Reducing User Discomfort in Direct Load Control of Domestic Water Heaters

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***Abstract*—Direct Load Control (DLC) is an effective instrument for achieving a guaranteed load curtailment. Unfortunately, if a customer considers that personal discomfort outweighs money savings after DLC shutting down of home appliances, DLC solution can be rejected. This paper proposes the way to remediate customer comfort concerns by pre-storing additional energy in electric loads before their disconnection from the grid. We take electric tank water heaters as an illustrative example of residential loads with storage. To illuminate our approach we first show how to balance electric consumption for pre-storing with user thermal discomfort for a single water heater. Then, we illustrate how the approach can be scaled-up to a multiple-boiler scenario, when ten remotely controlled boilers act next to fifty non-controlled boilers. The simulations for the latter case show that the expected user thermal discomfort can be significantly reduced at the cost of a reasonable increase of electricity demand preceding DLC event.**

***Index Terms*—Power system management, Power demand, Control systems, Optimal control, Power system stability.**

I. INTRODUCTION

Demand Response (DR) refers to a broad portfolio of demand-side management measures 'designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized' [1]. Utility companies motivate their customers to participate in price-based and incentive-based programs. Price-based DR programs rely on customers' choice to modify their consumption in response to a variable retail electricity rate (e.g., real-time pricing). Although this approach allows more freedom to the electricity consumers, uncertainties in consumer response to dynamic prices can impede resource planning for utility companies [2]. Due to unpredictable DR such programs cannot deal with real-time scenarios when utilities have to manage unexpected peak demands or when there are faults in the energy system [3]. On the other side of the spectrum, incentive-based programs provide grid operators with a transparent and reliable mechanism for balancing the grid.

Direct Load Control (DLC) is one of those incentive-based mechanisms where the utility or system operator triggers the load reduction directly without waiting for a customer-induced response. Consumers allow their electrical equipment to be shut down or *cycled* on a short notice by the utility. Thus, DLC can be effective in scenarios when a reliable load curtailment is required [4]. In return, DLC customers receive guaranteed incentive payments for limiting their load or face penalties for ignoring utility requests [5]. The payments are usually provided on the contractual basis regardless to discomfort customers might experience during the load disconnection.

Although DLC programs are relatively easy and inexpensive to implement, customers' concerns about potential comfort disruptions can hinder their participation in DLC projects [4]. If electrical equipment terminated during DLC fails to provide its regular service to users, participants might need to significantly modify their energy consumption habits, which can cause their discontent with DLC. To increase user uptake of DLC programs, the end-user comfort should carefully considered. This paper investigates how to increase the attractiveness of DLC for small residential consumers. We consider that end-user comfort enhancement is a key enabler for a successful implementation of DLC. The paper concentrates on loads with some form of energy storage. This is well justified as services they provide remain accessible to the user for some period after their disconnection from the grid [6].

Tank water heaters (WHs) are illustrative examples of residential loads with energy storage. Firstly, WHs are present in a prevailing number of European households and have been extensively studied in DLC applications over the years [7]-[9]. Secondly, similar to electric batteries, WHs can accumulate extra energy before their power shortage without affecting inhabitants. Finally, the drop of temperature inside their tanks during DLC can directly influence user comfort, causing user dissatisfaction. Pre-storing additional thermal energy before DLC appears to be a promising measure for improving end-user comfort during the period when WH is shut off. Specifically, by means of a set-point control one can raise the upper setpoint temperature of a WH and thereby force the unit to heat the water up to a higher temperature than usual [10].

The question of consumer satisfaction in DR of WHs has been previously raised in [6], [8], [9], [11]-[13]. Most often thermal discomfort is described as a mismatch between instantaneous values of the actual water temperature in the boiler and some predefined setpoint temperature threshold [6], [8], [9], [11]. A step forward towards tracking the temperature deviations including the intervals in which they occur has been done by [12], [13]. Our thermal discomfort modeling approach introduced in [14] is also built around the similar concept. This paper investigates how a combination of DLC and the set-point control can diminish negative consequences of turning off WHs. We specifically attempt to answer the question 'How preheating of a WH can improve user thermal comfort during its disconnection period?', tackling the problem of consumer involvement in DLC programs.

