Methodology to simulate the impact of a large deployment of a residential energy management system in the electricity grid

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ABSTRACT

The purpose of this work is to provide an insight for a possible methodology to implement demand response strategies at a city scale. The objective is to determine a range of values for the energy and power that can be made available through the large deployment of a residential energy management system. This work can help the distribution system operator to assess the impact of the usage of such technology at the grid level.

The paper describes a methodology that identifies the start of operation cycles of appliances and other loads on a given general load diagram, enabling the simulation of load shifting caused by the operation of residential energy management systems.

A simulation of an hypothetical 20% deployment of a residential energy management system on the city of Coimbra in Portugal, was performed. The results show the release of almost 3% of the demand on periods of higher price, but also the occurrence of a pronounced peak during the night period, an occurrence which may need to be dealt with, and for which some solutions are proposed.

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1. Introduction

In order to allow decision makers to select local, regional or national end-use energy efficiency policies, it is necessary to assess the technical, economic, environmental and societal effect of replacing or adopting a given equipment, technology or measure.

The deployment of Demand-Response (DR) [1] programs and the recent trend toward combining the use of advanced smart meters with automatic load management capabilities requires assessing their possible aggregated impact and, for that purpose, the knowledge of the household (hh) consumption pattern and its composition in terms of the individual end-uses is fundamental.

The common strategies to load modeling are normally based on top-down or bottom-up approaches, the first kind trying to derive load models from statistical data and the second kind building an aggregated model from engineering models of end-uses. These methodologies can be improved by the growing availability of data from smart-grids and smart-meters, thus taking advantage of these new types of data, as well as reducing costs associated with energy modeling, avoiding the complexity of models and reducing the time required to perform simulations.

This paper presents a methodology proposal to determine the impact of the deployment of a demand response technology such as the Energy Box (EB), a residential energy management system defined by Livengood and Larson [2], assessing the energy and power made available through load shifting on an hourly basis in response to a price signal. The Energy Box is the focus of a research conducted by a team to which the authors belong, as a research project in the framework of the MIT-Portugal Program [3].

The developed methodology assumes some randomness to be associated with the input data, scarce information being available on probability distributions of appliances schedules along the day. Some randomness is also associated to the hourly tolerance of consumers for postponing the starting time of their appliances. This simulation also intends to analyze the outcome of having a certain percentage of consumers from one city, county (or country) with Energy Box devices, using the information regarding the consumption of the area at, and taking a bottom-up approach.

1.1. Load research review

Similarly to what happened in other European countries, several studies regarding electrical energy use (especially consumption)

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have been developed in the past years giving a special attention to the Portuguese household sector. This attention is explainable due to the overall and growing importance of electrical energy consumption in this sector and its share of the total electricity consumption of the country (29.00% in 2010). Portugal accounts for a total of 3,927,733 households with electricity usage (13,946 GWh for 3,769,896 hh in Portugal mainland, 258 GWh for 77,222 hh in the Azores islands and 239 GWh for 80,615 hh in Madeira [4]).

Another reason for the existence of these studies has to do with the alleged homogeneity of the sector in terms of appliances or other equipment, energy usage patterns and energy behaviors, which allowed the development of typical load profiles that intend to represent the energy consumption in households. According to a recent study [4], electricity is the main source of energy used in Portuguese households with a share of 42.6%, clearly surpassing the 15.8% share in 1989 and 27.5% in 1996. The popularity of equipment/appliances that use electric energy increased significantly, contributing to the growing importance of the use of this type of energy in the household sector and motivating researchers to develop studies on the electrical energy usage in dwellings. An extended review of the state of the art regarding this subject was published by the authors in Ref. [5] focusing load studies regarding the Portuguese household sector. Another review with relevance for the present article, covering the simulation methodologies, and including bottom-up and top-down studies, was published in Ref. [6].

1.2. Load management

In order to increase security in energy supply and to reduce greenhouse gas emissions (GHG), Europe made a strong effort to integrate renewable energies (RE) in the electric grid. Several reasons could be pointed out for the European Commission and European Countries to devise concrete objectives for the expansion and integration of RE in the electricity grid, namely, the necessity of having a diversified energy mix, RE potential and several technological breakthroughs. From the available renewable energy sources, the most likely to be used at a larger scale are solar and wind, both of which are intermittent. Using current tools to manage load and supply fluctuations it is possible to deal with the intermittency of renewable energy sources at low levels of implementation. However, an increase of the share of energy supplied by RE of 10–30% requires new resources to balance the fluctuating supply to the also fluctuating load [7].

Another reason for the need to study new tools to balance supply and demand is that transmission networks in Europe, due to new market mechanisms, are becoming a platform to increasing energy flows as stated by the authors of [8,9] and more recently in [10,11].

In addition to this burden, technological advances imply new appliances that require more energy. Thus, the gap between electrical supply and demand is increasing in many countries [12,13].

