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Households' self-selection of a dynamic electricity tariff

Abstract:
Offering electricity consumers time-differentiated tariffs may increase demand responsiveness, thereby reducing peak consumption. However, one concern is that time-differentiated tariffs may also attract consumers who benefit because of their consumption pattern, even without a corresponding demand response. A discrete choice model applied to data from a residential dynamic pricing experiment indicates that higher demand flexibility increases the propensity of a household to select dynamic tariffs, while favourable consumption patterns do not influence the tariff choice. The offering of dynamic time-differentiated tariffs is then likely to increase the demand response among residential consumers.

Keywords: demand response, dynamic pricing, electricity tariff, self-selection, rate option.

JEL classification: D10, Q41

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1. Introduction

Deregulation of the Norwegian electricity market in 1991 improved efficiency (Bye and Halvorsen, 1999), but the continued reliance on tariffs with prices fixed for long periods of time lessens demand response among end-users and prevents the realisation of further efficiency gains.

Demand response implies decreased consumption during constrained peak periods and flattened load curves, deferring or avoiding the need for costly investment in production and transmission capacity. It may also reduce average power and network prices, stabilize volatile spot prices, improve system reliability, and decrease the likelihood of the exercise of market power (Caves et al., 2000, Braithwait and Eakin, 2002, Schwartz, 2003, Kristensen et al., 2004).

A number of different approaches can be used to increase demand response. One is to offer residential electricity consumers time-differentiated tariffs. These tariffs charge electricity consumers high prices in peak-load periods and low prices in off-peak periods, i.e., they better reflect wholesale real-time price variations than flat rates. Examples of tariffs are the time-of-use (TOU) rate, where prices vary by hours-of-the-day blocks. Another is the more dynamic critical peak pricing (CPP) rate, where higher prices may be imposed if the system is severely constrained as in cold winter periods. In this instance, end-users have an incentive to respond to short-term price variations by reducing peak consumption or by shifting peak consumption to off-peak periods.

An important question is the extent to which self-selecting time-differentiated rates attract price responsive customers. One would expect responsive customers to choose rates according to their ability to shift or reduce consumption, and thereby reduce electricity expenditure (Caves et al., 2000). Experiments with optional TOU rates have confirmed customers are more price responsive than the population as a whole (Aigner and Ghali, 1989, Train and Mehrez, 1994, Caves et al., 1989).

However, one concern with self-selecting time-differentiated rate programs is that some customers who benefit without any demand response also choose to participate. Typically, these are customers with low electricity consumption in peak-price periods and high electricity consumption during off-peak periods. If most participating customers have such favourable consumption patterns and little price response, differentiated rates may not be an efficient tool to increase demand response. Furthermore, revenues for the utility offering the rate will decrease because the participating customers pay less for electricity than before, while the cost of providing electricity remains the same. In turn, revenue losses are imposed on the utility or its shareholders, or shifted to the remaining customers through an increase in the general rate (Train and Mehrez, 1994). Such an outcome may well be justified as consumers selecting the differentiated rates are released from subsidizing other customers' expensive peak consumption (PLMA, 2002). However, if an increase in the standard rate is the result, it may be politically difficult to implement because of opposition from customers harmed through the rate increase (Williamson, 2002).[1]

Aigner and Ghali (1989) found evidence of participation based on favourable consumption patterns in their analyses of five TOU experiments. High peak-period consumption in the pre-experiment period resulted in a lower participation rate and higher off-peak consumption resulted in the opposite. Train et al. (1987) found similar re-

[1] MacKie-Mason (1990) and Train (1991) have shown that optional TOU rates can be designed that require those choosing the rate to adjust consumption in order to benefit, while others will not be negatively influenced by introduction of the new rate. However, designing such rates requires knowledge of all customers' consumption patterns, which utilities may not always have.

sults. Their results indicated that the probability of choosing TOU rates decreased if the electricity costs under these rates increased compared with the costs on a standard rate. Patric (1990), Train and Mehrez (1994) and Matsukawa (2001) also found that consumers volunteering for TOU rates possessed more favourable load shapes than consumers on standard rates.

However, the literature is inconclusive regarding customer participation as based on favourable load patterns. Caves et al. (1989), for example, found that consumption patterns do not influence the customers' choice of a TOU rate. Analysing data from a voluntary TOU experiment, and comparing their findings with earlier mandatory TOU programs, they found that volunteers do not take greater advantage of participation without shifting usage than the rest of the population. In a Canadian TOU program, Mountain and Lawson (1995) calculated monetary savings and losses for customers choosing TOU rates and standard rates, assuming no change in consumption patterns. They found no difference with respect to the distribution of savings. Baladi et al. (1998) compared consumption patterns of volunteers and non-volunteers from a pre-test period in a TOU experiment, and concluded that on-peak consumption shares were indistinguishable.

