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The Effect of Utility Time-varying Pricing and Load Control Strategies on Residential Summer Peak Electricity Use: a Review

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Abstract

Peak demand for electricity in North America is expected to grow, challenging electrical utilities to supply this demand in a cost-effective, reliable manner. Therefore, there is growing interest in strategies to reduce peak demand by eliminating electricity use, or shifting it to non-peak times. This strategy is commonly called “demand response”. In households, common strategies are time-varying pricing, which charge more for energy use on peak, or direct load control, which allows utilities to curtail certain loads during high demand periods. We reviewed recent North American studies of these strategies. The data suggest that the most effective strategy is a critical peak price (CPP) program with enabling technology to automatically curtail loads on event days. There is little evidence that this causes substantial hardship for occupants, particularly if they have input into which loads are controlled and how, and have an override option. In such cases, a peak load reduction of at least 30% is a reasonable expectation. It might be possible to attain such load reductions without enabling technology by focusing on

household types more likely to respond, and providing them with excellent support. A simple time-of-use (TOU) program can only expect to realise on-peak reductions of 5%.

Keywords

Demand Response, Load Shedding

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Abbreviated Title

Utility Programs to Reduce Residential Summer Peak Electricity Use

Introduction

Many jurisdictions in North America experience a peak demand for electricity on hot summer afternoons. This occurs when an increasing air-conditioning load is added to loads with (currently) relatively constant daytime profiles (such as commercial lighting and industrial processes), and other loads which tend to rise in the late afternoon, such as residential end uses¹. In such situations utilities must import additional capacity (often at a high cost premium), switch in peak capacity generators, or reduce demand.

¹ Some cold climate regions are winter-peaking. Winter peaks tend to occur in early morning and in the evening, when heating-related loads are added to increased lighting loads and residential activity loads. The focus of this paper, however, is summer peaks.

Failure to match supply and demand through these measures will result in brownouts or blackouts. There might not be the capacity to build additional generation, transmission, and distribution fast enough to accommodate projected demand growth, and therefore the frequency of peak demand problems is expected to grow² [e.g. Porter, 2009]. Indeed, in Ontario, Canada, for example, the peak demand for electricity is growing faster than total electricity use [Rowlands, 2008, Table 1].

As a result of this concern, there is growing interest in addressing this issue, at least partially, on the demand side [Piette et al., 2005; DRCC; Rowlands, 2008; IEADSM], that is, reducing the peak demand for electricity at critical times by eliminating some electricity use, or shifting it to non-peak times. This strategy is commonly called “demand response”, for which the US Federal Regulatory Commission provided this definition [FERC]: ‘Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.’ Methods to facilitate this are being explored in all building types, including residential buildings.

Households are major contributors to summer peak demand; Faruqui & Sergici [2009] state that in the US residential customers ‘... account for a third of over-all [electrical]

² The current economic downturn has substantially reduced peak demand in many jurisdictions, consequently lowering the urgency of addressing peak demand issues. However, peak demand growth is expected to re-emerge in the long-term, as the economy rebounds and populations grow.

energy consumption and for a larger share of peak demand.’ One of the primary methods pursued to reduce on-peak use of electricity in households is through behavioural modification, that is, encouraging people to eliminate on-peak electricity-using activities, or shift them to other periods. In order to provide an economic incentive for such behaviour change, many utilities have proposed a change in the residential electricity rate structure. This change is a move away from the traditional flat-rate per kWh model, to a structure that more closely follows the real cost of delivering electricity at the time it is used; in other words, a higher price during periods of higher system-wide demand, and a lower price at other times³. Another variation of this is to provide a payment to a customer for every kWh not used during system peak periods. These rate structures are usually designed such that the average customer who does not modify their behaviour will pay the same under the new, time-dependent rate structure as they would have done under the flat-rate structure.

Pricing programs have the following generic names (common abbreviations) and approaches:

- Time-of-use (TOU): The day is divided into contiguous blocks of hours. The price of a kWh varies between blocks, but not within blocks, with the highest

³ With a flat rate, households with load profiles that coincide with system peaks are effectively subsidized by households with flatter profiles. Thus, changing the rate structure to one that more closely reflects the real-time cost of electricity also increases fairness of billing.

price for the on-peak block. The same rate structure applies on every day⁴. For example, in an Ontario, Canada pilot study [Strapp et al., 2007] summer weekday⁵ TOU prices were: off-peak (10pm-7am) 3.5¢/kWh; mid-peak (7am-11am and 5pm-10pm) 7.5¢/kWh; on-peak (11am-5pm) 10.5¢/kWh. This contrasted with the conventional prevailing fixed price for non-pilot participants of 5.8¢/kWh for the first 600 kWh/month during summer, and 6.7¢/kWh for all additional use.

- Critical Peak Pricing (CPP): This is a similar concept to TOU, except that it is only applied on a relatively small number of “event” days. These event days are commonly advertised by the utility a day in advance, based on their forecast of a particularly high demand. The ratio of on-peak to off-peak price is higher on CPP event days than in a TOU program. The same rate structure is applied on every event day. For example, the Ontario, Canada pilot study [Strapp et al., 2007] also had a CPP group with summer weekday⁶ prices: off-peak (10pm-7am) 3.1¢/kWh; mid-peak (7am-11am and 5pm-10pm) 7.5¢/kWh; on-peak (11am-5pm) 10.5¢/kWh; CPP (applying for 3 to 4 hours on up to 9 event days) 30.0¢/kWh. Note that the off-peak price was 0.4 ¢/kWh lower than that paid by the TOU group, to offset the higher price paid by the CPP group during CPP

⁴ In some locations the block structure may vary by season.

⁵ Weekends and holidays were charged at off-peak prices all day.

⁶ Weekends and holidays were charged at off-peak prices all day.

events and retain revenue neutrality across groups. Sometimes CPP is applied on top of a regular TOU rate.

- Real Time Pricing (RTP): The price may vary hourly and is tied to the real market cost of delivering electricity. Thus, the price is not known far in advance, no two days have the same rate structure, and there can be much greater extremes of on-peak to off-peak price compared to CPP. For example, Summit Blue [2007] reports on an RTP pilot applied to over 1000 household in Illinois. The average summer price for electricity was about 5¢/kWh, but this varied from day-to-day, and spiked to over 35¢/kWh on two days.
- Peak Time Rebates (PTR): Customers receive electricity bill rebates for not using power (relative to a previously-established, household-specific baseline) during peak periods. For example, the Ontario, Canada pilot study [Strapp et al., 2007] also had a PTR group. This group paid TOU prices except during CPP event hours, during which they received a 30.0¢/kWh rebate for energy not used. In this case the baseline was calculated as the average usage during the same hours of the five previous non-event, non-holiday weekdays, multiplied by 1.25. The multiplier accounts for the fact that event days are days with high system-wide demand, which tend to be hotter days when air conditioner use is higher.

