A Physically-Based Model of Heat Pump Water Heaters for Demand Respose Policies: Evaluation and Testing

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***Abstract* — The development of Demand Response in residential segments is basic to develop a practical flexibility of demand, because these segments account for up to 40% of the overall demand. Energy Efficiency is another concern for these segments, but unfortunately present scenarios lack a practical coordination between Efficiency and Demand Response. This paper deals with an important problem in residential Demand Response: the determination of the flexibility and response on the demand-side, in this case through loads which can have a high potential for Demand Response and also a considerable interest for energy savings: Heat Pump Water Heaters. A residential load has been fully monitored (temperature, consumption, water flow) in the laboratory to obtain a Physically-Based Model which allows the evaluation of Demand Response options. Moreover, the model helps the aggregator obtain how the flexibility of demand (power, energy, energy payback or rebound effects) can be modified or limited, and how to deal with these characteristics and limitations to engage customers in Electricity Markets.**

Keywords—Demand Response, Renewable Sources, Energy Markets, Load Modeling, Energy Storage, Energy Efficiency

I. INTRODUCTION

The increasing participation of Renewable Energy Sources (RES) in the generation mix withdraws a considerable amount of flexibility in the Supply-Side. This lack of flexibility can be balanced in the Demand Side through the use of Demand Response (DR) and Energy Storage [1]. This flexibility is also of interest for designing the new internal market of electricity in the EU [2], in where the customer should play a new and more active role through energy aggregators, but these tasks need the development of new tools and methodologies such as that proposed in this work.

The main end-uses in residential segments according to energy consumption reports in Spain are: Electrical Heating (42.9%), Cooking (7.69%), Lighting (4.85%), Water Heaters (17.96%), Air Conditioning (0.98%) and other appliances (25.5%). This picture of end-uses is similar for other industrialized countries [3]. In this way, Electric Heating (EH) and Water Heating (WH) are first candidates to participate in Demand Response policies. Moreover, WH has an inherent capacity for energy storage and this is interesting for the response of residential customers to dynamic price tariffs, or also to consider thermal storage as an alternative to electrical storage (for example, for customers that own some kind of generation, the so called “prosumers”).

The idea of this paper is to develop and validate a load model (Physically-Based, PBLM) which is able to take profit from the possibilities of a “new” load: the Heat Pump Water Heater (HPWH) which also has a remarkable interest from the point of view of Energy Efficiency. From an economic point of view HPWH can help customer to reduce energy costs, or in other cases this load allows the participation of customers in Capacity Markets (through an aggregator) in both Energy Efficiency and Demand Response options [1]. The paper is organized in different sections. In Section II, the characteristics of HW loads are discussed; the PBLM model is presented, and validated through some tests. Then, in Section III, some DR simulation examples are described to show the ability of the model, followed by Section IV that concludes the paper.

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II. METHODOLOGY

Several models have been proposed in the literature for the inclusion of WH in the Demand Response portfolio [4-7]. The approach presented in [4] presents the idea of one or two node WH models which changes the height of the hot water (and model) to take into account the stratification of water, whereas [5] solves the problem of water stratification in the reservoir through Dynamic Fluid equations. This makes much more complex the model but it gains in accuracy. Other approaches use well know software platforms (EnergyPlus) to solve heat transfer processes in HPWH [6]. In [7] a learning-based, data-driven model is developed by using a nonlinear autoregressive network with external input. Mains problem of these approaches are that usually consider conventional WHs, and some of them [6] do not search for a physical explanation of load behaviour. Note that Heat Pump alternative is very sound from the point of view foreseeable participation of residential segments in capacity markets [8].

Fig. 1 shows two tests during the start of two WH (with different technologies). As it can be seen, the start and standby periods are different, but mainly they differ when the appliance is switched on and the reservoir is empty: i.e. charging time and standby cycling (and this is of interest in the case of the application of DR policies on these loads). This different behaviour and the importance of this end-use in residential segments justify the monitoring of this kind of load.

