Demand side management strategies for the residential sector

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ABSTRACT

The current technological is linked to a boost of resources expenditure and the inefficient habits of people are the main obstacle in the struggle for the achievement of energy efficiency. This work aims to take a step toward the upgrade of the energy and cost efficiency in the residential sector, through an active demand side management of the energy consumption and with a strong linkage to the Social Sciences. Such is undertaken through a calculation tool developed in this work, which automates (and enables) the estimate of the respective costs of the different profiles, as well as the daily average profiles. The approaches and main conclusions follow:

- Shifting the consumption of two refrigerators from "peak" times: the consumption and the costs tend to increase, although depending on the usage and on the model of the refrigerator;
- Connecting the dishwashing and washing machines to a pipe in which the water is heated by a gas water heater: the costs and the environment impact rise. If consumption to heat the water is not needed, a decrease at 52 and 89% in the costs and in the environmental impact is achieved, averagely;
- Analyzing the electricity consumption profiles of four different families and determining the potential savings by changing the tariff and the contracted power, eliminating the standby consumption during the night time, and deviating the usage of the washing and dishwashing machines to "off-peak" times: costs lowering up to 19.8% just by changing the contracted power, being the overall savings up to 47.1%, and consumption decrease of 4.9%.

The approaches followed in the second and third points would lead to a national consumption saving of 2.6%, corresponding to 1.4×10^3 GWh and 3.9×10^3 tonCO_2e per year.

Keywords: Energy efficiency, Consumption profiles, School buildings, Behavior change, Sustainable behavior, Refrigerator, Dishwashing machine, Washing machine, Demand side management.

1. Introduction

This work is directly associated to a Project named Net Zero Energy School (NZES), which is being developed by a partnership among the Instituto Superior Técnico (IST), the Laboratório Nacional de Engenharia Civil (LNEC), the Associação Nacional de Conservação da Natureza (QUERCUS) and the Instituto de Ciências Sociais (ICS), under the framework of the MIT Portugal program, a research partnership between the Massachusetts Institute of Technology and the Portuguese Universities. This Project intends to sensitize the students and their families to improve their domestic energy habits and, with that, their efficiency. This linkage allows a more effective contribution from this work to the domestic energy efficiency due to the unprecedented association between Engineering and Social Sciences, which opens a new path in breaking the friction between the inertia of the human habits and the technology innovation.

The importance of the energy efficiency at a residential level is notorious when one thinks about the share of the building sector in the national electricity consumption, which, in 2008, was 60%: 29% concerned to domestic buildings and 31% regarded to service buildings [1]. A high share of these buildings consume electricity in BTN ("baixa tensão normal", corresponding to electricity consumption with voltage levels under 1 kV, being the contracted power up to 41.4 kVA), which corresponds to 44.9% of the national consumption [2].

Reinforcing the urgency of improving the national energy efficiency, the 27 countries of the European Union (EU-27) must accomplish the following goals:

- Reducing 20% of the total energy consumption registered in 1990, until 2020 [3];
- Rising up the renewable energy share to 20%, until 2020 [4], which means, for Portugal, to raise the renewable energy share to 31% until 2020 [5];
- Improving the energy efficiency so that the energy expenditure reduces 20% [6].

  The national energy policy is based on a "supply follows demand" [7], which leads to an over-installed national power to serve the highest expected consumption, mainly in "peak" time, as shown by the national consumption in 2010 [8].

This system has the advantage of satisfying the energy needs but it has the disadvantage of allowing that the demand commands the amount of energy produced. By having an active role in the energy demand side – demand side management – one can control the consumption so that the national supply can be more efficient. This control must fall within boundaries and should not decrease the comfort level of the population, but it must be accurate enough in order to incentive the efficiency usage of electricity. The wished national consumption profile must be as homogeneous (flat) as possible to reach the best possible efficiency because, in this way, the consumption will dilute from "peak" time to the remaining periods of the day. This allows a decrease in the national instant electricity supply power with a lowering of the instantaneous pollution generation, as well as of the grid tension, what reduces the electricity loss by heat transmission [2].

This work aims to contribute to that general objective, by focusing on the optimization of the use of three utilities (refrigerator, dishwashing and washing machines) and searching for the most appropriate human behaviors, namely by comparing normal and proposed usages in terms of energy and cost, and by analyzing energy consumptions associated to the habits of four families.

The impact at a national scale is also assessed.

2. Experimental

The experimental section is divided in two parts:

- One concerning the management of the usage of the appliances (refrigerator, dishwashing and washing machines) in order to determine if the following proposals are environmentally and economically benefic:
  - Turning off the refrigerator during some daily periods;
  - Connecting the washing and the dishwashing machines to the hot water pipe (the same as the hot water tap of the kitchen), instead of the regular cold water pipe, during the working time.
- Another one, concerning the analysis of the electricity consumption profiles of four different families (two of which belonging to the NZES project study-target) and the daily average costs being determined according to the different possible tariffs, what enables the assessment of the adequacy of the chosen tariff by each family. Two behavior changes are proposed:
  - Change the dishwashing and washing machines consumption to "off-peak" periods;
  - Extinguishing the standby consumption during the night time.

Then, an overall analysis through the average consumption of these families is performed and other behavior changes are proposed:

- The implementation of, *e.g.*, a solar thermal device so that the consumed water in the dishwashing and washing machines does not require electricity to heat.

Having this. An extrapolation to a national level of the consumption habits change and of the potential savings is then undertaken.

The consumptions of the utilities were measured with one PlugMeter® that can register up to thirteen variables regarded to electricity consumption while the appliance is turned on. Concerning the consumption profiles of the four families, they were measured with the iMeter® kit, the PlugMeter of which is a complement but, in this case, the iMeter® registers the overall consumption of the dwelling.

With a particular significance to automation, it was developed, in this work, a calculus tool through a code in Visual Basic that analyzes the data saved by these gadgets (in format Coma Separated Value – CSV – file), which estimates the average daily consumption (accumulated and for the chosen interval) and the average daily costs according to all different tariffs for the different seasons of the year. This code is used in this work each time a daily average consumption and the associated costs are presented. Beyond the practical use for this work, this tool will remain available for further applications, *e.g.*, the NZES Project, what provides an added value.

2.1. Refrigerators

The shares of the refrigerator, the dishwashing and the washing machines in the domestic electricity consumption are 22%, 5% and 3%, respectively [9].