In some cases utilities offer enabling technology to automate household response to price signals, for example, a thermostat that can be programmed to automatically increase set-point temperature during peak hours in response to a CPP event signal from a pager or similar system. Note that some of these pricing and technology

approaches may have the added benefit of reducing energy use during non-peak periods, although this is not their primary purpose.

To facilitate such pricing structures, utilities must install household electricity meters that record usage at least hourly, instead of the traditional mechanical meter that displays cumulative total usage only. These hourly meters are often called “advanced meters”, “interval meters”, or “smart meters”. To explore the return on investment of installing advanced meters, many utilities have conducted pilot projects, installing the meters in a subset of houses and applying time-varying rates⁷, to gauge potential savings associated with demand reductions; i.e. avoided costs of generation, transmission and distribution infrastructure [e.g. Faruqui & Wood, 2008], against installation costs. Other economic benefits to the utility of installing advanced meters are the elimination of manual meter reading, and rapid automatic notification of power outages. In North America, the province of Ontario, Canada leads the way in widespread installation of advanced meters (every home and small business to have an advanced meter by the end of 2010 [OEB]); a recent US federal energy bill encourages demand-side management, including the installation of advanced meters to support time-varying pricing [US Congress, 2005 Section 1252], and the American Reinvestment and Recovery Act will support the deployment of ‘... more than 40 million smart meters in American homes and businesses over the next few years...’ [USDoE, 2009].

⁷ There is some evidence that simply providing people with immediate feedback on their energy use will lead to savings without the price signal. For a review of this work see [Darby, 2006].

A further measure designed to reduce peak use, which may be used independent of time-varying pricing, is direct load control (DLC). In this case utilities install equipment to allow them to modify the operation of appliances during peak periods. Typically such control is only invoked on a relatively small number of event days, determined in a similar way to CPP event days. In fact, the enabling technology sometimes used to automate response to CPP events is often the same technology used to implement DLC. Air conditioning (AC) units are the most common appliance to be controlled in such programs, and are the focus in this paper⁸. Such control is enacted in two generic ways:

- Increasing thermostat set-point: This results in an immediate large drop in cooling load as the AC unit is not required to come on until the interior temperature reaches the new set-point and cooling load may return to normal levels. For example, KEMA [2008] describes a pilot study conducted in California deploying this strategy. However, in an attempt to spread out the load reduction, the set-point increase was introduced gradually, by 1°F at the start of every hour, or every second hour.
- Limiting cycling run-time: The thermostat setting is maintained, but the AC unit is only allowed to run for a maximum period even if the set point is not reached, and is then turned off for a fixed period. For example, 50% cycling commonly means on for 15 minutes, then off for 15 minutes, and so-on. The

⁸ Other appliances that are sometimes controlled are electric water heaters, and pool pumps.

initial drop in cooling load is not as great as with the increasing set-point strategy, but this more modest drop is maintained over a longer period. The California pilot study [KEMA, 2008] also had a group with a switch to limit run time. In this case, the switch employed adaptive technology and enacted household-specific run-time limits based on prior usage. That is, if a particular AC unit would have run for 40 minutes in an hour, 50% cycling would result in 20 minutes of run-time per hour (not 30 minutes).

Utilities have conducted pilot projects involving time-varying pricing and DLC measures. This body of knowledge can now be examined to assess which strategies are most effective in lowering peak-time electricity use.

Reports on utility pilot studies and evaluations of alternative pricing models and DLC are often available on public websites: the utility's own website, that of their regulator, or an affiliated website. Although these reports may use sophisticated analysis techniques, they are rarely published in peer-review scientific journals. In reading these reports it is notable that they seldom refer to similar pilot studies conducted in other jurisdictions or compare their results to those of others. For an academic researcher such a comparison is an important part of validating and interpreting results. Of course, utilities don't operate in the same context as an academic researcher, and such comparisons may be considered outside of the study scope (especially if resources are limited), or simply judged of little value given the many methodological differences between the studies (as noted below). In this paper we

undertake such a comparison, and bring many of these studies together in order to explore trends so that we may gain a better understanding of the likely effects of applying these strategies to larger populations.

Methods

Faruqui & Sergici [2009] also grouped various utility studies together for the purposes of aggregating knowledge and experience, and to explore trends. Our paper is inspired by their methods and goals. We seek to expand Faruqui & Sergici's review, by adding more recent studies, reinterpreting their original sources, and adding more performance metrics. Further, we have also summarized DLC studies run independent of time-varying pricing.

To identify studies to include in this review we employed a variety of common bibliographic search techniques. We began by obtaining Faruqui & Sergici's original sources. Further, we conducted searches in major library and World Wide Web databases. If any of these primary sources referred to other studies we sought these secondary sources. Of the larger group of studies we identified, in this paper we focus on those conducted in North America, reported after 1997, and addressing summer peak issues. This subset was more relevant to our own stakeholders, and current practitioners⁹. Despite our extensive search for relevant material, and the limitations to our scope, we can make no claim to be comprehensive in our coverage. We expect

⁹ Examples of older studies are Heberlein & Warriner [1983] and Kempton et al. [1992].

Examples of studies with information on winter peak effects are Sulyma et al. [2008] and Ericson [2009].

that there are other studies in progress or recently completed that have not reported information in adequate detail, or that are not readily available. Nevertheless, we think that the breadth of studies presented in this paper provides a useful review, and is more comprehensive than other information previously published in the academic literature.