Conventional approaches to solve the above-referred problems are based on the expansion of the supply resources, even to serve only as idle backup power. These are usually high-investment solutions, planned to work for a very small fraction of the time. An alternative approach is then to manage the energy consumption, in order to compensate fluctuations, avoiding the need of new supply capacity [14–16].

Managing consumption helps controlling the energy production, allows relieving the transmission systems and helps the implementation of decentralized supply structures with small and autonomous energy systems.

Recently an extensive review of load management methods was published in Ref. [17], describing techniques and programs, many used in developed and developing countries. According to Ref. [17], and in the perspective that consumers should adapt their patterns of usage to the actual evolution of the cost of electricity, the tariff that better reflects the present situation of the electricity market is the real time tariff. This tariff has prices announced in advance, e.g., a day ahead, as assumed in the remaining of this article. However, this tariff scheme may require the temporary reduction of quality of service levels and increased needs for granularity of control and telemetry speed [18]. The possible benefit of DR, for the transmission and distribution operators, of deferring investment in network reinforcement or increasing the long-term network reliability stated by Ref. [18] requires comfortable evidence in order to enable a meaningful investment by interested parties.

The need for a methodology as the one described in this paper is also strengthened by the existence of studies [19] that state that DR can cause new demand peaks for electric utilities to deal with, when day-ahead hourly prices are applied. The question remains to know what their relevance is and how to avoid them.

1.3. Comparing load profiles

A methodology to evaluate profiles, aimed at comparing load profiles of the residential sector, with the ability to relate reference studies that developed load diagrams, was published by the authors in Ref. [5]. The general idea consisted in comparing the load profiles approved by the Portuguese national energy regulator (ERSE) with the typical load profiles provided by load research studies.

The profiles provided by ERSE and REN are demand values for each quarter of hour of an entire year in p.u. (kW), also including the power value.

Within this methodology, and considering the underlying concept of the regulator load profile, it was also possible to compare the profiles provided by Refs. [20,21] with the ERSE profile, normalized for the same integral of consumption over the entire period. Since the load profiles have the same sum and average, the maximum positive hourly variation (MPHV), the maximum negative hourly variation (MNHV) and the average variation (AV) are equal to the normalized unitary vector counterparts.

In Ref. [22] the author used the updated ownership rates of appliances published in Ref. [4] to change the hourly end-use impact of the consumption diagram presented in Ref. [20].

Using this information, the household equipment was grouped in three different types of loads, type I, II and III, as in Table 1. Type I loads can be scheduled or simply interrupted, type II the loads that can be interrupted but also allow the changing of settings, and type III are the non-controllable loads [2,23]. It is possible to verify that in average some kind of control can be applied to 48.79% of the loads.

Table 1
Type of load by possibility of control [5].

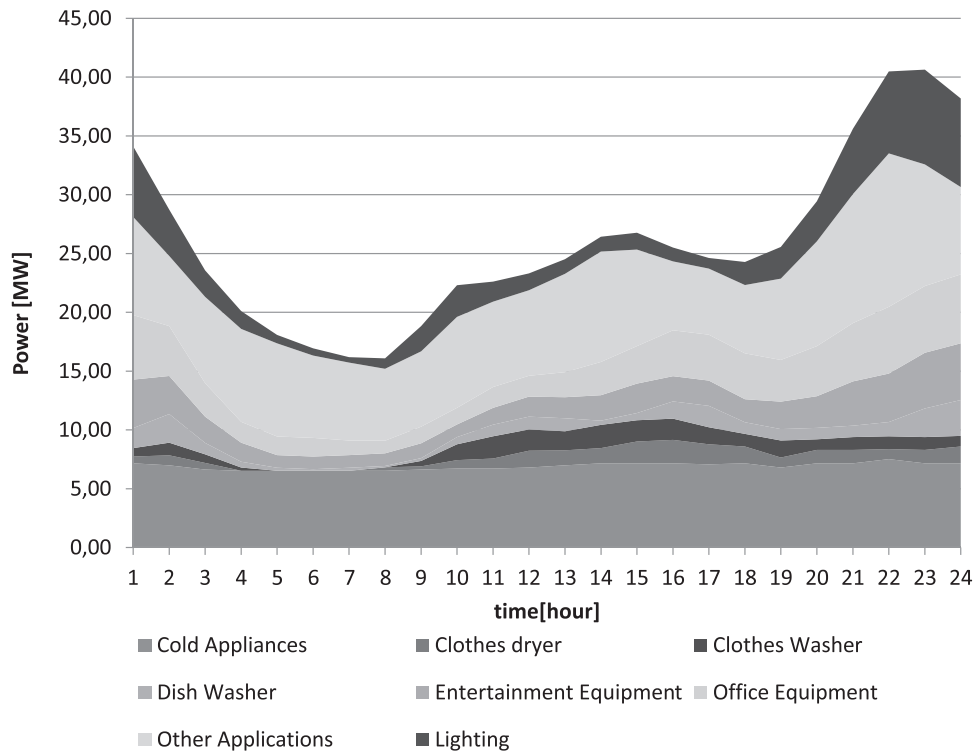| Type of loads (%)							
Type I			Type II		Type III		
Clothes washer	Dish washer	Clothes dryer	Lighting	Cold appliances	Office equipment	Entertainment equipment	Other applications
3.94	4.05	3.48	10.68	26.65	12.21	9.01	29.98
	11.46			37.33		51.21	

Fig. 1. Estimation of the distribution of electrical energy for the average day for the city of Coimbra with loads represented by decreasing regularity of the standard deviation [5].