The study focused on two refrigerators:

- One in the house of the author, which is a BOSCH KGN46A03, with energy labeling A+ [10], a compressor power of 150 W and a refrigeration heater power of 220 W. This refrigerator is a combined one, meaning that it has a freezer partition bigger than a regular refrigerator;
- Another in the MIT Portugal Program offices, at the IST campus TagusPark, which is an INDESIT R 28, with energy labeling B and a total power of 150 W. This refrigerator has an energy label lower than the BOSCH but less than half of its power.

The chosen schedules were:

(i) Working continuously;
(ii) Disconnected from 9 to 10 h and from 15 to 16 h, which corresponds to the "peak" times in electricity consumption;
(iii) Disconnected from 22 to 0 h, which corresponds to the "peak" time at the residential sector.

The temperature could not be measured, so it had to be estimated with the registered temperatures in the Barcarena and Amadora weather stations in [11] for the testing periods. The weekly room temperature variation is considered to be half of the weekly variation registered above, once this variation was noticed when the temperatures in both rooms were measured (after the experiments) and these values were crossed with the respective ones registered in [11] for that same period.

2.2. Dishwashing and washing machines

The measurements concerned the consumption of:

- A dishwashing machine, which is a BOSCH, model SMS40M02EU;
- A washing machine, which is a SIEMENS, model WM10E120EE.

Both are from the author's house. Two scenarios were simulated for each machine:

(i) Working normally, in a selected program;
(ii) Working with water coming from the pipe in which the water is previously heated by the water heater by combustion of natural gas.

The following potential scenario was also analyzed:

(iii) Heating the used water with a non pollutant and "cost-free" energy source, *e.g.*, a solar thermal device[1].

The tested programs were:

A. Dishwashing machine, working in program at 70°C;
B. Dishwashing machine, working in program auto at 45-65°C;
C. Washing machine, working in program at 40°C.

2.2.1. Estimate of the minimum gas flow

Although the maximum and minimum heating powers of the gas water heater (19.2 and 7 kW, respectively) and the maximum gas flow (2.3 m^3) are specified in the supplier manual, the minimum gas flow is unknown and should be determined, by using the following expression in which 7 kW is the minimum heating power, 0.8404 kg/m^3 and 45.1 MJ/kg the natural gas specific weight and lower heating value (LHV) [12], respectively:

$$\frac{7\ \mathrm{kW}}{0.8404\ \mathrm{kg/m^3} \times 45.1\ \mathrm{MJ/kg} \times 10^3\ \mathrm{kJ/MJ} \times \frac{1}{3600}\ \mathrm{h/s} \times 1\ \mathrm{kWs/kJ}} = 0.66\ \mathrm{m^3/h}$$

2.2.2. Estimate of variation of the water temperature

The water flow was regulated to a value of 4.3 L/min, which is the minimum experimental flow able to activate the water heater.

The used water in scenario (ii) is previously heated by combustion of natural gas in the water heater but not all the used water is heated. The heating inefficiency in this scenario results from two important factors:

- An often insufficient flow for the activation of the gas water heater (specially noticed in program A);
- Long intervals between the water consumptions, which causes a drop in the temperature of the stopped water in the pipe and, when the machine consumes water again, it is firstly consumed that less heated water and only after a certain continuous consumption, is the recently heated water consumed.

The lost heat in the pipe can be quantified as follows: In [18], this phenomenon is described and Eq. (1) is given to determine the heat loss (q_p), depending on the length, diameter and material of the pipe. Such equation gives a linear approximation of the heat decay, which is not quite what happens. The main inaccuracies are due to the error in the measurement of the pipe length and to eventual fluctuation in the air temperature between the pipe and the wall, which may not correspond to the registered average of 25°C, in the kitchen.

$$q_p = \frac{2\pi k_p L_p (T_1 - T_2)}{ln\left(\frac{D_o}{D_i}\right)} \quad [\mathrm{kJ/h}] \qquad (1)$$

In the experiment, the material of the pipe is a non insulated polyvinyl chloride (PVC) and the parameters values are [16]: K_p = 0.511 kJ/(m.°C.h) (thermal conductivity), L_p = 4 m (pipe length), D_o = 0.0419 m (outside diameter), D_i = 0.0329 m (inside diameter), T_1 = 70°C (for test A and B) and 45°C (for test B) (water temperature in the water heater), T_2 = 25°C (air temperature).

The rate of the temperature drop ($\Delta T/dt$) is given by [Eq. (3)] where C_p [Eq. (2)] is the mass thermal capacity of the water, $\partial Q = q_p/dt$ and m is the mass of the water. C_p values for the experimental temperatures are [17]: 4.179 (25°C = 298.15K), 4.185 (45°C = 282.15K) and 4.193 (70°C = 343.15K) kJ/(kg.K). The water mass is given by $m = V \times \rho$ (kg, where ρ = 1 kg/L).

$$C_p = \frac{1}{m}\frac{\partial Q}{dT}\ [\mathrm{kJ/kg.K}] \qquad (2)$$

Knowing that ∂Q is obtained by q_p, the rate of temperature drop is now obtained in Eq. (3):

$$\frac{\Delta T}{dt} = \frac{q_p \times 60^{-1}\mathrm{h/min}}{m \times C_p}\ [\mathrm{K/min}] \qquad (3)$$

[1] Though such device only reaches efficiencies of 50%, is able to heat the water at temperatures around 60°C and the heat loss still occurs in the water pipes [13], it is still established in this Thesis that such device is enough for the efficient heat purpose. The coupling with a photovoltaic panel is also not studied, which would eliminate the electricity consumption for these appliances and it can be enough to fulfill the energy need of a whole dwelling and, even, be enough to sell it to the grid, once the study only incises in the difference in the energy consumption for water heating in the dishwashing and washing machines.

$T_1 = 70^{\circ}C$, $T_2 = 25^{\circ}C$: dt = 19min; $\Delta T/dt = 2.36^{\circ}C/min$
$T_1 = 45^{\circ}C$, $T_2 = 25^{\circ}C$: dt = 13min; $\Delta T/dt = 2.28^{\circ}C/min$

This means that, for simulation A, if there is an interval between two gas consumptions of more than 19 min, the water in the pipe (and that is about to be consumed) is already at the air temperature of 25°C. For simulations B and C, that period is of 13 min. After these periods, the water heater only has an effect in the temperature of the consumed water if the water consumption lasts for enough time so that all the remaining water in the pipe is consumed and the just heated water passed through the pipe. This period is calculated by dividing the volume of the pipe by the water flow – the regulated water flow is of 4.3 L/min:

$$\text{Time for the water to cross the pipe} = \\ = \frac{\pi \times \left(\frac{0.0329\ \text{m}}{2}\right)^2 \times 4\ \text{m}}{4.3\ \text{L/min} \times 10^{-3}\ \text{m}^3/\text{L} \times 60^{-1}\ \text{min/s}} = 47\ \text{s}$$

The potential electricity saving corresponding to the theoretical scenario (iii) can now be estimated

Table **3.1-1-** Overall daily consumptions and costs concerning each measured scenario for the tested refrigerators at temperature of (i).

