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Demonstration of Electric Water Heater DR Possibility with Financial Benefit Analysis

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Abstract

The household small electrical appliances can participate in demand response events to support the local electrical infrastructures. Demand response (DR) plays a major role by reducing peak load consumption and controlling distributed generations. This paper presents a demonstration of DR participation of a water heater with financial benefit analysis by using a convenience tool. It also discusses a residential water heater DR possibility by analyzing the obtained data. The smart grid concept with building energy management system, DR flexibility and financial benefits are also discussed here. The main framework of the task consists of electric water heater modeling with several parameters and planning for the DR participation. The overall model is also demonstrated here with the execution of the planned tasks. The results obtained by using this tool is also represented graphically for the demonstration in the paper. It shows that the proposed methodological analysis is financially beneficial for both consumers and aggregators.

Keywords: consumption reduction, demand response, direct load control, financial benefit, modeling

1. Introduction

The idea of the smart grid (SG) concept is developed to support the vast possibilities of distributed energy resources and renewable energy generations with the latest information and communication technologies [1]. It also helps in developing advanced metering infrastructure for energy efficiency, both in demand side management and self-controlled electrical grid to maintain supply and demand reliability during peak consumption [2]. Use of building energy management system (BEMS) with the integration of SG technology can provide sufficient grid flexibility and energy efficiency. The main motivation of climate and energy targets for 2020 namely “20-20-20” is to provide an efficient energy system in every phase of the energy sector [3]. Electricity consumption in commercial and domestic buildings is increasing at a very high rate. The consumption by buildings is 70% in United States where consumption by commercial, industrial and residential buildings in Europe is about 40% [4].

Demand response (DR) provides flexibility in both the commercial and residential electricity management system [5]. The main objective of using DR is to make a balance between consumption and generation in the local electricity infrastructure. It can also provide emergency support to the grid, fill valleys and shave peak load for balancing electricity. Residential small appliances like Electric Water Heater (EWH), air conditioner, dish washer etc. have efficient DR potential. Among those appliances, EWH is considered one of the most suitable to participate in DR programs. It consumes a major amount (7.5% to 40%) of power in the traditional residences [6]. But it has a great potential in the field of power management system as it has storage capability with large adjustment space and the automation control system can easily be adapted by it.

Incentive-based DR program offers incentives to consumers for controlling their usage pattern during peak hours. Direct load control (DLC) is one of the types of incentive-based DR programs. In this method, the activities in demand side can be controlled (shutdown or cycle change) by the aggregator and they can perform this remotely [7]. The main focus of our work is to show the DR program implementation possibility with the financial benefit analysis in the proposed EWH. Additionally, it is also shown the demonstration of the working methodology of the proposed system.

Designing of an EWH based on DLC program is analyzed in [8]. An automatic DLC program for an EWH with overall consumption reduction and cost-effectiveness is determined in [9]. An optimization algorithm based on DLC for thermostatically controlled devices is shown in [10]. It describes the optimal control schedule and the benefit of the reduced load in the electricity market. A novel real-time water flow control approach for EWH in DLC is efficiently presented in [11]. It also describes the demand reduction by using thermostat control.

Our paper describes and analyze the overall consumption for a certain period by using the DLC method, total incentives obtained from the aggregator for participation in this program. The comparison between the total cost and total cost by using this method is also shows significant financial benefit here.

The rest of the paper is organized as follow. Section 2 represents the main framework and modeling of the system. An overall representation of demonstration is described in Section 3. Section 4 discusses the case studies with consumption and financial analysis for different periods of the year. Results analysis is included in section 5. Finally, the main conclusions of the paper are discussed in Section 6.

2. Main Framework & Modeling

Home appliances modeling is essential to understand demand response control strategy. Physical load model can be considered for the case of EWH modeling purpose. An improved physical model of an EWH is analyzed here for demand response purpose. The EWH's parameters are also considered for the analysis purpose. The obtained temperature profile shows the significant variations in the different temperature scenarios. The heater's flow chart parameters model is represented in the Fig. 1 below.