The rest of the paper is organized as follows. Section II describes the effect of DLC on personal comfort. In Section III we outline the thermal discomfort modeling concept and model system's thermal dynamics. We introduce our approach in Section IV. Section V represents and discusses the simulation results for the selected water activities. Some directions for the future work and our conclusions can be found in Section VI and Section VII respectively.

II. User Comfort after DLC execution

Historically, many DR programs fail not because they lack technical efficiency, but because there is a high impact on users for widespread acceptance [9]. Among other factors, the user acceptance can be related to a decrease of personal comfort. For instance, disconnection of WHs can demand customers to sacrifice their comfort, thus causing the decline of their tolerance to DLC and even dissatisfaction with the utility [15]. Because the question how an individual experiences thermal discomfort is entangled and subjective, there is a need to consider it in some detail before proceeding with modeling and simulation. This paper adapts the user thermal discomfort concept earlier introduced in [15]. To illustrate, a person performs an *8*-minute dish washing WA in running water and desires to have tap water temperature in the range ΔT_d = *40...45* [°C]. Assume that the user can tolerate a slight increase of tap water temperature above *45*°C as depicted in Fig. 1.

In case of cold water from the tap (T_{cw} = *15*°C) the user experiences the highest temperature discomfort during the entire WA as denoted by red area in Fig. 1. This corresponds to a fully discharged WH, i.e. the tank is filled with cold water. When the WH is sufficiently charged the user can achieve a lower temperature discomfort (light blue curve) or no discomfort at all (yellow line). In the last case the user is fully satisfied with the tap water temperature, because the curve $T_d(t)$ fits the preferred temperature zone. In second case the user senses the higher temperature than expected during the first minute of the WA, and the lower temperature during the last *4* minutes. Intuitively one can notice that not only instantaneous deflections of the tap water temperature from the preferred comfort zone are essential to the user, but also the time during which the user experiences them. Our thermal discomfort concept accounts for both the immediate temperature differences and periods when these deviations occur.

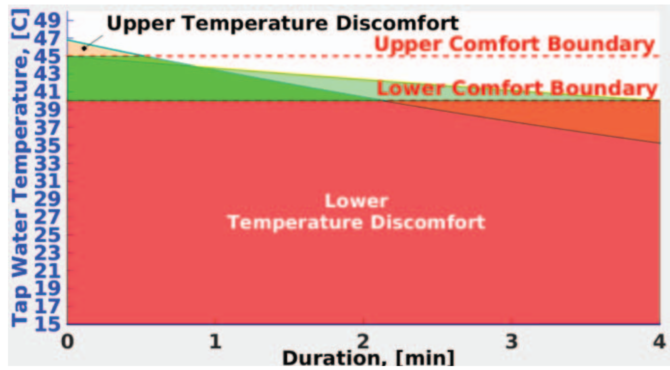

Figure 1. Thermal discomfort

III. Background on modeling thermal discomfort and WH thermodynamics

A. Thermal Discomfort Model (TUCM)

In this paper we consider the scenario of water usage when the user sets the fixed tap water flow in the beginning of the water activity (WA) and expects to get the comfortable tap water temperature during the entire event while having the WH terminated by DLC. We also assume that the user has a direct contact with hot water and is ready to tolerate some deviation of water temperature. As a modeling tool we adapt the user thermal discomfort model (TUCM) presented earlier in our studies [14], and further enrich it with some contextual information. In this way, we consider that different people typically have different tolerance to cold and hot water due to individual skin sensitivity [16]. We model the degree of user tolerance to water temperature via a linear relationship:

$$F_T(T_d) = \begin{cases} 0 & \text{, if } T_d \in T_c; \\ \alpha T_d + \beta & \text{, if } T_d \in \Delta T_{tol}; \\ 1 & \text{, otherwise;} \end{cases} \quad (1)$$

where $\alpha < 0$, $\beta > 0$ are some coefficients; $\Delta T_{tol} = \{T_{tol} : T_{tol} \in \Delta T_{tol}, \Delta T_c \subseteq \Delta T_{tol}\}$ is the zone of temperatures tolerated by the user.