	INDESIT			BOSCH		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)
kWh	1.115	1.177	1.189	1.028	1.113	1.075
kgoe	0.096	0.101	0.102	0.088	0.096	0.092
kgCO2e	0.210	0.221	0.223	0.192	0.210	0.201
€	0.124	0.130	0.131	0.115	0.123	0.118
Balance relatively to scenario (i)						
Δ kWh	-	0.062	0.074	-	0.085	0.047
Δ kgoe	-	0.005	0.006	-	0.008	0.004
Δ kgCO2e	-	0.011	0.013	-	0.018	0.009
Δ €	-	0.006	0.007	-	0.017	0.003

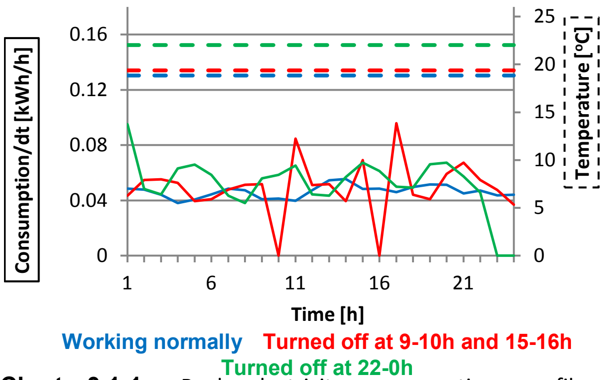

Chart 3.1-1– Real electricity consumption profiles (continuous lines) and average air temperatures (dashed lines) for the refrigerator INDESIT R 18, for the three different schedules.

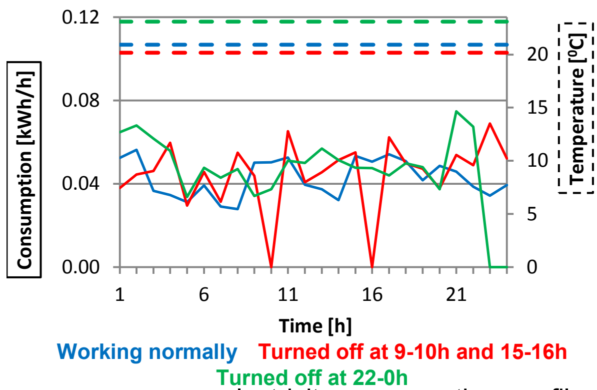

Chart 3.1-2 – Real electricity consumption profiles (continuous lines) and average air temperatures (dashed lines) for the refrigerator BOSCH KGN46A03, for the three different schedules.

2.3. Residential consumption profiles

Table 2.3-1 – Main features of the analyzed houses[a]

	House 1	House 2	House 3	House 4	Average
dishwashing machine	Yes	Yes	Yes	Yes	100%
washing machine	Yes	Yes	Yes	Yes	100%
refrigerator	Yes	Yes	Yes	Yes	100%
freezer	Yes	Yes	No	No	50%
electric water boiler	Yes		No	No	25%
oil radiator	Yes	Yes	No	Yes	75%
air conditioning	No	No	Yes	No	25%
number of rooms	4	4	3	4	3.75
number of people	4	6	4	5	4.75
existing tariff	Simple	Simple	Simple	Simple	Simple
contracted power (kVA)	-[a]	10.35	3.45	6.9	6.9

The analyzed profiles are not annual, meaning that not all the seasons are represented and, therefore, not all the consumption fluctuations are shown. Hence, in order to generalize the measured profiles to an annual level, it is considered that:

- During the winter period, the consumption increases 13% and with a constant profile (explained in the following paragraph);
- The annual vacation period is of 30 days, being 22 days (approximately three weeks) in summer and 8 days (approximately one week) enjoyed in winter;
- The standby consumption during the vacation period is lower than that during the normal period;
- Once all the houses have Normal tariff, they use the dishwashing and washing machines randomly during the day.

3. Results and discussion

3.1. Refrigerators

The simulations undertaken for the two refrigerators show different consumption profiles in the different scenarios (Charts 3.1-1 and 3.1-2). The overall consumption results are expressed in Table 3.1-1, as well as the CO_2 emissions of each one.

Table 3.1-1- Overall daily consumptions and costs concerning each measured scenario for the tested refrigerators at temperature of (i).

	INDESIT			BOSCH		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)
kWh	1.115	1.177	1.189	1.028	1.113	1.075
kgoe	0.323	0.341	0.345	0.298	0.323	0.312
$kgCO_2e$	0.524	0.553	0.559	0.483	0.523	0.505
€	0.124	0.130	0.131	0.115	0.123	0.118
Balance relatively to scenario (i)						
Δ kWh	-	0.062	0.074	-	0.085	0.047
Δ kgoe	-	0.018	0.021	-	0.025	0.014
Δ $kgCO_2e$	-	0.029	0.035	-	0.040	0.022
Δ €	-	0.006	0.007	-	0.017	0.003

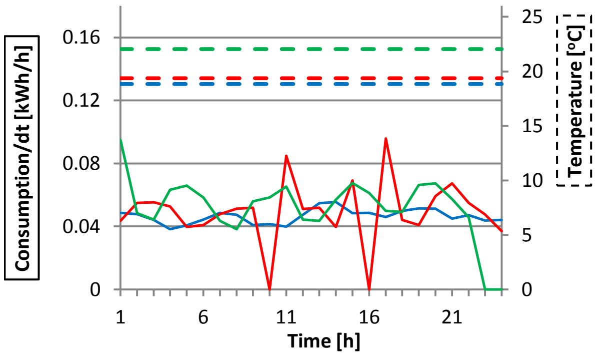

Chart 3.1-1– Real electricity consumption profiles (continuous lines) and average air temperatures (dashed lines) for the refrigerator INDESIT R 18, for the three different schedules.