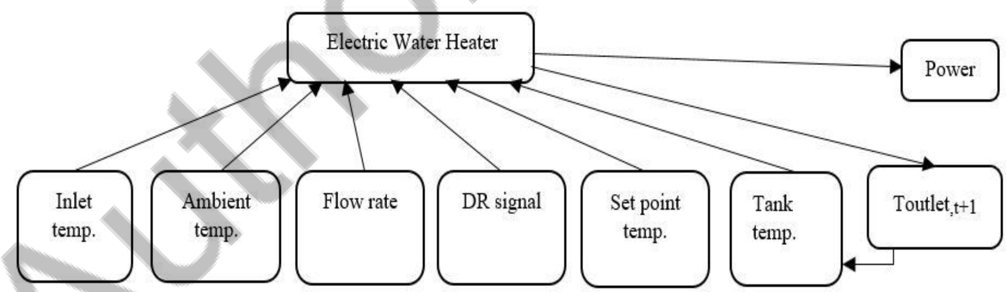


Fig. 6: Overview of Electric Water Heater parameters.

The effective control of the residential water heater depends on the accurate prediction of the heater's load and temperature. A previously established thermal model can be used to determine the real-time water tanks temperature [12]. This model can be found by using the solution of a differential equation:

$$T_H(t) = T_H(\tau)e^{-\left(\frac{1}{R'C}\right)(t-\tau)} + \{GR'T_{out} + R'T_{in} + QR'\} \times \left[1 - e^{-\left(\frac{1}{R'C}\right)(t-\tau)}\right] \quad (1)$$

Here, $T_H(t)$ is tank water temperature at time t (ºF), $T_H(\tau)$ is initial temperature, $R' = 1/(B+G)(W/^{o}F)$,

$C=$ (tank volume).(water density). $C_P\,(W/^{\circ}F)$, $G=SA/R\,(W/^{\circ}F)$, R is tank thermal resistance ($m^2.^{\circ}F/W$), T_{out} is outside tank temperature, T_{in} is incoming water temperature, Q is the input energy as a time function (W), τ is initial time (hour). For all the known parameters and for any given time, the water tank inside temperature can be determined by using this thermal model. If for any case the value of water demand (W_D) or input energy (Q) changes then the initial time (τ) value should be reset to zero [13]. This model is used to control the resistor's ON/OFF status [14].

Two different types of node model can be used for the EWH heat transfer process are one-node model and two-node model [15]. A uniform temperature is usually considered in the one-node model. The model validity can be established by measuring all hot or all cold water of empty or full tank. The heat transfer process in here can be modelled by using the first order differential equation:

$$Q_{elec} - \dot{m}C_p\left(T_w - T_{inlet}\right) + UA_{wh}\left(T_{amb} - T_w\right) = C_w\frac{dT_w}{dt} \tag{2}$$

Here, Q_{elec} is the resistor heating capacity (BTU/hour), $\dot{m}$ is the water flow rate (lb/hour), C_p is the thermal capacitance (BTU/(lb °F)), T_w is the water temperature (°F), T_{inlet} is the inlet water temperature (°F), UA_{wh} is thermal conductance (BTU/°F/hour) where BTU is British Thermal Unit, T_{amb} is the room temperature (°F), C_w is thermal capacitance (BTU/°F). The switching action of the heater can be controlled by measuring the actual temperature by any given time which can be calculated by this model. The following conditions can be implemented to achieve the set temperature ($T_{w,set}$) [14]:

1) $If\ T_w >= T_{w,set} + T_{w,deadband}$; The heater turns off.
2) $If\ T_w <= T_{w,set} - T_{w,deadband}$; The heater turns on.

