VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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AN EFFICIENT WATER FLOW CONTROL APPROACH FOR WATER HEATERS IN DIRECT LOAD CONTROL

Alexander Belov[1], Nirvana Meratnia[1], Berend Jan van der Zwaag[2] and Paul Havinga[1]
[1]Pervasive Systems Research Group, University of Twente, Enschede, the Netherlands
[2]Adaptive Systems, Hengelo (O), the Netherlands
E-Mail: a.belov@utwente.nl

ABSTRACT

Tank water heaters (WHs) are present in a prevailing number of European households. Serving as energy buffers WHs have come under the spotlight of various direct load control (DLC) programs over the last few decades. Although DLC has proven to be an efficient measure towards daily peak demand shaving, the payback effect might lead to a new peak in the grid. This payback phenomenon takes place every time a group of WHs under DLC is permitted to catch up. If not handled properly. This paper presents a novel real-time water flow control approach for domestic water heating systems aiming at decreasing the payback effect of DLC actions. We identify possible control strategies based on an analysis of the water system's thermal dynamics. We formulate the problem of optimal water flow control in terms of minimum WH payback demand and maximum user comfort satisfaction. User comfort is formalized by an integral energy characteristic. Simulations show that water flow control can significantly mitigate the DLC payback effect by reaching the fair compromise between energy savings and discomfort of an end-user.

Keywords: demand side management, direct load control, tank water heaters, water flow control.

INTRODUCTION

As reported by the Eurostat statistical office of the European Union, energy consumption of the residential sector in total has increased from 25.32% to 26.19% in EU-27 between the years 1990 and 2012 [1]. According to the European Environmental Agency indicators, the residential electricity consumption has increased by 39% in 27 European countries between 1990 and 2010, and continued growing by 1.19% to the year 2012 [2]. In response to the growing energy demand and in order to achieve electric energy reductions in residential sector, the European Commission initiated the Demand Side Management (DSM) Programme. Being an integral part of the DSM concept, Direct Load Control (DLC) is one the most widely applied measures.

DLC is defined as a program in which the system operator remotely shuts down or cycles customers' electrical equipment on a short notice [3, 4]. By participating in a DLC program, a customer receives guaranteed incentive payments or rate discounts regardless of his performance. Such programs can also penalize consumers for not following terms and conditions specified in their contracts. DLC programs are applied to appliances that can be turned off or cycled for relatively short periods of time. The most common applications of DLC programs involve domestic air-conditioners, water heaters and swimming pool pumps [5].

Tank Water heaters (WHs) are present in a prevailing number of European households. Since the average daily load profile of domestic WHs and the average total daily residential demand have the similar patterns, WHs make a significant contribution to the daily load peaks in the grid [6]. Serving as energy buffers, WHs are traditionally considered as perfect candidates for Demand Side Management programs. Therefore, WHs have been a target of DLC programs for many years [7-12].

Even though DLC has been successfully applied over the past few decades, the so-called ``payback'' (or ``cold load pickup'') side effect might create a secondary peak of demand in the grid. It basically happens because of the reconnection of WHs. When WHs that previously have been disconnected from the power supply come back to the normal operation condition, they require electric energy bounce. More precisely, those WHs whose heating elements have been switched on before the start of the DLC will demand the energy taken during the regulation back. In addition, water use and natural heat losses to the ambient during the control period can also bring extra load to the system. Over the years, numerous papers have been written considering this phenomenon [13, 16, 20-24].

This paper presents an approach for residential hot water management based on control of water flows in a domestic hot water system. The paper focuses on application of the proposed approach to the payback problem when a group of WHs participates in DLC. The approach realizes the real-time control of water flows considering the thermal dynamics of a domestic water heating system and comfort of the end-user. The control relies on the thermo-dynamic model of a domestic hot water system, hence allowing considering the individual technical characteristics and operating conditions of an individual WH. In addition, the user comfort model is used to reflect user comfort preferences associated with various household hot water activities. The different levels of discomfort tolerance for various household hot water activities can be exploited to achieve energy savings. A key contribution of the paper is thus in the development of the water flow control approach that accounts both for a user satisfaction with the quality of a hot water service provided and thermal dynamics of the system.

It is worth mentioning that the suggested control strategy can be implemented by the water flow controller mounted at the point of mixing of cold and hot water flows right before the user's tap without any effect on WH's internal circuits.

The rest of the paper is organized as follows. In the remainder of this section we discuss some related work to outline the essential factors for modeling and mitigation of the payback phenomenon. In Section 2 we formulate the payback energy problem and discuss existing approaches for the payback energy problem. In Section 3 we give an in insight into the new proposed approach providing a discussion of its benefits from a perspective of a utility company and an individual customer. We reformulate the problem according to the introduced approach in Section 4. We further consider different types of hot water events taking place during the DLC program in Section 5. In Section 6 and Section 7 we deal with modeling of the thermal dynamics of a hot water system. We introduce a user comfort model and flow control possibilities in the rest of the section. Two optimal control algorithms are presented in Section 10, and the results of our simulations are demonstrated in Section 11.

Related Work

The payback or the shape of the controlled WHs load is modeled in [13]. The net restore demand is statistically retrieved from empirical data obtained from field tests. The payback is represented as a function of energy which would be consumed during the control period under the normal operating condition. In [14] the concept of the cumulative deferred energy demand of the controlled device is applied to represent the payback effect. The amount of disconnected load of each control group of appliances is accumulated at every time step using the energy payback rate coefficients. The total deferred load is then returned back to the system at the end of DLC interval. It is worthy to mention that in case of controlled water heaters the values of the payback rate coefficients account for thermal losses or thermodynamic effects and are obtained empirically [15]. Another example of a payback model is used for the problem of system peak load reduction in [16]. Typical payback data comprising payback duration and payback energy demand for the group of WHs under DLC are exploited to represent the payback patterns. The payback patterns are then incorporated into the optimization problem constraints as the payback coefficients to indicate when and how much payback is generated each period. The detailed thermal dynamic model of the WH is applied to the regulation service control algorithm proposed by [17]. The control algorithm comprises the information about the number of loads, their states and system dynamics constraints allowing to limit the recovered load up.

Some other approaches to overcome the negative payback effect can be found in DLC applications to air conditioners (ACs). An approach to account for the payback demand applied to ACs is presented in [18]. The authors propose to break the total customer area under DLC into groups of loads on the basis of comfort deviation tolerance and preferred thermostatic settings criteria. The payback of each group is then dependent on the difference between energy levels of two criteria, i.e. (i) period of time when the loads are turned off under DLC and (ii) some empirical coefficients that reflect dynamics of cold load restoration. The payback model is then considered in the dynamic programming algorithm for the unit commitment problem. The Adaptive Control Strategy (ACS) proposed in [19] provides a real-time adjustment of scheduled ACs by using the reference load forecast model in order to eliminate the payback phenomenon. The proposed methodology adopts the payback model of [20]. The payback is computed on the basis of load reduction and energy payback ratios for the three preceding time steps. In fact, the payback ratios are determined by user behavior, weather conditions, etc., which makes them hard to define. Then the ACS tunes the amount of interrupted loads in real-time according to the error caused by the difference between the calculated payback and the real measured payback from the previous step. The optimal control algorithm is directly applied to the aggregated engineering model of a household to account for the system's thermal dynamics [21]. The physical model's aggregator constrains the final demand to limit the payback load.

As it can be seen from the above examples, one set of solutions models the payback based on the typical load recovery patterns [13, 14, 16, 18, 19]. It gives an opportunity to implicitly embody fuzzy and hardly definable factors in the models. However, another set of solutions explicitly designates such factors, for example, by modeling the thermal dynamics of individual TCAs [17, 21].

DISCUSSIONS

Analysis of the literature shows the essential factors that should be taken into consideration in order to adequately model and diminish the payback of a group of WHs. These factors include: (a) physical characteristics of WHs (i.e. design of the heater, number of heating elements and their capacity), (b) user related characteristics (i.e., preferred temperature ranges of outlet hot water, duration of water use events, frequency of water usage [22] and hot water flow rates), (c) environmental characteristics (i.e., inlet cold water temperature and ambient temperature of the water tank). It can be plainly seen that the payback modeling and reduction problem is a non-trivial task. Moreover, the detailed information about the aforementioned characteristics can hardly be collected by the utility company, hence DLC can potentially lead to a new peak demand in the energy system.