Table 2
Electrical energy consumption in the City of Coimbra in the year 2010 [24].

City	Average electrical consumption per household (kWh/year)	# Electricity consumers	Total domestic consumption (kWh)
Coimbra	2966.10	76,642	227,327,836.20

Given the differences of average consumption among cities, e.g., Bragança with 2307.70 kWh and Porto with 3948.70 kWh [24], confirmed the need for a methodology with the ability to evaluate the range of values of the power and energy that can be made available by the usage of the Energy Box, considering that the residential energy consumption may change from city to city. The city of Coimbra, featured in Table 2, was selected for this study.

The fitting process considered the updated ownership rate of appliances of [22]. The hourly impact (percentage) of each appliance/equipment was maintained, allowing the estimation of the distribution of the electrical energy demand in the city, as in Fig. 1.

2. Simulating the household energy usage in the city of Coimbra

According to Ref. [2,23] the Energy Box results better in a demand-sensitive, real-time pricing environment. The automatic decision capacity of the Energy Box will enable minute-by-minute decisions over the course of the day. The possibility to act on the load diagram is also an advantage and an old ambition, performing peak clipping, valley filling and load shifting, thereby potentially reducing the need for capacity expansion in electrical power generation and distribution. The Energy Box also manages on-site energy generation, storage and sale of electricity back to the grid. The use of the energy box should result in reduced electrical energy costs to the electric energy consumer. It is therefore relevant in a Smart Grid context to evaluate the Energy Box resource as a way to determine the motivation for a distribution system operator (DSO) to encourage or stimulate its installation.

2.1. Simulating schedulable and interruptible (S&I) loads (type I)

2.1.1. Clothes washer, clothes dryer and dish washer

In order to simulate the effect of the intervention of the Energy Box, a simulation of the current consumption for each load (or resource) under study is necessary.

The power demand curve for an average washing process of a clothes washer is presented in Fig. 2 [25] with an energy consumption of 0.89 kWh per cycle for an average load of 5 kg. This value was determined using a normal cotton washing program as reference, resulting in the following power demand curve in ¼ hour steps.

As published in Ref. [5] the energy used for the service of clothes washing in the city of Coimbra for an average day is 24.54 MWh.

It is then possible to determine an approximate number of daily running cycles for the clothes washer (Eq. (1)), by knowing the energy consumption of such equipment in the entire electricity network, using the information provided in Table 3 and the individual energy consumption of the average equipment.

$$\text{Number of cycles} = \frac{\text{Energy consumption (Average day) (kWh)}}{\text{Energy consumption (1 cycle) (kWh)}}$$

(1)

The calculated number of 27,574 cycles/day means that only 39.67% of the clothes washer appliances perform a complete cycle in an average day.

By multiplying the probability for each ¼ hour period, on a total of 96 values for one day, by the total number of cycles of the average day a final number of cycles to be simulated is found, as shown in Fig. 3.

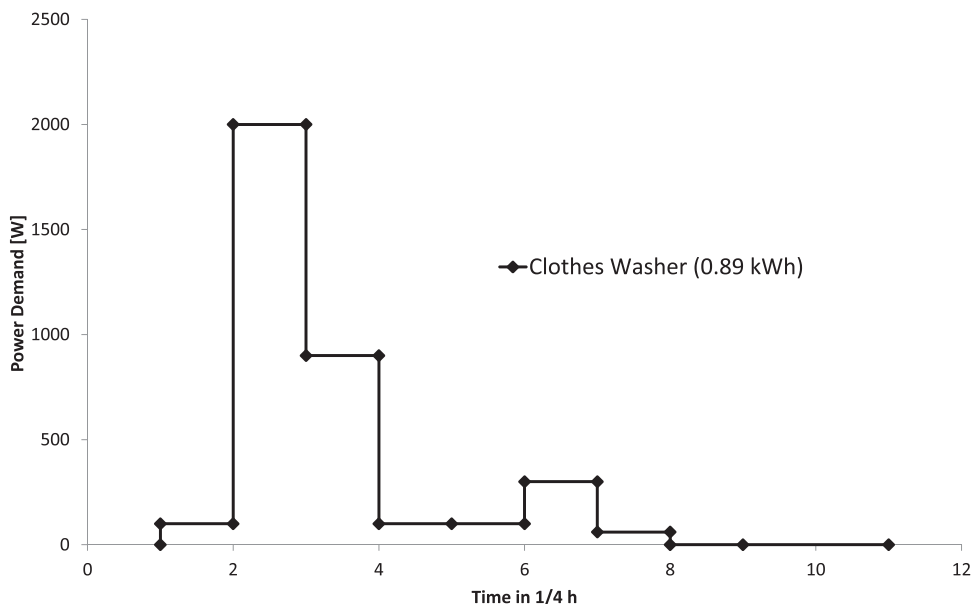Table 4 presents the comparison between the original data [5] and the performed simulation.