For the convenience of this work, the consumption data is considered as input while the obtained reduced consumption and financial gain by using the proposed DLC method is considered as output. The overall view and main framework of the method is shown in Fig. 2. It consists of five main parts which includes several sub parts also. The first part is about the EWH modeling and overall usage profile. The physical and thermodynamic model with parameters analysis is described in the modeling part. Usage profiling section considers and analyze user consumption pattern. The analysis of user consumption pattern is discussed in the usage profiling section.

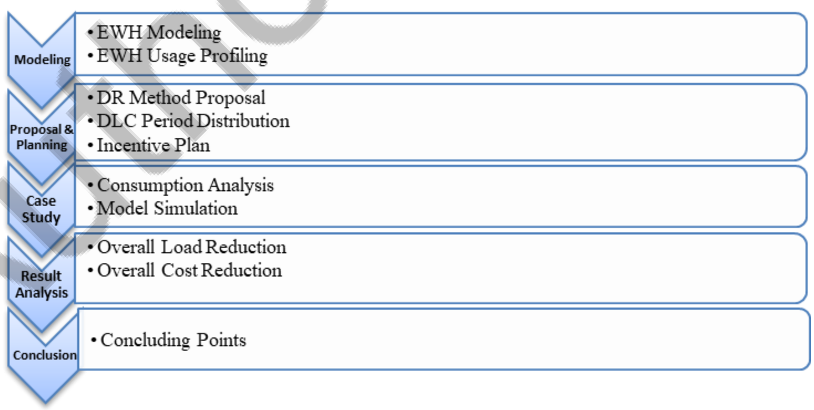


Fig. 7: The main framework of the DR DLC method.

DR method proposal, period distribution and incentive plan is explained in the next proposal and planning part. In where, DR method proposes the considered DR event program. The distribution period discusses the distributed months based on usage pattern for the considered period. In the yearly data, the months are distributed by high usage, medium usage and low usage months. Incentive plan can be made by the agreement between consumer and aggregator that discusses the total incentive for the consumers.

Overall consumption and the simulation model are discussed next in the case study part. The result part describes the total consumption reduction, total cost reduction and overall financial benefit gained by using the proposed method. Conclusion part describes the concluding points, decision and summary of the outcomes of the used method.

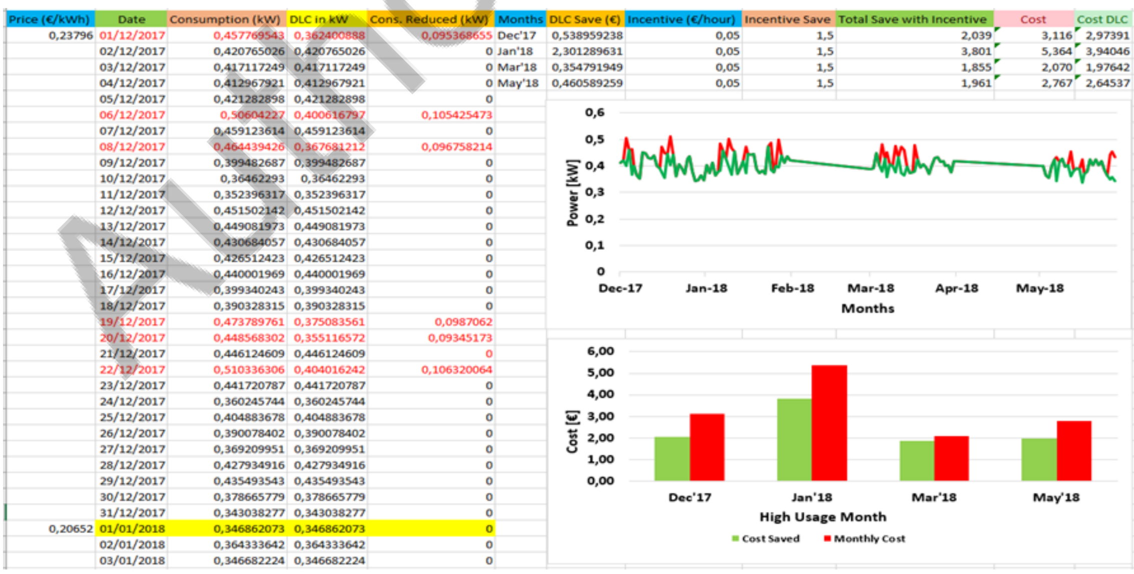
3. Demonstration

The demonstration of the proposed DR method with input data analysis and output result is discussed in this section. The proposed method is implemented and analyzed by using data integration Excel software. It is also used to illustrate the produced figures from the outputs.