The proposed approach to curtail the payback demand differs from the similar work previously done in four major aspects. Firstly, the payback problem is formulated taking into account different types of hot water events that occur during the DLC period. Secondly, the user comfort model is employed to respect for the end-user satisfaction with the quality of hot water service provided.

VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Thirdly, we utilized the thermo-dynamic model to consider distinct technical characteristics of individual WHs. Finally, we introduce the water flow control approach to control electric energy consumption of a single WH. In contrast to the conventional control of heating elements or thermostat settings, the proposed water flow control is capable to capture the dynamics of the tank discharge process, thus giving control over occupants' hot water usage activities.

PROBLEM STATEMENT

When water heaters participate in DLC programs, their energy consumption is shifted to the end of the regulation period resulting in a new peak of demand (Figure-1). Since the amount of the shifted consumption of WHs depends on a variety of hardly predictable factors such as differing amount of water consumption among households and frequency of hot water use, modeling and mitigation of the cold load pickup effect becomes a non-trivial task [22]. This so-called "payback" phenomenon takes place every time the interrupted thermostatically controlled load is connected back to the grid.

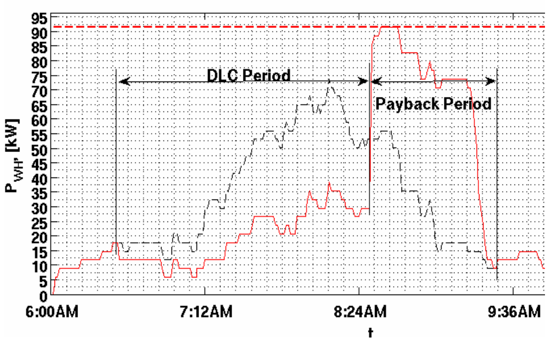

Figure-1. WHs under 2 hour DLC.

The stress of the secondary peak on the power system can consequently lead to increase of the total cost of electricity generation. Therefore, appropriate measures should be taken in order to soften the impact of the payback demand.

In case of DLC taken over a group of WHs, the total payback energy can be expressed through the energy demand of controlled WHs and unregulated loads which run during the payback period and contribute to the secondary peak using Eqn. (1).

$$W_{payback} = \sum_{i=1}^{N1} W_{ctrl_i} + \sum_{j=1}^{N2} W_{unctrl_j} \quad (1)$$

where $N1$ and $N2$ are the number of WHs in the controlled group and number of uncontrollable loads operating during the payback period, respectively; W_{ctrl_i} is the energy of controlled WHs and W_{unctrl_i} is the energy demand of uncontrolled load.

The problem of reducing the payback energy in general can be expressed as:

$$\sum_{i=1}^{N1} W_{ctrl_i} \rightarrow min \quad (2)$$

Approaches for Payback Problem Solving

There are two distinct approaches to address the payback problem in the literature. These approaches are directly related to the type of control used by the utility company.

Control of Heating Elements

One way to achieve the curtailment of demand of WHs is to turn their heating elements off for some period of time. The payback phenomenon following the regulation can be then attacked by solving the unit commitment problem [14, 16, 19]. The idea lies in determining the optimal control schedule by coordinating (cycling) the shut down and startup times of the controlled loads in order to satisfy some objective function (e.g., to minimize system operational costs, to shave the system peak demand or to reduce discomfort of customers). In connection with Eqn. (2) it presupposes that the original controlled group $N1$ can be divided into the smaller subgroups $N1 = \{N_1, N_2, \dots, N_k\}$ in such a way that the DLC is taken over the selected subgroups in every time interval.

One of the disadvantages of the above approach is that hot water storage is actually left uncontrolled every time its heating elements are switched off. Serving as a buffer for thermal energy the hot water tank has some state of charge (SoC) preceding the moment of its disconnection. That accumulated thermal energy can be then accessed after the heater has been turned off. This means that some limited amount of hot water remains available for a customer. In that regard, hot water events happening within the DLC period can lead to a heavy discharge of thermal energy inside the tank. As a result, a higher energy demand is needed to restore the WH when the regulation is finished. Additionally, a lack of electricity supply during the disconnection time makes it impossible to recharge the thermal energy in a cyclic manner. Therefore, once the hot water tank is completely discharged there is no hot water for inhabitants anymore. For example, in case of a multi-person family, intensive hot water usage during the DLC period can lead to unpleasant effect such as one of the members might not get enough hot water for personal needs.

Thermostat Control

Another way to reduce the demand of WHs is to regulate the thermostat temperature settings. The idea is to preheat the water to a higher temperature than normal by increasing the setpoint temperature prior to the peak-price period. One can then lower the setpoint letting the unit cool down (coast) without electricity consumption during the entire high price interval [23, 24]. The preheating and coasting approach can potentially give the same power reduction as that obtained through the peak shaving. Furthermore, lesser user inconvenience is expected, since there is no cut of power supply of a WH. However, this approach has some limitations as well.

The increase of the setpoint temperature delivers the spike comparable to the payback peak demand in the system. The only difference is that the peak is shifted to the time preceding the high price time interval. Whereas the payback effect takes place beyond that. Both the preheating and payback can stress the equipment of the energy system and affect its stability. Besides the impact on the grid, the raise of the setpoint temperature should be limited by a fixed threshold for safety reasons. Thus, only a certain amount of thermal energy can be added extra. It can result in a lack of hot water in a long run.

PROPOSED APPROACH OF WATER FLOW CONTROL

In contrast to the existing approaches we propose to control water flows in a hot water system. This type of control can be performed in combination with the traditional control of heating elements complementing it. In fact, the approach is realized in the mixing device mounted outside the WH. Therefore, it does not override the conventional DLC controllers.

One of the benefits of our proposed water flow control is that it allows to govern the state of charge of a hot water buffer during the whole period of disconnection. More specifically, the loss of thermal energy from the tank due to water use activities translates into a manageable and transparent process. The idea is to give a freedom to a customer to choose the preferred level of comfort by himself. Which can be beneficial both for the utility company and for the user.

Utility Perspective

The proposed control is beneficial for the utility company in that it facilitates the payback energy reduction. The introduced control strategy allows to lower the recovery time of a single WH by smartly regulating the requested hot water demand with regard for a customer's comfort. The intention is to provide the utility with an added supervision of the hot water buffer discharge process. It is assumed that the startup of the load control continues to be initiated by the utility. Unlike the conventional control of the heating elements, the utility is now able to monitor (and in emergency cases to regulate) the hot water discharge process during the power cut period of an individual WH.

Customer Perspective

Since DLC cycles can last up to five hours during the period of peak energy demand [25], the reasonable question can arise: ``How long can I expect to have hot water when the DLC program is being used?". Typically, the answer depends on two factors which are the size of the WH tank and its state of charge (SoC) before the control event. The latter factor is especially essential. Thus, no matter how big is the tank if there there has been an intensive water usage preceding the power cut of the WH, one should not expect hot water available for a long time. Of course, the utility allows program participants to opt out of a certain amount of cycling events per year. However, in case of emergency control there are no such options. It basically means for the customer that once the regulation has been initiated by the utility company, home occupants will experience inconvenience of the limited amount of hot water left.

Therefore, the problem of the rational water usage under circumstances of the restricted amount of hot water available comes to light. In some cases the occupants can desire to rearrange their hot water consumption patterns in order to prolong the access to the hot water. However, in other cases they might want to keep their comfort unchanged. Our suggested water flow control assists a customer in reaching the pursued level of comfort providing the possibility to manage the comfort settings for certain types of hot water activities. As a result, a better acceptance of load management programs by customers can be achieved.

PAYBACK PROBLEM REFORMULATION

Since WHs have an inherent storage capacity, disconnection of a WH from the power supply does not necessarily cause interruption of available hot water [26]. Taking into account hot water activities which occur during the time of regulation, we express the payback energy by Eqn. (3).

$$\sum_{i=1}^{N1} W_{ctrl.,i} = \sum_{p=1}^{N_{rec}} W_{rec.,p} + \sum_{k=1}^{N_{use}} W_{use.,k} = \sum_{p=1}^{N_{rec}} P_p \, \Delta t_{rec.,p} + \sum_{k=1}^{N_{use}} W_{DLC,k} + \sum_{k=1}^{N_{use}} W_{rem.,k} \quad (3)$$

where $N_{rec.}$ and $W_{rec.}$ are the number and consumption of the first group of switched off WHs that start to recover their storage immediately after the end of DLC; N_{use} and $W_{use.}$ are the number and demand of the second group of disconnected WHs that remain involved in hot water activities even after the DLC is finished; P_p is the capacity of the single WH from the first group; $\Delta t_{rec.,p}$ is the time required to restore the SoC of a single WH to the initial SoC; W_{DLC} is the consumption of the second group of WHs during the DLC time and $W_{rem.}$ is the remaining consumption of the second group of WHs.