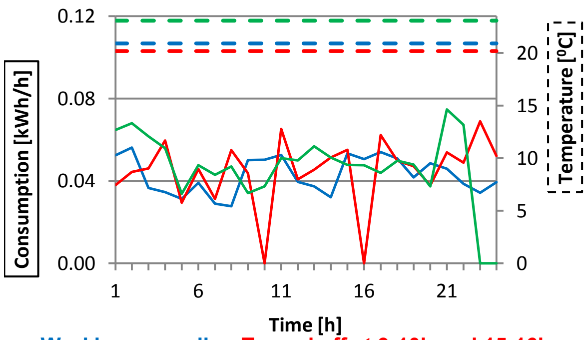

Chart 3.1-2 – Real electricity consumption profiles (continuous lines) and average air temperatures (dashed lines) for the refrigerator BOSCH KGN46A03, for the three different schedules.

The following results can be stressed:

a) After a perturbation, the refrigerator increases the consumption and stabilizes. Such can be noticed in scenario (iii).
   - Reckoning the refrigerator INDESIT, the consumption stabilizes after 1 h, maintaining a higher amplitude than in (i)
   - Concerning the refrigerator BOSCH, the consumption stabilizes after 5 h, maintaining roughly the same amplitude as in (i).

b) The refrigerator INDESIT has a consumption while working normally – (i) – with lower amplitudes than the BOSCH.

c) Scenarios (ii) and (iii) have an associated higher consumption than in (i), corresponding to different values in each refrigerator, proportional to the associated environmental impact.
   - The consumption registered in (ii) is higher than in (i), concerning the refrigerator INDESIT and BOSCH, by 5.6 and 9.9%, respectively.
   - The consumptions registered in (iii) relatively to the refrigerators INDESIT and BOSCH are, respectively, 6.6 and 4.6% higher than in (i).

d) The costs differ between the refrigerators within the same scenario.

- Concerning scenario (ii), the costs rise 4.8% in the refrigerator INDESIT but, for the refrigerator BOSCH, the costs increase 7.0%.
- Regarding scenario (iii), the costs increase 5.6% in the refrigerator INDESIT and 2.6% in the refrigerator BOSCH.

Firstly, one must keep in mind that the temperature measurements were not the most accurate ones but the important factor is the temperature variation, which is trusted to be accurately achieved. Also, though considering the use of the refrigerators as the same in each simulated period, this is a point that is impossible to be precisely controlled. Furthermore, one does not know the performances of the engine and the compressor, which are trusted to be the main influent factors in the consumption and in the performance losses during the "on-off" cycle [18].

The working way differs in the two refrigerators. Indeed, the refrigerator BOSCH shows higher consumption amplitudes and longer shut-down periods, and the INDESIT has a flatter profile, with shorter shut-down periods. The BOSCH is a combined refrigerator, with a power of 370 W, contrasting with the 150 W of the INDESIT, what means a higher consumption, even though it has a higher energetic certification. The dimensioning of the capacity of the refrigerator according to the dwelling's needs is an important factor that must be consider together with the energetic label.

The usage – concerning also the induced working periods – influences the consumption profiles. In fact, the refrigerator INDESIT has a high usage during the day at lunch time and the BOSCH has generally a high usage at lunch and even higher during dinner time. The effects of such differences are explained, as follows.

Concerning the refrigerator INDESIT, the shut-down periods in scenario (ii) occurred during the day, when the probability of being and the room temperature were higher, and with intervals of 5 h, which may not have given enough time to remove the extra heat that got in during the shut-down period. Such contrasts with scenario (iii), in which the probability of being used during, and after, the shut-down period is lower, which did not require such a high effort of the refrigerator to extract the accumulated heat during that period. Indeed, the high consumptions after the shut-down periods were 52.5% higher in scenario (ii) than in scenario (iii). This is justified by the usage. Indeed, it was expected a higher consumption peak after a shut down period of 2 h (scenario (iii)) than in the case of 1 h (scenario (ii)).

Concerning the refrigerator BOSCH, the consumption profile in (i) evidences the occurrence of periodical peaks which tend to be intercalated with the ones in (iii). Such may be explained by the fact of the turn off period in (iii) being at the arising of a new peak, which implies a delay in that peak and, as well, an increase afterwards, affecting the remaining peak periods by also delaying them. As for the highest peak noticed in (iii) which occurs before the shut down period, that peak consumption may have not been a consequence of a different usage but, instead, due to the temperature increase and the fact of that period corresponding to the normal high usage period. Such does not happen in (i) because the consumption peak tends to be earlier. The high consumptions after the shut-down periods were 2.3% lower in scenario (ii) than in (iii), which evidences a higher need to extract the heat that got inside during the longer continuous turn-off period in (iii).

The approach that led to these results must be taken rather cautiously. Indeed, the experiments were performed under some (and fair) considerations on the environments in which the two different refrigerators are placed. Surely, deviations have occurred in the usage that were not perceptive, but that is a feature of a real usage, with no exact routines by the users. Nonetheless, the relation was established concerning the induced shut-down of a refrigerator in two different schedules: an increase in the accumulated consumption at the end of the day and, furthermore, a rise in the costs, depending on the usage, on the refrigerator type and on the tariff. Concluding, the forcing shut-down of a refrigerator may contribute to reduce the peak loads but at the expense of higher energy consumption and clients costs. Thus, this measure *per se* does not lead to better environmental or monetary scenarios.

3.2. Dishwashing and washing machines

For the sake of simplification, the programs are now referred as follows: A – dishwashing machine, working in program at 70^{0}C; B – dishwashing machine, working in program auto at 45-65^{0}C; C – washing machine, working in program at 40^{0}C, intensive. In this way, one can better percept the efficiency of this methodology (scenario (i)) in the different tested programs for dishwashing and washing machines.

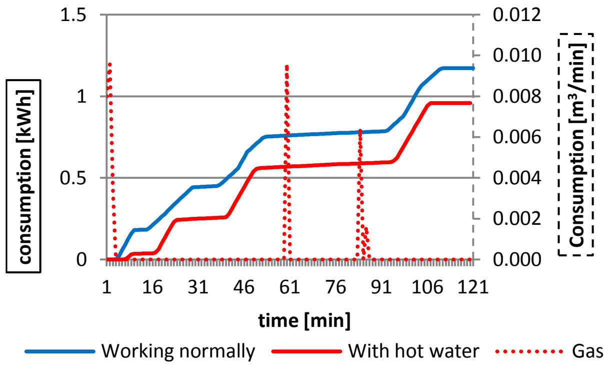

Chart 3.2-1 – Average accumulated electricity consumption profiles (continuous lines) and gas consumption (dashed line) for the dishwashing machine, in the program at 70^{o}C.