Ability to compare different pilot studies is clouded by the differences between the design and analysis of these studies. We do not detail individual studies in the text, for brevity, we summarize some of their key characteristics in the tables and graphs. The format of such an academic paper does not allow for very detailed notes on methodological differences between studies, for these the reader is referred to the individual study citations. Nevertheless, we think these studies are similar enough to be put side-by-side for exploration of general trends. Examples of methodological differences to be aware of are:

- Pricing regimes applied at different periods in the summer, and different hours of the day
- CPP events triggered by different criteria
- Communication of CPP events enacted in different ways
- Variation in sample composition; e.g., some targeted high-use customers only, some targeted customers with AC only, some had incentives for participation
- Savings calculated by various methods; e.g., regression, comparison to control group, comparison of CPP participants to themselves on non-event days

- Some tested statistical significance of effects, others did not
- Peak reduction effects calculated over different number of days or events
- Overall energy effects were calculated over differing periods, or not calculated at all
- Direct load control effects averaged over differing numbers of hours, or days
- Direct load control effects quoted only for peak hours, or days

Because of the large number of potential methodological differences, as well as differences in location and price ratios, one should be wary of comparing single studies with each other. Rather, our emphasis in interpretation is on more general trends suggested by the data.

Results

Table 1 lists the studies we reviewed relating to peak load reduction via the introduction of dynamic pricing, along with some key study characteristics. Figure 1, shows the reported average reduction in peak load for these studies, and Figure 2 shows the reported reduction in overall energy use; both figures show additional study details. In the Figures, different treatment groups in each study (where applicable) are shown separately, and the effects are rank ordered according to the size of the percentage peak load reduction.

Table 1. Studies relating to peak load reduction via the introduction of dynamic pricing.

Study Name	Period	Location	Enabling Technology	Reference
ADRS	Jul-Sep, 2004 & Jul-Sep, 2005	California	Programmable communicating thermostat	Rocky Mountain Institute [2006]

Ameren	Jun-Sep, 2004 & Jun-Aug, 2005	St. Louis, Missouri	Programmable Thermostat	Puckett & Hennessy [2004, 2006]
Anaheim	Jun-Oct, 2005	Anaheim, California		Wolak [2006]
Colorado	Jul, 2006-Jul, 2007	Denver, Colorado	AC switch, programmable communicating thermostat	Energy Insights [2008]
GPU	Jun-Sep, 1997	New Jersey	Programmable communicating thermostat	In Faruqi & Segici [2009]
Gulf Power	Summer, 2000 & 2001	Western Florida	Programmable communicating thermostat and load controller	In Levy et al. [2002]
Hydro One	May-Sep, 2007	Ontario	Real-time feedback	Hydro One [2008]
Idaho	Jun-Aug, 2006 & Jun-Aug, 2007 & Jun-Aug, 2008	Emmett, Idaho		RLW Analytics [2006], Idaho Power [2008, 2009]
Illinois	2005-2006	Illinois		Summit Blue [2006, 2007]
Laredo	Feb, 1994-May, 1997	Laredo, Texas	Programmable load control	Hartway et al. [1999]
MyPower	Jul, 2006- Sep, 2007	Cherry Hill & Hamilton, New Jersey	Programmable communicating thermostat, water heater control, pool pump control	Violette, D. et al. [2007]
Newmarket	Aug, 2005-Oct, 2007	Newmarket, Ontario	Programmable communicating thermostat	Navigant [2008]
Olympic Peninsula	Apr, 2006-Mar, 2007	Washington & Oregon	Communicating thermostat, and dryer, water heater load control	Hammerstrom et al. [2007]
Ottawa	Aug, 2006-Mar, 2007	Ottawa, Ontario		Strapp et al., [2007]
PG&E	May-Oct, 2008	Kern County, California		George & Bode [2008]
SPP	Jul, 2003-Dec, 2004	California	Programmable communicating thermostat, AC switch, water heater control, pool pump control	Charles River Associates [2005]

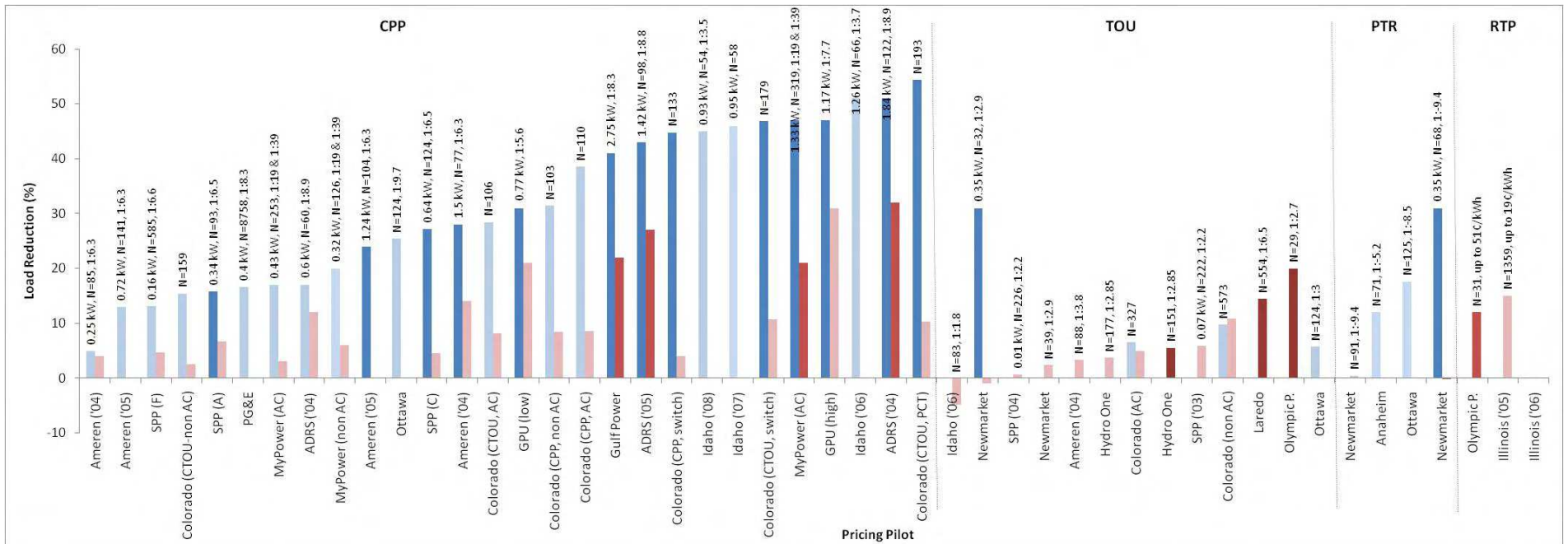


Figure 1. The reported average reduction in peak load for the reviewed time-varying pricing studies. Different treatment groups in each study (where applicable) are shown separately, and the effects are rank ordered according to the size of the percentage peak load reduction, and grouped according to the dynamic price option used. The blue-shaded bars indicate reductions during peak hours (variously defined) on critical event days, and the red-shaded bars indicate savings during those same hours, but on non-event days. The bars carry a label indicating the size of the average reduction in terms of kW per house, the number of houses involved in the study, and the ratio of lowest to highest price in effect. The darker-shaded bars indicate that an enabling technology was in use. Most studies involves a mix of customers with and without air-conditioning, but where studies presented results for these two groups separately, this is indicated by “AC” and “non AC” in the study label. The Colorado study involved both programmable communicating thermostats and AC switches as enabling technology, the results for these two groups are presented separately, as indicated by “PCT” and “switch” in the study label. The SPP study involved groups with different rate structures or drawn from different samples, the results for these groups are presented separately, as indicated by “F”, “A”, and “C” in the study label.