Then we reformulate the objective of the original payback problem as follows:

$$min\left[\sum_{p=1}^{N_{rec}} P_p \, \Delta t_{rec.,p} + \sum_{k=1}^{N_{use}} W_{DLC,k}\right] \quad (4)$$

It can be clearly seen from Eqn. (4) that to reduce the payback demand one can either change the number of controlled water heaters $N_{rec.} + N_{use}$ (the conventional control of the heating elements), or affect the recovery time $\Delta t_{rec.}$ of the first group of WHs and energy consumption W_{DLC} of the second group of WHs.

In this paper we aim at influencing the recovery time $\Delta t_{rec.}$ and energy consumption W_{DLC} of the first and second groups of WHs, respectively. More precisely, we consider only those water use events which overlap with

VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
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the DLC period. Three possible types of hot water usage events can take place in that respect, as discussed in Section 5.1 and Section 5.2.

HOT WATER EVENTS DURING DLC

Before considering the different types of events associated with hot water consumption we make the following assumptions. Firstly, we assume that there is no interruption of a circulator pump, if one is used for hot water supply in a household. This means that the hot water can be taken out of the disconnected hot water storage. Secondly, we assume that the inlet cold water valve of a WH is not switched off by the DLC request. This implies that there is a cold water inflow to the tank whenever the hot water tap is open.

When the DLC program coincides with domestic hot water usage, several possible types of hot water events can take place. We consider only those events which overlap with the DLC time interval as shown in Figure-2.

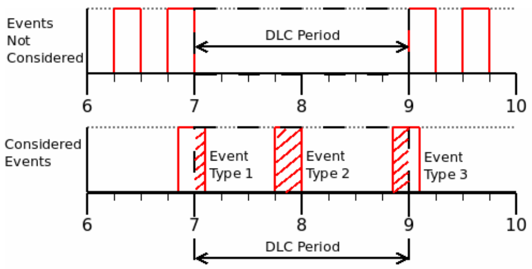

Figure-2. Considered and non-considered hot water events.

The hot water usage events of Type 1 intersect the start time of the DLC. The events of Type 2 are all events lying within the entire DLC period. Whereas the hot water events of Type 3 cross the upper boundary of the DLC period. The events of Type 1 and Type 2 are represented by the first term in the payback energy reduction in Eqn. (4). The hot water events of Type 3 are denoted by the second term in Eqn. (4). It is noteworthy that the shaded regions in the picture above designate the time when the water flow control is applied.

Hot Water Events (Type 1)

Let us consider an individual WH and the single hot water use event related to it. The hot water event consists of a cooling down time when a tap is open and warming up tail taking place after a user closes the tap. The start of the DLC program can then overlap either with the cooling or warming time spans. The hot water events of Type 1 have an intersection with the DLC startup during their cooling period as illustrated in Figure-3. As opposed to the events of Type 1, the hot water events whose warming up tails cross the DLC startup correspond to the hot water activities accomplished prior to the power cut. In that respect, there is no possibility to apply the water flow control to such events, so they are not taken into our consideration. It is notable that the event not interrupted by DLC (shown in dashed red at the top of Figure-3) experiences a slight decrease in temperature during the termination period due to the ambient losses.

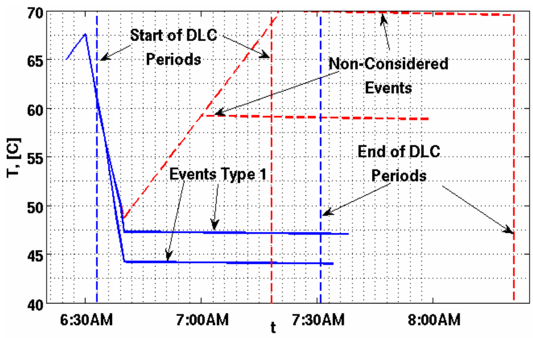

Figure-3. Single hot water event (6:30AM, 10min) under DLC (Start Time 6:30AM, 6:35AM, 7:00AM, 7:20AM, Duration 1 hour).

The recovery time needed to recharge the loss of internal energy in the tank will differ for the above-mentioned water use events as well, as illustrated in Figure-4.

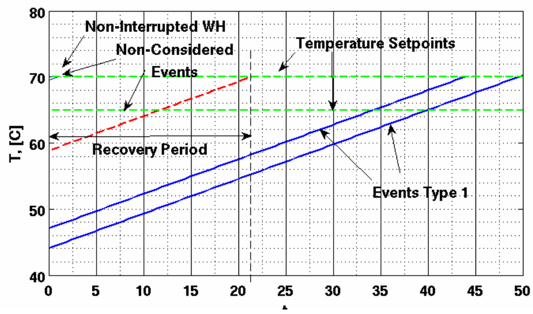

Figure-4. Recovery periods of the WHs after DLC.

As can be seen from Figure-4, the time needed for recovery of the non-interrupted event is negligible. On the other hand, the hot water events of Type 1 highly contribute to the payback demand.

Hot Water Events (Type 2 and Type 3)

The events of Type 2 address the hot water activities completed before the end of the DLC program as shown in Figure-5. In case of that type of events, recovery of the tank to the initial SoC happens right after the end of the DLC. In contrast to the events of Type 2, the SoC of the hot water buffer is restored with some delay in case of the events of Type 3. To be precise, the recovery takes place only after the water use activity has been fully accomplished. Since we aim at managing the SoC of the hot water buffer under conditions of the limited hot water

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reserve, the rest of the events initiated after the DLC are not taken into account.

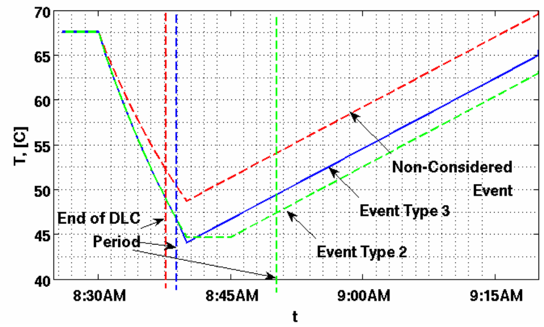

Figure-5. Single hot water event (8:30AM, 10min) under DLC (End Time 8:30AM, 8:35AM, 8:45AM).

THERMO-DYNAMIC MODEL OF THE WATER HEATER

In order to efficiently control domestic electric water heater loads, it is essential to model the heat transfer process of a WH considering energy losses. There are two sources of heat loss in a hot water tank: (a) standby losses due to the thermal convection with the environment and (b) hot water demand. Most of the time WHs consume electric energy because of the hot water usage rather than heat loss to the environment [27].

There is extensive literature available on the modeling of DEWHs [17, 28, 29]. Based on the existing literature we adopt the differential equation model of the well mixed cyclic type WH from the EnergyPlus simulator [30] as expressed in Eqn. (5).

$$MC\frac{dT}{dt} = P_{el.} + P_{cw} - P_{hw} - P_{loss} \quad (5)$$

where M and C are mass of water in the tank and specific heat capacity, respectively; P is the thermal power, whereas the subscripts of P show the movement of heat. Thus, $P_{el.}$ is the thermal power supplied by the heating element, P_{cw} and P_{hw} are the thermal power of inflow and outflow, respectively, and P_{loss} denotes the heat transferred to the ambient.

Water Heater Operation

The heating element turns on and off in a cyclic manner as the temperature of water in the tank T reaches the lower and upper setpoints. According to Eqn. (5) any hot water usage event P_{hw} with some mass flow rate of $\dot{m}$ [kg/sec] makes the internal energy of the hot water buffer drop $(MC\frac{dT}{dt} < 0)$. In case the hot water outflow $\dot{m}$ is greater than $\dot{m}_0 = (P_{el.} - P_{loss})/(CT_{sp} - CT_{cw})$ (T_{sp} - lower setpoint temperature of the WH), the temperature inside the tank decreases during the hot water usage. Consequently it forces the heating element to be turned on over time. Large water usage results in a high electricity consumption of heating elements, thus making a greater contribution to the payback demand.

