Load Shifting of Domestic Water Heaters under Double Price Tariffs: Bringing Together Money Savings and Comfort

Alexander Belov*, Vadim Kartak§ Alexandr Vasenev*, Nirvana Meratnia*, and Paul J.M. Havinga*
*University of Twente, The Netherlands, {a.belov, a.vasenev, n.meratnia, p.j.m.havinga}@utwente.nl
§Bashkir State Pedagogical University, Russia, kvmail@mail.ru

***Abstract*—Demand Side Management (DSM) programs can offer residential electricity consumers opportunities to cut their energy bills. However, if such programs significantly downgrade comfort of consumers, they can choose to opt them out. This impedes the DSM implementation in practice and declines the efficiency of DSM in overall. Finding ways how consumers can reduce their money expenses with least impact to their comfort is thus desirable.**

This paper focuses on tank electric water heaters (WHs) under double-price tariffs as a case of energy storage devices under simplified variable pricing. We investigate whether or not the WH load shifting can bring money savings while maintaining the user comfort based on the introduced expenses-comfort balancing approach. The proposed approach is based on day-night energy rates and the energy-comfort model suggested earlier. The refined energy model constitutes the first contribution of this paper. As the second contribution, we reformulate the energy-comfort balancing problem into the problem of 'expenses-comfort balancing'. By simulating diverse hot water usage we show that the proposed mechanism can enable monetary savings without significant drop of comfort. Specifically, the customers can reach up to 20% of daily money savings compared to the regular operation of the heater during weekdays. The reported research can be of interest to utilities that focus on improving consumer uptake of DSM.

I. Introduction

Demand Side Management (DSM) is recognized by the European Commission as an important instrument for improving energy efficiency and stability of the electrical grid [1]. In particular, DSM aims at modifying normal consumption patterns of residential electricity consumers to flatten an energy demand curve. While utility companies can optimize the use of networks, consumers can save their money.

As a first step towards using real-time price-based programs - claimed as the most straightforward and efficient DSM measures [2] - utilities currently offer a wide range of day-night Time-of-Use (ToU) tariffs. However, consumers may doubt if they will benefit from such tariffs. Some people with day-night tariffs actually realize that switching to a new tariff makes their bills more expensive, because the plan does not fit their lifestyles [3]. The last issue could be of paramount importance to the end-user. Thus, if dissatisfaction with comfort outweighs the desire to save money, customers might reject the advantages of such DSM. Therefore, besides showing the money saving potential, there is a need to assure the user that control of a home device is not in conflict with personal comfort. To make an informed choice, consumers should be able to relate their money savings with understanding of potential impact on comfort. Providing users with such feedback before a control action is taken can be a perspective step for gaining consumer trust.

978-1-5090-3358-4/16/$31.00

Considering that water heating is one of the most energy consuming activities in a household (13%) and the residential energy consumption is increasing (it accounted for 26.8% of the total energy consumption in EU-28 in 2013), optimizing energy consumption of water heaters (WH) is a highly relevant topic. WHs have been extensively used in DSM applications over the years [4], [5] and amongst others some DSM approaches concerned consumer response to dynamic prices [5], [6]. In spite of a widespread availability of day-night tariffs to residential consumers, only few studies investigated pros and cons of WH operation under these ToU plans [7], [8]. Other attempts to account for user comfort in DSM applications for WHs can be found in the literature [4]–[6], [9], [10]. Typically, user discomfort is modeled as a difference between the instantaneous values of the desired and actually obtained tap water temperature [4], [5], [9].

Although the comfort modeling was considered earlier, the topic of scheduling the WH load with respect to both comfort and money savings received less attention. This paper aims to bridge this gap by proposing a mechanism that considers an intricate interplay of multiple factors such as price changes, heat losses, water events and influence of energy consumption on user comfort. By providing the information about energy consumption and comfort, the paper aims to address a reasonable question the consumer can ask: "Will I benefit financially from joining a DSM program with double-price tariff without sacrificing my comfort?.

Specifically, this paper proposes a new approach for load shifting of domestic WHs to consider both the user's desire to benefit financially and aspiration of having a preferred level of thermal comfort during the water usage. The distinguishing feature of our approach as compared to [8] is that we pay special attention to user comfort issue. To quantify user thermal (dis-)comfort, we adapt the user comfort model introduced previously in [11], [12]. As follows from further discussion two goals that an end-user can pursue - minimizing costs for water heating and minimizing thermal discomfort during the water usage - can become at odds with each other. To explicitly interrelate these conflicting objectives, we apply a multi-objective optimization approach.