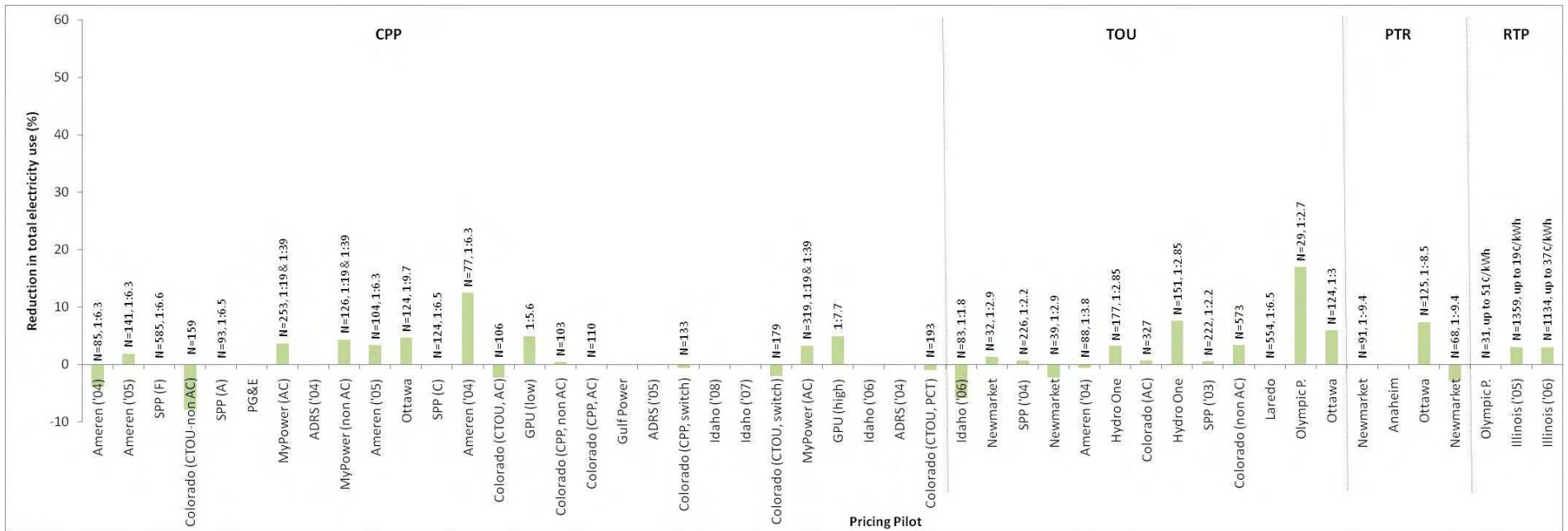


Figure 2. The reported average reduction in total electricity use for the reviewed time-varying pricing studies. Different treatment groups in each study (where applicable) are shown separately, and the studies are presented in the same order as Figure 1. The bars carry a label indicating the number of houses involved in the study, and the ratio of lowest to highest price in effect. For other explanatory notes, see Figure 1.

Table 2 lists the studies we reviewed relating to direct load control of air conditioning independent of time-varying pricing, along with some key study characteristics. Figure 3 shows the reported average reduction in peak load per house for these studies. In the Figure, different treatment groups in each study (where applicable) are shown separately, and the effects are rank ordered according to the size of the average peak load reduction per house.

Table 2. Studies relating to peak load reduction via direct load control of air conditioning, independent of time-varying pricing.

Study Name	Period	Location	Load Control Method	Reference
BGE	Jun-Aug, 2007	Baltimore, Maryland	Switch limiting run time	Greenberg & Straub [2008]
Con Ed	Aug, 2002	New York, New York	Thermostat increase, switch limiting run time	Egan-Annechino et al. [2005]
LIPAedge	Jul-Aug, 2002	Long Island, New York	Thermostat increase, switch limiting run time	Kirby [2003]
SDG&E	Jul-Sep, 2004 & Jul-Oct, 2005	Southern California	Thermostat increase	KEMA [2005, 2006]
PG&E	Jul-Sep, 2007	Stockton, California	Thermostat increase, switch limiting run time	KEMA [2008]
Idaho	Jun-Aug, 2004	Idaho	Switch limiting run time	Summit Blue [2004]