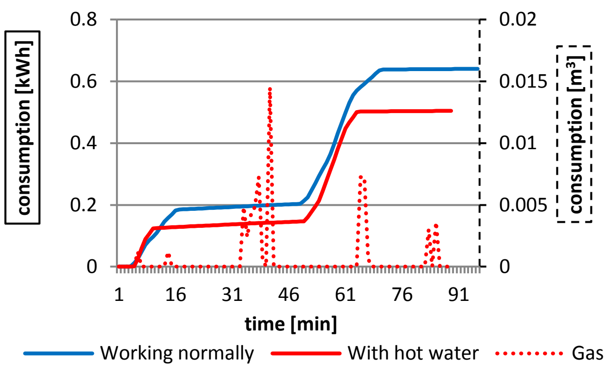

Chart 3.2-2 - Accumulated electricity consumption profiles (continuous lines) and gas consumption (dashed line) for the dishwashing machine, in the automatic program at 45-65^{0}C.

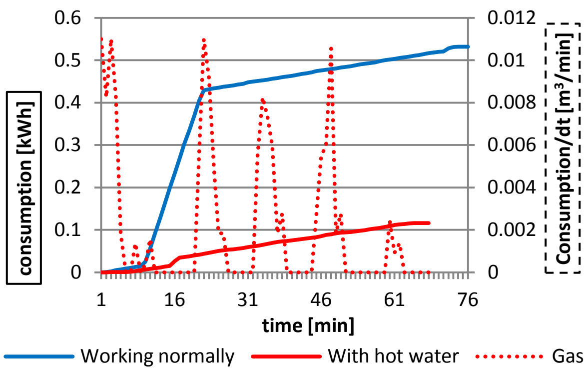

Chart 3.2-3 – Accumulated electricity consumption profiles (continuous lines) and gas consumption (dashed line) for the washing machine, in the program at 40^{0}C.

One can see that the increase in consumption in program A, comparing with B, in scenario (i), is due to the higher water temperature for that program (70^{0}C *vs.* 61^{0}C). Once it was not possible to measure the heated water in program A, as the water flow was insufficient to activate the gas water heater (therefore, the periods in which the dishwashing machine consumed water were not measured), one could not determine the heated water in scenario (i) and, thereby, the potential scenario (iii).

Concerning programs B and C, it is assumed that all the used water activated the gas water heater but, as it is referred in point 2.2.2, this does not mean that all the used water is at the desired temperature. The average temperature of the used water, at the entrance of the machine for B and C is 39.7 and 37.1^{0}C, respectively, which means that the machine had to heat the water by 21.3^{0}C and 2.9^{0}C, respectively. This reflects the inefficiency of this experimental methodology. In fact, the primary energy that is spent in scenario (i) rise 2 and 18%, respectively for programs B and C. Concerning program A, the primary energy consumption decreases 6%. The corresponding lowering in electricity consumption is, respectively for programs A, B and C, 17.9, 21.9 and 77.4%, as it is depicted in Table 3.2-1.

As far as the costs are concerned, scenario (i) corresponds, averagely, to an associated increase of 2.1, 2.3 and 82.6% for programs A, B and C, respectively.

Table 3.2-1 – Overall consumption and cost per cycle, concerning each measured scenario. Costs are averaged for all calculated tariffs[a].

	A		B		C	
	(i)	**(ii)**	**(i)**	**(ii)**	**(i)**	**(ii)**
Electricity	1.17 kWh 0.34 kgoe 0.55 $kgCO_2e$ 0.143 €	0.96 kWh 0.28 kgoe 0.45 $kgCO_2e$ 0.115 €	0.64 kWh 0.19 kgoe 0.30 $kgCO_2e$ 0.077 €	0.50 kWh 0.15 kgoe 0.24 $kgCO_2e$ 0.062 €	0.53 kWh 0.11 kgoe 0.25 $kgCO_2e$ 0.063 €	0.12 kWh 0.03 kgoe 0.06 $kgCO_2e$ 0.017 €
Gas	- - - -	0.04 m^3 0.04 kgoe 0.10 $kgCO_2e$ 0.025 €	- - - -	0.05 m^3 0.05 kgoe 0.12 $kgCO_2e$ 0.033 €	- - - -	0.14 m^3 0.13 kgoe 0.34 $kgCO_2e$ 0.098 €
Water	12 L	12 L	17 L	17 L	50 L	50 L
Water in heater	-	-[a]	-	17 L	-	50 L
Water temperature	25^{0}C	-[a]	25^{0}C	39.7^{0}C	25^{0}C	37.1^{0}C
Balances (i) - (ii)	- 0.21 kWh -0.02 kgoe + 0.04 m^3 - 0.003 € 0.0 $kgCO_2e$		- 0.14 kWh + 0.01 kgoe + 0.05 m^3 + 0.018 € + 0.06 $kgCO_2e$		- 0.41 kWh + 0.02 kgoe + 0.14 m^3 + 0.052 € + 0.15 $kgCO_2e$	
Electricity spent in water heating	-	-	0.33 kWh 0.07 kgoe 0.16 $kgCO_2e$ (52%)	0.17 kWh 0.04 kgoe 0.08 $kgCO_2e$	0.47 kWh 0.10 kgoe 0.22 $kgCO_2e$ (89%)	0.06 kWh 0.01 kgoe 0.03 $kgCO_2e$

[a] Could not be measured

Moreover, the CO_2 emissions of this methodology (scenario (i)) is defined, respectively for programs B and C, by an increase of 0.04, 0.06 and 0.15 $kgCO_2e$. Concerning program A, there is no variation.

3.3. Residential consumption profiles

The profiles analyzed above present features that do not differ much, as it is referred in

Table 3.3-1. Still, the electricity consumptions differ, as it is represented in

Table 3.3-1 – Overall electricity consumptions and associated costs of the analyzed families. The values are in €/day.

	House 1	House 2	House 3	House 4	Average[a]
Accumulated consumption [kWh]	10.74	12.55	12.02	10.26	11.39
Accumulated consumption [kgoe]	3.11	3.64	3.49	2.98	3.30
Accumulated consumption [$kgCO_2e$]	5.05	5.90	5.65	4.82	5.35
Average consumption [kWh/h]	0.45	0.52	0.50	0.43	0.47
Maximum consumption [kWh/h]	0.86	0.63	0.96	0.73	0.76
Minimum consumption [kWh/h]	0.25	0.41	0.12	0.22	0.25
Average cost [€]	1.42	1.66	1.59	1.36	1.51
Potential cost [€]	0.99	1.11	1.15	0.92	1.00

[a] Average of the analyzed profiles for the average consumption in each hour, through the calculation tool developed in this work.

