Home Energy Management in off-grid Dwellings: Exploiting Flexibility of Thermostatically Controlled Appliances

Abstract - In off-grid dwellings, proper energy management of different appliances, onsite generators and storage facilities is crucial to meet some monetary goals and environmental premises such as CO_2 emissions and diesel consumption reduction. Nowadays, this task may be performed by home energy management systems, which are able to efficiently coordinate the operation of the different home assets to achieve some predefined goals. In such cases, the operation of thermostatically controlled appliances such as heating-ventilation-air conditioning systems, electric water heaters and freezers, plays a vital role as this kind of devices allow certain degree of flexibility. This way, some thermal premises (such as thermal comfort, frozen food conservation or hot water temperature set-point) can be relaxed in order to achieve other complementary goals. This work analyses this aspect by proposing a home energy management model which incorporates flexible operational modes of various typical thermostatically controlled devices. Various results are presented on a benchmark isolated home which counts with a diesel engine as backup generator. Results show that energy generated by the backup generator can be reduced by 15% by operating the thermal-based appliances in a flexible way, while other relevant indicators such as fuel consumption, fuel cost and CO_2 emissions can be also improved by 12%. Other relevant aspects such as the impact of the photovoltaic array size and storage capacity are also investigated.

Keywords: Home Energy Management, Off-grid Dwellings, Thermostatically Controlled Appliances, Diesel Engine Generator

Nomenclature

Superscripts

DEG	Diesel engine generator
BES, dch/ch	Battery energy storage in discharging/charging mode
HVAC, h/c	Heating-ventilation-air conditioning system in heating/cooling mode
w, h/c	Hot/cold water
EWH	Electric water heating
Fr	Freezer
app	Appliances
PV	Photovoltaic
air, in/out	Indoor/outdoor air
sp/db	Set-point/dead-band
u/l	Upper/lower
food	Food
build	Building
$\overline{(\cdot)}/\underline{(\cdot)}$	Maximum/minimum value of a variable or parameter

Index(Set)

$s(\mathcal{S})$	Scenario
$t(\mathcal{T})$	Time
$i(\mathcal{N})$	Element of the building (wall, window…)

Parameters & Variables

π	Probability (pu)
$\Delta\tau$	Time step (h)
σ	Fuel cost ($/l)
a, b	Fuel consumption coefficients (l/kW)
μ	CO_2 emissions coefficient (kg/l)
γ	Penalty term ($)
η	Efficiency (pu)
m	Mass (kg)
C	Heat or thermal capacity
R	Equivalent thermal resistance
β	Inclination of the roof (º)
L_1, L_2, L_3	Dimensions of the building (m)
A	Area (m^2)
l	Thickness (m)
φ	Thermal coefficient ($\mathrm{J/(h \cdot m \cdot °C)}$)
ρ	Density (kg/m^3)
COP	Coefficient of performance (pu)
DOD	Depth of discharge (pu)
e2P	Energy-to-power ratio (h)
θ	Temperature (ºC)
ϑ	Solar irradiation (kW/m^2)
υ	Volume (gal)
ξ	Thermal dispersion (kW/ºC)
p	Power (kW)
κ	Portion of appliances demand satisfied (pu)

ε	Energy stored (kWh)
y	Commitment status of assets (Binary)

1.- Introduction

Even nowadays, around 725 million people do not have access to electricity supply through the world [1]. That is the case of some isolated and remote areas, where extending the grid network is unrealistic due to extreme cost and technical difficulties. In such cases, deploying onsite generators is frequently the unique mean to meet electrical demand in off-grid houses [2]. In this context, photovoltaic (PV) units are recognised as an effective way to provide electrical supply in off-grid installations [3] and achieve some environmental goals such as those established by the European Union [4]. However, meeting generation and demand in off-grid homes is normally very difficult due to the unpredictable and intermittent behaviour of PV-based generators. On the face of this situation, many end-users install backup units such as diesel engine generators (DEG), which ensures the continuous energy supply. However, the usage of these devices is normally expensive and pollutant [5]. Strong evidences demonstrate that storage facilities suppose an effective way to drastically reduce fuel consumption and better match the generation-demand balance in standalone dwellings [6]. However, efficient and effective coordination of renewable-based generators, backup units and storage facilities is a not trivial task that difficulty can be handled for residential customers by their own [7]. This fact has motivated the wide development of home energy management (HEM) systems in recent dates [8, 9], which are able to coordinate the operation of the different home assets to achieve some predefined goals.