We assume that every single user has a unique set of tolerance functions $\{F_{T,i,j}\}$ with parameters dependent on the individual skin perception of a user (*i*) and on a particular scenario of water usage (*j*). By incorporating this contextual information into the discomfort model we can differentiate between diverse combinations of temperature deviations and duration (e.g., *15*°C * *1* sec and *1*°C **15* sec). The thermal discomfort for the i-th user during the single j-th WA can be then expressed as (A_T is the area bounded by $T_d(t)$ and ΔT_e):

$$D_T(t)_{i,j} = F_T(T_d)_{i,j} A_T(t)_{i,j} \tag{2}$$

B. Modeling Water Supply Thermodynamics

The considered WH setup of the household hot water system is represented in Fig. 2. This setup has a mixing device that serves as a water flow controller [14]. The controller merges cold water from the water main and hot water from the boiler to provide the user with the demanded tap water flow during the WA.

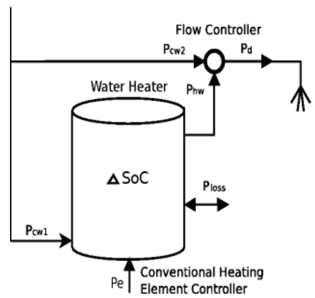

Figure 2. Considered Setup

While there is extensive literature available on the modeling of electric WHs [17]-[19], for the purpose of this paper we adapt the thermodynamic model of the well mixed cyclic type WH. This model is incorporated into the EnergyPlus simulator [20]:

$$MC\frac{dT}{dt} = P_e + P_{cw1} - P_{hw} - P_{loss} \tag{3}$$

where M is mass of water in the tank; C is the specific heat; P_e is the thermal power supplied by the heating element; P_{cw1} and P_{hw} are water inflow and outflow of the tank, and P_{loss} denotes the heat transferred to the ambient.

Energy and mass balance for the mixing unit can be written as:

$$\begin{cases} P_d = P_{hw} + P_{cw2} \\ \dot{m}_d = \dot{m} + \dot{m}_{cw2} \end{cases} \tag{4}$$

where P_{cw2} is the cold water from the main; $\dot{m}_d, \dot{m}, \dot{m}_{cw2}$ describe demanded, hot and main's cold water mass flow rates respectively.

Plugging (4) into (3) and solving the differential equation for $\dot{m} = 0$, i.e. no water usage while preheating, electric consumption for preheating E_e can be expressed as

$$E_e(\Delta t_{pre}) = P_e \Delta t_{pre} = \rho P_e log[\varphi f(SoC(0), SoC(\Delta t_{pre}))] \tag{5.}$$

where ρ and φ are coefficients dependent on engineering parameters of the WH; $SoC(0)$ and $SoC(\Delta t_{pre})$ are the SoCs of the WH in the beginning and at the end of the preheating period respectively.

IV. Our Approach

To tackle the problem of improving user thermal comfort during the WH disconnection periods, we propose to combine DLC with the set-point control presented in [10]. Unlike [10], where set-point control is applied to price-based scheduling of WHs, we provide the desired level of thermal comfort to the user by optimally preheating the boiler, rather than turning on the heating elements. The idea is to preheat the WH to a higher temperature than typical $60-70$ °C [21] before DLC starts. Some extra thermal energy is to be accumulated in the water tank and later can assist in maintaining user comfort at the preferred level. Fig. 3 illustrates the case when the set-point control helps increase tap water temperature before the Water Activity (WA).