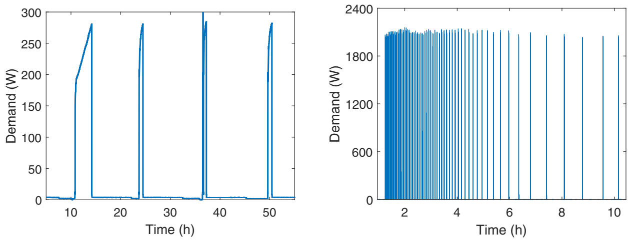

Fig.1.Water Heater behaviour: a) Heat Pump Water Heater (AristonNuos Evo 80l); b) Resistance (conventional) Water Heater (Junkers 75l)

A. *Laboratory test facilities*

The HPWH load that is considered in this work has two different heat sources: an auxiliary resistor and the Heat Pump, with three modes of service ("eco", "boost" and "auto", which select the use of compressor, resistor or both sources of heat according to customer choices and boundary conditions of the load and its environment). This duality in supply presents problems (rebound effects, peak demand due to HP inefficiencies at low temperatures in mode auto) and opportunities (more flexibility for DR if the customer or aggregator can change remotely the options for main supply of energy). Both are important concerns about what the paper aims to discuss. To evaluate the dynamic of the HPWH, a load has been installed in the Area of Electrical Engineering of the Universidad Miguel Hernández (Spain). The characteristics of load are shown in table I.

According to the experience described in [5], a broad monitoring system has been installed on the load and in its environment. Fig. 2 shows a scheme of the laboratory test facilities.

TABLE I. CHARACTERISTICS OF HPWH ARISTON NUOS EVO

Characteristic	**Value**
Capacity (l), Energy Label	80l, A+
Rated Power of Heat Pump (W)	250 (avg)/ 350 (max)
Performance, COP (outdoor air at 7ºC)	2.55
Max. Heating time (h)	5h35m
Max. WH Temperature (ºC)	55 (only HP)/ 62
Auxiliary Resistor (W)	1200

This system measures outdoor temperature and humidity, temperature of water flows and pipelines (especially cold and hot temperatures during water draws), the electrical consumption of the auxiliary resistor and the compressor of heat pump by means two independent electrical meters, one of them a switch with control of supply to simulate several DR policies. The system also has a water flow controller to simulate several water draw profiles. All the sensors and controllers use the Z-Wave protocol, except the secondary water flow meter which sends pulses to a data logger (1000 pulses/l). Load monitoring and power management is done by the automation software platform IP-Symcon [9] because this platform allows the management of several protocols at the same time (1-wire, F10, KNX, EnOcean, M-BUS, Modbus, Oregon Scientific, Siemens OZW/S5/S7 and Zwave).

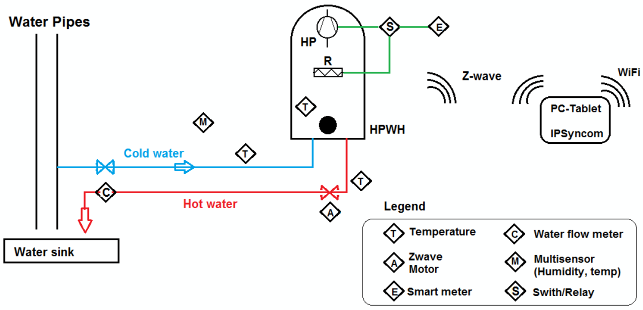

Fig.2. Scheme for measurement and control system for HPWH load

Fig. 3 shows some pictures of the load, sensors and actuators. The system has five sensors to measure: inlet and outlet water temperature, water flow, humidity and internal temperature of laboratory. Moreover, an actuator to control water flow, two demand meters and a controlled plug have been deployed. The interval between measures can be selected by php scripts from 5s to hours. In our case Zwave devices and IPSymcon are programmed to notify and record any change in variables (>5%).

B. *Elemental model of HPWH*

The PBLM model proposed for HPWH is a thermal-electric equivalent, specifically a lumped RxCx network being fed by two heat (current) sources. The model takes into account the water storage capacity in the tank (Cx parameter), heat losses (Gx), the heat losses due to inlets of cold water (a dependent current source in the model), outlets of hot water (again a dependent current source) and heat gains due to auxiliary resistor (H_R) or Heat Pump (H_{HP}) both current sources. The resistor and HP sources are selected by the user through the appliance menu of the load (MODE eco or boost).