MODELING THE POWER FLOWS

Analysis of hot water usage activities in residential buildings shows that the most frequent daily hot water activities involve sink, shower and bath usage [31, 32]. Furthermore, the average daily hot water demand of such hot water events significantly contributes to the average total hot water demand in a household. The thermal power flows of the typical hot water system setup are represented in Figure-6.

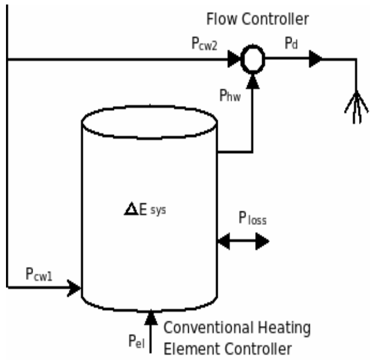

Figure-6. Power flows for a tap water system.

Energy and mass balance for the hot and cold water mixer can be written as

$$\begin{cases} P_d = P_{hw} + P_{cw2} \\ \dot{m}_d = \dot{m} + \dot{m}_{cw2} \end{cases}, \quad (6)$$

where P_d is the requested thermal power; $\dot{m}_d$, $\dot{m}$, $\dot{m}_{cw2}$ describe demanded, hot and cold water mass flow rates. Substituting Eqn. (6) into Eqn. (5) the internal energy of the tank can be expressed through the power demanded by the user as:

$$MC\frac{dT}{dt} = P_{el.} + P_{cw1} - P_{hw} - P_{loss} = P_{el.} + P_{cw} - P_d - P_{loss}. \quad (7)$$

The time of internal energy recovery at the end of the DLC period depends on the temperature of hot water inside the tank at the end of the DLC period and can be expressed as:

$$t_{rec.} = \frac{1}{b}\ln\left(\frac{\frac{a}{b}+T_{sp}}{\frac{a}{b}+T(t_{DLC})}\right), \quad (8)$$

where b and a are the fixed parameters dependent on the physical characteristics of the WH (tank insulation, heating element capacity, etc.) and ambient temperature; T_{sp} is the upper setpoint temperature of the WH; $T(t_{DLC})$ is the final temperature of the tank at the end of the DLC period.

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By integrating Eqn. (7), the final temperature of the tank for the hot water event that occurs within the DLC period can be expressed through the total energy demand.

$$T(t_{DLC}) = T(0) + \mu\Delta t_{DLC} + \varphi\int_0^{t_{DLC}} P_{cw}(t)dt - \omega\int_0^{t_{DLC}} P_d(t)dt - \sigma\int_0^{t_{DLC}} T(t)dt \quad , \qquad (9)$$

where $\mu, \varphi, \omega, \sigma$ are some constants.

The term weighted with the coefficient ω in the right side of Eqn. (9) expresses the total cumulative energy E_d delivered to the user during the time of event. We intend to use such formulation of the demanded energy E_d in the user comfort model.

COMFORT MODELING

Since control strategies for domestic WHs can have a significant impact on comfort of occupants, special attention should be paid to the comfort modeling. In order to regard for a user satisfaction with the quality of the supplied hot water service, there is a need to define a metric to measure the amount of such inconvenience.

The comfort model quantifies the user tolerance to the quality of the supplied hot water service by translating it to the discomfort notation. It allows a user to specify the amount of comfort he/she is ready to sacrifice in order to reach the desired energy savings. The control algorithm can further exploit the tolerated discomfort to adjust the quality of the hot water service accordingly.

We assume that various types of domestic activities which involve hot water consumption impose different requirements for the quality of hot water service. The hot water activities, moreover, provide diverse capabilities to tolerate the discomfort being dissimilar in nature and purposes which they pursue. For example, an inhabitant can tolerate some level of the hot water temperature discomfort when washing hands. However, the user might hardly desire to compromise the comfortable temperature when taking shower. In contrast, the resident would like to get a constant hot water flow rate when washing hands, but can sacrifice some temperature comfort of the hot water service wishing to leave home earlier. Unlike washing hands, the user who takes a shower might prefer to reasonably sacrifice hot flow rate for having the fixed comfortable hot water temperature, because of the limited amount of hot water available in a boiler. We propose to decouple the hot water temperature discomfort from the hot flow rate discomfort.

The energy $E_d(t)$ delivered to the user at any instant of time t fully describes the water usage activity and depends on the requested mass flow rate and the demanded temperature; hence it can be used to describe the quality of hot water service. Energy perceived by the user can be expressed as follows.

$$E_d(t) = \int_0^t P_d(t)dt = C\int_0^t m_d(t)T_d(t)dt \qquad (10)$$

During the water usage event the user naturally experiences some level of temperature discomfort. The temperature discomfort is caused by the fact that cold water replaces the amount of the requested hot water, making the internal energy of the buffer drop. Then the cumulative difference between the expected temperature $T_{exp}(t) = T_d(0)$ and the actually delivered temperature $T_d(t)$ can describe the amount of temperature discomfort perceived by the user:

$$D_T(t) = \int_0^t T_{exp}(t)dt - C\int_0^t T_d(t)dt \qquad (11)$$

Control of water flows can lead to a user dissatisfaction with the resulting mass flow rate. In that case the dissatisfaction of the user can be expressed as the cumulative mass flow discomfort:

$$D_{\dot{m}_d}(t) = \int_0^t \dot{m}_{exp}(t)dt - C\int_0^t \dot{m}_d(t)dt \qquad (12)$$

The resulting discomfort can then be defined as a piece-wise function.

$$D(t) = \begin{cases} 0, & \text{if } \dot{m}_d(t) = \dot{m}_{exp}(t) \text{ and } T_d(t) = T_{exp}(t) \\ D_T(t), & \text{if } \dot{m}_d(t) = \dot{m}_{exp}(t) \\ D_{\dot{m}_d}(t), & \text{if } T_d(t) = T_{exp}(t) \\ \gamma D_T(t) + \theta D_{\dot{m}_d}(t) & \end{cases} \quad , \qquad (13)$$

where γ and θ are the scaling coefficients.

We hypothesize that occupants can desire to rearrange their hot water consumption patterns under certain conditions (e.g., restricted amount of hot water available in the WH). One can then explicitly express the discomfort associated with domestic hot water activities (e.g., washing hands, taking a shower) in order to reach some personal objective (e.g., energy savings). As can be seen from Eqn. (13), there are 3 possibilities to compromise the comfort. In that respect, an individual can choose to sacrifice temperature comfort, demanded flow rate or both of them. Further we consider two possible scenarios of hot water usage which presuppose (a) the fixed mass flow rate $\dot{m}_d(t) = \dot{m}_{exp}(t)$ and (b) the fixed demanded temperature $T_d(t) = T_{exp}(t)$.

Scenario A - Fixed Mass Flow

In case the user tolerates temperature discomfort for a certain activity, but requests a fixed flow rate, the experienced discomfort can be expressed as $D(t) = \int_0^t T_{exp}(t)dt - E_d(t)/(C\dot{m}_{exp})$.

Without loss of generality here we make an assumption that $\dot{m}_d(t) = \dot{m}_{exp}(t) = const$, which is typical for average domestic activities.

As mentioned earlier, any water usage activity naturally presumes some amount of the temperature discomfort caused by drop of thermal energy inside the tank. That natural temperature discomfort then designates the zone of the temperature discomfort allowed by the

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user. More precisely, the allowed discomfort is caused by the difference between the initially demanded temperature $T_d(0)$ and the current temperature $T_d(t)$. The zone of the allowed discomfort $D(t)$ is nothing but an integral with a variable upper limit of integration determined by the area between the graph $T_{exp}(t)$ and graph $T_d(t)$ (shown in light red in Figure-7). Any immediate deviation of temperature from the desired one brings extra unacceptable discomfort (shown in red).