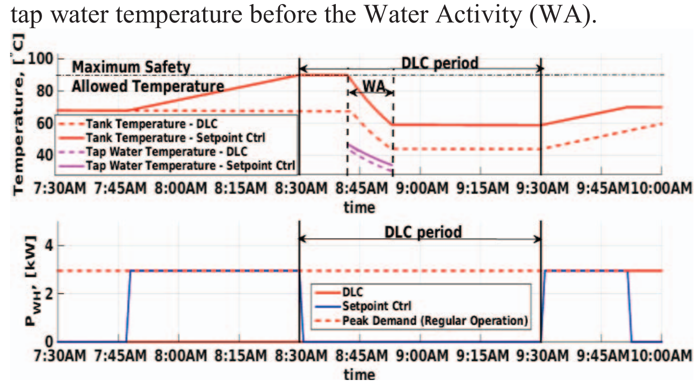

Figure 3. DLC Combined with Set-point Control

To implement the set-point control in the most efficient way there is a need to ensure that the resulting D_T is acceptable to the user and no extra time is spent for preheating. As follows from (5) and (3) reduction of $E_e(\Delta t_{pre})$ leads to a lower delivered energy $E_d(t_{WA})$ and consequent thermal discomfort D_T for the user, while the increase of $E_e(\Delta t_{pre})$ results in additional ambient losses of the unutilized heat during DLC and calls for extra time for the preheating procedure which might be not available due to water usage prior to DLC. We treat the objective of minimizing electricity expenses for preheating $E_e(\Delta t_{pre})$ and the objective of minimizing user thermal discomfort D_T as conflicting goals:

$$\begin{aligned} &min\left[\gamma\mu D_T + (1-\gamma)E_{e,pre}{}^2\right], \\ &D_T = D_{T,low}(t_{WA}) + \omega D_{T,high}(t_{WA}) \end{aligned} \tag{6}$$

subject to the following constraints:

$$\begin{aligned} &0 \le \dot{m} \le \dot{m}_d, \\ &T_{cw} \le T(0) \le T_{wh,max} \end{aligned} \tag{7}$$

where $\gamma \in [0,1]$ is the weight coefficient that indicates the importance of the temperature comfort satisfaction; $\mu > 0$ is a scale factor; D_T is the temperature discomfort reached by the end of the WA; $E_{e,pre}$ is the electric consumption during the preheating period; $D_{T,low}$ defines the Lower Temperature Discomfort when $T_d(t) < T_{c,min}$; $\omega \ge 0$ is the weight coefficient that enables the Upper Temperature Discomfort specified by $D_{T,high}$; T_{cw} is the cold water temperature and $T_{wh,max}$ is the safety maximum temperature for the tank.

The first term of the cost function in (6) addresses the thermal comfort satisfaction, while the second term describes the user desire to save energy for preheating. The algorithm shapes the curve $T_d(t)$ around the comfort zone ΔT_c according to the user preference γ. The returned solution is a couple of variables $\{T^*(\Delta t_{pre}), \dot{m}^*\}$, where $\Delta T^*(\Delta t_{pre})$ represents the SoC of the WH at the beginning of the WA $SoC(\Delta t_{pre})$ and $\dot{m}^*$ refers to the way the tank is discharged during the WA. In some situations the Upper Temperature Discomfort can be dangerous for the user, because of the risk to burn the skin.

One can take care about it by increasing the weight coefficient ω. If the user prohibits the water temperature greater than $T_{c,max}$, the coefficient ω can be set to zero and the following constraints should be then added to the original optimization problem:

$$T_d(0) \leq T_{c,max}, \quad T_d(t_{WA}) \leq T_{c,min}. \tag{8}$$

V. SIMULATIONS

This section describes the simulations how the proposed set-point control combined with DLC of the WH can affect the user thermal comfort during DLC and what are the corresponding electricity expenses.

First, we illustrate the approach in connection a single WH. For the purpose of simplicity, we do not consider parallel or overlapping WAs. Then, then we scale-up the approach for the case of multiple boilers using statistical data on hot water demand obtained within the Meppel project [22].

Table I lists the WAs used for simulations together with their estimated flow rates and volume values [23], [24]. Noticeably, the WAs parameters can vary, depending on the system parameters (e.g., hot water system design, water pressure)and on the context. With respect to a specific household, these parameters could be 'learned' based on the water usage patterns.