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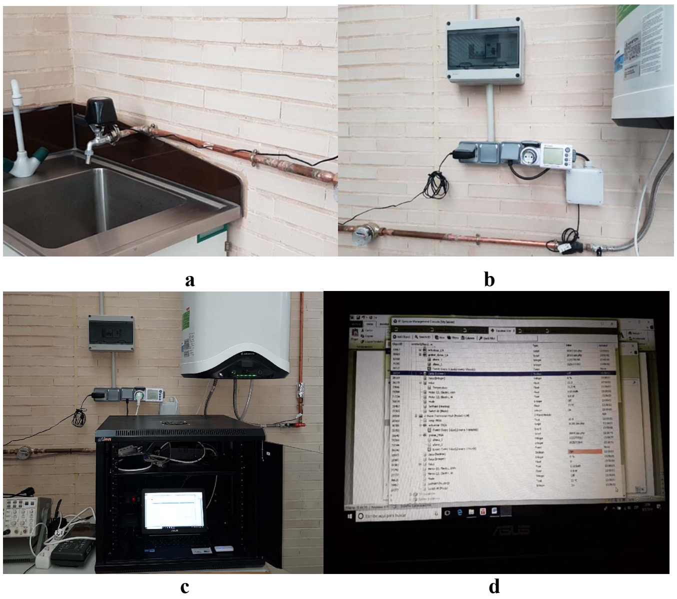

Fig. 3. HPWH monitoring: a) Valve for water flow control; b) Zwave Switch/meter (Fibaro), flow meter (Sensus ResidiaJet), temperature sensors (Qubino and DS18B20) and energy logger (Voltcraft); c) Overall system and rack for sensor supply sources, Zwave gateway and pulse transduction of secondary flow meter; d) PC and IPSymcon recording Zwave devices.

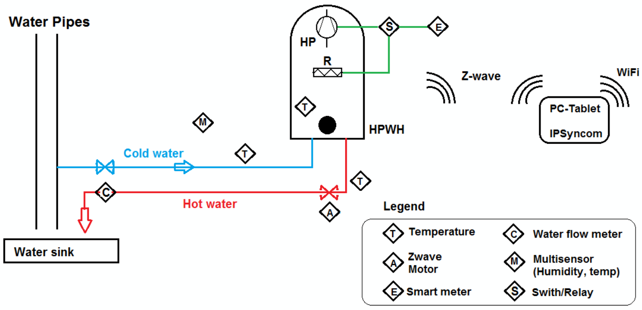

Fig.**4.** The electrical-thermal equivalent of a HPWH load.

The state-space representation for the model in fig. 4 is:

$$\begin{pmatrix} DX_1(t)\\ DX_2(t)\end{pmatrix} = \begin{bmatrix} -\frac{G_L+G_{C1}+G_{E1}+c_e q(t)}{C_1} & \frac{1}{C_1}G_L \\ \frac{1}{C_2}G_L & -\frac{G_L+G_{C2}+G_{E2}}{C_2}\end{bmatrix}\begin{pmatrix}X_1(t)\\ X_2(t)\end{pmatrix} + \qquad (1)$$

$$+\begin{bmatrix}\frac{1}{C_1}G_{e1} & 0 & \frac{1}{C_1}\\ \frac{1}{C_2}G_{e2} & \frac{c_e q(t)}{C_2} & 0\end{bmatrix}\begin{pmatrix}X_d(t)\\ X_p(t)\\ H_{HP}(t)\end{pmatrix}$$

Where:

- m(t): is the control mechanism which drives the demand: a thermostat in thermostatically controlled loads.

- X_1 and X_2: are the state variables that are temperatures; the temperature of the water inside the HPWH.

- q(t): water flow, i.e. the service of the load, in this case flow at a certain temperature level Xs (thermostat setpoint). This variable explains the energy requirements through specific heat c_e of water and inlet/outlet temperatures.

- MODE: the switch that drives the mode of use of the load (with an auxiliary resistor or the compressor).

The capacity of the reservoir (water tank) in the proposed model is split in two blocks (WH-1 and WH-2). The reason is that water heater suffers the so called water stratification (the hot water raises to the top of the tank reservoir and the cold water down to the bottom). This phenomenon has been described in the literature [6] and analysed through Fluid Dynamic equations. The model is developed using building energy simulation programs to model energy consumption, for example EnergyPlus platform [10]. In this paper, a more simple "grey-box" model is proposed which allows the interoperability with other platforms such as BRCM toolbox [11] and the possibility to apply aggregation methodologies previously applied for other PBLM models (HVAC) developed by authors [12].