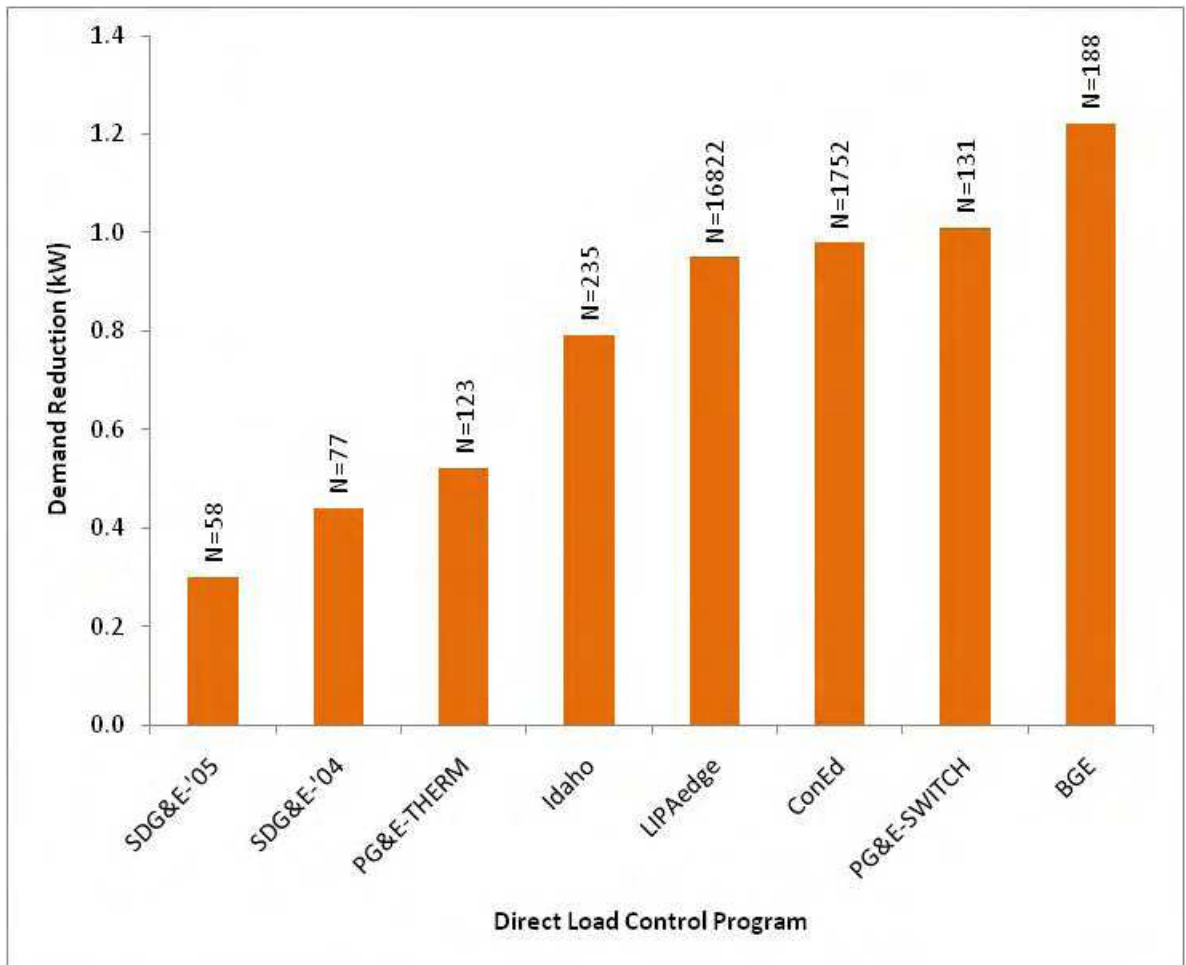


Figure 3. The reported average reduction in electricity use per house for the reviewed direct load control studies. Different treatment groups in each study (where applicable) are shown separately, and the studies rank ordered according to the size of the peak load reduction. Demand reductions are generally based on hourly data (and therefore, a more scientifically correct unit is kWh/h). The bars carry a label indicating the number of houses involved in the study.

Discussion

The large differences in study methodologies and reporting formats made it impossible to conduct a quantitative meta-analysis of predictive variables and their effect sizes, or to unequivocally address causation. However, in putting the studies side-by-side we can draw qualitative trends across them, as observed below.

It is clear that technology to automate response to price signals increases on-peak savings compared to using price signals alone. In Figure 1, in each of the study categories, there is a tendency for the studies that used enabling technology (the darker-shaded bars) to be found towards the higher end of assessed load reduction. This is in line with expectations: enabling technology allows the homeowner to choose preferred responses to price signals and then not have to remember to take manual actions on multiple, irregularly scheduled, event days. The participants in the Idaho CPP studies were clearly very effective without enabling technology, but they appear to be unusual in this regard. This suggests that the Idaho participants were highly engaged in the program, but why this was the case is not directly addressed in the published reports. In surveys, around 90% of Idaho participants said they were “very satisfied” or “somewhat satisfied” with the program, and the main reason for satisfaction was that participants saw a reduction in their utility bill [Clearwater Research Inc., 2006]; actual savings were around \$25 over the summer season [RLW Analytics, 2006]. The level of satisfaction with how well the utility provided information, overall and directly related to the best time to use electricity, was rated as very high, >4.5 on a 5-point scale [Idaho Power, 2006]. In a study of thermostat setting on heating energy use, Nevius & Pigg [2000] found that the presence of a programmable thermostat on its own did not lead to energy savings, energy savings were achieved when people who were more oriented towards conservation had technology that enabled them to setback temperature during the night and periods of

absence. This type of interaction between enabling technology and attitudes might go some way towards explaining the pattern of results in Figure 1.

Within the CPP and TOU studies, there is no clear trend for an effect of on-peak:off-peak price ratio on peak load reduction. However, Faruqui & Wood [2008] recommend higher ratios to promote savings, suggesting that higher prices act as a financial motivator for households to take action, and Charles River Associates [2005] found evidence with the California pricing pilot that higher prices during CPP events led to greater on-peak reductions. Faruqui & Wood also observe that some utilities have been wary of adopting high ratios in opt-in programs, thinking that high prices will scare customers away.

It is clear that CPP is generally very effective at reducing peak loads, whereas TOU is generally much less effective. However, the generally small effects of TOU are not necessarily unimportant from a utility perspective. For example, Rosenzweig et al. [2003] estimated that a reduction of only 2-5% in system-wide demand at peak times could reduce the spot price for electricity by 50% or more, and Faruqui et al. [2007] estimated that a 5% reduction in US demand during the highest 1% of demand hours would save \$3 billion per year. The reasons that CPP is more effective than TOU may be many fold. One reason, in contrast to the above paragraph, may be price. The on-peak:off-peak price ratio in CPP studies is generally much higher than in TOU studies, typically by a factor of about three. A second reason may be frequency of occurrence [Faruqui & Wood's, 2008]; homeowners may be more willing to respond to a CPP

program with a relatively small number of specially-called events (often with a sense of urgency implied), especially in the absence of enabling technology. In this context they may be willing and able to make large changes in electricity-using behaviour knowing that they can go back to their former ways soon. With TOU pricing they are asked to change their behaviour every single day, which may be much more difficult to sustain. Nevertheless, Figure 1 does show that in many cases CPP studies were somewhat effective in reducing electricity use during peak hours on non-event days. This does suggest that behaviours formed on event days may be deployed more frequently.