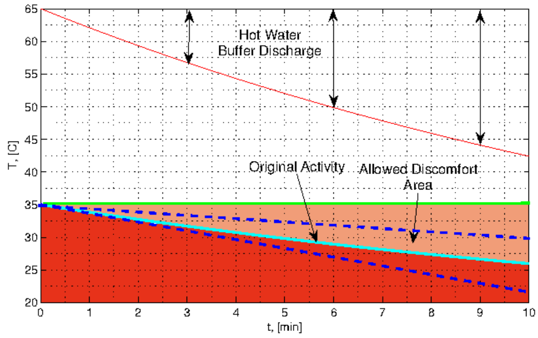

Figure-7. Temperature inside the tank (red), demanded original temperature (cyan).

More specifically, the area above the expected temperature $T_{exp}(t) = T_d(0)$ should be also considered as the discomfort zone.

$$D(t) = \begin{cases} \int_0^t T_d(t)dt - T_d(0)\Delta t, \text{ if } A(T_d(t)) > A(T_d(0)) \\ \int_0^t T_{ref}(t)dt - \int_0^t T_d(t)dt, \text{ if } A(T_{ref}(t)) > A(T_d(t)) \end{cases}, \quad (14)$$

where $T_{ref}(t)$ is the temperature that reflects the original water usage without control; $A(T(t))$ denotes the area below the graph of $T(t)$.

Scenario B - Fixed Demanded Temperature

While washing hands and dish washing can be performed with a lower temperature of hot water, shower and bath activities typically require a fixed temperature. The flow rate discomfort for the case with the strict temperature requirements can be expressed as $D(t) = \left|\int_0^t \dot{m}_{exp}(t)dt - \frac{E_d(t)}{CT_{exp}}\right|$, assuming that $T_d(t) = T_{exp} = const$.

The flow rate discomfort can be then represented as an area between the expected (or reference) flow rate $\dot{m}_{exp}(t)$ and the resulting flow rate $\dot{m}_d(t)$ as shown in Figure-8.

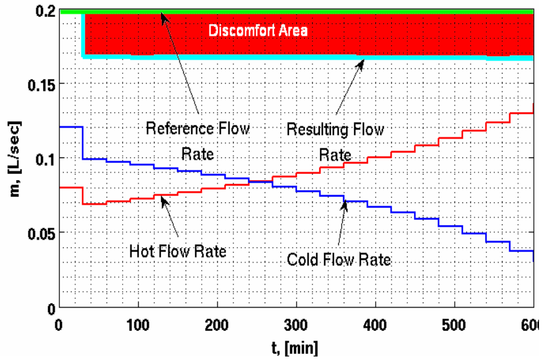

Figure-8. Mass Flow Rate Discomfort (red region).

CONTROL OF WATER FLOWS

One can obtain from Eqn. (6) that the ratio between the hot water and cold water flow rates in the mixer depends on the temperature of water inside the tank and demanded temperature at every moment of time. This ratio can be expressed as:

$$k(t) = \frac{\dot{m}(t)}{\dot{m}_{cw2}(t)} = \frac{T_d(t) - T_{cw}}{T(t) - T_d(t)} \quad (15)$$

The possibilities of controlling the temperature inside the tank $T(t)$ and demanded temperature $T_d(t)$ by manipulating the hot water and cold water mass flow rates in the mixer (Table-1) can be derived from the analysis of Eqn. (15).

Table-1. Possibilities of Water Flow Control (symbol ↓/↑ denotes direction of decrease/increase, number of symbols denotes the strength).

Case No.	$\dot{m}(t)$	$\dot{m}_{cw2}(t)$	$T_d(t)$	$T(t)$
0	↓	↑	↓↓↓	↓
1	$const$	$const$	↓↓	↓↓
2	↑	↓	↓	↓↓↓
3	↑↑	↓↓	$const$	↓↓↓↓
4	↑↑↑	↓↓↓	↑	↓↓↓↓↓

The simulation results of the above control strategies demonstrate possibilities to control the SoC of the WH by regulating the user discomfort. The results corresponding to the hot water activities that fall into Scenario A are illustrated in Figure-9.

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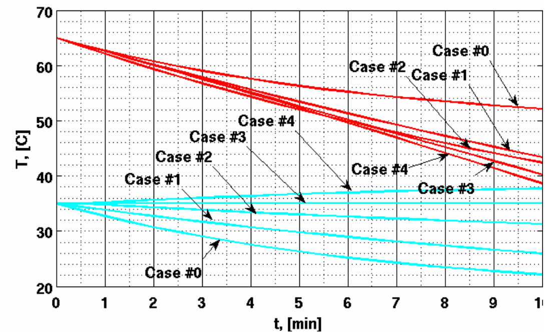

Figure-9. Water flow control simulation results (temperature inside the tank (red), demanded temperature (cyan)).

Pursuing the goal to reduce the payback peak demand, the utility company desires to limit hot water activities of its customers. On the other hand, customers would like to keep their comfort unchanged. Therefore, a fair compromise between the energy savings from hot water demand limitation and the end-user discomfort should be found. In order to reach that trade-off the optimization problem should be solved. In the next section we formulate the optimal control problem and propose two optimal control algorithms for the hot water activities that satisfy Scenario A and Scenario B.

OPTIMAL CONTROL PROBLEM

The control objective is to minimize the energy needed to recover a single WH tank after the DLC while minimizing the user discomfort. We assume that the control is implemented in the mixer by regulating the ratio between the hot and cold water flows determined by Eqn. (15) at every step of time.

Mathematically, the optimal control problem for a single mixer can be formulated as

$$min[\propto D(t_i) + (1-\propto)\Delta SoC(t_i)]_{t_i} \tag{16}$$

where $\propto$ is the weight coefficient that indicates the importance of comfort satisfaction; $D(t_i)$ is the user discomfort reached at the i-th time step; $\Delta SoC(t_i)$ is the drop of internal energy of water inside the tank at i-th instant of time.

The above general objective in application to Scenario A and Scenario B results in two distinct control algorithms listed below.

Algorithm 1 (Control for Fixed Flow Rate Scenario)

The optimal control problem for the hot water activities that satisfy the requirements of Scenario A ($\dot{m}_d(t) = \dot{m}_{exp}(t) = const$) can be expressed as

$$min\left[\propto \left| \int_{t_{i-1}}^{t_i} T_{ref_i}(t)dt - \int_{t_{i-1}}^{t_i} T_d(t_i, \dot{m}_i)dt \right| \dot{m}_d C + (1-\propto)(T_{sp} - T(t_i, \dot{m}_i))MC\right]_{t_i}, \tag{17}$$

subject to the following constraint:

$$0 \le \dot{m}_i \le \dot{m}_{max}, \tag{18}$$

where $\propto \ge 0$ is some weight coefficient; $T_{ref_i}(t)$ is the calculated reference temperature corresponding to the case when no control is performed (Case #1 in Table-1); $\dot{m}_i$ is the decision variable that determines the hot flow rate at i-th time instant; T_{sp} is the upper setpoint temperature of the WH; T is the current temperature inside the tank; $\dot{m}_{max}$ is the maximum hot flow rate defined by the maximum allowed temperature of water from the tap $T_{d,max}$.

Control Algorithm 1 finds the optimal solution for the objective function (Eqn. (17)) with respect to constraints (Eqn. (18) in a step by step manner. The first term in the utility function (Eqn. (17)) addresses the comfort satisfaction, whereas the second term represents the desire to save energy. More precisely, the term weighted with $\propto$ is the difference between the reference temperature discomfort $D_{T_{ref}}(t)$ and discomfort of the controlled event $D_{T_d}(t)$. The term weighted with $(1-\propto)$ is the change of internal energy of the tank that is related to the time of its recovery as shown by Eqn. (8).

As can it be seen from Figure-7, the original uncontrolled hot water event implies some allowed discomfort (light red), which means that the acceptable control solution $\dot{m}_i$ should create the temperature $T_d(t)$ within the allowed discomfort area.

The coefficient $\propto$ represents the trade-off between the discomfort of the user and the amount of savings achieved. The range of $\propto$ depends on the duration of the hot water event and initial conditions. For example, for a 10 minute event under the initial conditions of the requested temperature $T_d(0) = 35°C$, constant flow rate $\dot{m}_d(t) = 12$ [L/min] and SoC defined by the tank temperature $T(0) = 65°C$, the weight coefficient can be chosen from the graph shown in Figure-10. The user can simply specify the minimum allowed temperature which represents the maximum allowed discomfort for a particular hot water activity and pick the corresponding value of the weight coefficient.