TABLE I. WAs SELECTED FOR SIMULATIONS

WA	Volume, [L]	Estimated Flow Rate, [L/min]	Flow Range, [L/min]
Wash Hands[a]	0.7 ... 7.5	6	2 ... 9
Shower[b]	32 ... 225	15	8 ... 25
Dishwashing[c]	38 ... 75	9	6 ... 25

a. Bath tap, running water.
b. Mains fed.
c. Kitchen tap, running water.
Note: There is little statistical data on hot water usage per activity available. Some of the missing data per activity is replaced by data per water source location..

A. Single WH

First, we illustrate the approach for the case of a single WH. The parameters of WAs are listed in Table II. To make it possible to compare the simulation results, we applied the tolerance values $\Delta T_{tol} = [T_{c,min} - 2°C,\ T_{c,max} + 1°C]$ in all our simulations. To account for multiple possibilities of $SoC(0)=MCT(0)$ unknown to us beforehand, we varied the temperature $T(0)$ in the allowed range of water temperatures $[T_{cw}, T_{wh,max}]$°C.

TABLE II. THE RECOMMENDED VALUES FOR SIMULATIONS

Sim. Round	WA Type	Duration, [min]	Tap Flow, [L/min]	Comf. Zone, [°C, °C]
I	Very Short	0.5	9	[40,45]
	Short	4		
	Medium	7		
	Long	15		
II	Low Flow	7	2	[40,45]
	Med. Flow		12	
	High Flow		20	
III	Cold	7	9	[18, 23]
	Med.Temp.			[30, 40]
	Hot			[60, 65]
	Fixed Temp.			40

I - Distinct duration of WAs.
II - Varied tap water flow rates of Was
III - Different comfortable temperature zones

The user's desire to satisfy the temperature comfort is specified by the weight coefficient γ in the range [*0*, *1*]. All the simulations were held with the step Δγ = *0.01*. It is worth mentioning that in case γ = 1 the algorithm can sometimes produce multiple solutions. In this case we picked only the one solution closest to the preceding step. Additionally, identical scale factor $\mu = C\dot{m}_d = 4184$ [J/(kgK)]**9*[L/min] was applied to D_T in all the simulations to compare the resulting values of discomfort. The coefficient ω was set to a small value in order to prevent the skin burn.

The number of optimal solutions for WAs of varied duration is shown in Fig. 4. Every colored point in the plot represents a single solution $\{SoC^*(t_{pre}), \dot{m}^*_{hw}\}$. While the corresponding labels describe this information in the format $[T(t_{pre})$°C, $\dot{m}$ L/min], telling what outflow from the tank $\dot{m}$ should be established during the WA, if the WH has been preheated to temperature $T(t_{pre})$, so that user comfort is maintained at the particular level. The labeled double-arrows represent the difference between the final SoC at the end of preheating and initial SoCs when the temperature inside tank is *27*°C and *65*°C respectively. The labels refer to the time that should be spent for preheating to provide the minimum thermal discomfort. The obtained multiple solutions form Pareto front where any switching between neighbor solutions improves one of the terms of the cost function in (6) and degrades another.

The maximum and minimum values of $E_e(\Delta t_{pre})$ and D_T in diverse scenarios of water usage are summarized in Table III. The table exhibits the results of classical DLC and DLC combined with the proposed set-point control for a single WH.