PTR is similar to CPP, except that it provides a “carrot” – a bill rebate for electricity not used on peak – rather than a “stick” – a high price for electricity used on peak. The number of studies in this review employing PTR was small, but the data we do have suggests PTR is less effective than CPP. One hypothesis is that people respond less well to carrots than sticks in this context. Research on the psychology of decision making supports this; Kahneman & Tversky [1984] summarize by saying that ‘... a loss of \$X is more aversive than a gain of \$X is attractive.’ So people would be more motivated to take steps to avoid losing money via CPP than they would be to take steps to gain money via PTR. In addition, PTR is likely more costly for utilities to implement, because of the need to develop very accurate, household-specific, baselines. Imprecise baselines can compromise the fairness and economic viability of the program. Further, Wolak [2006] notes that PTR provides an incentive for householders to elevate their electricity use during the period in which baselines are established, and found evidence for such behaviour. All of this suggests that CPP is a better option than PTR.

DLC of residential air-conditioning is very effective at reducing peak loads even in the absence of time-varying pricing. This might be expected from an automated system, and knowledge of the effect of enabling technology in CPP and TOU studies. Although indoor temperature (and humidity) will inevitably be higher than the householder's default preference during events, there is little evidence of substantial discomfort penalties [Greenberg & Straub, 2008; Summit Blue 2004; Kirby, 2003]. This may be because the temperature rise is slow and is not perceived over the few hours of the event [Newsham et al., 2009], or because occupants are willing to tolerate the higher temperatures in the context of the threat to grid stability. Nevertheless, there is evidence that override rates do increase as the length of service curtailment increases [Greenberg & Straub, 2008; KEMA, 2006; Kirby 2003]. This is presumably comfort-driven, and suggests that there is a limit on how long occupants will tolerate deviations from preferred conditions, and a consequent limit on the persistence of load reductions.

People are used to an arrangement with their utility in which customers receive all the power they want, whenever they want it, provided they pay their bill. A curtailment of service during the very time period when AC (for example) is most needed may be difficult to accept without an override option. The fact that overrides are invoked indicates their usefulness, but it is also noteworthy that they are not invoked to such an extent that the load reduction across all households is marginalized. This suggests that the override option provides people with the "insurance" they desire, while preserving the peak demand reduction value for the utility.

Time-varying pricing programs are not very effective at reducing overall energy use. This should not be surprising because at their core these programs are designed with load shifting, rather than (persistent) load shedding in mind. Higher prices on peak may encourage householders to shift their electricity-using activities to off-peak periods, but are unlikely to result in the activity not happening at all. Clearly, the ability to load shift depends on the activity. It may be possible to run the dishwasher later in the evening to take advantage of lower prices, but it is much more difficult to shift the time of watching a favourite TV show. Note also that AC load curtailed on peak is often used at an equivalent level after the peak period to bring temperatures back to normal (this is known as “snapback”, “payback” or “rebound”, see George & Bode [2008]; Violette et al. [2007]; Hartway et al. [1998] for examples). It is also conceivable that some homeowners will pre-cool their houses prior to CPP events. Reducing overall energy use can be achieved more effectively by measures that permanently improve the efficiency of house components and systems, such as higher insulation levels, reduced infiltration, passive design, more efficient heating and cooling, and more efficient appliances [e.g. Parker, 2009].

Pilot studies often survey participants on their satisfaction with the load reduction strategy’s structure and implementation. It is less common to collect detailed information on the household’s physical and socio-economic characteristics, and to use these variables as predictors of household load reduction (or satisfaction with the program). Charles River Associates [2005] is one rare example of a study that did do this to some extent, with the sub-sample designated by “SPP(F)” in Figure 1. Among

several effects they found, for example, that households with an income of $\geq \$100,000$ reduced peak energy use during a CPP event by 16.2%, whereas the reduction for households with an income of $\leq \$40,000$ was only 10.9%; and, if the head of the household was a college graduate the energy use reduction during a CPP event was 18.5%, as opposed to only 8.6% for non-graduates¹⁰. Such information may be very useful in better targeting future load reduction programs towards households that are more likely to respond, and to provide larger load reductions when they do respond. This might represent a more effective use of resources than a blanket invitation and marketing campaign for opt-in programs [Rocky Mountain Institute, 2006; see also Herter, 2007].

Conclusions

The key objective for most utilities in demand response programs is to reduce peak demand over a period of a few hours on a relatively small number of event days, as a hedge against potentially very damaging grid instability. In this context, the data from recent pilot studies in North America suggest that the most effective of the common strategies is a CPP program with enabling technology to automatically curtail loads on event days. There is little evidence that this causes substantial hardship for the occupants, particularly if they have input into which loads are controlled and how, and have an override option. In such cases, a peak load reduction of at least 30% is a reasonable expectation. A simple TOU program can only expect to realise on-peak

¹⁰ One can expect income and education to be inter-correlated. One should control for this in more complex analyses.

reductions of 5%. The reviewed pilot studies covered lengthy periods, in some cases several years, so it is reasonable to expect that these reductions will be maintained over time. Although a CPP program with enabling technology would be relatively expensive to roll-out at a large scale, it may be a reasonable alternative to developing new, on-peak supply capacity, and may be facilitated by the current large-scale investments in Smart Grid infrastructure.

The data also suggests that focusing programs on households with certain characteristics, such as higher income, education, and underlying conservation orientation, and providing these households with excellent utility support services, might realize high peak demand reductions without the expense of enabling technology. However, data on these socio-economic factors is relatively sparse, and more research on this topic should be a strong priority.

Finally, with the roll-out of advanced meters across North America, the ability and motivation to conduct additional studies of peak load reduction strategies will be elevated. We recommend a greater effort to standardize the methodology of study design and analysis, in order to facilitate analysis across studies, and thus to glean more value from studies that are expensive to conduct.

References

Charles River Associates. 2005. Impact evaluation of the California statewide pricing pilot.

URL: <http://energyarchive.ca.gov/demandresponse/documents/index.html#group3> (last visited 2009-11-17)

Clearwater Research Inc. 2006. Idaho Power Emmett Study Year 2 Final Report. Submitted to the Idaho Public Utilities Commission, Case No. IPC-E-06-05.

URL: <http://www.puc.idaho.gov/internet/cases/summary/IPCE0605.html> (last visited 2010-01-08)

Darby, S. 2006. The effectiveness of feedback on energy consumption: a review for DEFRA on the literature on metering, billing and direct displays: A review for DEFRA of the literature on metering, billing and direct displays. Environmental Change Institute, University of Oxford.