The successful implementation of this method is illustrated in Fig. 3. Three main processes revealed by this proposed method are average consumption data (daily) calculation [16], overall average cost calculation and total reduced consumption calculation with the analysis of financial benefit. The heater's yearly consumption data is categorized based on the user consumption pattern.

The overall monthly, daily and hourly consumption profile is divided by using this convenient tool. For the data analysis convenience, the months are divided into three different periods are low usage months (LUM), medium usage months (MUM) and high usage months (HUM). Then the average daily consumption data for each month in each period is obtained by using Excel. The temperature profile of the heater is also discussed here. It is important to consider the DR participation of the heater. And it is the only parameter that can decide whether consumers can participate in direct load control (DLC) event or not. The residential EWH's monthly data [8] is calculated to obtain the desired output profile. From this data, the highest usage days from every month considered to be used in load control model. The model also gives the scope to the aggregator to control, change or modify data in order to obtain the desired result. In order to calculate the cost and overall financial benefit, real-time electricity price is included in this model.

Fig. 3 presents the cost calculation with financial analysis. The total cost for normal consumption is calculated by using the real time electricity price. The total cost for load-controlled method is also calculated then a comparison between both costs is also studied. The model also shows the total reduced consumption and the total cost saved by using this method. The proposed method proposes incentive-based tariff for the consumer here [17]. The described tool is used to calculate the overall financial benefit in this method. The normal power consumption profile and the consumption profile after using DLC method is also shown in the Fig. 3. The demonstration of the total cost and the total cost saved by using this program is also depicted in the Fig. 3. The result shows that the use of the proposed method is not only beneficial for the consumers but also for the aggregators. The cost difference, consumption difference, incentive achievement, power saved by the proposed method and all other related tasks can be obtained by this model too.



Price (€/kWh)	Date	Consumption (kW)	DLC in kW	Cons. Reduced (kW)	Months	DLC Save (€)	Incentive (€/hour)	Incentive Save	Total Save with Incentive	Cost	Cost DLC
0,23796	01/12/2017	0,457769543	0,362400888	0,095368655	Dec'17	0,538959238	0,05	1,5	2,039	3,116	2,97391
	02/12/2017	0,420765026	0,420765026	0	Jan'18	2,301289631	0,05	1,5	3,801	5,364	3,94046
	03/12/2017	0,417117249	0,417117249	0	Mar'18	0,354791949	0,05	1,5	1,855	2,070	1,97642
	04/12/2017	0,412967921	0,412967921	0	May'18	0,460589259	0,05	1,5	1,961	2,767	2,64537
	05/12/2017	0,421282898	0,421282898	0							
	06/12/2017	0,50604227	0,400616797	0,105425473							
	07/12/2017	0,459123614	0,459123614	0							
	08/12/2017	0,464439426	0,367681212	0,096758214							
	09/12/2017	0,399482687	0,399482687	0							
	10/12/2017	0,36462293	0,36462293	0							
	11/12/2017	0,352396317	0,352396317	0							
	12/12/2017	0,451502142	0,451502142	0							
	13/12/2017	0,449081973	0,449081973	0							
	14/12/2017	0,430684057	0,430684057	0							
	15/12/2017	0,426512423	0,426512423	0							
	16/12/2017	0,440001969	0,440001969	0							
	17/12/2017	0,399340243	0,399340243	0							
	18/12/2017	0,390328315	0,390328315	0							
	19/12/2017	0,473789761	0,375083561	0,0987062							
	20/12/2017	0,448568302	0,355116572	0,09345173							
	21/12/2017	0,446124609	0,446124609	0							
	22/12/2017	0,510336306	0,404016242	0,106320064							
	23/12/2017	0,441720787	0,441720787	0							
	24/12/2017	0,360245744	0,360245744	0							
	25/12/2017	0,404883678	0,404883678	0							
	26/12/2017	0,390078402	0,390078402	0							
	27/12/2017	0,369209951	0,369209951	0							
	28/12/2017	0,427934916	0,427934916	0							
	29/12/2017	0,435493543	0,435493543	0							
	30/12/2017	0,378665779	0,378665779	0							
	31/12/2017	0,343038277	0,343038277	0							
0,20652	01/01/2018	0,346862073	0,346862073	0							
	02/01/2018	0,364333642	0,364333642	0							
	03/01/2018	0,346682224	0,346682224	0							

