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Energy Procedia 12 (2011) 1074 – 1082

Energy Procedia

ICSGCE 2011: 27–30 September 2011, Chengdu, China

Control Strategy for Domestic Water Heaters during Peak Periods and its Impact on the Demand for Electricity

Alain Moreau*

Hydro-Quebec's Research Institute. Shawinigan, Québec, CANADA

Abstract

Because they store hot water, water heaters are easily-shifted loads that can be controlled to reduce peak demands. However, load shifting may have some detrimental consequences on the domestic hot water supply temperature if the heating element is deactivated for a long period of time. Furthermore, a new peak may be caused if a significant number of heaters are reactivated at the same time. This study presents a control strategy for water heaters that minimizes the pick-up demand when the heating elements are reactivated at the end of a load shifting period and that ensures, in all cases, the client's hot water supply. The study is based on a simulation model of a water heater that was experimentally validated and takes into account the diversity of the population's hot water withdrawal profile. More specifically, the data of 8,167 real water withdrawal profiles of several clients were input into the simulation model in order to evaluate the performance of water heaters under different operating conditions.

Selection and/or peer-review under responsibility of University of Electronic Science and Technology of China (UESTC).

Keywords: Control; load shifting;peak reduction; pick-up demand; strategy;water heater.

1. Introduction

In Québec (Canada), about 91% of the province's domestic water heaters are electric and they account for approximately 1,700 MW of the grid's peak demand. A very large majority of these water heaters are equipped with 180- or 270-litre tanks. Because water heaters have the capacity to store energy, it is only natural that they be studied to reduce the demand by shifting part of the utility's power demand from peak hours to off-peak hours.

Past literature includes a large number of studies on the management of domestic water heaters. These studies are generally divided into 2 major categories: 1/ those that focus on the configuration of water heaters and 2/ those that focus on the control of water heaters. Lacroix et al [1], for example, studied a

* Corresponding author. Tel.: +819-539-1400 (1421)
E-mail address: moreau.alain@lte.ireq.ca.

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doi:10.1016/j.egypro.2011.10.140

variety of water heater concepts where the load can be shifted for 16 consecutive hours without favouring bacterial contamination. Long and Zhu [2], on the other hand, proposed an air source heat pump water heater with phase change material (PCM) for thermal storage to take advantage of off-peak electrical energy. As far as Nehrir et al [3] are concerned, their study describes a control strategy for water heaters based on fuzzy logic, whereas Atwa and Salama [4] describe an artificial neural network to shift the demand of water heaters from peak to off-peak periods.

In this article, we present a control algorithm that can be directly integrated in water heaters and that can be very useful in the context of a direct or programmed control of water heaters (e.g. a timer) to minimize the pick-up demand when the heating elements are reactivated at the end of a load shifting period and to ensure, in all cases, the hot water supply for the customers.

Our study was based on a water heater simulation model that was experimentally validated and took into account the diversity of the Québec population's hot water withdrawal profile. More specifically, the data of 8,167 real water withdrawal profiles of several clients were input into the simulation model in order to evaluate the performance of water heaters under different operating conditions. The aggregated results of all the simulations provide the diversified power demand of water heaters throughout the population.

2. Evaluation Method

2.1. Description of the software used for the simulation of the water heater

There are several models that allow the simulation of water heaters. In particular, TRNSYS provides 5 models that allow to simulate water heaters (3 models in the standard library and 2 in the TESS library). A comparative exercise of the models allowed us to conclude that all the models are able to accurately predict the outlet water temperature and the electricity demand of water heaters [5]. In this study, the TRNSYS Type 60c model was retained because the input parameters are particularly suitable for the definition of electric water heaters like the ones found in Québec and, generally, in North America. This is a one dimensional nodal model that takes into account the vertical stratification of the temperatures in a water heater.