URL: <http://www.eci.ox.ac.uk/research/energy/electric-metering.php> (last visited 2009-11-19)

DRCC. United States Demand Response Coordinating Committee.

URL: <http://www.demandresponsecommittee.org/> (last access: 2009-11-18)

Egan-Annechino, E.; Lopes, J.S.; Marks, M. 2005. Lessons learned and evaluation of 2-way central a/c thermostat control system. Energy Program Evaluation Conference (New York).

URL: <http://www.mass.gov/Eoeea/docs/dpu/electric/09-31/7109fgeraga8a.pdf> (last visited 2009-11-01)

Energy Insights. 2008. Xcel Energy TOU Pilot Final Impact Report. Personal communication with Donald E. Garretson, Xcel Energy.

Ericson, T. 2009. Direct load control of residential water heaters. Energy Policy, 37(9), 3502-3512.

Faruqui, A.; Wood, L. 2008. Quantifying the benefits of dynamic pricing in the mass market. Edison Electric Institute Report, prepared by The Brattle Group.

URL:

http://www.eei.org/ourissues/electricitydistribution/Documents/quantifying_benefits_final_append.pdf

(last visited 2009-11-19)

Faruqui, A.; Segici, S. 2009. Household Response to Dynamic Pricing of Electricity – A Survey of the Experimental Evidence, prepared by The Brattle Group.

URL: http://www.hks.harvard.edu/hepg/rlib_rp_standard_mkt_dsgn.html (last visited 2009-11-17)

FERC. Federal Energy Regulatory Commission Survey on Demand Response, Time-Based Rate Programs/Tariffs and Advanced Metering Infrastructure, Glossary. General Information Section, FERC-727 and FERC-728, OMB Control Nos. 1902-0214 & 1902-0213, Expiration Date 4/30/2008.

URL: <http://www.ferc.gov/industries/electric/indus-act/demand-response/2008/survey/glossary.pdf>

(last visited 2009-11-24)

George, S.S.; Bode, J. 2008. 2008 Ex post load impact evaluation for Pacific Gas and Electric Company's SmartRate Tariff Final Report, prepared by Freeman, Sullivan & Co.

URL: <http://www.edisonfoundation.net/iee/reports/> (last visited 2009-11-17)

Greenberg, D.; Straub, M. 2008. Demand response delivers positive results. Transmission & Distribution World.

URL: http://www.tdworld.com/customer_service/demand_response_delivers_results/index.html (last visited 2009-11-17)

Hammerstrom, D.J.; Ambrosio, R.; Brous, J.; Carlon, T.A.; Chassin, D.P.; DeSteele, J.G.; Guttromson, R.T.; Horst, G.R.; Jarvegren, O.M.; Kajfasz, R.; Katipamula, S.; Kiesling, L.; Le, N.T.; Michie, P.; Oliver, T.V.; Pratt, R.G.; Thompson, S. Yao, M. 2007. Pacific Northwest GridWise Testbed Demonstration Projects, Part 1. Olympic Peninsula Project. Pacific Northwest National Laboratory Report Number PNNL-17167, prepared for US Department of Energy under Contract DE-AC05-76L01830.

URL: http://tpd.pnl.gov/publications/publications_grouplist.asp (last visited 2009-11-17)

Hartway, R.; Price, S.; Woo, C.K. 1999. Smart meter, customer choice and profitable time-of-use rate option. Energy, 24 (3), 895-903.

Heberlein, T.A.; Warriner, G.K. 1983. The influence of price and attitude on shifting residential electricity consumption from on- to off-peak periods. Journal of Economic Psychology, 4(1), 107-130.

Herter, K. 2007. Residential implementation of critical-peak pricing of electricity. Energy Policy, 35(4), 2121-2130.

Hydro One. 2008. Time-of-Use Pricing Pilot Project Results. Report Number EB-2007-0086 delivered to the Ontario Energy Board.

URL:

<http://www.oeb.gov.on.ca/OEB/Industry+Relations/OEB+Key+Initiatives/Regulated+Price+Plan/Regulated+Price+Plan+-+Ontario+Smart+Price+Pilot> (last visited 2009-11-17)

Idaho Power. 2006. Time-of-Day and Energy Watch Pilot Programs Final Report. Submitted to the Idaho Public Utilities Commission, Case No. IPC-E-05-02.

URL: <http://www.puc.idaho.gov/internet/cases/summary/IPCE0502.html> (last visited 2010-01-08)

Idaho Power. 2008. 2007 Energy Watch and Time-of-Day Programs Annual Report. Submitted to the Idaho Public Utilities Commission, Case No. IPC-E-07-05.

URL: <http://www.puc.idaho.gov/internet/cases/summary/IPCE0705.html> (last visited 2009-11-17)

Idaho Power. 2009. 2008 Energy Watch and Time-of-Day Programs Annual Report. Submitted to the Idaho Public Utilities Commission, Case No. IPC-E-07-05.

URL: <http://www.puc.idaho.gov/internet/cases/summary/IPCE0705.html> (last visited 2009-11-17)

IEADSM. IEA Demand Side Management Programme.

URL: <http://www.ieadsm.org/> (last visited 2009-11-18)

Kahneman, D.; Tversky, A. 1984. Choices, values, and frames. *American Psychologist*, 39 (4), 341-350.

KEMA. 2005. 2004 Smart Thermostat Program Impact Evaluation. Report for San Diego Gas and Electric Company.

URL: <http://www.title24dr.com/index-4.html> (last visited 2009-11-17)

KEMA. 2006. 2005 Smart Thermostat Program Impact Evaluation. Report for San Diego Gas and Electric Company.

URL: <http://sites.energetics.com/madri/toolbox/pricing.html> (last visited 2009-11-17)

Kempton, W.; Reynolds, C.; Fels, M.; Hull, D. 1992. Utility control of residential cooling: resident-perceived effects and potential program improvements. *Energy and Buildings*, 18, 201-219.

Kirby, B.J. 2003. Spinning reserve from responsive loads. Oak Ridge National Laboratory Report Number ORNL/TM-2003/19.

URL: <http://certs.lbl.gov/certs-load-pubs.html> (last visited 2009-11-17)

Levy, R.; Abbott, R.; Hadden, S. 2002. New Principles for Demand Response Planning. Electric Power Research Institute (EPRI) Technical Report, Report Number 1006015.

Navigant. 2008. Evaluation of Time-of-Use Pricing Pilot. Presented to Newmarket Hydro, and delivered to the Ontario Energy Board.