By simulating diverse scenarios of water usage with different personal comfort preferences we demonstrate that applying the proposed technique for WH load shifting one can derive multiple trade-offs between money expenses and thermal comfort of a user. A number of these non-dominated optimal solutions forms Pareto front.

The rest of the paper is organized as follows. In Section II we highlight the difficulties related to the WH load shifting and point out the need for solving energy planning problem. We give some background information on the utilized energy model in Section III. Our approach for the expenses-comfort balancing problem can be found in Section IV, while the simulation results and conclusions are presented at the end of this paper.

II. Difficulties of WH Load Shifting

Using the ToU day-night tariffs electricity consumers pay a lower electricity price at night than during the daytime (e.g., Economy 7 tariff in UK). Thus, it can be more profitable to heat up all water for the following day overnight [3]. By preheating all the water at night some customers can experience comfort disruptions, because they find that water is warmer in the morning and cooler in the evening [3]. To this extend, they can save money at the cost of their comfort.

However, calculating possible money savings in relation to comfort is not a trivial task. While minimization of money expenses in case of a flat tariff can be projected onto the task of minimization of energy consumption, in case of double-price tariffs this relation can be entangled. A number of intricate interdependencies that influence actual money savings from the load shifting including users' comfort requests, energy prices, heat losses to the ambient, and others, should be considered with respect to the WH pre-heating. In this connection, finding the optimal plan of power injections considering interplay of such factors can be seen as a cornerstone for efficient WH load shifting.

A. Effect of WH Load Shifting on Cost

Shifting the WH load can become unprofitable for consumers in particular situations. This subsection illustrates it by illuminating a simplified, yet close to real-life, scenario based on two cases. In this scenario the reduced energy rate is available from 24:00AM to 7:00AM in the weekdays and a hot water usage takes place in the period of high electricity prices. The *rate difference* between day and night periods is assumed to be 0.10 €.

In the first case, a 5-minute hot water event occurs at 8:00AM. Suppose that the WH is initially discharging during the entire 7-hour night period without electricity use as shown in Fig. 1. When the temperature inside the tank hits the thermostat lower setpoint temperature of $65°$C at 7:00AM the heater turns on to warm it up again (this logic corresponds to typical WH control operations). By shifting this warming

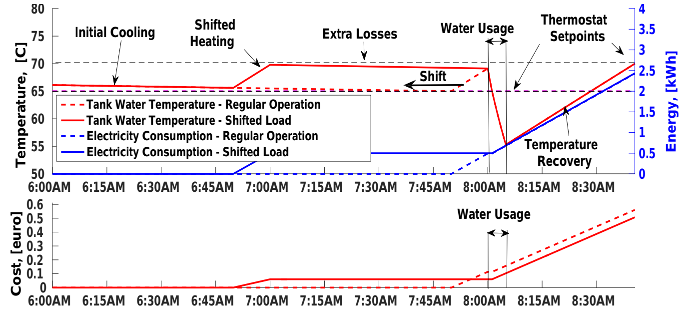

Fig. 1. The case of money savings due to the WH load shifting.

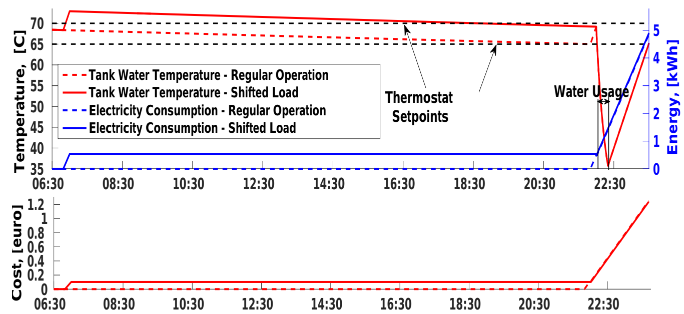

Fig. 2. The case of no money savings.

procedure to the cost-effective night period one can save 0.05 €.