Some HEM programs have been specifically developed for off-grid homes. Hou and Augenbroe [10] developed a model predictive control for an off-grid home with PV and wind-based generators and a battery energy storage (BES) system. The objective was to control a heating-ventilation-air conditioning (HVAC) system in order to minimize the non-served load while the thermal comfort of users is kept within acceptable limits. The problem of optimal scheduling home appliances in off-grid PV-wind-BES home systems has been profusely studied by Tuktun and other authors in several references [11-13]. Several metaheuristic techniques were proposed for solving the problem of optimally scheduling a series of controllable appliances with the aim of reducing the operational cost of the system. Results revealed that operation cost can be reduced up to 22% by using HEM algorithms. A heuristic algorithm was proposed in [14] for appliances scheduling of an isolated PV-DEG-BES residential system. The developed approach aimed at increasing the system efficiency by scheduling some controllable appliances at hours with high PV penetration. Ogunjuyigbe et. al. [15] used the Modified Mild Intrusive Genetic Algorithm for optimally scheduling domestic appliances on the basis of priority rules with the aim of reducing the non-satisfied demand on an off-grid PV-BES domestic system. Results showed that up to 99.84% of home demand was successfully satisfied by using the developed algorithm without necessity of backup generation. In [16] a HEM program was developed for managing an isolated residential PV-wind-BES system, which counts with a fuel cell as alternative backup generator. The proposed HEM performed on the basis of fuzzy logic rules, with the objective of fully satisfying the home demand reducing the usage of backup generation at minimum. Results showed that energy injected by the fuel cell can be reduced up to 4% through a year. Some planning software incorporate deterministic management routines for coordinating self-generation and storage facilities in off-grid systems. Such is the case of the software HOMER Pro® [17], which has been used by some authors in [5, 18] for optimally design standalone wind-DEG-BES home systems. The authors in [19] considered the Clonal selection algorithm for developing an optimal appliances scheduling tool for common residential feeder, in which the user scheduling preferences are considered within the objective function. Bouakkaz, et. al [20] demonstrated that peak demand can be notably reduced in isolated dwellings by incorporating HEM scheduling routines. The authors in [21] developed a HEM program which is solved by using the Particle Swarm Optimization technique for energy saving on an off-grid PV-wind-DEG-BES home system. Up to 64% energy saved can be reached by means of the scheduling algorithm. Cho and Valenzuela [22, 23] developed a Mixed-Integer linear optimization framework for HEM on an PV-BES isolated system. The studied approach takes into account priority operation of home appliances. Results revealed that BES sizing has a stronger influence on energy saving than PV array peak power.

Space heating-cooling and water heating supposed ~79% of overall energy consumption in European Union households through year 2018 [24]. This data reveals the importance of thermostatically controlled appliances such as HVAC, electric water heaters (EWHs) and freezers on energy saving [25, 26]. For off-grid users, temperature-controlled appliances offer even wider capabilities. Rightly, such devices can be operated in a flexible way, relaxing the user thermal requirements in order to improve other indicators such as monetary expenditure, diesel consumption or reliability. This fact was clearly noticed in [27], where the authors reported that storage needs of an isolated PV-BES home system can be reduced up to 50% if thermal inertia of thermostatically controlled appliances is taken into account. Despite these evidences, to the best of our knowledge, the state-of-art HEM systems for isolated dwellings do not fully exploit the flexibility of temperature-based appliances. From our point of view, the following literature gaps are especially remarkable.

- Although inertia of temperature-controlled appliances is correctly interpreted in [27], thermal characteristics of the building are not considered at all.