Fig. 2. Example, general pattern of a power demand curve of a washing machine cycle in 1/4 h steps [25].

Table 3
Data regarding the penetration for the selected appliances in the city of Coimbra [4,24].

Number of electricity consumers	Ownership rate (INE2010)			Number of households with		
	Clothes washer	Clothes dryer	Dish washer	Clothes washer	Clothes dryer	Dish washer
76,642	0.907	0.223	0.408	69,514	17,091	31,270

The two set of results are statistically rather similar, providing a reliable representation of the aggregate load diagram of appliances by the performed simulation.

2.2. Possible control over S&I loads

For the purposes of the selected simulation an indirect load management method was chosen, based on a real time pricing program. However, in order to implement a simulation, the amount of time that consumers allow the postponement of the operation of appliances, as well as information on, the consumer acceptance of this kind of technological aid are needed. The Smart-A project [26] can shed some light on this topic. The acceptance of smart operation by consumers, assessed by [26], was very high for all three operation modes. This acceptance ranged from 88–97% for the clothes washer, to 85–96%
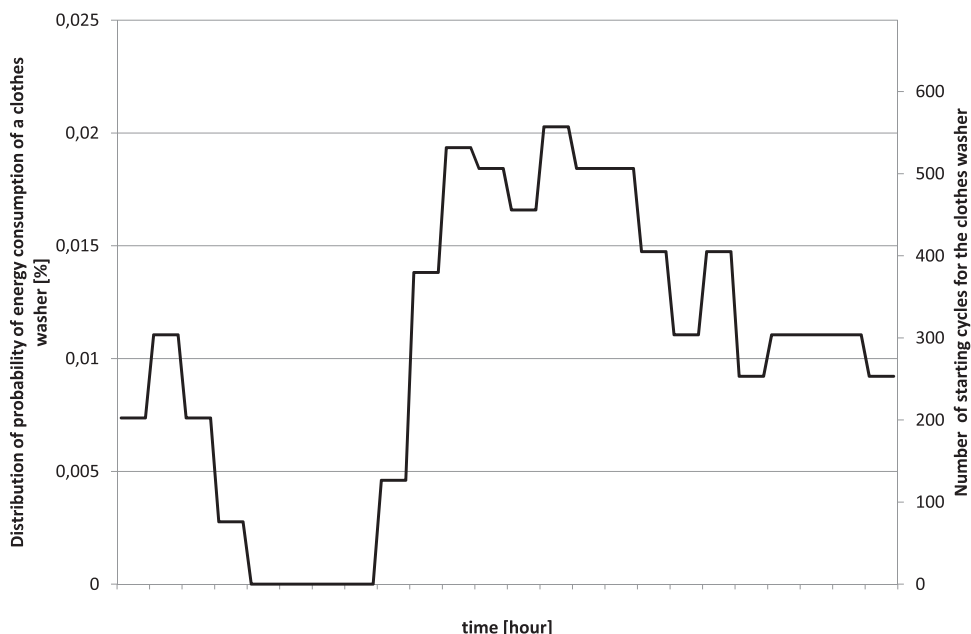

Fig. 3. Probability of energy consumption and number of cycles for an average day of a clothes washer in the City of Coimbra.

Table 4
Descriptive statistics for the aggregated diagrams of the selected appliances.

	Descriptive statistics	Clothes washer		Clothes dryer		Dish washer	
		Original	Simulation	Original	Simulation	Original	Simulation
Power (MW)	Mean	1.0225	1.0217	0.9025	0.8918	1.0501	1.0508
	Standard Error	0.0651	0.0629	0.0604	0.0571	0.0782	0.0706
	Median	1.0827	1.0495	0.8550	0.9582	0.9740	0.9758
	Standard Deviation	0.6374	0.6164	0.5916	0.5597	0.7658	0.6921
	Variance	0.4063	0.3800	0.3500	0.3133	0.5865	0.4789
	Minimum	0	0	0	0	0.1218	0.1798
	Maximum	1.9850	1.9399	1.99499	1.93664	3.0439	2.7216
	Consumption (MWh)	24.54	24.52	21.66	21.40	25.20	25.22

for the clothes dryer and between 88% and 96% for the dish washer.

Although the consumers that participated in the Smart-A project [26] expressed a very high acceptance, they also conveyed the message of some concern regarding the automatic operation of appliances. For instance, in regard to the clothes washer, consumers are afraid that clothes may be damaged due to smart operation, that the clothes might get moldy or the quality of the wash may be affected due to a long stay in the machine or even that the noise of the machine working in the night may disturb people who want to sleep in the household.