In another case, WH load shifting may be unprofitable though. For instance, the day tariff start-up and the actual water usage can have a long time lag in-between as shown in Fig. 2. The heat losses within the shifting period can thus lead to extra energy and money expenses, making load shifting unfavorable. Together, these two cases indicate that actual money savings are directly connected to *hot water consumption patterns*. In addition to pricing schemes, the maximum amount of heat stored in a WH is limited by its *engineering parameters*. As such, the maximum tank water temperature is typically constrained by safety reasons. If State of Charge (SoC) of a WH exceeds this maximum allowed temperature, the pressure building up in the tank can cause the WH to blow up [13]. Therefore, only water activities (WAs) that meet the criteria $SoC_{\text{WA}} < SoC_{\max}$ would allow to shift the WH load to the low-price periods. Besides, the WH insulation (U-factor) can influence the rate how the stored energy. Because the prestored heat naturally emits through the walls of the storage tank, to provide the user with the desired comfort, this heat leakage should be compensated by preheating the WH to $SoC_{\text{WA},1} > SoC_{\text{WA}}$. Finally, the maximum amount of the heat in the tank is linked to its volume.

B. Effect on User Comfort

Because of the factors listed above, the SoC of the WH can be insufficient and a user can experience cooler tap water temperature. We illustrate it based on the example of an outdated WH with a poor insulation [14] and equipped with a timer that shuts the WH unit down in the day time when tariff rate is high (Fig. 3). Since this WH has significant standby losses, shifting the its load to the night period, before

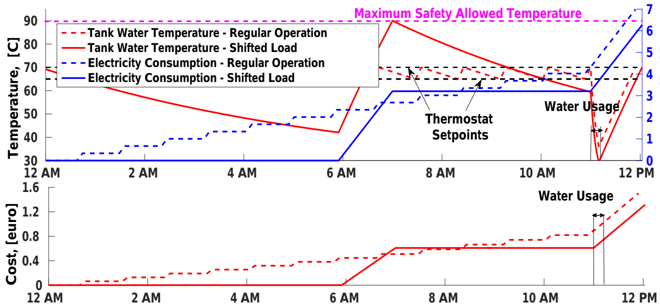

Fig. 3. Lower SoC at the WA's start-up.

7:00AM, would require pre-heating all the water to nearly the boiling point of $100°$C. To avoid such extreme WH operation, the maximum safety temperature is limited to $90°$C in our case, however, pre-heating the WH to the maximum $90°$C can provide only $60°$C, but not the wanted $70°$C at 11:00AM because of the heat losses. Thus, even though the user will gain money savings via load shifting, the he might experience a steeper fall of tap water temperature as compared to the regular operation of the WH.

In short, *engineering parameters* of the WH and in particular *heat losses* can impact both money savings (from the WH load shifting) and user comfort. Meanwhile, *day-night tariff rate difference* as well as *hot water usage daily patterns* mainly influence money savings. All these parameters are important for load shifting algorithms and they form the basis for an optimization problem.

III. Background on Aligning Energy Consumption to Comfort

As a continuation of the energy-comfort balancing problem solved in [15], finding optimal power injections into a WH that lower the costs while preserving the user comfort, can yield the optimal plan for the new *expenses*-comfort balancing problem. In [15] we proposed a solution for balancing energy vs. comfort by applying the multi-objective optimization to resolve two conflicting objectives, i.e. minimizing electricity consumption of the WH and minimizing thermal comfort disruptions.

The energy-comfort balancing was conducted under several assumptions. First, we considered a *single-person apartment* equipped with the medium-size WH (in our case, 80 L) that served sequential water events (no parallel water usage). Second, we used a *discrete time model* with a finite horizon equal to one day ahead. The step size t_{SP} min was linked to the intra-day timescale and $k \in \mathbb{Z}_{+}, k \geq 0$ represets the index on this timescale. Furthermore, we considered that the tank water temperature T_k can take only *discrete values* in the range of $[T_{\mathrm{cw}}, T_{\mathrm{WH,max}}], T \in \mathbb{Z}_{+}\}$. Moreover, we assumed that the information about the WAs expected in the following day is available from the forecast and comfort preferences are also known in advance from user input or learned based on hot water usage patterns. Further the above two objectives are considered in detail.