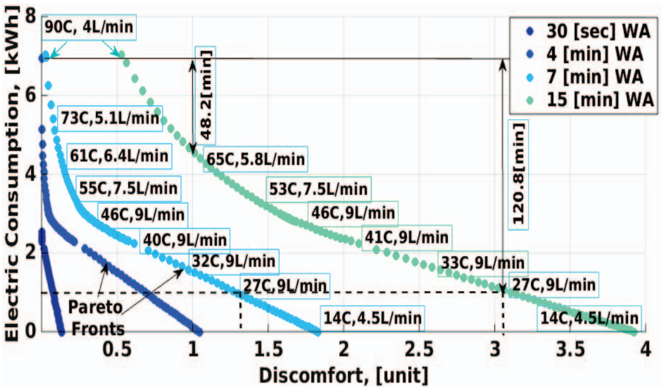

Figure 4. Pareto fronts for WAs of varied duration

TABLE III. SIMULATION RESULTS FOR A SINGLE WH

WAs	DLC	DLC with Set-point Ctrl					
	$D_{T,\,max}$, [units] †	$E_{e,min}$, [kWh]	$D_{T,\,max}$, [units]		$E_{e,max}$, [kWh]		$D_{T,\,min}$, [units]
		I&II	I	II	I	II	I&II
Very Short	0	0	0	0.13	0	2.71	0
Short	0.01	0	0.01	1.05	2.24	6.98	0
Med.	0.11	0	0.11	1.83	2.36	7.04	0.02
Long	0.96	0	0.96	3.92	2.36	7.04	0.53
Low Flow	0	0	0	1.83	0	3.07	0
Med. Flow	0.28	0	0.28	1.83	2.36	7.04	0.11
High Flow	1.17	0	1.17	1.83	2.36	7.04	0.58
Cold	0	0	0	0.07	0	0.32	0
Med. Temp.	0	0	0	1.10	0	3.65	0
Hot	0.78	0	0.78	3.29	2.36	7.04	0.44
Fixed Temp.	0.22	0	0.22	1.83	2.36	7.04	0.13

(I & II) - simulation results in case of the initial SoC at T (0) = 65°C and T (0) = 15°C respectively
(†) Temperature discomfort DT is scaled with the factor $\mu = C\, \dot{m}_d = 4184$[J/(kgK)]∗9[L/min] for all the simulations;
Note: All the values are grouped in compliance with Table II.

B. Multiple WHs

For the case of multiple WHs we utilized morning hot water peak demand data from the Meppel project. The corresponding distribution can be expressed by the following distribution $P_{preak} = 1/(1.2\sqrt{2\pi})exp((7.7^2 - t)/0.6)$. Hot water profiles contributing to the morning peak hot water demand were generated for *60* households of which *10* households enrolled in the DLC program. Furthermore, all households are equipped with identical water heating units. Comfort parameters for WAs are $\Delta T_c = [40, 45]$ °C, $\Delta T_{tol} = [T_{c,min} - 2°C,\ T_{c,max} + 1°C]$, $\dot{m}_d = 9$[L/min]. The duration of each water use event was also taken fixed and equal to *10* [min] for all the considered WAs. The simulation results for multiple WHs, are illustrated in Fig. 5. Fig. 5 also represents the share of the obtained D_T and $E_e(\Delta t_{pre})$ of their maximum values for *10* boilers shut off by DLC.

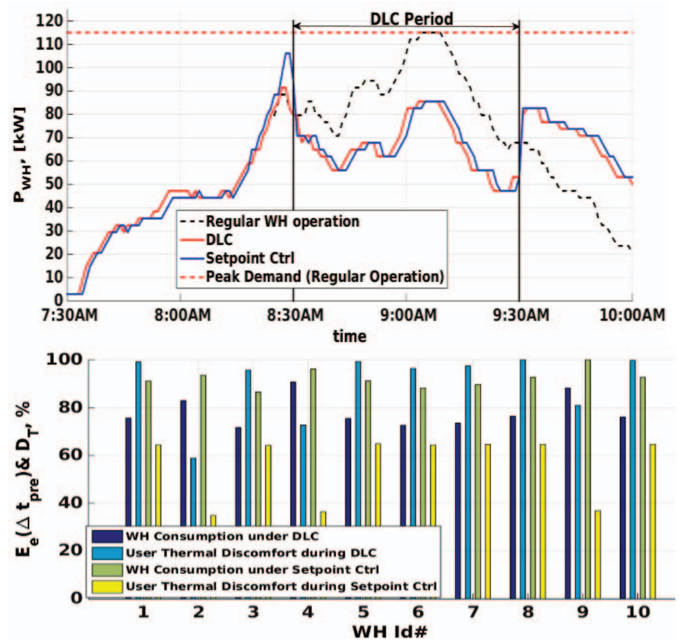

Figure 5. Set-point Control of Multiple WHs (medium comfort benefits for the user)