As for concerns of consumers regarding the automatic operation of the clothes dryer, and despite the fact that the acceptance was very high, a postponement does not make a sense for consumers because they have to wait for the end of the washing cycle. According to the authors of [26], this acceptance might be explained because the clothes dryer is seen as a non-ecological appliance. However, the appearance of a smart clothes washer is seen as positive issue for the environment. Another objection had to do with the quality of the dry process as consumers are afraid that leaving the laundry in the machine for an extended period of time can wrinkle clothes.
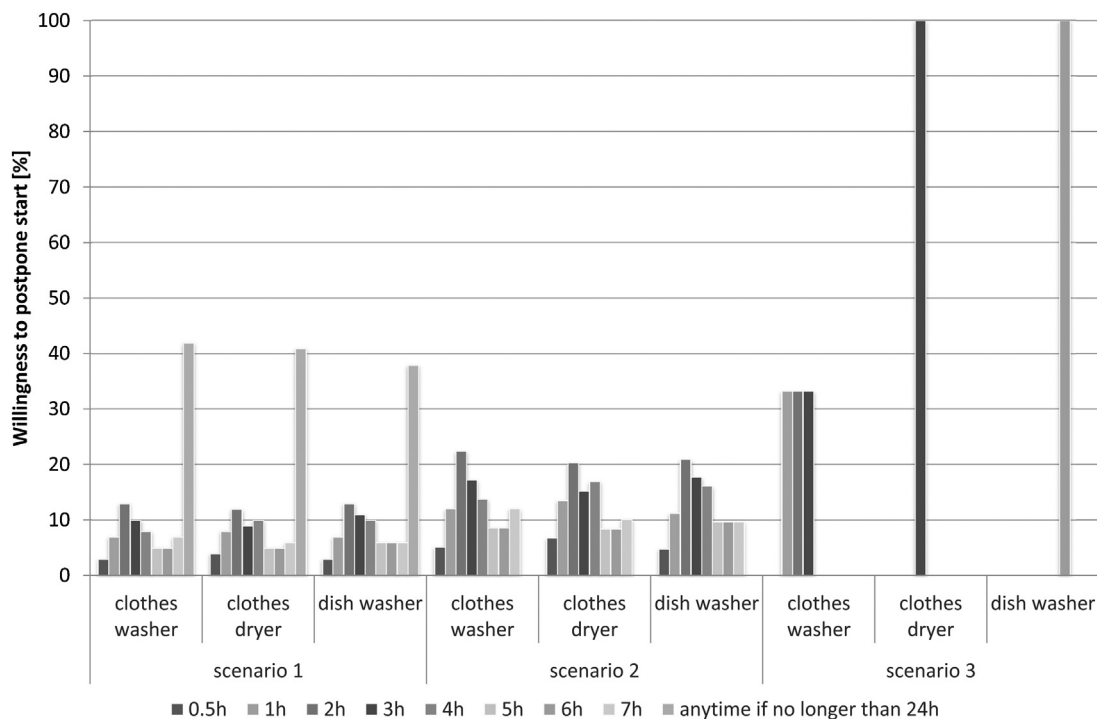
The dish washer is the appliance that consumers see as more flexible. This might be explainable because consumers are not concerned with the time of operation of this appliance and because its operation, being less noisy, already occurs at night or when consumers are not at home.

However, without further information it is difficult to predict the overall acceptance and access of consumers to smart operation as well as other restrictions to the operation of appliances.

In Fig. 4, the three scenarios of consumer tolerances that were used in the simulation for postponing the start of appliances are presented.

2.3. Model explanation

The initial idea for the development of this model consisted in the attempt to primarily represent the domestic consumption diagram for the city of Coimbra. It was intended that the developed model could be capable of incorporating information regarding the consumption patterns through a random choice of the operating cycles of equipment (controllable loads only), taking into consideration the probable schedules, based on the exhibited load diagram.