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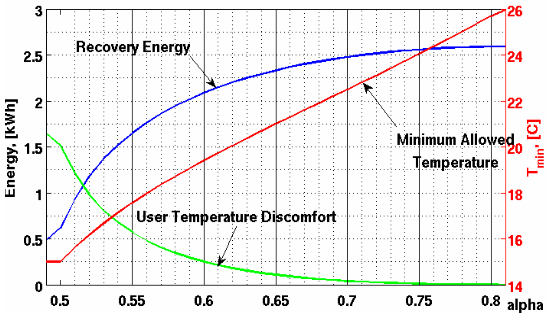

Figure-10. Trade-off between the temperature discomfort and energy savings (Scenario A).

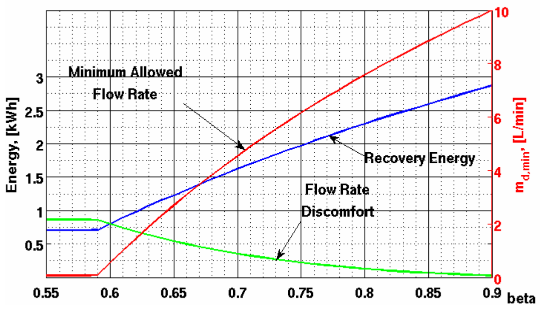

Figure-11. Trade-off between the temperature discomfort and energy savings (Scenario B).

Algorithm 2 (Control for Fixed Demanded Temperature)

The objective function for the hot water activities that fall into Scenario B ($T_d(t) = T_{exp}(t) = const$) can be determined as

$$\min\left[\beta T_d C \Delta t_{stp} (\dot{m}_{d,ref_i} - \dot{m}_{hw,i} - \dot{m}_{cw,i})^2 + (1 - \beta)(T_{sp} - T(t_i, \dot{m}_{hw,i}, \dot{m}_{cw,i}))MC\right]_{t_i} \quad , (19)$$

subject to the following constraints:

$$0 \le \dot{m}_{hw,i} + \dot{m}_{cw,i} \le k\dot{m}_d(0); \quad \frac{\dot{m}_{hw,i}(T(t_i) - T_d) - \dot{m}_{cw,i}(T_d - T_{cw})}{MC} = 0, \quad (20)$$

where $\beta \ge 0$ is some weight coefficient; Δt_{stp} size of the step; $\dot{m}_{d,ref_i}$ is the reference demand flow equal to the initial flow $\dot{m}_d(0)$; $\dot{m}_{hw,i}, \dot{m}_{cw,i}$ are the decision variables which describe the inlet hot and cold water flows in the mixer at i -th time instant; $k \ge 1$ is some constant to account for the maximum allowed flow rate;

The objective function explicitly incorporates the flow rate discomfort weighted with coefficient β and the SoC of the tank weighted by the coefficient $(1 - \beta)$. The coefficient β is dependent on the duration of the hot water activity and initial conditions. For instance, for a 10 minute event under the initial conditions of $T_d(0) = 35°C$, constant flow rate $\dot{m}_d(t) = 12$ [L/min] and SoC defined by the tank temperature $T(0) = 65°C$, the weight coefficient can be derived from the graph shown in Figure-11. Similar to Scenario A the user can define the minimum allowed mass flow rate which corresponds to the maximum allowed flow rate discomfort for a certain hot water activity and get the value of the weight coefficient β.

SIMULATION RESULTS

In this section we present the simulation results to demonstrate how the compromise between the user discomfort and the energy savings can be achieved.

Our first goal is to show the capabilities of two control strategies to mitigate the payback effect. Control algorithms are applied to the hot water events during the DLC. In other words, we aim to test the efficacy of the control algorithms to mitigate the secondary system peak under circumstances of intensive hot water usage considering the limited availability of domestic hot water source. Due to this fact we execute the control only for the hot water events of Type 1, Type 2 and Type 3, as illustrated in Figure-2 (shaded regions).

Our second goal is to check whether the achieved levels of discomfort and payback energy are in compliance with the expected ones. In order to reach that aim we predetermine the maximum allowed discomfort and payback energy by specifying the values of the weight coefficients $\propto$ and β (as discussed in the Section 10).

We run simulations on the basis of data obtained from a village of houses during the Meppel Energie Project [33]. The morning hot water peak demand can be expressed by

$$\dot{Q}_{HW} = \frac{1}{1.2\sqrt{2\pi}} e^{\left(-0.5\left(\frac{t-7.7}{1.2}\right)^2\right)}.$$

The effect of the two developed control algorithms was studied for a group of households equipped with similar medium-sized WHs. Hot water profiles corresponding to the morning peak hot water demand were generated for 50 houses of which 25 households are enrolled in the DLC program. The DLC period was taken fixed from 6:30AM to 8:30AM for all the simulations. The duration of the water use event was also taken fixed and equal to 10 minutes. It needs to be emphasized that due to the random nature of the generated start times of the hot water events, the initial conditions for every hot water event vary.

Simulations for Scenario A

For the first set of simulations the morning hot water demand profile was generated as shown in Figure-12.

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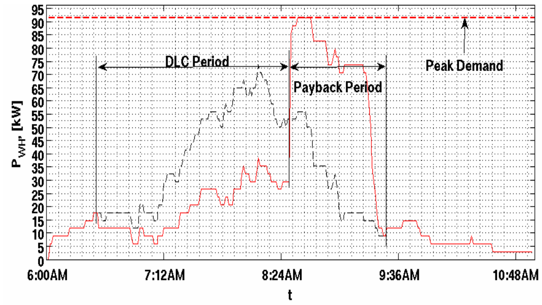

Figure-12. Original morning peak (black), morning demand after DLC (red).

The resulting payback demand reached the peak of 91.45 kW with the duration of about 1 hour.

The control Algorithm 1 was applied to the group of WHs with the settings of the weight coefficient ∝ equal to 0.49, 0.52 and 0.8. The results of the Algorithm 1 that demonstrate peak reduction addressing the first goal of our simulations are illustrated in Figure-13, Figure-15 and Figure-17. Pursuing the second goal of the simulations, the levels of the individual temperature discomfort, payback energy and energy savings for the selected group of 10 households are shown in Figure-14, Figure-16 and Figure-18.

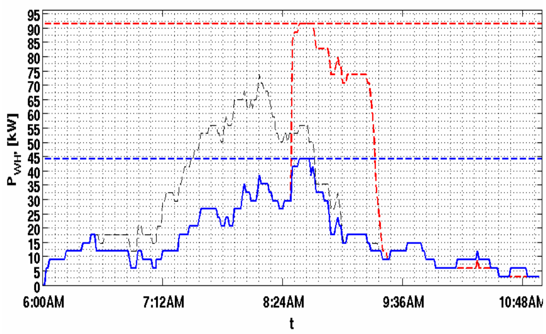

Figure-13. Algorithm 1 - Maximum payback reduction ∝=0.49 (shown in blue).

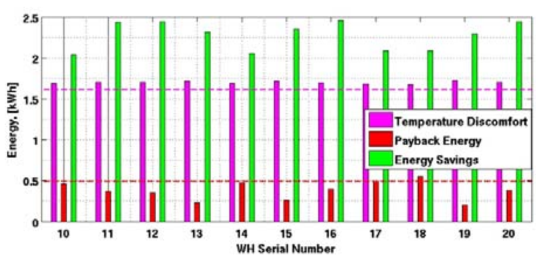

Figure-14. Algorithm 1 - Individual Temperature Discomfort (∝=0.49).

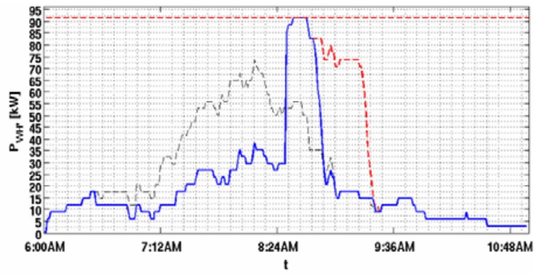

Figure-15. Algorithm 1 - Fair trade-off between payback reduction and user discomfort ∝=0.52 (shown in blue).