C. Results Discussion

Pareto fronts for WAs of distinct duration in Fig. 4 show that the minimum D_T can be achieved at the expense of higher $E_e(\Delta t_{pre})$ for long WAs as compared to the WAs with the shorter duration. Furthermore, zero discomfort D_T can be reached only for relatively short WAs whose duration does not exceed *7* minutes. The limited capacity of the boiler's tank can be an explanation for it: longer WAs require more hot water. However, the WH's tank can be preheated only to the maximum temperature allowed for safety reasons (in our setup $T_{wh,max} = 90$°C). As follows from Table III the set-point control under $T(0) = 65$°C without the preheating procedure ($E_e(\Delta t_{pre}) = 0$) produces equal results as conventional DLC. Whereas compared to the classical DLC the set-point control can yield up to *5.5* times smaller D_T at the expense of the relatively small energy consumption for preheating $E_e(\Delta t_{pre}) = 2.36$ [kWh] (e.g., for WAs with medium duration). In the worst case scenario when $T(0) = T_{cw} = 15$°C the same level of D_T can be achieved at the higher cost of $E_e(\Delta t_{pre}) = 7.04$ [kWh]. Moreover, in case of $T(0) = 15$°C without preheating the maximum user dissatisfaction with the tap water temperature D_T can get *4* times more severe (e.g., WA with $\Delta T_c = [40, 45]$°C) as compared to the situation when the WH initially cycles. As can be seen from Fig. 5 the suggested set-point control of *10* WHs can significantly lower D_T during the DLC disconnection. The maximum increase of thermal comfort reached *54.5*% for the WH#*9* at the cost of extra *0.4* [kWh] per simulation period. The lowest enhance of user comfort by *40*% was for the WH#*2*. The peak demand for the thermostat control period increased to *106* [kW] (≈ *90*% of the peak demand in case no DLC was taken). Noteworthy, the peak demand in the preheating period can exceed the maximum peak load without DLC, if all the households under DLC aim at the minimum D_T.

Overall, in reply to the question raised in the introduction, the simulations suggest that without exceeding the peak demand the maximum improvement of comfort for an individual household can reach $\approx 55\%$ at the relatively small cost of $\approx 14\%$ with respect to the simulation period.

VI. FUTURE WORK

The set-point control proposed in this paper aims at improving user thermal comfort during DLC given the information about user comfort preferences for single water events. We assume this information is available from the forecast. However, comfort levels can drastically vary among individuals, and from one WA to another. Moreover, a person might alter her comfort desires for a given WA. The future work can be focused on how a forecast can accurately set detailed comfort parameters of WAs, as well as to account for their variability over time.

This paper considers a simplified scenario of water usage when a user withdraws hot water during some standalone WA. In reality multiple WAs (some of them overlapping) can occur in a home environment. The proposed set-point control of the thermostat should be extended and generalized for more realistic scenarios.

Implementing the set-point control for multiple boilers can sometimes result in a new peak of demand in the grid. This disadvantage can be eliminated in the further research by limiting the aggregated power demand when calculating Pareto fronts by means of optimization.

We see the described case as illustrative for a larger scope of storing additional energy in households before DLC events. However, additional research should consider specifics of other storage capacities, such as rechargeable electric batteries.

VII. CONCLUSION

In this paper we propose a simple yet efficient mechanism to mitigate user thermal comfort disruptions during DLC disconnection of a domestic water heaters. By preheating the boiler to a higher setpoint temperature before a DLC event and tuning the outflow from the tank, the approach can increase user satisfaction with the quality of hot water service within DLC periods. We see the proposed approach as suitable for pre-storing additional energy before DLC events in households. The link between electric expenses for pre-storing additional energy before DLC and user discomfort can increase user awareness about how DLC impacts their lifestyles. Also, the utility could consider providing possibilities for pre-storing additional energy before DLC events. Together, it can increase the attractiveness of DLC programs for customers.

REFERENCES

[1] D. Kathan, S. Bennett, C. Cammarata et al., "Assessment of demand response and advanced metering," U.S. F.E.R.C. Commission, Staff Rep., Dec. 2008.

[2] S. Borenstein, M. Jaske, and A. Rosenfeld, "Dynamic pricing, advanced metering, and demand response in electricity markets," UCEI, Berkeley, CA, CSEM WP 105, 2002.