A detailed analysis of ON times, but especially of OFF times in the load tests (as shown in fig. 1), reflects that a "mixed tank model" (i.e. the premise that a homogeneous temperature in the tank exists) does not work very well. Tests show that ON times are nearly constant (fig 5.a) whereas OFF times go up during a certain time but then they remain constant (fig 5.b). The switching pattern shows the changes in charging/storage processes due to hot water convection flows (i.e. the water near the condenser coil of HP or the resistor is heated, but the flow of warm/cold water mixes flows and drops the internal temperature; then the thermostat goes ON again). When this mixing process, driven by Fluid Dynamic laws, in the tank finishes, switching times are only due to thermal losses from tank to the external dwelling. For these reasons, a two-mixed tank model is preferred to reflect the stratification of the tank shown in tests (fig 5b).

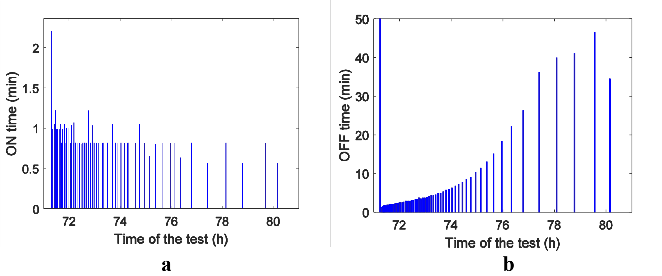

Fig 5. ON and OFF times during the real test shown in figure 1 (conventional WH or HPWH in mode resistor): a) ON times; b) OFF times.

C. *Model calibration and validation*

The model (1) has been implemented in Matlab©. The knowledge of the physical behaviour and the characteristics of the load (i.e. the basis of the methodology PBLMs provides a first value of the model parameters. For instance:

$$C = C_1 + C_2 = V\rho c_e = (80l)(0{,}99kg/l)(4.18kJ/kg^{o}K) = \\ = 331kJ/^{o}K \qquad (2)$$

$$H_{HP}(t,X) = P_{HP}^{avg}COP(X_d, X_1) \approx 250*2.4 = 600J/s$$

Where: V is the volume of the WH tank, ρ is the water density (from 0.998 at 20ºC to 0.983 at 55ºC) and specific heat c_e of water. P_{HP} is the power of HP (in average) and COP is the

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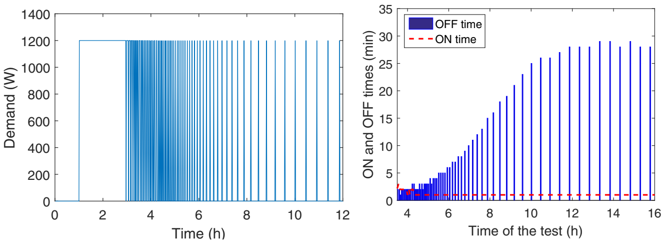
coefficient of performance which depends on temperatures of heat sink (warm water) and heat source (external/dwelling air) of HP thermodynamic cycle.

With this procedure, the knowledge of materials, the dimensions of HPWH, and some studies from the literature (old but exhaustive tests and studies on WH performance [13]), preliminary values of the coefficients of the model have been introduced in the software and tested with different requirements for the HPWH. An example is the warm up test of HPWH load shown in fig.1. This is a necessary test for tuning the model, and specially thermal losses, i.e. G_{E1}, G_{E2}, G_{C1}, G_{C2}. The output of the model and ON/OFF switching times is shown in fig. 6.



a **b**

Fig 6. HW simulation in MODE "Resistor": a) Demand; b) OFF times (from 3 to 16h)

As it can be seen the model suits well the behaviour of the load in this state, demonstrated by ON (nearly constant) and OFF periods (an over-damped response and then a constant steady state). The coefficients for the model are presented in table II.