Figure 1 illustrates the results of the validation of the model in relation to experimental data obtained with a 270-litre water heater where the elements were deactivated between 6 AM and 10 AM and 4 PM and 8 PM (the darker surfaces on the graph). The Figure compares the daily demand profiles of the water heater and the outlet hot water temperature when it is subjected to a daily water withdrawal profile of 225 L/d, as referenced in [5].

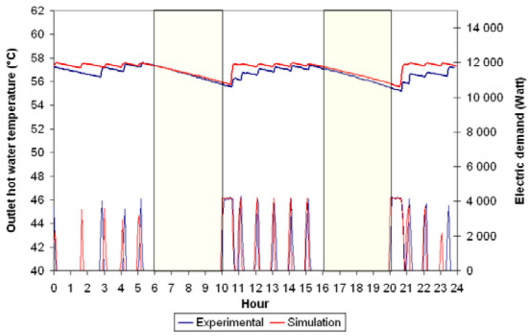

Fig. 1. Comparison between the experimental and theoretical values of the outlet water and the electric demand of a 270-litre water heater.

The Figure also demonstrates that the model accurately predicts the electricity demand and the hot water temperature leaving the tank during a daily water withdrawal cycle. It should be noted that the duration of the pick-up demand after the load shifting period is accurately evaluated by the model and that the temperature variation of the outlet water over the load shifting period is also exact.

2.2. Hot water withdrawal profiles

The diversified electrical demand of domestic water heaters represents the average load recorded by the grid for a group of water heaters, considering the diversity of the water withdrawal profiles. In the context of this study, the demand diversity was obtained by providing the water heater simulation model with a multitude of daily hot water withdrawal profiles. More specifically, a group of 8,167 real hot water withdrawal profiles was used to create the diverse hot water requirements. These profiles were based on data that were metered every 5 minutes in 51 client premises for, on average, 160 consecutive days. Reference [6] provides a comprehensive analysis of the water withdrawal profiles of the sampling. Drawn from this reference, Table 1 shows the make-up of the sampling based on the number of occupants per household.

Table 1. Make-up of the sampling based on the number of occupants per household

Occupants per Household	Number of Households
1-2	16
3	8
4	18
5	6
Not available	3
Total	51

Figure 2 illustrates the average daily profile of the 8,167 hot water withdrawal profiles. It is important to note that this daily profile includes the days of the week, week-end and statutory holidays. The daily water consumption associated with this average profile is 189 litres. For the sake of comparison, ASHRAE [7] and RETScreen [8] both suggest a daily hot water consumption of 240 litres per day for a family of 4 whereas Knight et al [9] suggest a consumption of between 200 and 250 L/d for an average Canadian household. This profile is typical of the daily hot water consumption profiles that are found in literature [6]. It is characterized by high hot water consumption in the morning and evening and a very low hot water consumption during the night.

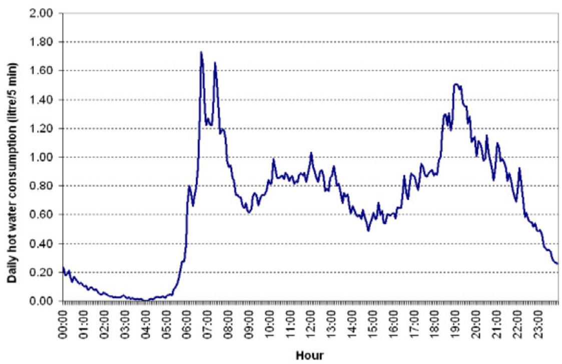

Fig. 2. Average daily water consumption profile

The profile in Figure 2 is provided as a reference. It does not represent the actual daily profile of a client in particular. There is indeed a wide diversity of water withdrawal profiles in the population, either in terms of specific customers or in the different daily hot water consumption statistics of a same customer. For example, the daily hot water consumption in the database is spread over several values of between 0 litre/day and 720 litres/day (Figure 3). However, most of the daily consumption statistics fall between 80 and 180 litres/day and 95% of these are lower than 440 L/day.