Fig. 4. Willingness to postpone start (%) for the considered appliances, scenario 1 based on Ref. [26], scenario 2 adapted from Ref. [26] without the possibility to postpone start 24 h, scenario 3 adapted from Ref. [27].
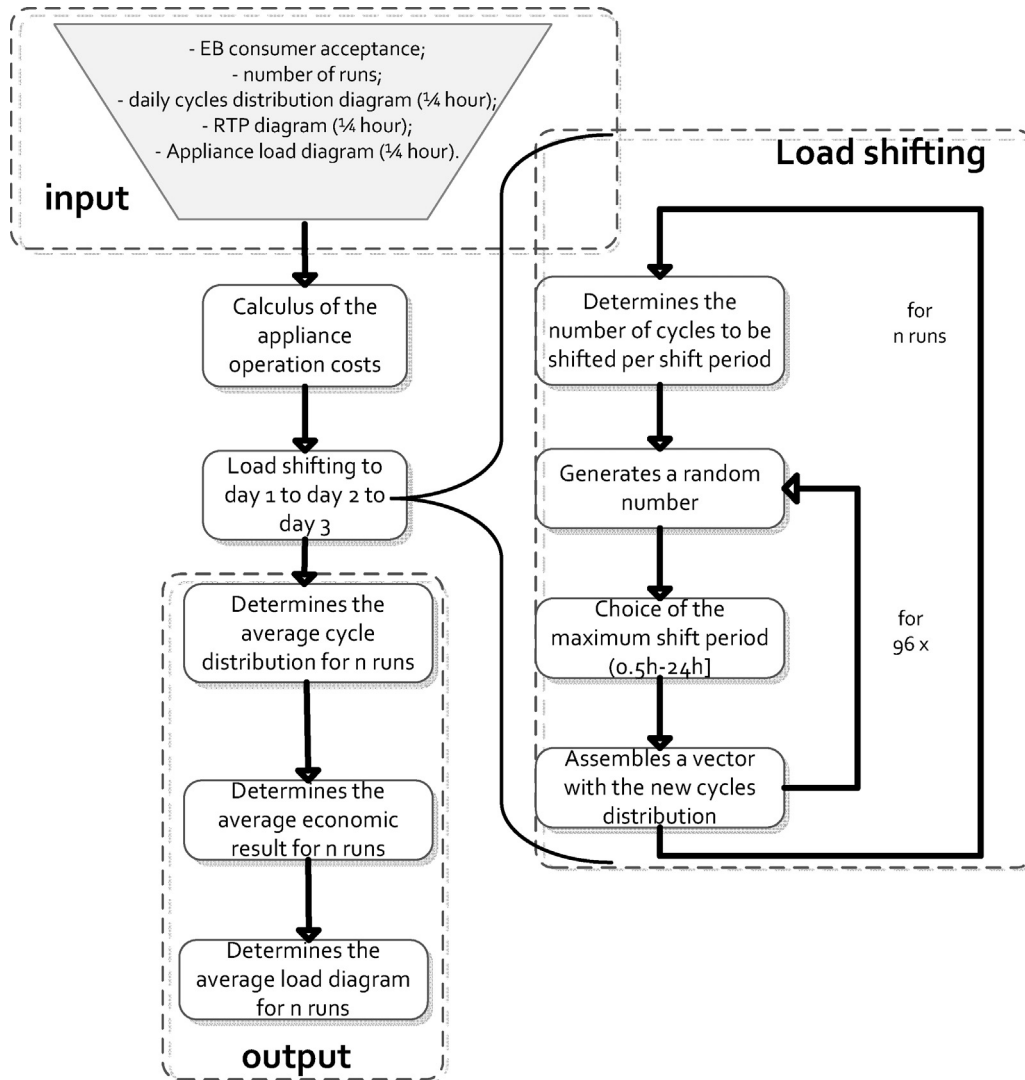
Fig. 5. Structure of the developed simulation routine.

The diversity of the energy boxes programming, consequence of the diversity of the preferences of the household owners, assure a degree of randomness when reacting to price stimuli. However, this means that fundamental questions still remain:

- What is the value for the grid of the aggregated resource composed by the total number of deployed energy boxes? What power can be made available to the grid in each hour or quarter-hour by the combined effect of all the energy boxes and what is the resultant rebound?

In order to answer these questions it was necessary to set up an additional simulation that made use of DR actions, e.g., postponing the start of appliances. However, it was necessary to have some things in mind while doing so.

Some assumptions were made to simulate the operation of the EB and for that matter the acceptance of the delay on the operation of appliances: the consumer tolerance for postponing the start of operation does not depend on the time of day and there is no priority among appliances for delaying their operation. The methodology assumes that each energy box decides whether the new schedule of operation of the equipment is more economical, depending on the current appliance cycles schedule over a price signal. Simultaneously, the availability of consumers that allow to postpone the start of their appliances is taken into account.

The selected or chosen method of operation of the energy box (for controllable appliances with potential of postponing the operation) must consider a percentage of acceptance, as well as the level of deployment of the energy box (which were based in the results of the tolerance or willingness of users to delay the operation of appliances according to economic criteria). These two inputs are provided by the user each time the routine is called. As for the daily cycles distribution diagram, the day ahead prices and the appliance load diagram, are included in the variable list. Since the operation of the energy box follows a price signal, load shifting was based on the spot price for an average day of 2012 according to the Iberian Energy Derivatives Exchange (OMIP website) [28]. This allows determining the cost of running the appliance starting at each of the quarter-hour of the three days.

The consumption was delayed/rescheduled according to the willingness to postpone the start of appliances, following the energy price, (which can ultimately include also renewable energy preferences or other preferences to be monetarily valued).