TABLE II. PARAMETERS OF HPWH MODEL

Parameter	Value
Capacity C1=C2 (kJ/ºK)	150.5
Heat source H_{HP} (avg)/ H_R (J/s)	600/1200
GL (J/sºK)	60.6
GE1=GE2 (J/sºK)	0.26
GC1=GC2 (J/sºK)	0.15
Thermostat deadband (ºC)	55-50

D. Mechanical latency of HPWH compressors

An important problem for the ability of load to contribute to some services in power systems (for instance Ancillary Services) through DR is the so called "lock-out" (a mechanical delay) of compressors of HPWH units. This problem has been reported in the literature for elemental HVAC loads [14] and for an aggregated group [15]. This mechanism is used to prevent a rapid recycling of a compressor avoiding mechanical damages. From the point of view of DR, it can cause a delay when applying ON/OFF and thermostat control signals. To evaluate the effect and characterize, from an statistical point of view this process, the HPWH appliance has been tested with the help of a Fibaro [16] Z-wave wall plug switch which receives DR signals from IP-Symcon [9] through USB static controller (USB gateway). To evaluate mechanical latency, both IP-Symcon software and plug meters have been set to perform immediate power reports to the main controller with the highest priority. This test consisted of periodic curtailments in supply (10 minutes ON and 5 minutes OFF) which was sent to a controllable plug load. One of these tests is shown in fig. 7.

As it can be observed in fig.7, latency times are around 2-3 minutes, and the switching ON of compressor is reached after some time with exhibits low consumption. This effect can also be seen in other heat pumps, but with a time delay around 30-50s.

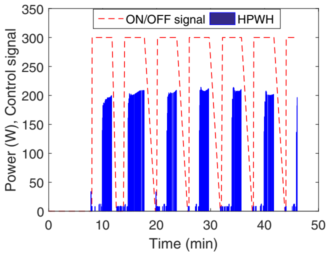


Fig 7. Latency behaviour of HPWH compressor

E. Electrical model of compressor: $H_{HP}(t, X)$

Another important factor in the modelling tasks of heat pumps is that demand changes with the change of temperatures in the environment and in the system to be heated, this is called the "lift" of the HP, i.e. in our case X_l and X_d, due to the efficiency of HPWH thermal cycle. This is evaluated through several efficiency indices [17]. A commonly used measure for efficiency is the Coefficient of Performance (COP), which gives the heat output/production in W (H_{HP}) or J divided by the electrical input/demand (D_{HP}, also in W or J). Heat pumps in EU are tested at 7ºC external temperature (dry bulb). The American standards use different testing conditions and the Energy Efficiency Ratio (EER) instead of COP. The difference is that H_{HP} is measured in Btu or Btu/h (instead of W or J). COP can be converted in EER values using the equation:

$$COP = \frac{H_{HP}(Wh)}{D_{HP}(Wh)} = \frac{EER}{3.412} \quad (3)$$

Inverter heat pumps have the ability to reduce or increase demand according to heat flow temperature conditions (the "lift"). From the point of view of HP simulation integrated into building energy models (see for example [16]) complex models can be found, but for DR simulation requirements, a more simple model to estimate HP performance has been chosen [15]: First, the user obtains some COP values from the manufacturer technical manual, and second compute a quadratic regression of these values, so the COP can be evaluated from the difference ("lift", ΔX) of temperatures X_l and X_d. X_l can be evaluated with eq. (1) and X_d is an input in (1). In this case, and through the use of data from laboratory tests (fig. 8) the expression of COP is:

$$COP(\Delta X) = 3.74 - 0.07\Delta X + 0.00063\left(\Delta X\right)^2 \quad (4)$$
$$5 \le \Delta X \le 45^{o}\,C$$

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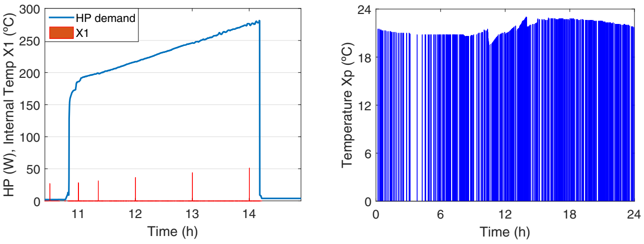