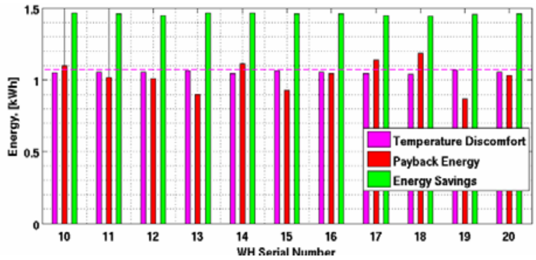

Figure-16. Algorithm 1 - Individual Temperature Discomfort (∝=0.52).

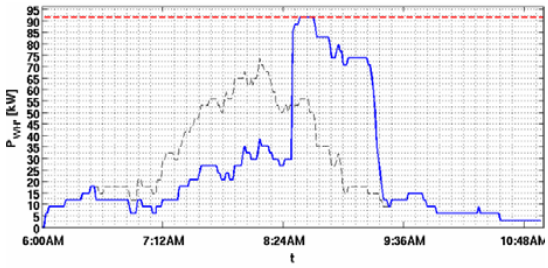

Figure-17. Algorithm 1 - Maximum user comfort ∝ = 0.8 (shown in blue).

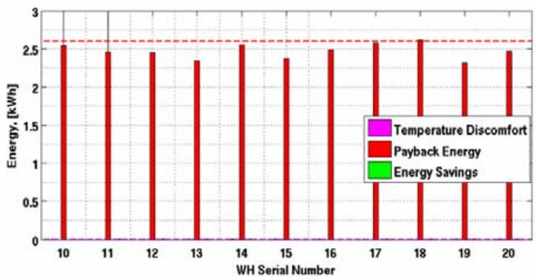

Figure-18. Algorithm 1 - Individual Temperature Discomfort ∝ = 0.8).

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Simulations for Scenario B

For the simulations of hot water activities associated with the Scenario B the demand profile was generated as shown in Figure-19.

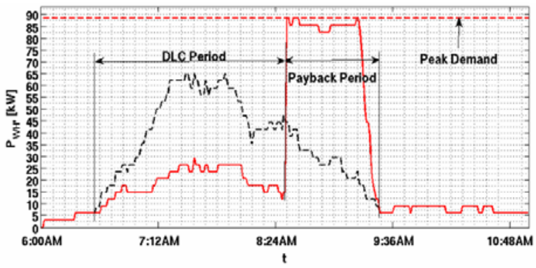

Figure-19. Original morning peak (black), morning demand after DLC (red).

The payback reached the peak of 88.5 kW with the duration of about 1 hour. According to the first goal of our simulations, the impact of the different weight coefficients β equal to 0.55, 0.6 and 0.83 on the payback peak curtailment was tested as illustrated in Figure-20, Figure-22 and Figure-24. Following the second goal of the simulations, the levels of the individual flow rate discomfort, payback energy and energy savings were obtained for the selected group of 10 houses as illustrated in Figure-21, Figure-23 and Figure-25.

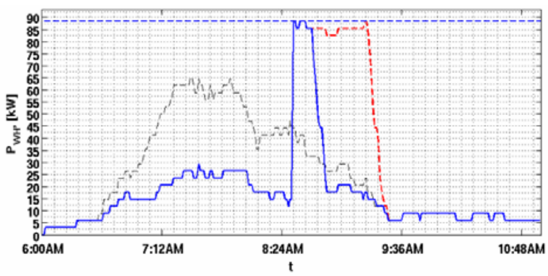

Figure-20. Algorithm 2 - Maximum payback reduction β = 0.55 (shown in blue).

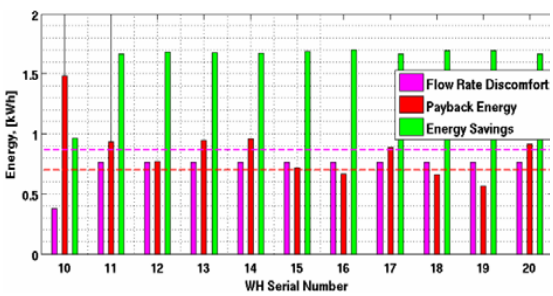

Figure-21. Algorithm 2 - Individual Flow Rate Discomfort ($\propto$ = 0.55).

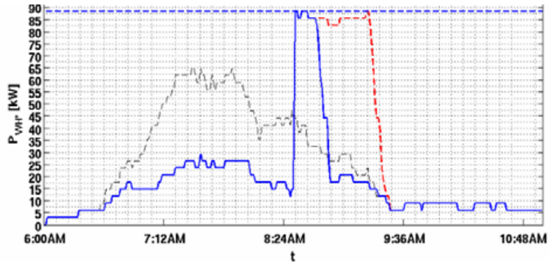

Figure-22. Algorithm 2 - Fair compromise between payback reduction and user discomfort β = 0.6 (shown in blue).

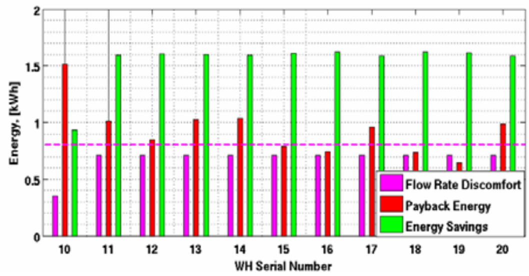

Figure-23. Algorithm 2 - Individual Temperature Discomfort (β = 0.6).

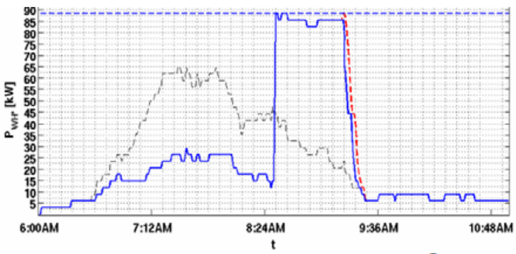

Figure-24. Algorithm 2 - High user comfort β = 0.83 (shown in blue).

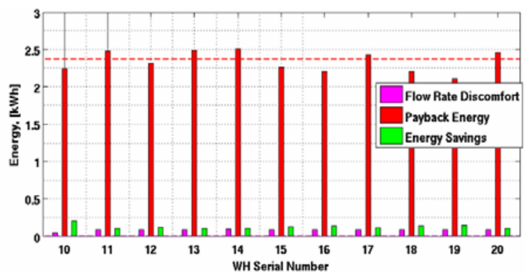

Figure-25. Algorithm 2 - Individual Temperature Discomfort (β =0.83).

The final results for two simulations are listed in the Table-2.

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Table-2. Results of simulations.

Alg. No.	α/β	Peak DCR [kW]	NRG DCR [kWh]	Min/ Max/ Excess WH $D(t)$, kWh	Min/Max /ExcessWH Payb. NRG, kWh	Min/Max WHNRG Sav., kWh
1	0.49	47.2	42.99	0.51/1.73/ 0.12	0.13/1.88/ 1.39	0.45/ 2.46
	0.52	0	27.35	0.11/1.07/0	0.85/2.26/ 1.19	0.11/1.47
	0.80	0	0	0/0/0	2.29/2.62/ 0.02	0/0
2	0.55	0	38.89	0.03/ 0.76/ 0	0.57/ 2.10/ 1.41	0.16/1.7
	0.60	0	37.17	0.03/ 0.76/ 0	0.64/2.10 /1.3	0.16/1.63
	0.83	0	3.25	0.02/0.09/ 0.09	2.11/2.55/ 0.18	0.09/0.21

DISCUSSIONS

Simulation results for the Algorithm 1 demonstrate that the maximum payback peak curtailment of 47.2 kW and maximum payback energy reduction equal to 42.99 kWh can be achieved with the weight coefficient $\propto$=0.49. In case of the maximum temperature discomfort ($\propto$=0.8) the resulting graph of energy demand fully coincides the original graph when only DLC is applied. However, when the weight coefficient $\propto$=0.52 the Algorithm 1 shows only the capability to reach payback energy savings, while no payback peak shaving can be achieved. Which means that to reach the payback peak clipping goal one has to choose weight coefficient $\propto$ closer to 0.49.

The levels of the temperature discomfort and payback energy for the individual WHs are satisfactory distributed around the expected thresholds (shown in dashed lines). The slight deviation can be explained by the variation of initial conditions for different hot water events caused by the randomness of hot water demand in the households.