The lack of consensus concerning participation and consumption patterns calls for further study in new tariff programs. Further, to the author's knowledge, the extent of participation in time-differentiated programs based on load patterns and/or price responsiveness has only been investigated in the context of TOU programs. Compared with traditional TOU pricing, dynamic pricing schemes may entail more uncertainty for end-users with respect to the frequency and the timing of high peak prices. Consequently, it is more difficult for electricity consumers to assess whether they will benefit from the dynamic rate without load shifting. It may be hypothesized that this uncertainty will reduce the extent of customer participation based on consumption patterns, and increase instead the extent of participation based on the customers' ability and willingness to respond to the price signals. Since dynamic pricing (e.g. critical peak pricing) of electricity has recently been the subject of much interest (see, for instance, Faruqui and George (2002, 2005)), there is a need for further examination of dynamic rate programs.

This paper investigates these questions using data from a Norwegian residential dynamic pricing experiment. A qualitative response model is used to test whether the customers' choice between the dynamic rate and the standard rate was based on their consumption patterns. The model is also used to test whether the group that chooses the dynamic rate differs from the group that retains a standard rate with respect to the ownership of appliances suited for load reduction or shifting. In addition, the socio-economic characteristics of households are included in the econometric model in order to reveal other important factors that may help explain customers' choices.

2. The dynamic pricing experiment

The effects of dynamic pricing on residential electricity consumption were tested in a Norwegian experiment in 2003. Households with annual electricity consumption above 8,000 kWh had new technology installed that enabled hourly automatic metering of consumption. These households were offered a critical peak pricing (CPP) network rate, and could choose between this and the standard rate already in place.[2]

The CPP network rate had a two-level structure. It was dynamic in the sense that *peak periods* were defined as the hours 8–11 and the hours 17–20 on working days, *only*

[2] The total electricity price facing the consumer consists of the network price plus the power price (plus taxes and VAT).

when temperatures fell below –8 °C (during winter). The peak price was approximately 1.15 NOK/kWh.[3] *Off-peak periods* were defined as all other hours of the year. The off-peak price was approximately 0.15 NOK/kWh. Summer was defined as the months May to October, and winter as November to April. The standard network price was approximately 0.20 NOK/kWh; that is, somewhat higher than the off-peak CPP price and substantially lower than the peak CPP price.

The CPP tariff was designed to be revenue neutral for the network company. The peak and off-peak prices were chosen so that if the *average* customer, as defined by the average consumption pattern, did not change his or her consumption pattern under the CPP rate, electricity revenues would be unchanged, as compared to revenues from the average customer on a standard rate. Based on statistical data, peak periods were assumed to occur in eighteen days during the winter. Few electricity consumers actually have an average consumption pattern. This means that if all customers chose the CPP rate, while not changing load patterns, many customers would gain while the rest would lose (Williamson (2002), studying a TOU rate program found that about half would win while the other half would pay more than on the fixed rate).

3. Who will choose the dynamic rate?

This section describes the factors that may have influenced customers' choice between the CPP and standard rates, i.e., the customers' load patterns and their price responsiveness. Their choice will be taken under uncertainty because the customers do not exactly know their consumption in the next year due to variations, for instance, in

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[3] NOK 1 ~ EUR 0.12 / 0.15

temperature or the acquisition of new appliances. In addition, the frequency of hours with peak prices is uncertain, as it depends on future (unknown) temperatures.

Let V^{CPP} and V^{std} indicate the next year's expected indirect utility for a household choosing either the CPP rate or the standard rate, respectively, and ΔV the difference. Indirect utility depends on the expected annual expenditures under the two rate alternatives, Y^{CPP} and Y^{std} and ΔY is the difference between expected expenditures.[4] A consumer is posited to select the CPP rate if the indirect utility under the CPP rate exceeds utility under the standard rate, i.e. to select the CPP rate if $\Delta V>0$. This is equivalent to saying that the consumer will select the CPP rate if expenditures are less under this rate than the standard rate, i.e. if $\Delta Y<0$. That is, the CPP rate is selected if:

$$\Delta Y = Y^{CPP} - Y^{std} = \left(p^{CPP,off}Q^{CPP,off} + p^{CPP,on}Q^{CPP,on}\right) - p^{std}Q^{std} < 0\,, \tag{3.1}$$

where $p^{CPP,off}$ is the CPP off-peak price, $p^{CPP,on}$ is the CPP on-peak price and p^{std} is the standard rate electricity price, all customers face the same prices. $Q^{CPP,off}$ and $Q^{CPP,on}$ denote expected annual consumption under the CPP rate in the respective off-peak and peak periods, and Q^{std} denotes expected annual consumption under the standard rate.