Fig. 8: Used interface of the proposed method for DR.

In the end, the last part allows the user to discuss and analyze the obtained results from the executed method. It also gives the scope to the users to consider whether the proposed method with the considered incentive plan is suitable or not. The obtained figures, charts and, even the datasheet can be stored for future use also. These figures can be used to elaborate the importance of the method and the selection of the period for DR scopes.

4. Case Study & Methodology

A single element electric water heater's one-year data is considered for the analysis purpose. The heater is taken from our research group (GECAD). It is used approximately by 15 people for daily washing purpose only not for taking a shower or other work. The outlet water temperature is measured by a sensor what is placed just outside of the water line. In our case, we consider the outlet water temperature as the heater's inlet water temperature. After analyzing the consumption data, it is classified into three different periods are High Usage Month (HUM), Medium Usage Month (MUM) and Low Usage Month (LUM). The considered months in HUM period are January, March and May; the months in MUM period are July, October, November, April and June; the months is LUM period are August, September and February.

The average daily consumption behavior of the HUM period is represented in the Fig. 4. As we can see in the figure that December has the highest consumption which is approximately 422 watts and January has the lowest consumption is approximately 418 watts. The calculated consumption cost for this period is depicted in the Fig. 5 below. It shows that the highest average daily cost of this period is in December and the lowest cost is in March.

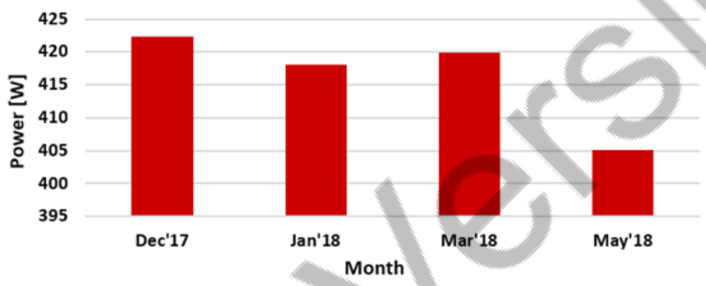


Fig. 9: Daily average consumption profile for HUM period.

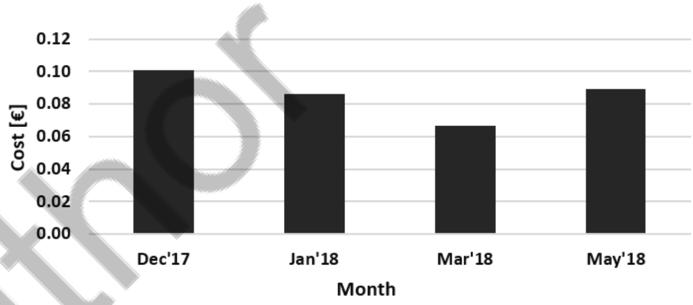


Fig. 10: Daily average cost for HUM period.

Fig. 6 shows the heater's daily average consumption profile for medium usage months. The highest daily average consumption for the MUM period is in November which is about 412 watts and lowest average consumption is in July is about 400 watts. And, Fig. 7 represents the daily average cost for the same period. The highest average daily cost of this period is in November and the lowest is in April.