A. User Thermal Comfort Model (TCM) and Minimization of Thermal Discomfort

In this paper we utilize the user thermal comfort model introduced earlier in our studies [11] and further improved with some contextual information in [12]. The model not only accounts for the potential deviation of the actual tap water temperature $T_{\mathrm{d}}(t)$ from the user-desired temperature at every moment of the water usage, but also for the time during which (s)he experiences such temperature differences. The model employs this information in the form of personal temperature tolerance functions $\{F_{\mathrm{T}}(T_{\mathrm{d}})\}$. Thus, every single user has a unique set of tolerance functions $\{F_{\mathrm{T},\, i,j}\}$ with parameters dependent on the individual skin perception of a user (i) and on a particular scenario of water usage (j). Then the thermal discomfort of the i-th user during the single j-th WA can be expressed as:

$$D_{\mathrm{T}}(t)_{i,j} = F_{\mathrm{T}}(T_{\mathrm{d}})_{i,j} A_{\mathrm{T}}(t)_{i,j} \tag{1}$$

where A_{T} is the area bounded by $T_{\mathrm{d}}(t)$ and the user comfortable temperature zone $\Delta T_{c,i,j} = [T_{\mathrm{c,min}}, T_{\mathrm{c,max}}]_{i,j}$.
Due to the considered scenario of hot water usage (single-person apartment), the first objective for the comfort and money balancing energy planning problem can be set as $min[F_1] = min[\sum_{j=1}^{N_{\mathrm{WA}}} D_{\mathrm{T}}(t)_j]$.

B. Water Supply Thermodynamics and Minimization of Energy Consumption

We adopt the thermodynamic model of the well mixed cyclic type WH from the EnergyPlus simulator:

$$MC\frac{dT}{dt} = P_{\mathrm{e}} + P_{\mathrm{cw}} - P_{\mathrm{hw}} - P_{\mathrm{loss}} \tag{2}$$

where M is mass of water in the tank; C is the specific heat; P_{e} is the thermal power provided by the heating element; P_{cw} and P_{hw} are cold water inflow and hot water outflow from the tank, and P_{loss} stands for the heat transfer to the ambient.

By solving the differential equation (2) for time, electric consumption for preheating E_{e} can be expressed as:

$$E_{\mathrm{e}}(\Delta t_{\mathrm{pre}}) = P_{\mathrm{e}}\Delta t_{\mathrm{pre}} = \alpha P_{\mathrm{e}} ln\Big(\frac{\beta - SoC(\Delta t_{\mathrm{pre}})}{\beta - SoC(0)}\Big) \tag{3}$$

where α and β are the coefficients dependent on engineering parameters of the WH (no water is drawn from the WH during pre-heating, i.e. $\dot{m} = 0$); $SoC(0)$ and $SoC(\Delta t_{\mathrm{pre}})$ are the SoCs of the WH in the beginning and at the end of the preheating period Δt_{pre} respectively.

The second objective for the *energy*-comfort balancing problem was $min[F_2] = min[\sum_{j=1}^{N_{\mathrm{WA}}} E_{\mathrm{e}}(\Delta t_{\mathrm{pre}})_j]$.

IV. Our Approach

In our approach for the *expenses*-comfort balancing problem we improve and adopt the energy model previously used for solving the problem discussed in Section III.

A. Updated Energy Model

In [15] we introduced the optimization model for balancing electricity consumption of a WH and user comfort as a mechanism for regulation of electricity expenses for hot water service with respect to the end-user thermal comfort. The model used a finite-time planning horizon $N_{\text{SP}} \triangleq \frac{24*60}{t_{\text{SP}}} \geq 1$ to solve a multi-objective integer liner programming problem. The idea was to compute vector of heat injections into the WH $\mathbf{P}\text{e}_{\;[N_{\text{SP}}\text{x}1]}$ that ensures the optimal user thermal comfort during the hot water usage and keeps energy consumption as small as possible. The model required the input matrices $\boldsymbol{A}^{-}$, $\boldsymbol{A}^{+}$ of size $[N_{\text{SP}}\text{x}M]$ that describing tank water temperature transitions T_{k+1} for N_{SP}-intervals provided the input temperature $T_k \in [T_{\text{cw}}, T_{\text{wh,max}}], T \in \mathbb{Z}$ for each of two possible states of the WH $x = \{0, 1\}$ (on/off respectively).

One of the downsides of the model was the inability to account for the standby losses when the discrete step size was relatively small (e.g., $t_{\text{SP}} = 5$[min]). Specifically, the t_{SP} can be insufficient to make T_k cool down by at least 1°C ($x = 0$), As a result, the rows of $\boldsymbol{A}^{-}$, $\boldsymbol{A}^{+}$ can become indistinguishable for the solver and the solver can end up with multiple solutions $\mathbf{P}\text{e}_{\;[N_{\text{SP}}\text{x}N_{\text{sol}}]}$ some of which could be less efficient in real-life because of the heat emission to the ambient. On the other hand, bigger t_{SP} can result in the overheating/cooling of the WH, since the decision to consume or not to consume energy is taken for the entire interval t_{SP}.