Calculation of the expenditures under each rate alternative is complicated by uncertainty on how much electricity the consumer will consume next year. The choice between tariffs is therefore assumed to be based on the consumption pattern in the last year, and the ability to adjust consumption to the CPP rate structure. The consumers thus anticipate next year's consumption pattern to be similar to last year's consump-

[4] Other costs related to the selection of the CPP rate, such as differences in the fixed costs of the two rates, or transaction costs related to the inconvenience of switching to the new rate, may also influence choice. However, the rates had equal fixed costs, and for simplicity, I disregard transaction and other costs.

tion pattern, with the exception that consumption may be adjusted to price variations if the CPP rate is chosen.[5]

It is convenient to separate consumption under the standard rate into the same periods as the CPP rate, such that

$$Q^{std} = Q^{std,off} + Q^{std,on}. \quad (3.2)$$

Consumption under the CPP rate will then be given as:

$$Q^{CPP,off} = Q^{std,off} + \Delta Q^{CPP,off} \quad \text{and} \quad Q^{CPP,on} = Q^{std,on} + \Delta Q^{CPP,on}, \quad (3.3)$$

i.e., consumption under the CPP rate equals consumption under the standard rate, plus annual adjustments in consumption to the CPP prices ($\Delta Q^{CPP,off}$ and $\Delta Q^{CPP,on}$), in off-peak and peak periods respectively. Inserting (3.2) and (3.3) in (3.1) suggests the CPP rate will be selected if:

$$\Delta Y = \left(p^{CPP,off}\left(Q^{std,off} + \Delta Q^{CPP,off}\right) + p^{CPP,on}\left(Q^{std,on} + \Delta Q^{CPP,on}\right)\right) - p^{std}\left(Q^{std,off} + Q^{std,on}\right) < 0. \quad (3.4)$$

It is further assumed that consumption adjustments can take the form of consumption *reductions* during peak hours, or consumption *shifting* from peak to off-peak hours. Hence, the terms $\Delta Q^{CPP,off}$ and $\Delta Q^{CPP,on}$ can be written as:

$$\Delta Q^{CPP,off} = S^{CPP,on} \quad \text{and} \quad \Delta Q^{CPP,on} = -S^{CPP,on} - R^{CPP,on}, \quad (3.5)$$

which implies that the expected change in consumption in off-peak hours equals an amount of electricity, $S^{CPP,on}$, that is *shifted* from peak hours to off-peak hours (left-hand side equation), and that the expected adjustment to the price for peak hours

[5] Next year's consumption may also change if new appliances are purchased, if the number of family members changes, etc. However, for most households, such changes are likely to be of minor significance since the period under consideration is relatively short (a single year).

equals the same amount, $S^{CPP,on}$, of electricity *shifted* to off-peak hours, and in addition an amount of electricity, $R^{CPP,on}$, that is *removed* during peak hours (right-hand side equation). Inserting (3.5) in (3.4) and rearranging yields:

$$\Delta Y = \left(p^{CPP,on} - p^{std}\right)Q^{std,on} - \left(p^{std} - p^{CPP,off}\right)Q^{std,off} - \left(\left(p^{CPP,on} - p^{CPP,off}\right)S^{CPP,on} + p^{CPP,on}R^{CPP,on}\right) < 0 . \quad (3.6)$$

The different terms in expression (3.6) imply that whether the consumer selects the CPP rate or not is dependent on the extra expenditure if peak consumption is charged by the CPP peak price instead of the standard price ($\left(p^{CPP,on} - p^{std}\right)Q^{std,on}$), the expenditure savings if off-peak consumption is charged by the CPP off-peak price instead of the standard price ($\left(p^{std} - p^{CPP,off}\right)Q^{std,off}$), the expenditure savings if peak consumption is shifted from the CPP peak price period to the CPP off-peak price period ($\left(p^{CPP,on} - p^{CPP,off}\right)S^{CPP,on}$), and the expenditure savings if peak consumption is reduced during CPP peak price hours ($p^{CPP,on}R^{CPP,on}$).

The last two terms indicate a household's ability to shift and reduce consumption when facing the CPP rate. These terms are collected into a single 'adjustment' term:

$$adj^{CPP} = \left(p^{CPP,on} - p^{CPP,off}\right)S^{CPP,on} + p^{CPP,on}R^{CPP,on} . \quad (3.7)$$

Inserting (3.7) in (3.6) and rearranging, we find that the consumer will choose the CPP if:

$$\frac{\left(p^{std} - p^{CPP,off}\right)}{\left(p^{CPP,on} - p^{std}\right)} > \frac{Q^{std,on}}{Q^{std,off}} - \frac{adj^{CPP}}{\left(p^{CPP,on} - p^{std}\right)Q^{std,off}} . \quad (3.8)$$

Formulation (3.8) conveniently expresses the fact that the consumer's choice depends on the ratio of the differences between the standard price and the off-peak CPP price to the difference between the peak price and the standard price (first term), the ratio of consumption in peak hours to the consumption in off-peak hours (second term), and the customer's savings made possible by consumption adjustments (third term). This means that the consumer will consider all prices (i.e. the price ratio), and then select the CPP rate if: i) the consumption ratio is small enough; and/or ii) if the benefits related to consumption adjustment are sufficiently high.