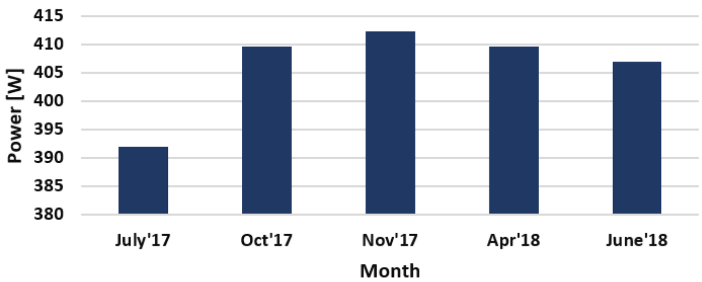


Fig. 11: Daily average consumption profile for MUM period.

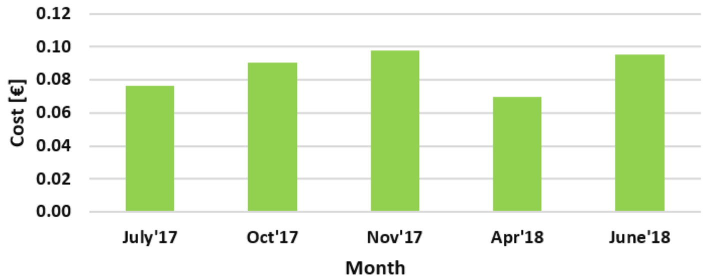


Fig. 12: Daily average cost for MUM period.

Finally, the average daily consumption profile and average cost profile for low usage month is shown in the Fig. 8 and Fig. 9 respectively. It has the smallest duration among the proposed periods. From the Fig. 8 it can be seen that February has the highest average daily consumption where August has the lowest daily average consumption in LUM period.

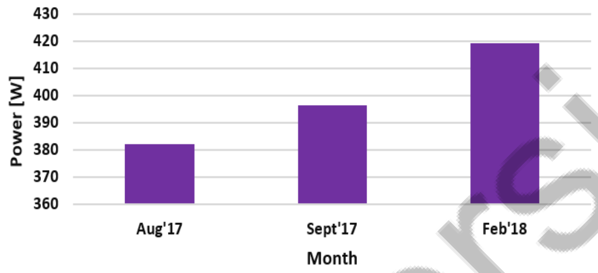


Fig. 13: Daily average consumption profile for LUM period.

According to the Fig.9, it is obtained that the daily average cost is highest in February but the lowest in August as it has the similar pattern in the consumption which is depcited in the previous figure.

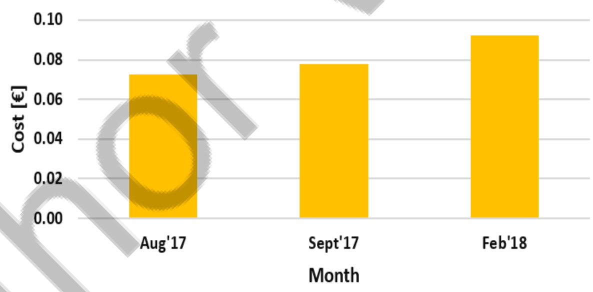


Fig. 14: Daily average cost for LUM period.

During the DR events, it is challenging to keep the temperature in a comfort [18] level. The daily temperature profile of the heater is represented in Fig. 10 below. It shows that the consumers temperature comfort level is approximately at 40ºC. It is also observed from the figure that the temperature is high during summer months. The limitation of the work is that, the measured data is the data of heater's outlet water data so the ambient temperature can be included in this profile too. As a result, it can have some faulty data though we are considering the data values are accurate if we ignore ambient temperature effect.