We mitigated this issue in [15] by breaking the whole planning horizon into the time chunks $\Delta t_{\text{ch},\ i\in[1,N_{\text{ch}}]}, N_{\text{ch}} > N_{\text{SP}}$ consisting of only neighboring WAs and separately solving optimization subproblems each for every time slice of the day. The size of time-chunks Δt_{ch} was defined based on the sparsity of WAs in the hot water consumption profile. Dividing the planning horizon into chunks with WAs allows to segment multiple separate, yet connected optimization subproblems that can be solved sequentially. Each subproblem was interconnected with the next one by passing the tank temperature at the end of the current time chunk $T(\Delta t_{\text{ch},\ i})$ to the input of the following optimization subproblem $i+1$ subtracting the temperature fall caused by the standby losses. Importantly, that each solution $P_{\text{e},i}$ was was always limited to only one chunk which can be inefficient when the necessity of WH's load shifting is dictated by higher electricity prices. Thus, for instance, the water might be heated up in the lower-price chunk if financial benefit outweighs standby costs.

In this paper we propose a different and more efficient way to account for standby losses. Instead of breaking the input matrices $\boldsymbol{A}^{-}$, $\boldsymbol{A}^{+}$ we propose to squeeze them vertically across the intervals $\Delta t_{\text{no WA},i}$ of no hot water usage. It is clear that the minimum time Δt_{cool} it takes to cool down the tank water by 1°C due to the heat losses is when the WH is charged to $T_{\text{wh,max}}$. Suppose that the i-th interval between adjacent WAs consists of $N_{\text{no WA},i} = \lfloor \frac{\Delta t_{\text{no WA},i}}{t_{\text{SP}}} \rfloor$ number of discrete steps and assume the worst time that might be needed to heat up the the boiler (from T_{cw} to $T_{\text{wh,max}}$) contains N_{pre} of steps t_{SP}. Then one can localize n-number of intervals that can fit/encapsulate both $N_{\text{cool}} = \lfloor \frac{\Delta t_{\text{cool}}}{t_{\text{SP}}} \lfloor$ and N_{pre} by checking the inequality $\frac{N_{\text{no WA},i} - N_{\text{pre}}}{\Delta t_{\text{cool}}} \geq 1, i \in [1, N_{\text{no WA}}]$. These located intervals can be then deleted from the matrices $\boldsymbol{A}^{-}$, $\boldsymbol{A}^{+}$ and replaced by n-single extra rows which contain the tank water transitions during the entire corresponding intervals. Therefore, the size of the resulting matrices $\boldsymbol{A}^{-}$, $\boldsymbol{A}^{+}$ boils down to $[N_{\text{SP,new}}\text{x}M] = [N_{\text{SP}} - \sum_{i=1}^{n} N_{\text{no WA},i} - N_{\text{pre}} + n\text{x}M]$. By doing so, we not only incorporate the losses directly into the optimization model, but also reduce the total number of decision variables to be found. In contrast to the segmentation approach in [15], the proposed approach allows to find the optimal plan of heat injections regarding all WAs present in the planning horizon, hence enables more flexible load shifting. Whereas preserving the N_{pre}-rows in the original matrices in the vicinities of the located intervals should guarantee that there is enough time to prepare hot water service even under the maximum user comfort request.

B. Integrating Price Information into Energy Planning Problem

Updating the energy model further with the information about the energy prices gives users an opportunity to not only gain money savings due to the reduced energy consumption, but can also let them benefit from the WH load shifting to low-price periods. Having the information about the upcoming water usage from the forecast, we search for the optimal time to start the night pre-storing of heat, so that the cost for preheating and personal thermal discomfort are minimized.

We apply a multi-objective approach to solve this problem. The optimization problem can be formalized and solved in a two-stage process. On the first stage we find the SoC of the WH (related to temperature inside the tank T_{WA} at the beginning of the WA) for all WAs in the forecast:

$$min[F_1] = min[\sum_{i=1}^{N_{\text{WA}}} D_{\text{T}}(t)_i]. \tag{4}$$

The optimal solution for F_1^* represents a binary vector of the WH's power demand at every time interval k $\boldsymbol{x} = \{x_k\}, x_k = \{0, 1\}$ of size $[N_{\text{SP,new}}\text{x}M]$ that ensures the optimal SoCs of the WH with respect to the maximum user comfort. This solution is then fed to the next stage:

$$min[F_2] = min[\boldsymbol{\lambda}_{\text{low}} \boldsymbol{E}^T_{\text{e,low}} + \boldsymbol{\lambda}_{\text{high}} \boldsymbol{E}^T_{\text{e,high}}], \text{ s.t.} \tag{5}$$

$$F_1(\boldsymbol{x}) \leq F_1^* + \epsilon_p, \tag{6}$$

$$T_{\text{cw}} \leq T_{\text{WA}} \leq T_{\text{wh,max}}, \forall k \in [0, N_{\text{SP,new}} - 1] \tag{7}$$

where $\boldsymbol{\lambda}_{\text{low}}, \boldsymbol{\lambda}_{\text{high}}$ denote the price vectors for the low and high-price periods respectively (double-rate tariff); $\boldsymbol{E}^T_{\text{e,low}}, \boldsymbol{E}^T_{\text{e,high}}$ are the column vectors of energy consumption during these periods.

The constraint (6) specifies the preferred level of comfort that should be maintained, while (7) preserves the tank from overheating. To attain the solutions corresponding to comfort levels in the range from the maximum to the minimum, the problem in (5) can be solved multiple N times with different parameter $\epsilon_p \in [0, max(F1) - F1^*]$.

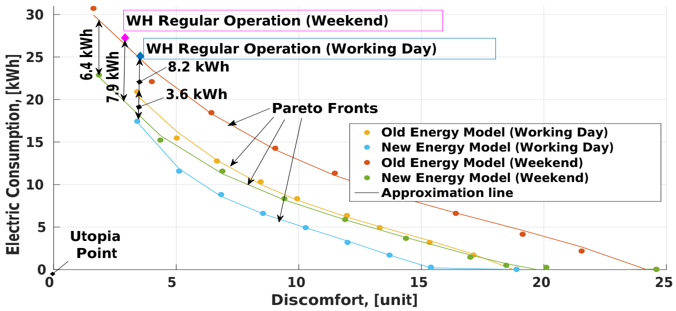

Fig. 4. Pareto fronts for the energy models.

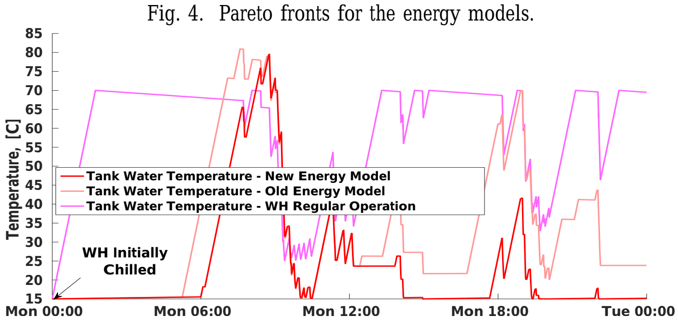

Fig. 5. The effect of the heat losses embedded in the new energy model.

V. Simulations

To estimate the updated energy model claimed as the first contribution of this paper, we performed the simulations for a collection of working days and weekends and compared the results with the existing energy model and regular operation of the WH. We used hot water consumption profiles for a single-person apartment generated by means of the Load Profile Generator (LPG) software [16]. We linked this information to the user comfort preferences based on the publicly available statistical averages [17].

To justify the applicability of the updated energy model to the expenses-comfort balancing optimization task (4-7), we performed a set of single day and weekly simulations and compared the results with the results of the original energy model and normal operation of the WH, while mapping their energy consumption on the day-night tariff price vector (for demonstrative purposes was taken tariff $\Delta\lambda = 0.10$ €, $\lambda_{\text{high}} = 0.23$ €/kWh).

A. Simulation Results

1) Effect of Energy Model Update: The positive effect of the improvements introduced to the old energy model is shown for working days and weekends in Fig. 4. The thermal discomfort is represented as a sum of discomfort levels for the individual WAs, i.e. any single discomfort value refers to cumulative discomfort of the whole set of WAs.

The two solutions corresponding to user's maximum comfort request in the old and updated energy models are shown together with the WH's regular operation in Fig. 5.

The solutions obtained by proposed price model, the old energy model and during the regular operation of the WH are depicted in Fig. 6.