We now discuss the *consumption ratio* term and the *consumption adjustment* term on the right hand side of the inequality (3.8) in further detail to evaluate which customers may benefit from choosing the CPP rate, and which may not. We will also discuss whether it is likely that the customers' knowledge and *information level* is adequate to make the calculations necessary for accurate comparisons between the rate alternatives.

3.1. The consumption ratio

The effect of the consumption ratio may be more conveniently illustrated when decomposed into consumption in different periods:

$$\frac{Q^{std,on}}{Q^{std,off}} = \frac{Q^{std,winter,on-peak}}{Q^{std,summer} + Q^{std,winter,off-peak}}. \qquad (3.9)$$

As discussed, peak consumption consists of the sum of consumption in the hours 8–11 and 17–20 on working days in the winter when the temperature is below –8 °C. Off-peak consumption then consists of total electricity consumption in other winter hours and in all summer hours.

A household will benefit from the CPP rate, given an unchanged consumption pattern, if its consumption ratio is lower than the price ratio. As the price ratio is calculated using the consumption pattern of an average customer, we may put this differently; a household will benefit if its consumption ratio is lower than the consumption ratio of the average customer. From (3.9) it is clear that low on-peak consumption or high off-peak consumption contributes ceteris paribus to a consumption ratio that may be smaller than the price ratio.

It is likely that certain household electricity consumption behaviour affects normal load patterns. For instance, households who normally lower their electricity consumption during night hours may not benefit, unless they change their consumption pattern. This is seen from (3.9), as the off-peak consumption in night hours in the winter will be smaller, thereby giving a higher ratio. If these households are unwilling to change their way of using electricity for heating, the probability they will not choose the CPP rate increases. Likewise, lower electricity use during off-peak weekends in winter will contribute to a higher ratio.

Households who also normally use little electricity during daytime are likely to have ratios in their favour, and thus benefit from choosing the CPP rate, even without changing their pattern of consumption.

3.2. Consumption adjustments

Consider a customer with an equal or larger peak/off-peak consumption ratio than the price ratio. The only way this customer can benefit from the CPP rate is by reducing consumption in the peak period, or shifting peak consumption to the off-peak period.[6] Of course, customers with smaller consumption ratios than price ratios will benefit further from consumption adjustments if they choose the CPP rate. However, whether consumption is flexible enough and suited for adjustment to the price will vary across

[6] I disregard other possible benefits such as automatic meter reading, which is both convenient and time-saving.

households. Accordingly, it is likely that certain household characteristics will increase their propensity to select the new rate offered, and vice versa.

For instance, consumers with energy management systems can program their electric heaters in order to shift peak consumption to off-peak hours. These households can more easily take advantage of the CPP rate and save money on their electricity bill than other households. One can then expect ownership of energy management systems to increase the propensity of households to choose the CPP rate.

Another way of taking advantage of the price structure is to reduce peak electricity consumption through heating the dwelling with a wood-burning stove instead of electricity. Some households do not normally use oil/paraffin/gas furnaces, even if already owned, and may decide to do so once they select the CPP rate. Ownership of alternative heating equipment may therefore increase a household's interest in the alternative rate.

Furthermore, households who only use electricity for space heating may find it easier to adjust consumption than those without electricity for heating at all, as a higher consumption level may increase flexibility (for instance, Mountain and Lawson (1995) found price responses to be larger for households with electric heating, air conditioning and electric water heating, compared with households without these appliances). Such households may have a higher probability of choosing the CPP rate.

The timing of use of electric appliances, such as washing machines, dishwashers, vacuum cleaners, televisions, personal computers, electric cookers, outdoor electric ground heating, engine heaters, etc., may easily be shifted from peak to off-peak hours. Consequently, we may expect households with a large stock of electric appliances to be more interested in the CPP rate than those with fewer appliances. This is supported by studies elsewhere that have found households with relatively more appliances to have higher price responses (see, for instance, Caves et al. 1984, Baladi et al., 1998).

The income of the household can also influence the willingness to participate in the CPP rate program. Households in the highest income groups may care less about their electricity bill, if it constitutes only a small part of total expenditure. Hence, we may expect customers in the lowest income groups to have the highest propensity to choose the CPP tariff since they are likely to be most price responsive (see for instance Reiss and White (2005)).

3.3. Information level

All things considered, the decision on selecting the CPP rate is a difficult task for consumers. The uncertainty with respect to how many peak hours will be charged the peak price during the winter season introduces a problem for the household when trying to calculate which rate will yield most benefits. Moreover, customers do not usually have any information on how much electricity they normally use each day, week or year. This makes it difficult in practice to undertake the necessary calculations. Besides, it is unlikely that every household will actually undertake these calculations. On the other hand, customers may rely on a rule of thumb to assess whether they wish to use the CPP rate. If they know their consumption is small during the hours of the day when the peak price may be activated, they may believe that they will benefit from choosing the rate. However, such consumers may be a minority in the population, as electricity consumption may not be of major concern to most households. It may be more likely that most customers will base their decision on information and knowledge they actually have and their ability and willingness to reduce consumption in peak price periods or shift consumption in such periods to off-peak periods.