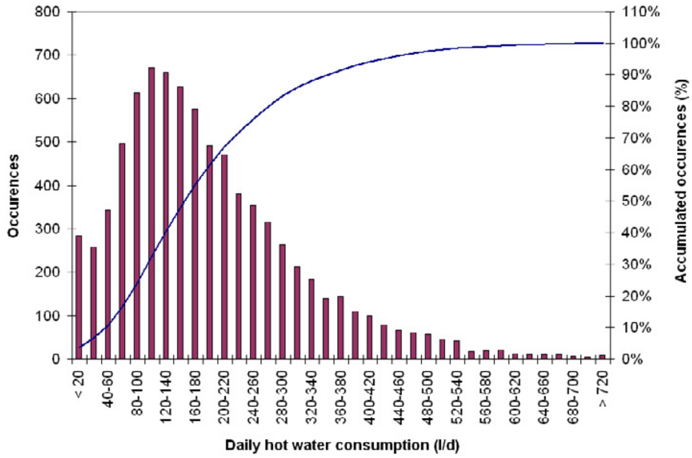

Fig. 3. Distribution of the number of daily hot water consumption occurrences

3. Diversified Electrical Demand of Water Heaters

An automated procedure was developed to simulate the daily demand profile of a water heater corresponding to each of the 8,167 daily water withdrawal profiles. The aggregated electricity profiles provide the diversified daily demand curves of a group of water heaters.

Figure 4 illustrates the diversified simulated demand profiles of two of the most popular models of domestic water heaters in Québec: 270-litre and 180-litre heaters; these two models respectively represent 47% and 45% of the individual domestic electric water heater market in Québec. The grid's daily profile on a peak day is also provided on the Figure in order to compare the profiles. For comparison purposes, the Figure also shows the demand profile measured by Laperrière on several 270-litre water heaters [10]. It should be noted that the water heaters measured by Laperrière were operated alternately on a daily basis according to two different operating modes, which affected the normal demand profile of the water heaters under conventional running conditions when shifting from one mode to the other around 10 PM. Nevertheless, Figure 4 also demonstrates the great similarity, in terms of shape and values, between the simulated profiles and the metered profile. The Figure also clearly demonstrates that the maximum diversified electric demand of the water heaters is coincidental with the grid's peak, which confirms the relevance of controlling water heaters during peak demand periods.

Although they are very similar, there are slight differences between the diversified curves of 270-litre and 180-litre heaters. On average and on a daily basis, the diversified demand of a 270-litre water heater is approximately 43 watts higher. This difference is essentially attributed to two reasons: 1/ the heat losses are higher in the case of a 270-litre water heater and 2/ since it is larger and more powerful, a 270-litre water heater is better adapted to meet the hot water needs of customers than a 180-litre heater in situations where the hot water consumption is significant, which, in turn, results in an electricity demand that is more significant.

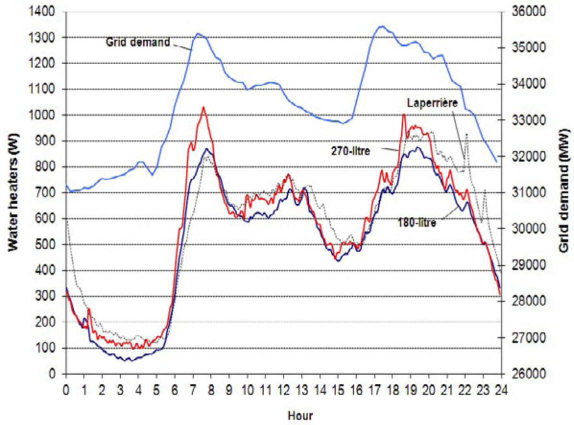

Fig. 4. Diversified demand profile of domestic water heaters

4. Diversified Electrical Demand of Water Heaters with Load Shifting Periods

With the calculation method described previously, the diversified electricity demand of water heaters was estimated when the elements were deactivated during the grid's peak demand periods. In this study, the peak periods were defined as four consecutive hours between 6 AM and 10 AM in the morning and as five consecutive hours between 4 PM and 9 PM in the evening. Over these periods, the electric elements of the water heaters were deactivated, on the condition however, that the hot water delivered to the client be higher than a threshold value of 50°C. Hence, even during peak periods, the elements could reactivate if the hot water temperature fell below 50°C. This last value was selected for two reasons: 1/ a water temperature of 45°C is considered to be an inferior limit to meet the hot water needs of customers; setting a threshold value of 50°C therefore added a security factor; 2/ legionella bacteria begin to die at temperatures above 50°C [11].