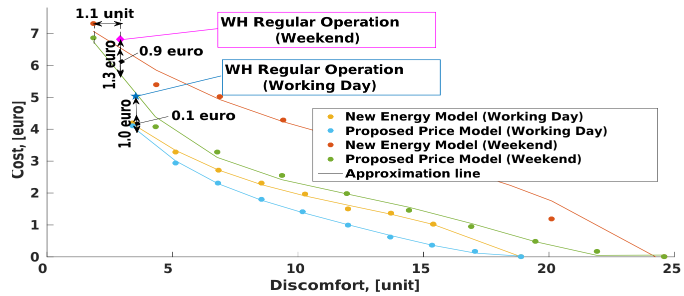

Fig. 6. Pareto fronts under the double-price tariff.

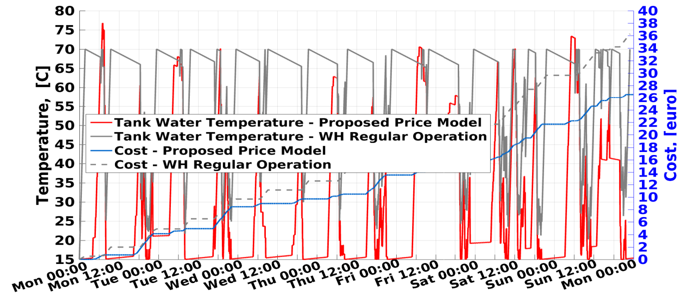

Fig. 7. The best found weekly energy plan (maximum comfort setting).

2) Multiple Days: We also simulated weekly periods to investigate the profitability of the proposed price model in a long run provided that every day of a week a user had the maximum thermal comfort preference. The simulation results for one typical week obtained through the price model are shown in Fig. 7.

B. Results Discussion

As can be seen from Fig. 4 the updated energy model demonstrates certain improvement in energy consumption for both the simulated working days (by 24%) and weekends (by 33%) as compared to the original energy model. This improvement can be explained by more accurate heating of water with respect to the heat losses. As shown in Fig. 5 now the solver schedules heating cycles closer to the actual WAs which allows to avoid unneeded heat wastage.

It follows from Fig. 6 that the suggested price model can yield both financial savings and improved thermal comfort as compared to the regular operation and modified energy model. Specifically, money savings can account for 19% (1 €) and 20% (1.3 €) at the weekend day and working day respectively and comfort savings can reach up to 1.1 unit during the weekend as compared to the same comfort level in the WH regular operation. It can be explained by a more intense hot water usage at weekends and hence bigger amount of electric energy that can be potentially shifted to the low-price period. At the same time, the increased heat losses make the standard operation of WH less efficient during the weekends, which thereby results in the lower share of saved energy of the total during regular operation in the weekends (Fig. 6 and Table I).

The price model better mitigates thermal discomfort at the weekends than at the working days, which points out that during the working days, where water events can be sparse in time, there might be multiple solutions which can ensure

TABLE I
SIMULATION RESULTS

Period	Proposed Price Model					Updated Energy Model					Reg. Oper.		
	C_{min}, [€]	$D_{\mathrm{T,max}}$, [unit]	C_{max}, [€]	$D_{\mathrm{T,min}}$, [unit]	E_{e}, [kWh]	C_{min}, [€]	$D_{\mathrm{T,max}}$, [unit]	C_{max}, [€]	$D_{\mathrm{T,min}}$, [unit]	E_{e}, [kWh]	C_{e}, [€]	D_{T}, [unit]	E_{e}, [kWh]
I	0	18.9	4.1	3.4	21.4	0	18.9	4.2	3.4	17.5	5.1	3.5	25.1
II	0	24.6	6.9 (5.5)	1.8	33.2	0	24.6	7.0 (6.5)	1.8	22.9	6.8	2.9	32.4
week	0	156.4	26.5	7.0	136.7	0	156.4	27.7	7.0	136.2	36.3	32.8	169.5

the same level of comfort. In other words, it means that the total user comfort request, i.e. preferred comfort for the whole day on Pareto front, can be re-distributed differently across multiple WAs during a day so that the total comfort for all the WAs will remain the same. In comparison with the the updated energy model the potential of the price model to cut the costs for water heating unfolds especially during the weekends (0.95 €) rather than on the working days (0.11 €).

Considering the variability of hot water consumption across the days, the price model could enable $19\% - 26\%$ (Fig. 7) money savings as apposed to the WH regular operation.

This paper addressed the problem at a level of an individual user and suggested a way to anticipate benefits from employing double tariffs. The future work can be focused on distinguishing Pareto optimal solutions for individual WAs which can be handy for a user. The simulation part can be extended in the future to embrace other dynamic pricing. To obtain a plausible water consumption model in practice, the work can be further focused on 'learning' approaches for WAs.