To represent the individual decisions made by each Energy Box owner, regarding how long a delay is allowed in the operation of a certain end-use (0.5 h, 1 h, 2 h, 3 h to 24 h), a Monte-Carlo based procedure was used, generating random numbers to represent

Table 5
Energy average day simulation results in MWh for the household sector in the City of Coimbra.

Scenario	Energy (MWh)/day						
	Original	Original simulated	Energy Box deployment (%)				
			20%	40%	60%	80%	100%
1	2490.72	2490.13	2491.16	2491.24	2492.67	2493.89	2495.42
2			2490.64	2490.99	2491.22	2492.05	2491.98
3			2490.97	2491.57	2492.20	2491.07	2493.30

possible decisions to each of the considered energy boxes in each run. In order to increase reliability, the routine executes a batch of runs and stores the results.

Fig. 5 presents the structure of the developed routine.

The model uses three consecutive days in order to obtain a clean outcome of the central day, avoiding first-day and last-day effects that would be minimized in the long run.

The total number of load cycles of the appliances is maintained during the three-day simulations.

As a final result, what is intended is to understand the value of the aggregated energy boxes for the system operator, by calculating the power that can be made available in every hour of the day. The output of the model provides the distribution of the average cycles for n runs, the average economic results and the average load diagram per appliance. For the purpose of this work, only the average load diagram will be considered.

2.4. Results

Table 5 presents the average residential aggregated consumption for the city of Coimbra, based on 100 simulation runs.

The original simulated values are the outcome of the MATLAB simulation without any demand response intervention, based on the original data, as plotted in Fig. 1. The intention of the developed routine is to reproduce the results in terms of the distribution of energy and power along the day at a city scale. The simulation of the energy box deployment provides the energy consumed for the average day in the city of Coimbra considering a defined consumer acceptance measured as a percentage.

Table 6
Transferred energy in simulations for all scenarios with different deployment percentages.

EB deployment (%)	Transferred energy in simulations (MWh)/day		
	Min-reference (power delivery)	Max-reference (rebound)	(Max-reference) +(Min-reference)
20	−24.07	28.48	4.41
40	−48.98	56.66	7.68
60	−72.98	84.65	11.15
80	−98.04	113.61	15.57
100	−121.26	140.49	19.23

Table 6 exhibits the values regarding the minimum value obtained in each of the demand response scenarios. From the results provided in Table 6 it is possible to verify that in all considered deployment scenarios, the difference between the maximum increase to the intervened load diagram is bigger than the difference between the original simulated diagram and the minimum power after reduction. Having in mind the need for energy conservation in the simulation, this suggests the introduction of new peak demand at some moments and a demand alleviation along the day through the energy boxes. However, in this case these new peak demands are not meaningful in an aggregated vision as perceivable in Fig. 6.