It is also known that "House 2" has the greatest number of people (six) and the number of existing rooms is four, which is the same for the remaining houses with exception of "House 3", which has three. These factors may justify the highest consumption for this house but it can easily be noticed that the number of people and the number of rooms are not the only factors of the consumption, once "House 3" has the second highest consumption and has the lowest number of people (four) and the lowest number of rooms (three). This stretches the neediness of a larger study sample for establishing a relation between consumption and dwelling features [19], namely, for this case study, the income in each house, which is unknown but constitutes a major determining factor [20].

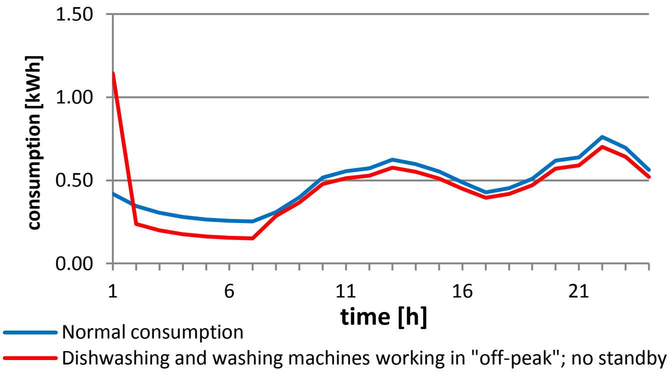

Chart 3.3-1 – Average daily electricity consumption profiles for the four studied houses, determined for the whole year for the normal scenario and that with the washing and dishwashing machines operating during "off-peak" time and by eliminating the unnecessary standby consumption during the night.

Table **3.3-2**. At this stage, the determination of the corresponding $kgCO_2e$ in each house is undertaken. The overall analysis is completed with the calculation of the average results.

It can be noticed that the highest consumption is in "House 2", being 4.4% higher than in "House 3" (the second highest consumption) and 22.3% higher than in "House 4" (the lowest consumption).

If the minimum consumption is considered for each house as the standby consumption, it can be seen that "House 2" has, again, the maximum value, being 64% higher than in "House 1" (the second highest standby consumption) and 142% higher than in "House 3" (the lowest standby consumption), which may correspond to a higher number of equipments and a disregard in the usage as well, by not turning off them completely during the night. This standby consumption has a share that cannot be turned off (*e.g.*, the refrigerator, some air cooling or heating equipments that are turned on during the night and, thereby, not wished to be turned off by the users). However, there is a share that can be turned off (*e.g.*, audiovisuals and computers). In order to assess this consumption, one must know the periods during the day in which no one is in the house. Such cannot be known with these results. Indeed, the minimum consumption during the day is 0.43 kWh, which represents consumptions that were noticed during the measured days. Therefore, an estimate is made, according to the reported standby consumption for Portugal [21]: 5% of the overall consumption (11.39 kWh in this case). This consumption occurs mainly during vacation and sleeping times; during the day, it is not possible to predict, but one can suppose that it happens during hours of lowest consumption. Therefore, this share is subtracted to a considered period, the sleeping period – from 1 to 7h. This is a rough approximation, mainly because the standby consumption occurring during the day cannot be securely predicted. The resulting consumption profile follows.

Ergo, by taking the results obtained in this work regarding these four dwellings, one obtains an average daily consumption during a year and the associated costs that are represented in Chart 3.3-1 and in Table **3.3-2**, respectively. The potential scenario with the dishwashing and washing machines working during "off-peak" times and with turning off the determined unnecessary standby consumption during the night is also given.

The average consumption for these families displays an overall consumption of 1.56 kWh, with a "two-peak" consumption profile, one during lunch time (from 11 to 13h) and another during dinner time (from 19 to 22h). The "peak" consumptions are, for the normal consumption, 0.63 kWh, at 12 h, and 0.76 kWh, at 21h. The lowest consumption occurs from 3 to 6 h and is 0.26 kWh, in average, being this the considered standby consumption for these houses during a normal period. The lowest consumption during the day time occurs from 15 to 17 h and is 0.43 kWh, in average.

For the analyzed houses, the Simple tariff, with a contracted power above 2.3 kVA, corresponds to the worst cost scenario (1.51€ per day). Just by changing the tariff, these families could enjoy a save between 1.3% and 28.5%. Moreover, if simple change of the consumption habits concerning the use of the dishwashing and washing machines to the "off-peak" time, associated to the elimination of the disposable standby consumption during the night and the vacation period, would correspond to a saving up to 5.6%, maintaining the same tariff. Furthermore, "House 3" has a contracted power of 3.45 kVA, which is the lowest contracted power within these families, and, more than that, this is the family with the highest registered "peak" consumption (0.96 kWh). Such means that, considering a instantaneous consumption variation in agreement with the hourly consumption variation, "House 2" and "House 4" have an over-contracted power (as it was said, it is not known the contracted power in "House 1").

Consequently, they are paying, respectively, 89% and 179% more than "House 3". This increases the electricity bill in 9.86 € (19.8%) and 4.93 € (12.1%) per month, respectively.

Table 3.3-2 – Costs associated to the calculated annual consumption of the four presented houses, distinguishing the use of the dishwashing an washing machines during "off-peak" time. The values are in €/day [numbered from the lowest (1) to the highest (6) one].

Tariff	All year	
	Normal use	Operation in "off-peak" and elimination of disposable standby
"Two rate" tariff; Weekly cycle	**1-** 1.08	**1-** 1.01
"Three rate" tariff; Daily cycle	**2-** 1.15	**2-** 1.09
Simple; <2.3 kVA	**3-** 1.17	**3-** 1.11
"Two rate" tariff; Daily cycle	**4-** 1.33	**4-** 1.25
"Three rate" tariff; Weekly cycle	**5-** 1.49	**6-** 1.40
Simple; >2.3 kVA	**6-** 1.51	**5-** 1.43

The potential costs saving is **45.2%,** for the scenario with "Two rate" tariff with the potential scenario conditions and with a benefit of 12.1% by changing to the sufficient contracted power. Associated to this, there is a consequent reduction of 8% in consumption in "peak" and "shoulder" times during the normal period. The total consumption reduction that can be achieved is **5.3%** (10.79 kWh against 11.39 kWh).