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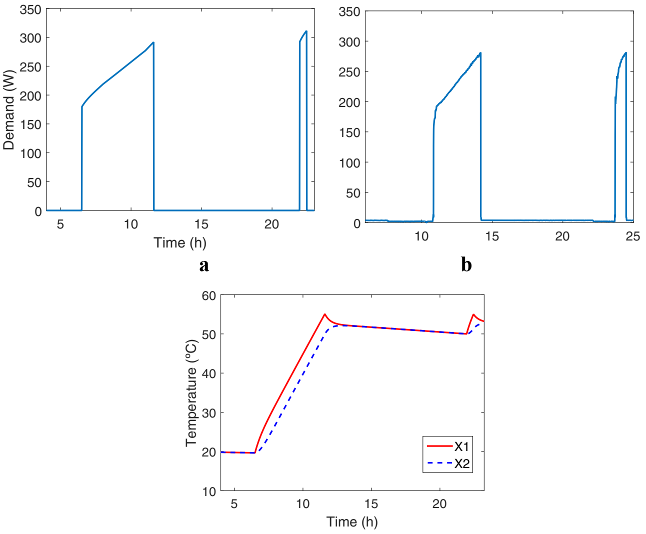
Fig 8. COP adjustment: a) Demand P_{HP} and internal temperature Xi; b) Daily profile of temperature of inlet water

In this way, (4) is applied through the knowledge of m(t) (control mechanism, i.e. the thermostat) and ΔX to obtain the consumption of HP compressor. Several "open-flow" test (i.e. q(t)=0) were performed in the laboratory to test demand and temperatures of real HPWH load in comparison to model outputs. The results are shown in fig. 9. As shown in fig. 9a&b, the model suits well the dynamics of electrical consumption, and also OFF periods between ON/OFF switching (steady state), the necessary demand to maintain internal temperature into the tank (10 hours delay in this test, see fig. 9a&b). It is interesting to note that the water stratification is lower with HP than in conventional WH with auxiliary resistor (fig. 6) because the hot water has time enough to mix its flow with warm/cold water (fig. 9c). These state variables are very important for simulation, as it can be explained in next paragraphs.



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c

Fig 9. An "open-flow" test: a) Demand P_{HP} (model); b) Demand P_{HP} (real load); c) Profile of internal temperatures X1; X2 (model)

III. RESULTS

Finally, the potential of HPWH for energy efficiency and the use of cycling control to limit peak demand have been applied through PBLM individual model (taking into account the service to customer, i.e. maintaining the temperature of water draws above 30ºC) to test the model and obtain some characteristics on load flexibility and, moreover, the limits of DR according to boundary conditions (outdoor temperature, temperature of water in the pipeline or hot water temperature). Some similar analysis, with different models and approaches, can be found in the literature [18-19].

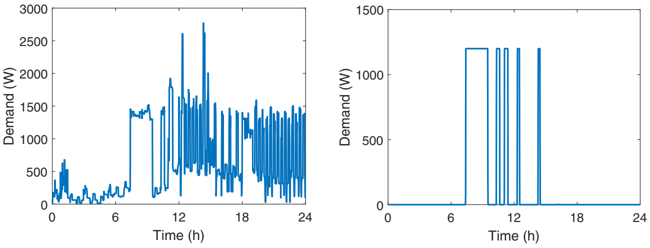

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Fig 10. Residential customer profile: a) Overal demand; b) HW demand.

Fig. 10a represents the daily demand profile of a residential customer being monitored in Spain, whereas fig. 10b shows the WH end-use (resistor WH) extracted through Non-Intrusive Load Monitoring technologies [20]. This last profile has been used to obtain a profile for water draws q(t).

A. Evaluation of Energy Efficiency

First policy that has been simulated is the change of end-use technology (from resistor WH to HPWH) [20]. Notice that old and new water heaters have been selected with the same rated power (HPWH mode resistor) and capacity (75 vs. 80l). The changes on power and energy are of interest both for the customer and aggregator to run economic and technical models such as the one proposed in [8] and, in this way, evaluating benefits from the participation of customer in Capacity Markets in the future (usually three or five years ahead). In the case analysed, the customer reduces WH daily energy consumption by 50% and the overall daily demand (fig. 10a) by 13% (table III). Taking into account HPWH prices (€900) this policy is cost-effective for the customer. The rate of return depends on subsidies and market prices [8].