4. Econometric specification

The households' decision to select the CPP rate or the standard rate is formulated with a discrete choice participation model. This statistical model is used to test whether there are statistically significant differences between two groups that have chosen differently between the rates, with respect to their characteristics.

Let the expected indirect utility V for a customer under each of the rates depend on the consumption pattern of the customer (i.e. consumption in the off-peak and peak periods), electricity prices, income, and other household characteristics. Then $\Delta V = V^{CPP} - V^{std}$ indicates the difference in a household's indirect utility between choosing the CPP rate and the standard rate. A household will choose the CPP rate if $\Delta V>0$, i.e. if the indirect utility on the CPP rate is higher than on the standard rate. The utilities are unobservable, but in a linear random utility framework we observe the choice between the two rate alternatives, and this choice is assumed to reveal the one with the greatest utility. Let

$$CPP = \begin{cases} 1 & \text{if } \Delta V > 0 \\ 0 & \text{otherwise} \end{cases}, \qquad (4.1)$$

and $V^{CPP}= X\beta^{CPP}-\varepsilon^{CPP}$, $V^{std}= X\beta^{std}-\varepsilon^{std}$, so that $\Delta V=X(\beta^{CPP} - \beta^{std}) - (\varepsilon^{CPP}-\varepsilon^{std}) = X\beta-\varepsilon$, where X is the deterministic component, ε is the stochastic component which, for instance, may represent unobserved preferences for comfort (indoor temperature, lighting, amount of hot water spent on showering or bathing, etc.), environmental concerns (if they regard peak consumption reductions as an environmental measure), transaction costs of a shift of tariff (such as time and effort spent on understanding the new rate alternative). β are unknown coefficients to be estimated. As described in Section 3, the systematic part of ΔV depends on the difference in expenditures between the two rates, $\Delta Y = Y^{CPP} - Y^{std}$. Then customer *i*'s probability of choosing the CPP rate is given by:

$$P\left(CPP_i = 1\right) = P\left(\Delta V_i > 0\right) = P\left(\varepsilon_i < X_i\beta\right) = P\left(\varepsilon_i < \alpha + \beta_1 Q_i^{std,off} + \beta_2 Q_i^{std,on} + Z_i^{CPP}\gamma\right), \quad (4.2)$$

where $\beta_1 Q_i^{std,off}$ and $\beta_2 Q_i^{std,on}$ gives the effect on utility of annual consumption in off-peak and peak periods under the standard rate. As discussed in Section 3 regarding the consumption ratio, a consumer with high off-peak consumption will have a low consumption ratio, and one may expect such a consumer to select the CPP rate. The sign of β_1 is then hypothesised to be positive. The opposite is likely to be true for β_2, which is attached to the on-peak consumption variable. The consumption variables in (4.2) will thus pick up the impact of peak and off-peak consumption on the propensity to participate separately, instead of in a single ratio term. $Z_i^{CPP}\gamma$ gives the effect on the utility of consumption adjustments to the prices for each household. The vector Z_i^{CPP} is approximated by variables indicating the households' ability or willingness to reduce or shift consumption in peak periods. γ is expected to be positive/negative for variables that are likely to increase/decrease a household's likelihood of selecting the CPP rate. The stochastic error term (ε_i) is assumed to be logistic and independently distributed. The unknown parameters in (4.2) are estimated using a bivariate logit model (see, for instance, Greene, 2003).

5. The data

In the experiment, automatic meter reading technology provided measurements of each customer's hourly electricity consumption. All customers were asked to answer a survey by post or Internet that requested socio-demographic information about the household. Twenty percent of households responded to the survey (see Andersen et al., 2004, and Sæle, 2004, for details). The consumption and survey data are used in this analysis to investigate systematic differences between households choosing the CPP rate and those retaining the standard rate. This section describes the data and the variables included in the analysis.

One objective of the analysis is to study whether the customers' consumption patterns have affected their choice of tariff. As described in Section 3, the households will make their decision based on the previous year's pattern of consumption. Data from the experiment period is used as an indicator of the consumption pattern before the participation decision was made.[7]

In November and December 2003 (during the experiment period), temperatures never fell below –8°C and the peak price was never activated. Hence, customers that chose the CPP tariff faced flat off-peak prices, and had no incentive to adjust their daily load patterns.[8] It is then reasonable to assume that the CPP group (as well as the standard group) behaved in the same manner in this period with respect to their consumption patterns, as they did prior to the experiment period.

