching to different electricity retailers? 1–42.

Nicholson, M., Fell, M.J., Huebner, G.M., 2018. Consumer demand for time of use electricity tariffs: A systematized review of the empirical evidence. Renew. Sustain. Energy Rev. 97, 276–289. https://doi.org/10.1016/j.rser.2018.08.040

Parks, R., Weitzel, D., 1984. Measuring the consumer welfrae effects fo time-differentiated electricity prices. J. Econom. 26, 35–64.

Schneider, I., Sunstein, C.R., 2017. Behavioural considerations for effective time-varying electricity prices. Behav. Public Policy 1, 219.

Schulz, A.W., 2016. Altruism, egoism, or neither: A cognitive-efficiency-based evolutionary biological perspective on helping behavior. Stud. Hist. Philos. Sci. Part C Stud. Hist. Philos. Biol. Biomed. Sci. 56, 15–23. https://doi.org/10.1016/j.shpsc.2015.10.006

Simmons, S.I., Rowlands, I.H., 2010. TOU rates and vulnerable households : Electricity consumption behavior in a Canadian case study. Development.

Stern, P.C., Deitz, T., Kalof, L., 1993. Value Orientations, Gender, and Environmental Concern. Environ. Behav. 25, 322–348. https://doi.org/https://doi.org/10.1177/0013916593255002

Yoon, J.H., Bladick, R., Novoselac, A., 2014. Demand response for residential buildings based on dynamic price of electricity. Energy Build. 80, 531–541. https://doi.org/10.1016/j.enbuild.2014.05.002