Results of simulations for the Algorithm 2 demonstrate only the capability for the payback energy reduction. The maximum payback energy decrease of 38.89 kWh is achieved when the weight coefficient β is equal to 0.55. There is a very low difference between the graphs of the electricity demand for β =0.55 and β =0.6. It can be explained by the very close location of the point of fair compromise (β =0.6) to the extreme discomfort (β =0.55) as illustrated in Figure-11.

Most of the results of the individual flow rate discomfort and individual payback energy are acceptably distributed within the predetermined thresholds. One of the WHs from the selected group (WH#10) has significantly different results as compared to its neighbours, as shown in Figure -21 and Figure-23. It can be explained by the fact that the hot water event corresponding to the WH#10 belongs to the Type 1, thus it contributes to the payback much higher than other WHs.

CONCLUSIONS

This paper proposes a novel approach to control domestic tank water heaters by executing the optimal water flow control in the mixing device. The efficiency of the approach is demonstrated in application to the group of households participating in the Direct Load Control (DLC) program. The two control algorithms suggested in the paper demonstrate the opportunity to mitigate the payback effect taking place after load disconnection under DLC. The algorithms implement the real-time control over the customers' water heaters during the DLC period allowing to reach a fair trade-off between the desired quality of hot water service and energy savings.

The suggested approach can be profitable both for the utility company and for the end-user. The utility benefits from the capability to monitor the state of charge of individual water heaters that participate in the DLC program. In case of emergency the utility can also take control over the hot water discharge process of the controlled heating units, which results in the peak load curtailment. On the other hand, the end-user benefits from the opportunity to rationally manage the hot water usage according to the individual comfort preferences, for instance, during the periods when the limited amount of hot water is available (DLC periods). As a result, hot water can be accessible for longer time in a household. Additionally, the customer obtains money savings due to the reduction of electric energy consumption.

The introduced control strategy relies on the user comfort model derived from the analysis of the system's thermal dynamics. The model is intended to provide a quantitative expression of the user comfort preferences associated with various hot water activities in a household. Particular comfort settings are further respected by the appropriate control algorithm.

The thermo-dynamic model of a domestic electric water heater allows to accurately account for different physical characteristics of the boilers and conditions of the surrounding environment. The presented analysis of the domestic tap water mixer illustrates the possibilities to perform the external control of the water heater without affecting its internal circuits.

The recommended approach can be used in home/building energy management systems to: (a) stimulate integration of households in the Demand Side Management programs; (b) motivate dwellers to use hot water more rationally; and (c) identify habitual water usage patterns of residents to perform a better planning of the utility programs.

ACKNOWLEDGEMENT

We would like to express our gratitude to the Go-Green Project and its members for their support. We would also like to thank the Meppel Energie Project for the useful data provided.

REFERENCES

[1] Eurostat European Commission. 2014. Final energy consumption, by sector. http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables. Last visit: 01/03/2014.

[2] European Environment Agency. 2013. Overview of the electricity production and use in Europe (ENER 038) Assessment. http://www.eea.europa.eu/data-and-maps/indicators. Last visit: 01/03/2014.

[3] Albadi M.H. and El-Saadany E.F. 2008. A summary of demand response in electricity markets. Electric Power Systems Research. 78: 1989-1996.

[4] Osborne J. 2007. A primer on demand response. A White Paper on a Facet of the Industrial Growth Sector. Thomas Weisel Partners. pp. 1-45.

[5] Strbac Goran. 2008. Demand side management: benefits and challenges. Energy Policy. 36(12): 4419-4426.

[6] Nehrir M.H. and LaMeres B.J. 2000. A multiple-block fuzzy logic-based electric water heater demand-side management strategy for leveling distribution feeder demand profile. Electric Power Systems Research. 56(3): 225-230.

[7] Dolan P.S., Nehrir M.H. and Gerez V. 1996. Development of a Monte Carlo based aggregate model for residential electric water heater loads. Electric Power Systems Research. 36(1): 29-35.

[8] Elgazzar K., Howard L. and Chang L. 2009. A centralized fuzzy controller for aggregated control of domestic water heaters. In proceedings of CCECE'09. IEEE. pp. 1141-1146.

[9] Ghent Bobby A. 2005. Demand side management of water heater systems. Google Patents. US Patent. 6, 861, 621.

[10] Jia Runmin and others. 2007. Power management of aggregate electric water heater loads by voltage control. 2007 IEEE Power Engineering Society General Meeting. pp. 1-6.

[11] Nehrir M.H., LaMeres B.J. and Gerez V. 1999. A customer-interactive electric water heater demand-side management strategy using fuzzy logic. Power Engineering Society 1999 Winter Meeting, IEEE. pp. 433-436.

[12] Sepulveda A., Paull L., Morsi W. G and others. 2010. A novel demand side management program using water heaters and particle swarm optimization. In proceeding of the EPEC-2010, IEEE. pp. 1-5.

[13] Lee S.H. 1983. A practical approach to appliance load control analysis: a water heater case study. Power.

[14] Chen J., Lee F.N., Breipohl A.M. and Adapa R. 1995. Scheduling direct load control to minimize system operation cost. IEEE Transactions on Power Systems. 10(4): 1994-2001.

[15] Cohen A.I. and Wang C. C. 1988. An optimization method for load management scheduling. IEEE Transactions on Power Systems. 3(2): 612-618.

[16] Kurucz C.N., Brandt. D and Sim S. 1996. A linear programming model for reducing system peak through customer load control programs IEEE Transactions on Power Systems. 11(4): 1817-1824.

[17] Kondoh J., Lu N. and Hammerstrom D.J. 2011. An evaluation of the water heater load potential for providing regulation service. 2011 IEEE Power and Energy Society General Meeting. pp. 1-8.

[18] Bhattacharyya K. and Crow M.L. 1996. A fuzzy logic based approach to direct load control. IEEE Transactions on Power Systems. 11(2): 708-714.

[19] Huang Kun-Yuan and Huang Yann-Chang. 2004. Integrating direct load control with interruptible load management to provide instantaneous reserves for ancillary services. 19(3): 1626-1634.

[20] Wei Deh-chang and Chen Nanming. 1995. Air conditioner direct load control by multi-pass dynamic programming. IEEE Transactions on Power Systems. 10(1): 307-313.

[21] Ruiz N., Cobelo I. and Oyarzabal J. 2009. A direct load control model for virtual power plant management. IEEE Transactions on Power Systems. 24(2): 959-966.

[22] Ericson Torgeir. 2009. Direct load control of residential water heaters. Energy Policy. 37(9): 3502-3512.

[23] Lu N. and Katipamula S. 2005. Control strategies of thermostatically controlled appliances in a competitive electricity market. IEEE Power Engineering Society General Meeting. pp. 202-207.

[24] Rautenbach B and Lane I.E. 1996. The multi-objective controller: a novel approach to domestic hot water load control IEEE Transactions on Power Systems. 11(4): 1832-1837.

[25] Energy Wise Home Program. https://www.progress-energy.com. Last visit: 30/07/2014.

[26] Al-Shakarchi M. and Abu-Zeid N. 2002. A Study of Load management By Direct Control for Jordan's Electrical Power system. Journal of Science and Technology. 7(2): 25-30.

[27] Du Pengwei and Lu Ning. 2011. Appliance commitment for household load scheduling. IEEE Transactions on Smart Grid. 2(2): 411-419.

[28] Dolan P.S., Nehrir M.H. and Gerez V. 1996. Electric Power Systems Research. 36(1): 29-35.

[29] Lane I.E. and Beute N. 1996. A model of the domestic hot water load. IEEE Transactions on Power Systems. 11(4): 1850-1855.

[30] Energyplus engineering reference. 2013. The Reference to EnergyPlus Calculations. DOE, US.

[31] Hendron Robert and Burch Jay. 2007. Development of standardized domestic hot water event schedules for residential buildings. In proceeding of the ASME 2007 Energy Sustainability Conference, 531-539.

[32] Widen J., Lundh M. Vassileva I and others. 2009. Constructing load profiles for household electricity and hot water from time-use data-Modelling approach and validation. Energy and Buildings. 41(7): 753-768.

[33] Meppel Energie. http:// www.sgmeppelenergie.nl. Last visit: 01/07/2014.

[34] Go-Green Project. http://gogreen-project.nl. Last visit: 30/07/2014.