Consumption during the hours 8–11 and 17–20 in the coldest days in November and December are therefore used to approximate peak consumption, while the remaining

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[7] Metering of the households' electricity consumption commenced at the beginning of the experiment period.

[8] The small difference in price between the off-peak CPP price and the standard price 0.20-0.15=0.05 NOK/kWh is assumed to be negligible. Moreover, it should not influence the shape of the load curve, since none of the rates varies across the day.

consumption in these months is used to approximate off-peak consumption. The number of peak hours used is approximately the same as the number of hours with temperatures below –8°C that normally would occur in November and December.[9] Although consumption behaviour for temperatures below –8°C is not measured, temperatures lay below zero for several days. This makes it likely that the data still reflects any consumption differences between the households.

The other objective of the analysis is to investigate whether customers who selected the CPP rate did so because they are more flexible in consumption when prices vary. As indicators of flexibility, characteristics of the households and residences are used, as these may influence price responsiveness and the decisions to select the CPP rate (Train et al., 1987, Caves et al., 2000). Dummy variables are included to indicate households with an energy management system, households with electricity as their only space-heating source, households with electricity and wood-heating furnaces, households with electricity and oil/gas/paraffin and households with oil/gas/paraffin as their only space-heating source. Dummy variables also indicate whether the household is a single-member family (zero otherwise), whether there is at least one family member living at home (zero otherwise), and whether the total annual income of the household belongs to one of four income intervals (zero otherwise). In addition, dwelling size and age are included in the analysis as continuous variables.

Descriptive statistics for 107 households in the group choosing the CPP rate and 167 households choosing to remain on the standard rate are given in Table 1.

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[9] Data from the remainder of the experiment period could not be used due to technical problems with the metering system and missing data.

Table 1. Summary statistics of household electricity consumption and characteristics for CPP and standard rate.

	Critical peak pricing				Standard rate			
Number of households	107				167			
Binary variables	*Percent*				*Percent*			
Energy management system	25.2				10.8			
Heating: Not electricity	3.7				10.2			
Heating: Electricity + oil/gas/paraffin	46.7				55.7			
Heating: Electricity + wood	39.3				26.9			
Heating: Only electricity	10.3				7.2			
Dwelling: Detached	75.7				56.3			
Dwelling: Semi-detached	11.2				13.8			
Dwelling: Undetached	8.4				9.6			
Dwelling: Flat	4.7				20.4			
Income: 0–250,000 [NOK]	15.0				26.9			
Income: 250,000–500,000"	38.3				30.5			
Income: 500,000–750,000"	32.7				25.7			
Income: 750,000–"	14.0				16.8			
Single-member family	10.3				26.9			
Living at home	45.3				52.0			
Continuous variables	*Mean*	*Std.*	*Min*	*Max*	*Mean*	*Std.*	*Min*	*Max*
Peak consumption [kWh]	103.8	42.5	14.6	216.2	90.6	44.2	5.3	234.7
Off-peak consumption [kWh]	4326.4	1789.3	651.5	8496.8	3800.6	1875.1	242.5	10161.0
Peak/Off-peak cons. ratio	0.0240	0.0016	0.0206	0.0289	0.0238	0.0018	0.0165	0.0320
Age of dwelling [in years]	28.5	18.4	4	131	52.0	29.0	9	155
Dwelling size [m^2]	146.3	51.5	40	275	143.8	65.8	40	350

1 NOK ~ 0.12 EUR / 0.15

Table 1 shows that both mean peak and off-peak electricity consumption is higher for the CPP group. However, peak/off-peak consumption ratio is almost the same. The share of households with an energy management system in the CPP group (25.2 percent) is also larger than in the standard group (10.8 percent).

Households are divided into four groups with respect to their heating equipment: dwellings with no electric heating (which means they use oil, gas or paraffin instead); dwellings with electricity and oil/gas/paraffin heating systems; dwellings with electricity heating and wood-burning furnaces; and finally, dwellings with electricity heating only. The percentage share of households with electricity heating only is somewhat larger for the CPP group, and the share of customers with oil/gas/paraffin heating in addition to electricity heating is somewhat larger for the group choosing the standard rate. The share of households with electricity heating and wood-burning stoves is nearly fifty percent larger in the CPP group, and the share of households without electricity heating in the CPP group is only a third of the share in the standard group.

In terms of dwelling type, about three quarters of CPP households, and only about half of the households in the standard group, are living in detached houses. The share of the households living in flats in the CPP group is about a quarter of the share in the standard group. The share of households living in semi-detached and undetached houses is quite similar for the two groups. With respect to the total annual income of households, we can see the share in the lowest income group (income less than NOK 250,000) is nearly half in the CPP group compared to the standard group, and somewhat larger in the two middlemost income groups. We also see that the two groups do not differ significantly for the highest income level.