[3] M. Frincu and Z. Gima, "A bottom-up approach to sustained curtailment and comfort for controlled demand response," in *Proc. 2014 IEEE Conference on Technologies for Sustainability*, pp. 61-68.

[4] M. Alizadeh, Y. Xiao, A. Scaglione, and M. van der Schaar, "Incentive design for direct load control programs," in *Proc. 51st Annual Allerton Conference on Communication, Control, and Computing*, 2013, pp. 1029-1036.

[5] M. H. Albadi and E.F. El-Saadany, "A summary of demand response in electricity markets," *Electric Power Systems Research*, vol. 78, pp. 1989-1996, 2008.

[6] H. Jorge, C. H. Antunes, and A. G. Martins, "A multiple objective decision support model for the selection of remote load control strategies," *IEEE Trans. Power Systems*, vol. 15, no. 2, pp. 865-872, 2000.

[7] M. Nehrir, B. LaMeres, and V. Gerez, "A customer-interactive electric water heater demand-side management strategy using fuzzy logic," in *Proc. 1999 IEEE Power Engineering Society Winter Meeting*, vol. 1, pp. 433-436.

[8] K. Elgazzar, H. Li, and L. Chang, "A centralized fuzzy controller for aggregated control of domestic water heaters," in *Proc. 2009 IEEE Canadian Conference on Electrical and Computer Engineering*, pp. 1141-1146.

[9] A. Sepulveda, L. Paull, W. G. Morsi et al., "A novel demand side management program using water heaters and particle swarm optimization," in *Proc. 2010 IEEE Electric Power and Energy Conference*, pp. 1-5.

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

[11] P. Du and N. Lu, "Appliance commitment for household load scheduling," *IEEE Trans. Smart Grid*, vol. 2, no.2, pp. 411-419, 2011.

[12] M. A. A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Coordinated scheduling of residential distributed energy resources to optimize smart home energy services," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 134-143, 2010.

[13] A. Gomes, C. Antunes, and A. Martins, "A multiple objective approach to direct load control using an interactive evolutionary algorithm," *IEEE Trans. Power Systems*, vol. 22, no.3, pp. 1004-1011, 2007.

[14] A. Belov, N. Meratnia, B. J. Van der Zwaag, and P. Havinga, "An efficient water flow control approach for water heaters in direct load control, " *Journal of Engineering & Applied Sciences*, vol. 9, no. 11, pp. 2106-2120, 2014.

[15] S. Mecum, "A wish list for residential direct load control customers," Quantum Consulting, Berkeley, CA, Tech. Rep. Summer Study on Energy Efficiency in Buildings, 2002.

[16] V. J. Robertson, A. Ward, J. Low, and A. Reed, "Electrotherapy explained: principles and practice,". Elsevier Health Sciences, 2006.

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

[18] P. Dolan, M. Nehrir, and V. Gerez, "Development of a monte carlo based aggregate model for residential electric water heater loads," *Electric Power Systems Research*, vol. 36, no. 1, pp. 29-35, Jan. 1996.

[19] I. Lane and N. Beute, "A model of the domestic hot water load," *IEEE Trans. Power Systems*, vol. 11, no. 4, pp. 1850-1855, 1996.

[20] U.S. Department of Energy, "The Reference to EnergyPlus Calculations," EnergyPlus engineering reference, Apr. 2013.

[21] J. Bartam, Y. Chartier, J. V. Lee et al., "Legionella and the prevention of legionellosis," World Health Organization, 2007.

[22] Meppel Energie Project (2013, Jan.), [Online]. Available: http://www.utwente.nl/ctit/research/research_projects/national/topsectors/meppel_energie/

[23] J. Widén, M. Lundh, I. Vassileva et al., "Constructing load profiles for household electricity and hot water from time-use data: modelling approach and validation," *Energy and Buildings*, vol. 41, no. 7, pp. 753-768, 2009.

[24] J. Kaye, "Action a2a Development of concept and offering RENEW : Development of concept and offering", Energy Saving Trust Limited, Waterwise Project, UK, 2009.