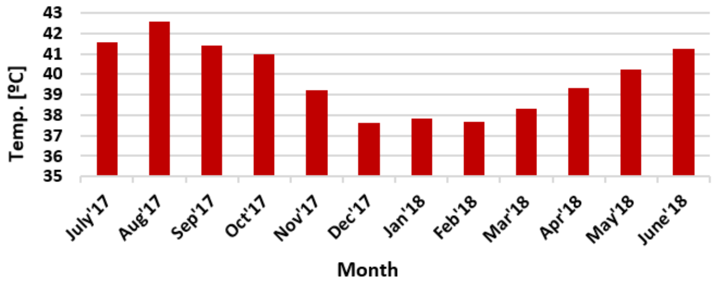


Fig. 15: Daily average temperature profile of the EWH for a year period.

In this part, it is discussed the proposed methodology for implementing the load control program to the heater. It is also discussed the overall cost calculation method using real-time market price. The initial market real-time price scheme is obtained from the Portuguese sector of Iberian Electricity Market (MIBEL) (www.omie.es).

Among different types of existing DR method, incentive-based DR program is considered here [19]. In this type of program, customer changes their consumption or stop their consumption for a certain period so that peak demand can be reduced. As a result, they can earn some extra financial benefits in their electricity bill. It is already mentioned before that direct load control DR program is considered in our work. As a part of the incentive program, the DLC method is proposed to apply in six high usage days the HUM period. In each of those days five highest consuming hours are selected to use. In MUM period, DLC is proposed to apply in five high usage days for four hours in each of those days. And, in LUM period, DLC is proposed in two high usage days for five hours in each of those days. The total hours considered to use in the DLC control is 250 hours.

For Incentive program, a daily flat plan is proposed in this work which varies from one period to another. For high usage months, the daily incentive is proposed to 5 cents per unit. For the medium usage months, the daily incentive is proposed to 3.5 cents per unit. And, for the low usage months, the daily incentive is proposed to 1.7 cents per unit. It is a contractual plan and the plan will only be executed if the consumer is agreed to control their load in the planned periods.

5. Results Analysis

This section describes the obtained results and outputs of the proposed analysis. A comparison between the average daily consumption and the average daily consumption after using the proposed DR DLC method is described here. The result indicates a significant decrease in the consumption. It is not only able to provide demand reduction fascility during peak load time, but also creates the scope to gain financially.

From the result, it is obtained that the average daily power reduction for every high usage month is 18.86 W. And, it is a significant amount for residential users. The value is obtained by subtracting to the daily average load controlled consumption from the daily average consumption. The daily reduced consumption for the medium usage months is approximately 12.20 W. Additionally, there is consumption reduction in low usage months though it is not very significant but in an acceptable range. The daily average reduction in low usage period is about 6.10 W.

The total financial gain is also discussed in this section. The daily average can be cost saved by using the proposed method for high usage months period is 5.20 cents. And, it makes a significants amount of money if consumers accumulate the incentives of all the days of the HUM period together. It is calculated by adding the obtained incentive value and the saved value for consumption reduction.

Fig.11 shows the cost difference between the daily average cost for normal period and daily average cost after using the DLC for HUM period. In the figure, the column in red is the daily average normal cost and column in green is the cost after DLC. The use of the proposed DR program reduces the electricity cost to 50% during HUM period. In some special cases, it can be even more.

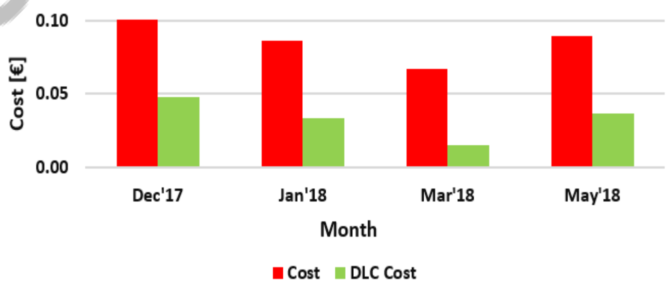


Fig. 16: Daily average cost difference for HUM period

The financial gain for medium usage months is described in this part. The daily average cost can be saved by using the DLC method for medium usage month is 3.70 cents. And, it is also a good amount of money that is considered for the MUM period. This gain includes the proposed obtained incentive value and the financial gain from consumption reduction.