- Thermostatically-controlled appliances are not considered in most HEM systems while those proposed in [10, 27] only operate them in a rigid manner, which does not allow to fully exploit their capabilities.
- To the best of our knowledge, a comparative study among the most typical thermostatically-controlled appliances have not been carried out yet, in order to determine which one provides more flexibility and enables greater benefits in off-grid dwellings.

This research develops a Mixed-Integer linear thermal models of the building comprising HVAC system, EWH and freezer which are integrated in a developed scenario-based HEM framework. Specifically, the main contributions which aim at filling the gaps listed above are:

- The developed HEM framework includes a thermal model of the building, which serves to determine the indoor temperature as a function of the outdoor temperature and the constructive characteristics of the dwelling.
- Two operational modes for thermostatically controlled appliances are proposed, by which these devices can be operated in either a flexible or non-flexible way. While the former operational mode is oriented to energy saving goals, the latter one pursues to satisfy the thermal comfort objectives of the home users.
- Various results are obtained on a standard off-grid PV-DEG-BES house, which serve to illustrate the flexibility capabilities that temperature-controlled appliances can offer to enable a more efficient operation of standalone dwellings.

Remainder of this paper is organized as follows. Section 2 overviews the off-grid HEM structure studied in this work. Section 3 details the flexible and non-flexible operational modes of several thermostatically controlled appliances proposed in this research. Section 4 describes the objective function of the proposed HEM system. The mathematical models of the home components are described throughout Section 5. Section 6 provides and explains various relevant results. Finally, this paper is concluded with Section 7.

2.- Overview of the off-grid home system under study

Isolated home systems typically involve a series of devices and components (see Fig. 1), which are briefly described below:

- Small renewable-generation: onsite generators on both off-, and on-grid homes are normally based on renewable sources such as wind and solar energy [28]. Generation of these units is normally subjected to unpredictable and stochastic behaviour of weather parameters.
- Backup generation: off-grid homes normally incorporate a backup generator based on fossil fuels such as a DEG. Nevertheless, other kind of units have been considered like fuel-cells [16]. The backup generator ensures the continuous supplying of electrical energy to home loads.
- Storage facilities: battery-, thermal-, or hydrogen-based storage facilities are frequently used in off-grid homes to manage with intermittent behaviour of renewable-based units. A typical operating cycle in PV-BES systems consists of charging the storage system during central hours, when PV generation is available, and injecting the energy stored during night [23].
- Conventional appliances: it refers to TV, washing machine, computers or whatever other typical device used for home inhabitants. It is assumed that such kind of appliances cannot be controlled, as them are operated under user decisions.
- Thermostatically controlled appliances: this kind of appliances are controlled based on temperature set-points. Such set-points are typically set in thermostats and correspond with the desired temperature of different elements such as indoor

air, hot water or frozen food. Typical examples are HVAC systems, EWHs and freezers.

- HEM system: it is devoted on efficiently managing the different energy resources available in the home. A HEM system for an isolated dwelling should be able to optimally schedule the operation of generation units, storage facilities and controllable appliances in a coordinate perspective, with the aim of achieving some goals such as diesel consumption reduction.

Henceforth, it is assumed that some necessary weather parameters (e.g. solar irradiation and outdoor temperature), can be day-ahead forecasted with sufficiently accuracy. These data serve as input for the HEM system, which performs a day-ahead optimal scheduling program for the onsite generator, storage systems and thermostatically controlled appliances deployed through the home.

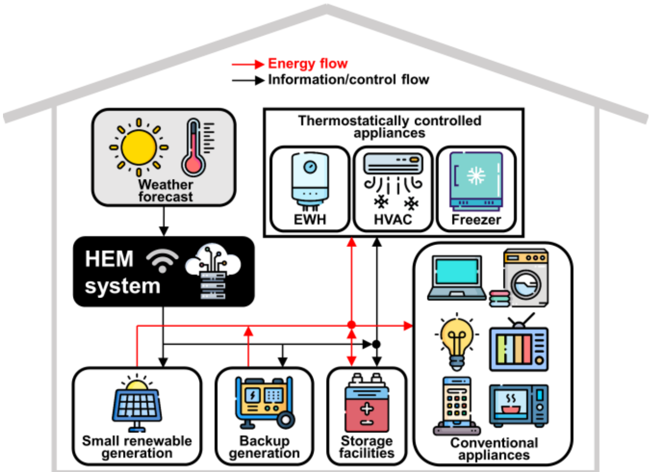

Fig. 1 Pictorial representation of a typical off-grid home system

3.- Proposed flexible operational modes of thermostatically controlled appliances