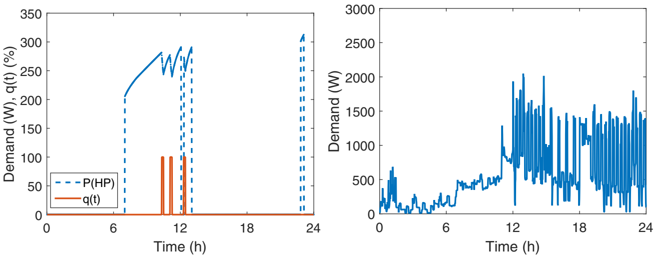

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Fig 11. Evaluation of efficiency of HPWH replacement: a) New end-use demand; b) New customer profile (with respect to fig.10).

B. Price and Event response (DR)

Other policies of interest are price-response and event-response. In these cases, the customer should reduce its demand according to a high volatility of prices in the market or due to constraints in distribution/transport levels. With PBLM models, the change both in end-use demand and the overall demand can be evaluated, as well as the temperature of the tank (state of charge). Some results are shown in table III. The demand during a control period (from 10 a.m. to 3 p.m.) with a duty cycle of 25% achieves 9% of peak clipping which

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is an interesting potential for DR in residential segments. Note that control (fig. 10b) does not entail a problem with load service (tank temperature is over 35ºC in the control period).

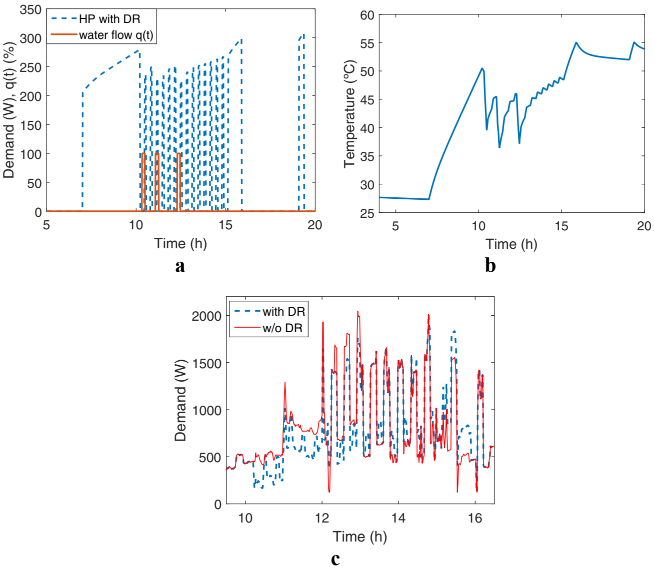

Fig 12. A DR test (cycling control from 10 to 15h, duty cycle 25%): a) Demand P_{HP} (simulation) and water flow q(t); b) Profile of internal temperature X1; c) Daily demand of the customer (without and with DR).

TABLE III. EE AND DR RESULTS (PBLM SIMULATION)

Variable/policy	**Value**	**Percentage or change**
Daily energy, Peak (baseline)	15.96 kWh, 2.78kW	100%
Daily WH consumption (old WH)	3.78 kWh	23%
Daily HPWH consumption (EE)	1.56 kWh	- 13.9%
Peak demand (after EE)	2.05 kW	-26%
Energy from 10 to 15h (w/o control) after change from WH to HPWH	4,42 kWh	100%
Energy from 10 to 15h (with DR) after change HPWH	4.02 kWh	-9.1%

IV CONCLUSIONS

This paper presents a new model (through PBLM methodologies) of using electricity in residential segments for a main end-use in these segments: the Electric Water Heater. An adapted simulation model, which is well known in the literature, has been validated by laboratory test and their parameters explained and tuned for the case of an efficient version of load: HPWH. The model has the potential to evaluate Energy Efficiency and DR policies in several markets: energy, Capacity and Ancillary Services. Results demonstrates the efficiency and DR potential of this end-use: energy savings around 14% and peak shaving near 9%. The advantages of this approach are: the universality of the model (aggregation procedures, data exchange with other models and platform), the analysis and consideration of mechanical latencies, the state of customer service provided by the appliance, and finally a fast response and interpretation of results. The next step in this methodology is the aggregation of individual models to define rules and limits for load aggregation.

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