Figures 5 and 6 illustrate the diversified demand profiles of 180-litre and 270-litre water heater models. In this study, the nominal demand of the electric elements of the two models was set at 4.2 kW (270-litre model) and 2.8 kW (180-litre model), which is equivalent to a supply voltage of 232 volts (as opposed to 240 volts).

Three demand pick-up scenarios at the end of the peak periods were simulated. They are shown on Figures 5 and 6.

- Scenario 0: the demand pick-up at the end of the load shifting period is not controlled.
- Scenario 1: the pick-up is controlled according to a prioritized random function spread over a range of one hour after the peak period.
- Scenario 2: the pick-up is controlled according to a prioritized random function spread over a range of two hours after the peak period.

The prioritized random function (Scenarios 1 and 2) consists in randomly reactivating the water heaters at the end of the load shifting period but giving priority to those that are the coolest. The timeframe for the reactivation of the water heaters at the end of the load shifting is based on a random function and on the water temperature at the end of the load shifting period.

A prioritized random function is a compromise between a purely random water heater pick-up and a prioritized pick-up based only on the hot water temperature prevailing in the tanks at the end of the load shifting. The advantage of a purely random pick-up is that the reactivation process of the water heaters can be effectively phased, but its disadvantage is that it does not take into account the water temperature constraint to prioritize the reactivation of the elements: as an instance,, a water heater with a water temperature of 50°C at the end of a load shifting period could be reactivated later than a water heater where the temperature is 60°C. On the other hand, a pick-up strategy based only on the heater's hot water temperature has a lesser effect on phasing the demand pick-up than a random function strategy since the simulation data on all the water withdrawal profiles demonstrate that the water temperatures at the end of the load shifting period are focused on a relatively constrained range of values. Among the several demand pick-up strategies that were simulated, the prioritized random function proved to provide very good results.

Figures 5 and 6 demonstrate the following:

- The electricity demand of a 270-litre water heater can be almost totally erased during the peak periods in the morning and evening in spite of a temperature threshold constraint of 50°C. On the other hand, because of their smaller tanks, this fact is less significant in the case of 180-litre water heaters because their electric elements must activate more frequently to maintain a water temperature that is higher than 50°C. However, in spite of this, the curbed demand remains significant.
- If the demand pick-up is not controlled (as in Scenario 0), after a load shifting period, the demand is significant and is approximately equal to the nominal power of the water heaters. In this case, a new peak demand could be created if a large number of heaters are controlled within the same peak period timeframe.
- Based on a prioritized random function, the demand pick-up is significantly reduced after a load shifting period. For example, phasing the reactivation within two hours (as in Scenario 2) cuts by half the pick-up demand with no phasing.

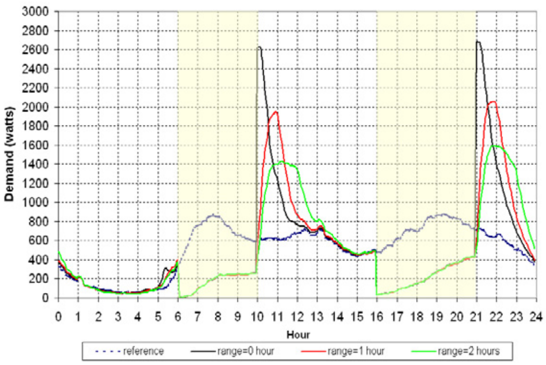

Fig. 5. Diversified profile of the electricity demand of water heaters where there was load shifting (180-litre tank).