3.4. Behaviors to change and saving potentialities

The determined saving potentialities are applied to the previously determined average electricity consumption profile and an extrapolation to a national scale is assessed. The numbers that must be known (or remembered) for this extrapolation are the following ones:

- Percentage of consumers with Simple tariff: 78.4%, corresponding to 26.5% of the national electricity consumption [2];
- Percentage of electricity consumption in BTN: 44.9% [2];
- Percentage of energy loss by GWh in the distribution in BTN [22] and [8]:
    - "Peak" time: 9.2%;
    - "Off-peak" time: 6.9%.
- Percentage of the electricity consumption by appliance [9]:
    - Refrigerator: 22%;
    - Dishwashing machine: 3%;
        - The potential scenario allows a saving in electricity consumption of 52%.
    - Washing machine: 5%.
        - The potential scenario allows a saving in electricity consumption of 88%.

Moreover, the following relevant factor must also be taken into account: the potential scenarios for the dishwashing and washing machines are dependent on an alternative energy source beyond natural gas and electricity. In fact, these scenarios require an investment that varies according to the chosen technology, but the corresponding cost quantification is not estimated, once it is not within the scope of this work. If a dwelling adopts this kind of measurement, the overall water heating energy consumption

decreases (not only in these appliances), resulting in a lower expenditure in electricity and/or natural gas.
Concerning the refrigerator, as established in the conclusions of the results analysis, none of the tested scenarios brings any environmental and economical benefit. Thus, the habits in this appliance must be maintained.
Regarding the dishwashing and for washing machines, the potential scenarios require an investment in a technology that does not consume natural gas or electricity (*e.g.*, solar panels). Putting aside this investment, the potential savings are 52%, for the dishwashing machine (program auto, with temperatures between 46 and 65°C), which correspond to an overall 1.6%, and for the washing machine (program at 40°C, intensive), they are 88%, corresponding to an overall 4.4%.
The potential savings in electricity consumption by extinguishing the needless standby consumption during the "sleeping period" (0 to 07h) are 39%, corresponding to an overall 6.7%.
Adding the potential savings determined in this work, and referred in the previous paragraphs, the concerned potential scenario is established, as it is represented in Chart 3.4-1.
The accumulated consumption reduces, in the potential scenario, from 11.39 to 10.29 kWh (9.7%). Keeping the same tariff, the costs can decrease up to 9.7% and the best scenario is the "Two rate" tariff with weekly cycle, corresponding to a lowering in 35.0% in the costs. Adding to this, it must be considered a lack of dimensioning of the contracted power, which can correspond to a boost from 12.1% to 19.8%. Considering the minimum percentage, the cost reduction can reach **47.1%** in a family bill (see Table 3.4-1).

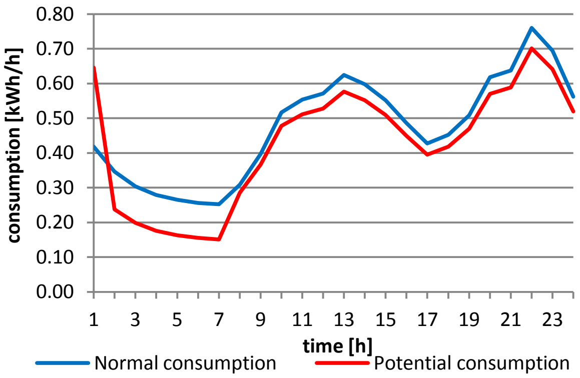

Chart 3.4-1 - Average daily electricity consumption profiles of the four presented houses, determined for the whole year, concerning the normal and the determined potential consumptions.

For a better understanding of the impact of such measures on the national electricity consumption, Chart 3.4-2. displays the variation of the electricity consumption profile if all the 78.4% of the domestic sector (corresponding to the percentage with Simple tariff) or if 6 or 3 million inhabitants adhere to these consumption behaviors.

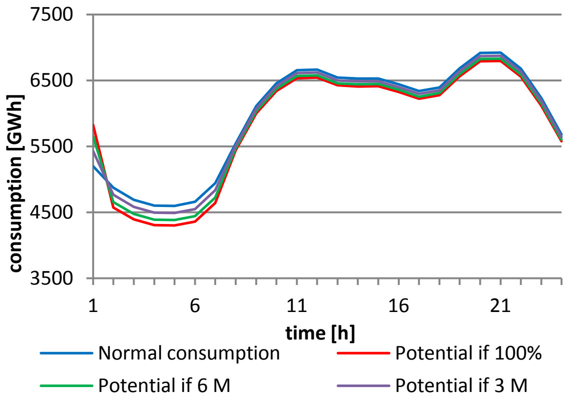

Chart 3.4-2 – National daily average electricity consumption and impact of the potential consumption scenario, concerning three hypothesis: with adhesion of 100% of the residential sector, 6 million (M), and 3 M inhabitants (the total number of inhabitants is 10,55 M [23]).

Table 3.4-1 – Costs associated to the calculated annual consumption of the four presented houses, distinguishing the normal and the potential consumptions. The values are in €/day [numbered from the lowest (1) to the highest (6) one].

Tariff	All year	
	Normal consumption	Potential consumption
"Two rate" tariff; Weekly cycle	**1-** 1.08	**1-** 0.98
"Three rate" tariff; Daily cycle	**2-** 1.15	**3-** 1.05
Simple; <2.3 kVA	**4-** 1.17	**2-** 1.06
"Two rate" tariff; Daily cycle	**5-** 1.33	**4-** 1.21
"Three rate" tariff; Weekly cycle	**6-** 1.49	**6-** 1.36
Simple; >2.3 kVA	**7-** 1.51	**5-** 1.36