Fig. 6 represents the aggregated original and simulated diagrams of the household electricity consumers of the City of Coimbra and the resulting diagrams of three different scenarios of operation, for a 20% deployment of the energy box.
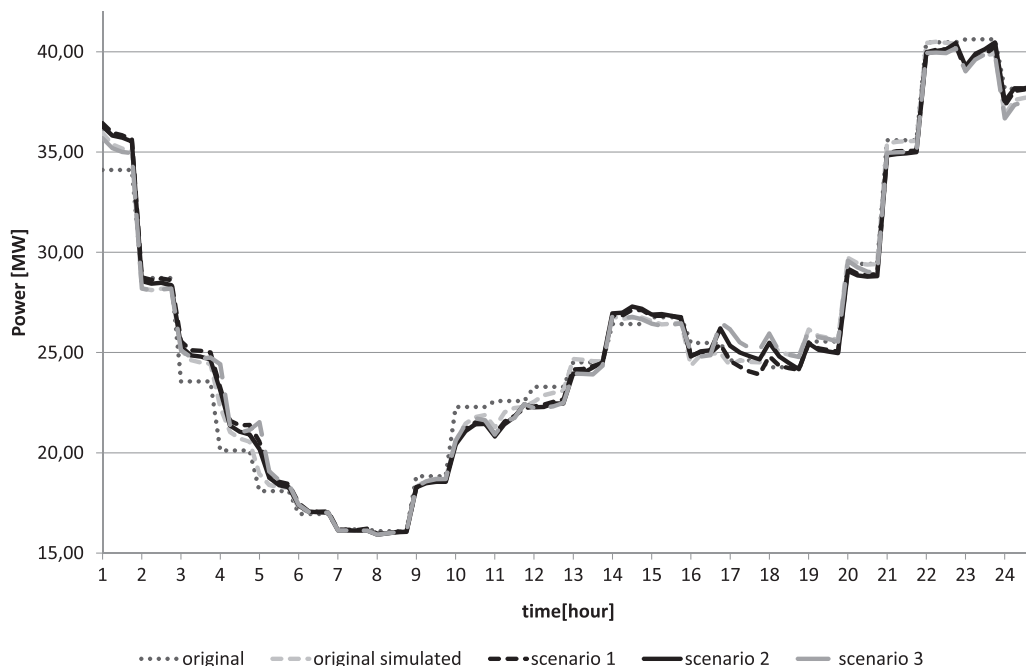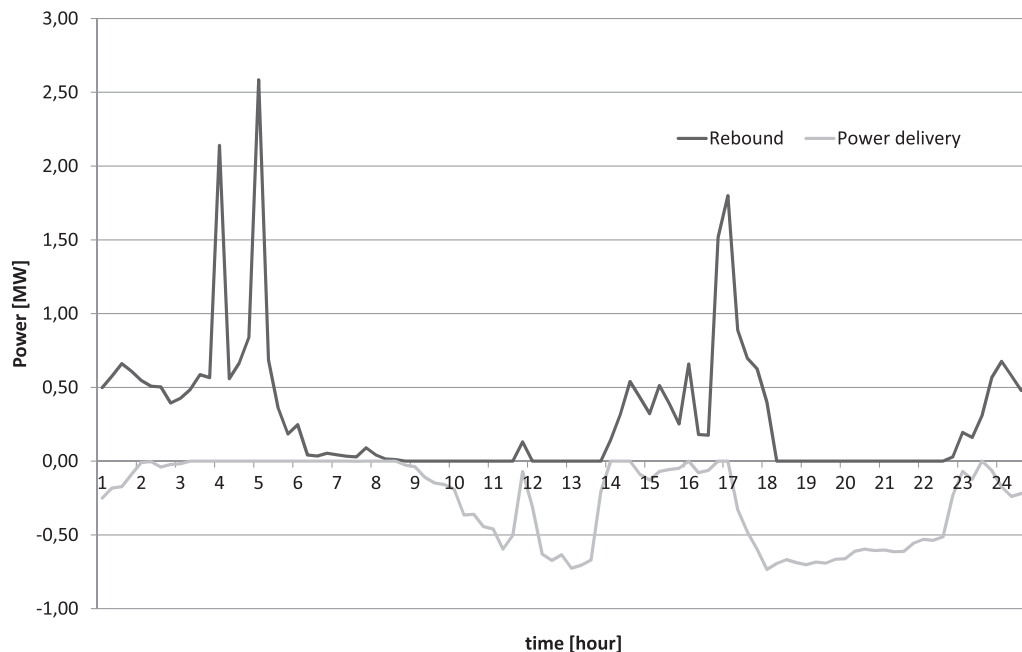

Fig. 6. City of Coimbra, simulation results for 20% deployment of the Energy Box (100 runs).

Table 7
Maximum and minimum power verified in the load diagrams at a certain time.

		Original	Original simulated	20% EB Scenario 1	20% EB Scenario 2	20% EB Scenario 3
Maximum diagram power	Power (MW)	40.63	40.50	40.32	40.47	40.18
	Occurred at:	23h00m	22h15m	22h45m	23h45m	22h45m
Minimum diagram power	Power (MW)	16.09	15.92	15.96	15.92	15.92
	Occurred at:			8h00m		

Fig. 7. Range of the power delivery and rebound for a 20% deployment of the Energy Box in the city of Coimbra.

The power that the aggregated energy boxes may deliver in each quarter-hour may be assessed by the difference between the reference demand and the minimum demand obtained in the simulations. The rebound that can occur is also obtained by the difference between the maximum demand obtained in the simulations and the reference load diagram (Fig. 7). The purpose of calculating these values to estimate the possible range of the variation interval as a function of the dissemination of an automatic load management system such as the Energy Box, as in Fig. 7.

The results presented in Fig. 7 show that the aggregated resource may deliver around 700 kW between 12:30 and 13:30 and between 18:30 and 22:30, to a maximum of circa 3% of the demand on that period. But the rebound may represent an additional load of 2.5 MW at 5 a.m. or 1.8 MW at 5 p.m. if the energy boxes are allowed to switch on all their interrupted loads immediately when possible.

This diagram accounts for a maximum power of 40.63 MW and a minimum power of 15.92 MW, as can be confirmed through the reading of Table 7.

3. Conclusions

This work presents a possible methodological approach for evaluating the impact at grid level of the deployment of a demand response technology. However, the simulation results depend of the type and availability of the considered loads in a particular framework.

The purpose of the developed work consists of identifying the size of the aggregated energy box resource, in equivalent of a generation resource, considering the possible postponement of the available loads that usually operate during peak and partial peak hours. From that perspective, this work considers particularly important to identify the period where energy consumption may be reduced, but also the periods when the rebound resulting from the switching-on of the interrupted/shifted appliances will occur.

A possible introduction of new peak demand periods in the diagram implies the need to take into consideration management strategies.

One possible management hypothesis would be the introduction of a random delay in the firmware of each EB when defining the re-start of the various load management devices. Peak coincidence would thus be avoided and the resulting aggregated diagram would be smoother. A different possibility may imply the DSO to have some degree of control, imposing a queue in order to only enable the switching-on of controlled appliances, by the connected energy boxes, on an established maximum rate.

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