The share of households in the CPP group living as a single-member family is nearly one third of the standard group. Households where at least one of the family members is living at home during the daytime do not differ much between the two groups, though the share is somewhat lower in the CPP rate group. Finally, we can see that the average age of dwellings for the CPP group is nearly half that of the standard group, but the average dwelling size is approximately the same.

6. Estimation results

As shown in the previous section, the summary statistics indicate differences between households choosing the CPP rate and those choosing to remain on the standard rate. A cross-section logit model is used to analyse the joint impact of the variables on the participation decision. Results from the estimated logit model, using Stata 8.0 (StataCorp, 2003), are presented in Table 2.[10]

Table 2. Estimated logit model results.

Variable	**Coef.**	**Robust Std. Err.**	**P>|z|**
Energy management system	0.9873	0.4201	0.019
Peak consumption	–0.0272	0.0232	0.241
Off-peak consumption	0.0007	0.0005	0.187
Heating: Electricity + oil/gas/paraffin	0.4444	0.6618	0.502
Heating: Electricity + wood	1.1778	0.7162	0.100
Heating: Only electricity	1.6842	0.9033	0.062
Dwelling: Semi-detached	–0.8183	0.5157	0.113
Dwelling: Undetached	–1.3333	0.5966	0.025
Dwelling: Flat	–2.3886	0.6804	0.000
Income: 0–250,000 [NOK]	0.4991	0.6433	0.438
Income: 250,000–500,000 [NOK]	0.9920	0.5709	0.082
Income: 500,000–750,000 [NOK]	0.3358	0.5226	0.521
Single-member family	–0.8991	0.5485	0.101
Living at home	–0.3007	0.3441	0.382
Dwelling size [m^2]	–0.0081	0.0040	0.043
Age of dwelling [in years]	–0.0468	0.0107	0.000
Constant	1.5554	1.1796	0.187
Log pseudo-likelihood =	–130.14876	Wald chi2(16) =	49.95
Pseudo R^2 =	0.2863	Prob>chi2 =	0.0000

Note: The left-hand side binary variable is one for households choosing the CPP rate and zero for households choosing to remain on the standard rate. Detached dwelling, Heating with only oil/gas/paraffin, Multi-member family and Income 750,000– are omitted to avoid multicollinearity.

[10] To correct for possible misspecification in the model, the Huber/White/sandwich estimator is used to obtain a robust estimate of the asymptotic variance-covariance matrix of the estimated parameters (StataCorp, 2003).

A positive sign on an estimated coefficient in this table indicates the increased propensity of a household to select the CPP rate; negative signs indicate greater reluctance to select the CPP rate.

The peak and off-peak consumption parameter estimates display a negative and a positive sign, respectively. This indicates reluctance of consumers with large peak and/or low off-peak consumption to choose the CPP rate. Alternatively, it indicates the interest of consumers with small peak and/or large off-peak consumption to take advantage of their consumption pattern by choosing the CPP rate. However, none of the estimated coefficients is significant. Jointly testing the two variables' significance with an F-test also fails to indicate any statistical significance. This suggests that with respect to electricity consumption patterns, households selecting the CPP rate do not differ significantly from the households who do not.

One reason may be that the consumers do not have accurate information about their consumption during the day, in either peak or off-peak periods. This complicates the task of calculating how their consumption during different parts of the day across a year affects expected expenditure. One should also recall the dynamic feature of the CPP rate; that is, the peak price is only charged when the temperature is below –8°C. Although the customers were informed how often these temperatures normally occur, it introduces additional uncertainty, which further complicates the calculation of peak and off-peak consumption and its related costs. These uncertainties and difficulties may be the main reason why the consumption differences in peak and off-peak periods are insignificant. Baladi et al. (1998) suggests another explanation for similar findings: instead of making decisions based on accurate consumption information, customers may rely on perceived usage patterns, which are not necessarily correct.

In this case, instead of choosing between rate alternatives based on consumption patterns, households may have based their decision on their ability and willingness to adjust usage. Estimates for the remaining variables indicate whether this was the case.

The effect of the energy management system variable, as expected, is positive and significant (at the 2 percent level). Since these households display a higher ability to shift consumption between peak and off-peak periods, this is likely to be the reason why their probability of choosing the CPP rate is higher than other households. This implies that the group of customers selecting the rate has greater potential to be demand responsive than those selecting the standard rate. However, and as shown in Table 1, there are still some households with energy management systems who did not choose the CPP rate, even though they would have probably benefited. This suggests that the marketing campaign for the CPP tariff could have focused more on the saving potential of energy managing systems. This would then have increased the demand response potential for the households on the CPP rate.

The results also indicate that households with electricity heating only and households with wood-burning furnaces in addition to electricity are significantly more interested (at the 10 percent level) in the CPP rate than households without electricity heating (those with only oil, gas, paraffin heating). The interest of the former may be explained by their higher potential for changing consumption, as they use more electricity for heating and then have greater consumption to reduce or shift. The latter may be explained by the ability to substitute electricity consumption in peak-price hours with wood. The group with electricity heating in addition to oil, gas or paraffin is not significantly different from the group with oil/gas/paraffin heating only. These groups may be reluctant to participate because their electricity usage is not as flexible as households who use electricity, or electricity and wood, to heat their residences.