VI. CONCLUSION

This paper proposes a control mechanism to schedule a domestic tank electric water heater (WH) under the double-price tariff. The distinguishing feature of our approach is that, being based on the information about water activities, it highly respects user comfort.

In this paper we investigate how users can benefit financially from the WH load shifting while maintaining hot water service at the preferred comfort level. We modify the existing energy model by incorporating the heat losses and further utilize it for balancing comfort and monetary costs for water heating. To solve the latter problem, we apply a multi-objective optimization approach that yields the needed relation between the heating costs and user thermal comfort in the form of Pareto front. This relation can give a consumer an insight about potential money savings and the possible impact on comfort before implementing DSM, while the utilities can use practice DSM programs in a more consumer-attractive way, which might increase consumer uptake of DSM programs in overall.

By simulating diverse scenarios of hot water usage in a single person apartment, we demonstrate the capability of the proposed mechanism to enable up to 20% daily money savings as compared to the WH regular operation under the same comfort request.

REFERENCES

[1] UE. (2012, Nov.) Directive 2012/27/eu of the european parliament and of the council. Official Journal of the EU. [Online]. Available: http://eur-lex.europa.eu/

[2] M. Frincu and Z. Gima, "A bottom-up approach to sustained curtailment and comfort for controlled demand response," in *Proc. IEEE Conference on Technologies for Sustainability (SusTech'14)*, 2014, pp. 61–68.

[3] Uswitch. (2015) What is economy 7 meter and how does the tariff work? [Online]. Available: http://www.uswitch.com/gas-electricity/guides/economy-7/

[4] H. Salehfar, P. J. Noll, B. J. LaMeres, M. H. Nehrir, and V. Gerez, "Fuzzy logic-based direct load control of residential electric water heaters and air conditioners recognizing customer preferences in a deregulated environment," in *Proc. IEEE Power Engineering Society Summer Meeting'99*, vol. 2, 1999, pp. 1055–1060.

[5] P. Du and N. Lu, "Appliance commitment for household load scheduling," *IEEE Transactions on Smart Grid*, vol. 2, no. 2, pp. 411–419, 2011.

[6] 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 Transactions on Smart Grid*, vol. 1, no. 2, pp. 134–143, 2010.

[7] J. Baker, "New technology and possible advances in energy storage," *Energy Policy*, vol. 36, no. 12, pp. 4368–4373, 2008.

[8] R. Hawley, "Advanced control of energy consumption," in *Proc. IEEE Seminar on Practical Experiences with Predictive Control*, 2000, paper 2000/023, pp. 1–4.

[9] A. Sepulveda, L. Paull, W. G. Morsi, H. Li, C. Diduch, and L. Chang, "A novel demand side management program using water heaters and particle swarm optimization," in *Electric Power and Energy Conference (EPEC), 2010 IEEE*. IEEE, 2010, pp. 1–5.

[10] N. G. Dlamini and F. Cromieres, "Implementing peak load reduction algorithms for household electrical appliances," *Energy Policy*, vol. 44, pp. 280–290, 2012.

[11] A. Belov, N. Meratnia, B. Jan 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, 2014.

[12] A. Belov, A. Vasenev, N. Meratnia, B. J. van der Zwaag, and P. J. Havinga, "Reducing user discomfort in direct load control of domestic water heaters," in *Proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia'15)*, vol. Online ISSN IEEE Xplore = 2378-8542. IEEE, 2015, pp. 1–6.

[13] InterNACHI. Inspecting water heater tanks in residential dwelling units. [Online]. Available: http://education.nachi.org/coursemedia/course-44/documents/Water_Heater_Materials.pdf

[14] U. D. of Energy. Savings project: Insulate your water heater tank. [Online]. Available: http://education.nachi.org/coursemedia/course-44/documents/Water_Heater_Materials.pdf

[15] A. Belov, V. Kartak, A. Vasenev, N. Meratnia, and P. J. Havinga, "Hierarchical scheme for balancing user comfort and electricity consumption of tank water heaters," in *ISGT NA 2016*. IEEE, 2016, accepted.

[16] N. Pflugradt, "Load profile generator - user manual," 2015. [Online]. Available: http://www.loadprofilegenerator.de/

[17] J. Kaye, "Action a2a development of concept and offering renew : Development of concept and offering," Energy Saving Trust Limited, Waterwise Project, United Kingdom, Tech. Rep., 2009.