Now, Fig.12 shows the cost difference between the normal daily average cost and daily average cost after DLC use for medium usage months. In this figure, the column in blue is the daily average normal cost and column in orange is the cost after using the DLC. The use of the proposed DR program reduces the electricity cost to 40% during this period.

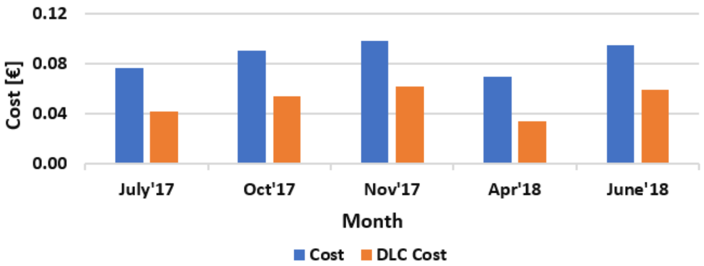


Fig. 17: Daily average cost difference for MUM period.

Next, the financial gain for lower usage months is discussed. The daily average cost saved by using the DLC method for lower usage months period is 1.80 cents. Fig.13 shows the cost difference between the daily average cost and daily average cost after DLC use for this period. In this figure the column in yellow is daily average normal cost and another column is the cost after DLC. The use of the proposed DR program reduces the electricity cost to 20% during this period.

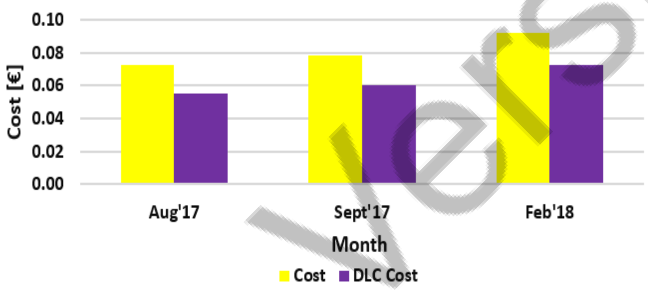


Fig. 18: Daily average cost difference for MUM period.

The results describe the changes in the consumer's consumption pattern due to the participation in the proposed method. But, these changes do not hamper user comfort level significantly which is on an acceptable level. It also analyses the overall reduction in consumption, the financial benefit by incentives in reducing electricity bill. This benefit will encourage people to participate in this type of DR program. Thus, the complexity in the traditional grid can be reduced too.

6. Conclusion

Traditional electrical infrastructure is facing more challenges to balance supply and demand due to the increasing penetration and uncertainties of renewable and distributed energy resources. Demand response with smart energy management system can help to solve these issues. It plays an important role to support the residential energy management system.

The experiences and findings regarding the considered demand response method are obtained here by using the Excel tool. The used tool allows users to analyze an optimized model of the EWH by using the consumption profile. It demonstrates the heater's different models and parameters for analysis purpose. The used tool is also capable of doing data analysis, data integration, and graphical analysis. The model and the tool are a part and parcel of the proposed work which turns into a successful implementation of the work. Additionally, it is a combination of different characteristics with a set of useful programs that helps to initiate the proposed model and end up with an event of successful results.

An aggregated direct load control system for the heater is possible to develop by using the proposed DR method. The real-time data of the heater are used for the analysis and DLC method is used for establishing the DR purpose. The load controlling method, the incentive benefits and other related task are discussed here. A single element water heater's consumption pattern is discussed here as it is the only existing heater of our building. This method can be implemented for dual element water heater or any other heater analysis purpose also.

The demonstrated model is an essential part of the DR analysis of residential electrical appliances. It will enable the users and the aggregators to calculate and understand the use of DR possibility with the financial benefit. In the end, the result of the analysis brings fruitful outcomes through the financial benefits. This work has a few shortcomings which will be improved in future work.

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