The results also indicate that customers living in detached houses are more likely to select the CPP rate than households living in other house types. Households living in flats were least likely to select the CPP rate. One reason may be that detached houses usually have more rooms, which makes it easier to reduce consumption in parts of the house that are not frequently in use. Another reason is that households living in detached houses are more likely to own more electric appliances than those living in other and smaller dwellings (some examples of appliances are listed in Section 3). With more appliances, it should be easier to alter the time of usage between price periods. If we interpret dwelling types as a proxy for electric appliances excluded in the estimation, this may explain why house type significantly affects the choice of CPP.

In terms of total annual income, the results indicate that households in the second-to-lowest and lowest income groups are most likely to select the CPP rate, when compared with the highest income group. The reason why households with the highest income have a lower interest may be that they do not care about saving the relatively small share of income used on electricity consumption. However, only the coefficient for the second-to-lowest income group differs significantly from that for the highest income group.

The coefficient for single-member families displays a negative sign. Singles are assumed less likely to select the CPP rate, as compared to families of two or more members. One possible explanation may be that the adjustments in consumption necessary to take advantage of the rate may be more easily accomplished if there are more people in the household, i.e., the time budget spent on making consumption adjustments is shared across household members. Another explanation is that more members infers higher consumption and with that, higher adjustment potential. The estimate is nearly significant at the 10 percent level.

The effect of the variable that indicates whether people are home during the daytime is negative. The reason for this reluctance to choose the CPP rate may be an unwillingness to reduce consumption during colder periods during the day as the household may have small children or elderly occupants. The estimate is, however, not significant. The significant negative estimate of the coefficient for net floor space indicates that larger dwellings decrease the likelihood of participation. The size of the dwelling (in square metres) is likely correlated with both income and dwelling type, which are controlled for in the regression. However, income is defined in quite broad intervals, and the income dummy variables may therefore not have picked up all of the explanatory power related to the income effect. The negative coefficient may be thought of as a further support for higher income groups' low interest in the CPP rate.

We further show that the age of the dwelling is highly significant with a negative sign. This indicates that households in newer dwellings are more likely to choose the CPP rate. This variable picks up standard and energy efficiency differences between dwellings, e.g., electric floor heating is more common in newer dwellings. With electric floor heaters, energy is stored in the floor due to its higher heating capacity. Households with these heating systems are more time-of-use flexible, and hence better suited for switching consumption between price periods. Newer dwellings also tend to be better insulated. This decreases heat loss from the dwelling and lessens the loss of comfort if, for instance, electric heaters are turned off during high price periods.

Finally, the Wald-statistic (which is χ^2-distributed with the degrees of freedom equal to the number of slope coefficients) is used to test the hypothesis that all coefficients (except the intercept) are jointly equal to zero. This hypothesis is rejected at a high level. This indicates that the model explains outcomes quite well.

7. Conclusions

This analysis indicates that, on average, the consumption pattern does not influence the households' decision on whether to select the critical peak price (CPP) rate or the standard rate. Ownership of energy management systems and wood-burning furnaces increases the probability of joining the CPP program. Households can use this equipment to shift peak consumption to off-peak hours, or to reduce peak consumption and reduce electricity expenditures. The results indicate that the offering of CPP tariffs may increase the demand response among residential electricity consumers since the tariff appears to attract customers with a higher ability to respond to varying prices than the population as a whole. Moreover, the CPP tariff does not, on average, appear to attract customers that may materially benefit without making any consumption adjustments.

One possible explanation for the results is that customers' lack of information and knowledge of when and how electricity is used prevents decisions being taken with respect to consumption patterns. Instead, their decisions appear to be based on the knowledge they have in place, such as their own motivation and ability to be price responsive. The data also show that a larger share of households with energy management systems and with wood-burning furnaces could have been attracted to the CPP rate. This suggests that marketing campaigns may attain a higher share of possible price responsive households if a greater effort was made to inform them about the expenditure saving potential of the CPP rate.

Technologies supplying hourly consumption data to households will probably be more common in the future. Such technologies may ease the comparison of expenditure with different rate alternatives. With such information, it is likely that the customers' selection of time-differentiated rates will increasingly be taken on the basis of consumption patterns. If customers with advantageous consumption patterns mainly choose differentiated tariffs, this may in turn erode the benefits associated with demand response programs based on time-differentiated tariffs. On the other hand, new technologies are also likely to manage electricity usage in more advanced ways, and may offer automatic calculation of the possible savings from price adjustment. This may increase the participation of price responsive customers, which in turn will increase the benefits of demand response programs.

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