URL:

<http://www.oeb.gov.on.ca/OEB/Industry+Relations/OEB+Key+Initiatives/Regulated+Price+Plan/Regulated+Price+Plan+-+Ontario+Smart+Price+Pilot> (last visited 2009-11-17)

Nevius, M.J.; Pigg, S. 2000. Programmable Thermostats that Go Berserk? Taking a Social Perspective on Space Heating in Wisconsin. Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, CA), 8.233-8.244.

URL: http://www.ecw.org/resource_detail.php?resultid=239 (last visited 2010-01-08)

Newsham, G.R.; Mancini, S.; Veitch, J.A.; Marchand, R.G.; Lei, W.; Charles, K.E.; Arsenault, C.D. 2009. Control strategies for lighting and ventilation in offices: effects on energy and occupants. *Intelligent Buildings International*, 1 (2), 101-121.

URL: <http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc49249/nrcc49249.pdf> (last visited 2009-11-19)

Piette, M.A.; Watson, D.S.; Motegi, N.; Bourassa, N. 2005. Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities. Lawrence Berkeley National Laboratory/Demand Response Research Center, Report Number LBNL-58178, under Contract 500-03-026.

URL: <http://drcc.lbl.gov/pubs/58178.pdf> (last visited 2009-11-18)

Parker, D.S. 2009. Very low energy homes in the United States: Perspectives on performance from measured data. *Energy and Buildings*, 41(5), 512-520.

Porter, A. 2009. Britain facing blackouts for first time since 1970s. *Daily Telegraph*, August 31st.

URL: <http://www.telegraph.co.uk/finance/newsbysector/energy/6118113/Britain-facing-blackouts-for-first-time-since-1970s.html> (last visited 2009-11-18)

Puckett, C.D.; Hennessy, T. 2004. AmerenUE Residential TOU Pilot Study - First Look Results. Prepared by RLW Analytics.

URL: http://www.oeb.gov.on.ca/documents/cases/RP-2004-0203/2005-07-submissions/cdm_trccomments_toronto_supplementary2.pdf (last visited 2009-11-16)

Puckett, C.D.; Hennessy, T. 2006. AmerenUE Residential TOU Pilot Study - Load Research Analysis - 2005 Program Results. Prepared by RLW Analytics.

URL: <http://sites.energetics.com/madri/toolbox/pricing.html> (last visited 2009-11-16)

RLW Analytics. 2006. 2006 Analysis at the Residential Time-at-Day and Energy Watch Pilot Programs Final Report. Submitted to the Idaho Public Utilities Commission, Case No. IPC-E-06-05.

URL: <http://www.puc.idaho.gov/internet/cases/summary/IPCE0605.html> (last visited 2009-11-17)

Rocky Mountain Institute. 2006. Automated Demand Response System Pilot, Final Report.

URL: <http://sites.energetics.com/madri/toolbox/pricing.html> (last visited 2009-11-16)

Rosenzweig, M.B.; Fraser, H.; Falk, J.; Voll, S.P. 2003. Market power and demand responsiveness: letting customers protect themselves. *The Electricity Journal*, 16(4), 11-23.

Rowlands, I.H. 2008. Demand Response in Ontario: Exploring the Issues. Prepared for the Independent Electricity System Operator (IESO).

URL: http://www.ieso.ca/imoweb/pubs/marketreports/omo/2009/demand_response.pdf (last visited 2009-11-18)

Sulyma, I.; Tiedemann, K.; Pedersen, M.; Rebman, M.; Yu, M. 2008. Experimental evidence: a residential time of use pilot. Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, CA), 2.292-2.304.

OEB. Ontario Energy Board.

URL:

[http://www.oeb.gov.on.ca/OEB/Industry+Relations/OEB+Key+Initiatives/Smart+Metering+Initiative+\(S+MI\)](http://www.oeb.gov.on.ca/OEB/Industry+Relations/OEB+Key+Initiatives/Smart+Metering+Initiative+(S+MI)) (last visited 2009-11-18)

Strapp, J.; King, C.; Talbott, S. 2007. Ontario Energy Board Smart Price Pilot Final Report. Prepared by IBM Global Business Services and eMeter Strategic Consulting for the Ontario Energy Board.

URL:

<http://www.oeb.gov.on.ca/OEB/Industry+Relations/OEB+Key+Initiatives/Regulated+Price+Plan/Regulated+Price+Plan+--Ontario+Smart+Price+Pilot> (last visited 2009-11-17)

Summit Blue. 2004. Load Reduction Analysis of the 2004 Air Conditioning Cycling Pilot Program, Final Report. Prepared for Idaho Power.

Summit Blue. 2006. Evaluation of the 2005 Energy-Smart Pricing Plan Final Report. Prepared for Community Energy Cooperative.

URL:

[http://ies.lbl.gov/drupal.files/ies.lbl.gov.sandbox/Evaluation%20of%202005%20Energy_Smart%20Plan.p](http://ies.lbl.gov/drupal.files/ies.lbl.gov.sandbox/Evaluation%20of%202005%20Energy_Smart%20Plan.pdf)
[df](#) (last visited 2009-11-17)

Summit Blue. 2007. Evaluation of the 2006 Energy-Smart Pricing Plan Final Report. Prepared for CNT Energy.

URL: <http://www.smartgridnews.com/artman/uploads/1/2006-espp-evaluation.pdf> (last visited 2009-11-17)

US Congress, 2005. Energy Policy Act of 2005. One Hundred Ninth Congress of the United States of America, at the First Session.

URL: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_bills&docid=f:h6enr.txt.pdf (last visited 2009-11-18)

USDoE, 2009. President Obama Announces \$3.4 Billion Investment to Spur Transition to Smart Energy Grid. US Department of Energy Press Release.

URL: <http://www.energy.gov/news2009/print2009/8216.htm> (last visited 2009-11-19)

Violette, D.; Erickson, J.; Klos, M. 2007. Final Report for the MyPower Pricing Segments Evaluation. Submitted to Public Service Electric and Gas Company by Summit Blue Consulting.

URL: <http://sites.energetics.com/madri/toolbox/pricing.html> (last visited 2009-11-17)

Wolak, F.A. 2006. Residential Customer Response to Real-Time Pricing: The Anaheim Critical-Peak Pricing Experiment.

URL: <http://www.stanford.edu/~wolak/> (last visited 2009-11-16)