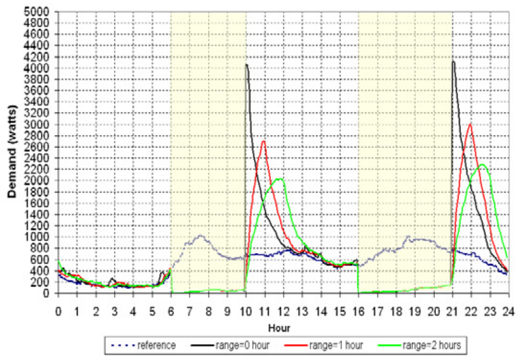

Fig. 6. Diversified profile of the electricity demand of water heaters where there was load shifting (270-litre tank).

The impact of load shifting water heaters on their capacity to deliver hot water to clients is shown on the histograms on Figures 7 and 8. As demonstrated, the load shifting of water heaters has very little impact on their capacity to deliver hot water. Indeed, in the case of both the 270-litre and 180-litre water heaters, the results show that the hot water supplied to the clients is, 90% of the time, at a temperature higher than 55°C in all the simulations and, close to 100% of the time, it is higher than 50°C. This favourable result can be explained by the temperature threshold constraint of 50°C. In addition, the impact of phasing the pick-up is minor on the hot water temperature supply. Hence, in the case of the 270-litre water heater, the percentage of a supply temperature higher than 55°C changes from 97.3% to 96.5% depending on whether the phasing of the reactivation is spread over a period of 0 hour and 2 hours. This represents a reduction of only 0.8%. The 180-litre water heater showed the same results. A prioritized reactivation of a water heater based on its water temperature at the end of the load shifting period explains the fact that spreading out its pick-up has no impact on its capacity to deliver hot water.

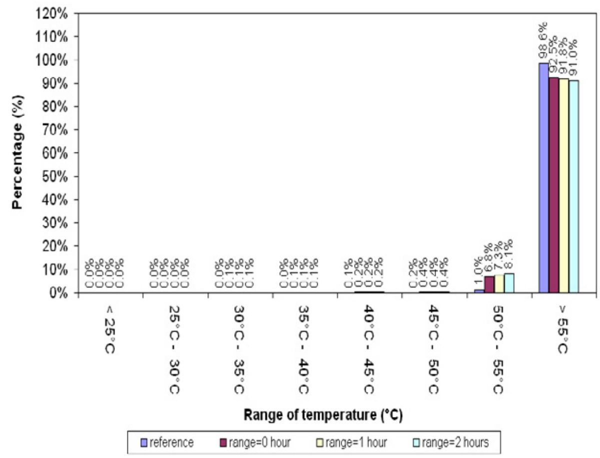

Fig. 7. Percentage of occurrences in supply temperatures for 180-litre domestic water heaters to deliver hot water when they are operated in a demand-side management context (results for all hot water withdrawal profiles).

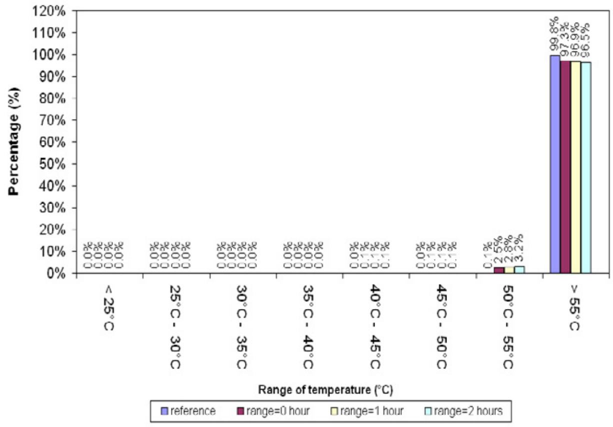

Fig. 8. Percentage of occurrences in supply temperatures for 270-litre domestic water heaters to deliver hot water when they are operated in a demand-side management context (results for all hot water withdrawal profiles).