4. Conclusions

This work comprises a detailed data analysis of several electricity consumption profiles, which could not be achieved without the development of an automation analysis and calculation tool. The tool developed in this study analyzes each consumption profile, divides it into consecutive days and estimates the daily average accumulated consumption, the daily average consumption in each hour and the daily average costs according to the ruling tariffs in Portugal for BTN.
Concerning the *refrigerator*, the tests showed that a forced turn-off period results in a higher daily accumulated consumption, as well as higher costs, which demystifies the belief sustained in [24]. Indeed,

the consumption raise depends on the working schedule and on the refrigerator type, reaching values between 4.6% and 9.9%. Furthermore, the costs do not increase at the same rate as the consumption, being this within 2.6% and 7.0%.
The applied methodology had the purpose of testing real scenarios, leading to realistic results. However, more detailed experiences must be done in order to analyze the real effects of an induced shut-down on the functioning of the refrigerator It may induce a deregulation of the engine and compressor and may cause a temperature drop which may affect the stored food. The tests in this work concerned two different refrigerators in two distinct environments, what constitutes a limited sample. Hence, further studies must be performed in order to prove irrefutably if this behavior is, or not, benefic or harmful to the refrigerator, the food, the environment, and also in terms of costs. Nevertheless the practical results sustain that such actions induce a consumption increase, as well as a cost boost, within general controlled usage and temperature.
Concerning the *dishwashing and washing machines*, the general results of the tested methodology (scenario (ii)) show, for programs B and C, worse energetic and economic scenarios than in the normal working way (scenario (i)), once the consumed gas for heating the water has a high impact. As for program A, the CO_2 emissions maintain but the costs and the primary energy consumption decrease slightly, the main reason being that the electricity consumption in this program is higher and the gas consumption is lower than in the other tested programs, which means that the gas consumption does not have the same impact as in the other two tested programs. Hence, for the dishwashing machine working in program auto, at 45-65^{o}C, the costs increase 23.4%, and, in the washing machine working in program at 40^{o}C, they rise 82.5%.
The CO_2 emissions raise until 60%, meaning that, indeed, this methodology is worse environmentally and economically, being also due to the temperature loss in the water pipe between periods with no water consumption. Nevertheless, the electricity spent in heating the water by the machines was determined and a potential scenario was established, assuming an investment in a technology that does not need a non-renewable energy source to heat the water (*e.g.*, solar panels). Such scenario is known to be unlikely at a large scale due to the costs in a house that does not have such a kind of technology but, even so, this is the potential scenario, which results in a saving in the electricity consumption and in the CO_2 emissions of 52% (0.33 kWh and 0.16 kgCO_2e) and 89% (0.47 kWh and 0.22 kgCO_2e), for the dishwashing and the washing machines, respectively. The value concerning the dishwashing machine (52%) contradicts, though, the 90% depicted in [25]. Though the later value cannot be compared with our because the conditions in which it was obtained are not known, such value makes sense in a way that the electricity share, for the dishwashing machine, for heating water must be superior to that (89%) for the washing machine. Inaccuracies in the experimental conditions eventually can account for this.
Concerning the electricity consumption profiles of the analyzed families, the differences were perceptible but, with such a small sample, it was not possible to establish a relation between the consumption and the dwellings features. Nevertheless, a lack of dimensioning of the contracted power was noticed, resulting in a cost increase between 12.1 and 19.8%. Moreover, in the overall analysis, two behavior proposals were presented, one by using the dishwashing and the washing machine only during "off-peak" times and another one by shutting down the unnecessary standby consumption during the night time. That reflects in a potential reduction in costs – together with changing from Simple tariff to the lowest associated cost, "Two rate" tariff, with weekly cycle – of 45.2% and a reduction of 8% of consumption during "peak" and "shoulder" times, as well as an overall lowering of 5.6% in the consumption (10.79 kWh against 11.39 kWh).
According to the results observation, the number of people and the number of rooms are not the only factors of the consumption. This stretches the neediness of a larger study sample for establishing a relation between consumption and dwelling features [19], namely, for this case study, the income in each house, which is unknown but constitutes a major determining factor [20].
Concluding, the overall potential scenario has four associated positive changes determined in this work: adapting a technology that heats the water and, therefore, does not imply electricity spent in heating the water in the dishwashing and washing machines; deviate the consumption of these appliances to "off-peak" times; eliminate the assumed standby consumption (5%); and changing the tariff from Simple with contracted power above 2.45 kVA to "Two rate" tariff with weekly cycle, as well as dimensioning properly the contracted power. The outcome benefits from these behavior changes are a cost reduction up to **47%** and a consumption reduction of **9.3%**, which traduces in a national consumption reduction of **2.6%**, reflecting in a decrease in the year consumption of 1.4 TWh in final energy and 4.1 x10^{5} toe in primary energy. Such means a lowering of the environment impact of **6.6 x10^{5} tonCO_2e** per year.
The applied methodologies in this work followed some considerations and calculated approximations in order to define the most realistic conditions as much as possible. However, concerning the tests to the refrigerators, in order to assess more precisely the influence of the forced turn-off during the day, further

tests have to be done, evaluating the performance of the engine and the compressor, as well as extending the studies to a wider range of different equipments. Only in this way one can relate the main influence factors on the refrigerator consumption with the induced turn-off. Indeed, the author could not find any bibliography with such tests and, even so, some registered statements were found [24], defending that such usage way traduces in environment an economic benefits, contradicting the conclusions of the tests made in this work.

The water heating technology must improve, so that it can be more economically reachable by a normal family, as a cheap solar panel costs more than 2,000 € [26]. The efficiency of the heating equipments and water pipes isolation is suggested to be improved as well, once a solar panel cannot convert all the heat power of the sun to the water, reaching efficiencies of 50%, and, also, accumulate it perfectly during the night or colder and cloudy periods [13]. Also, the heat loss in the pipes is considerable and the cold water remaining in the pipes is often wasted before the heated water reaches the tap. In this way, the energy spent in water heating may decrease, reflecting as well in the dishwashing and the washing machines.

All the conclusions on a potential environment benefit accomplishment are dependent on the human behavior. Indeed, 78.4% of the users in BTN have Simple tariff [2], showing that people are not sensitive to consume more energy in "off-peak" time. Therefore, more studies must be undertaken with different approaches, so that more (environment and economic) benefits can be determined and, in this way, motivate people to change their consumption behavior. Allied to the deviation of consumption from "peak" time, there is a rooted energy spare concern. This kind of reactions and thoughts must be well studied by Social Sciences and be coupled with Engineering. Indeed, not many studies can be found that link Social Sciences with Engineering, but one should stress the importance of such "marriage", as these results suggest and as expected for any other studies that depend on behaviors [27], [28].

Energy efficiency is mandatory for the accomplishment of sustainability. In a global matter, the best possible efficiency should be searched for. Concerning the residential sector, studies must continue toward that aim, for all the resources expenditure. Energy efficiency must have engineering accomplishments but, even more important, it cannot exist without efficient – sustainable – behavior.

Science must accomplish the best scenarios in a way that is sustainable and embraced by the humans.

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