5. Impact on the Grid's Peak Demand

The impact of managing water heaters on the grid's peak demand depends on the number of water heaters that are controlled during the peak period. The grid's peak demand will diminish in conjunction with an increase in the number of controlled water heaters. However, beyond a critical number of controlled water heaters implemented, which we call optimal number, the reactivation of the heaters at the same time at the end of the peak period could create a new peak. The optimal number therefore corresponds to the quantity of heaters that are controlled, which in turn corresponds to a maximum reduction of the grid's peak demand.

Insofar as the three scenarios simulated in this study are concerned, Figure 9 allows to quantify this optimal number for the province of Québec. The Figure provides an outline of the relationship between the grid's peak demand and the number of controlled water heaters. For the purpose of this study, the data of a peak week on Québec's grid were used to develop the Figure and it is presumed that both water heater models (180-litre and 270-litre) were controlled. The importance of spreading out the reactivation of water heaters after a load shifting period is clearly demonstrated in the Figure. Phasing the reactivation of the electric elements has the effect of significantly accentuating the potential reduction of the grid's peak by delaying the occurrence of a new peak due to the reactivation of water heaters at the same time. Hence, phasing the reactivation of a water heater within two hours (Scenario 2) after the end of the peak period can result in tripling the potential peak demand reduction as compared to an uncontrolled reactivation (Scenario 0). Indeed, the peak reduction potential is approximately 595 MW with a reactivation phased within a period of two hours, whereas it is 225 MW in the case of an uncontrolled reactivation.

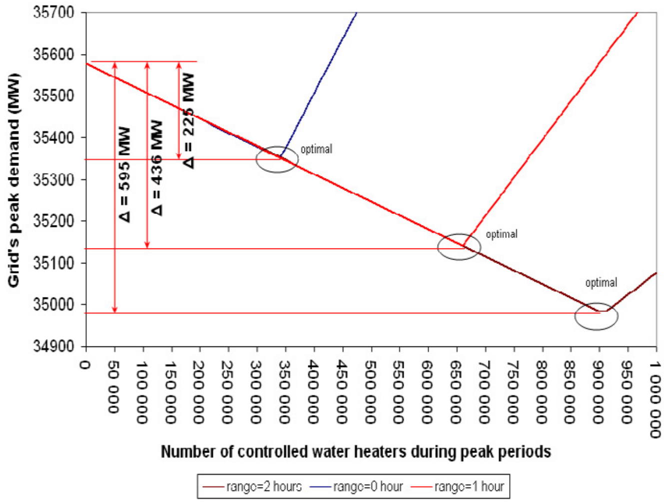

Fig. 9. Impact of the number of controlled water heaters on the grid's peak demand for three demand pick-up strategies.

6. Conclusion

Because water heaters are able to store energy and can be easily controlled, they are often used by utilities to reduce their demand by shifting part of the utility's power demand from peak hours to off-peak hours. The demand pick-up of water heaters after load shifting periods can be detrimental to the efficiency of this management measure if it is not adequately controlled. In areas where the penetration rate of water heaters is high, like in Québec, this is all the more true since there is the possibility that new peaks could be created on the grid after load shifting periods when the elements reactivate. In this study, we have proposed a control algorithm that can be directly integrated in water heaters and that can be very useful in the context of a direct or programmed control of a water heater (e.g. a timer) that minimizes the pick-up demand when the heating elements are reactivated at the end of a load shifting period and that ensures, in all cases, the hot water supplied to customers. As demonstrated in this study, this algorithm, known as prioritized random function, allows to reduce the maximum diversified demand of water heaters by half when the elements are reactivated as compared to an uncontrolled reactivation When applied to an electricity grid, it allows to almost triple the reduction of the grid's peak demand by delaying the occurrence of a new peak when water heaters reactivate. Moreover, with a prioritization measure, phasing the reactivation within a 2-hour period does not affect the availability of hot water for the clients.

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