This paper is focused on thermostatically controlled appliances. As commented, this kind of devices are operated on the basis of temperature signals, which are sent by the HEM system. The main objective of the temperature-based appliances is to keep some thermal parameters within acceptable limits and as close to the temperature set-point as possible. However, in most cases these thermal requirements might be relaxed if other benefits are obtained as counterpart. In other words, the thermostatically controlled loads can be operated in flexible and non-flexible modes. Typically, the HEM system is capable to decide when a thermal device should be operated under each mode on the basis of user preferences. In this research, flexible operational modes of three common thermostatically controlled appliances (namely HVAC system, EWH and freezer) are developed. The introduced strategies are based on allowing wider operational ranges which are assumed not to be desired but acceptable yet for home users. The developed operational modes are illustrated in Fig. 2 and explained through the following sub-sections.

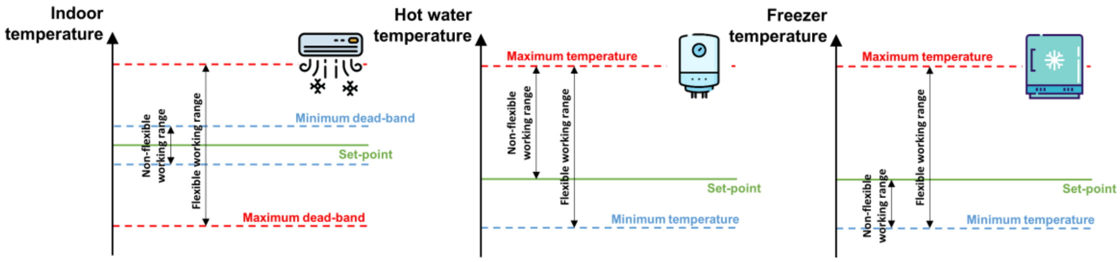

Fig. 2 Illustration of the principles of flexible and non-flexible operational modes of HVAC system (left), EWH (middle) and freezer (right)

3.1.- HVAC system

The main end of a HVAC system is to keep the indoor temperature within acceptable comfort premises. To this end, this appliance can be operated in heating and cooling modes as required. The HEM program sends a temperature set-point to the HVAC system, which corresponds to the desired room temperature. A dead-band is typically established around the set-point in order to avoid an undesirable frequent operation of the HVAC system [29]. In the developed HEM framework, it is assumed that the HVAC operational dead-band can be adjusted within a predefined range (maximum-minimum dead-band). Intuitively, thermal comfort is compromised as dead-band is made wider, however, a more flexible operation of the home system is expected since thermal constraints are relaxed.

3.2.- EWH

Under normal control premises, operational range of the EWH spans over a set-point and a maximum hot water temperature threshold, which is established for security [29]. In order to make the operational principle of the EWH more flexible, let us assume that home users may be willing to set the hot water temperature on some point below the specified set-point, which corresponds in this case with the most comfortable hot water temperature. Thus, operational range of the EWH would span from the established minimum temperature threshold to the maximum one. Obviously, some benefits should be obtained as counterpart as it is assumed that the lowest threshold does not suppose a comfortable, but acceptable yet, water temperature for home user applications such as shower and dish washing.

3.3.- Freezer

A freezer is used to maintain a temperature level that allows proper conservation of the food inside it. Normally, a freezer is operated over a narrow interval which spans from a minimum temperature to the specified set-point, i.e. the most adequate temperature for a proper conservation of the food inside the freezer. Nevertheless, this device could be operated in a more flexible way allowing the temperature varies from the established minimum temperature to a specific upper bound above the set-point. The allowable high temperature of the freezer would be assumed as non-ideal but suitable yet for food conservation [30].

4.- Objective function of the developed HEM system

This section is devoted on describing the objective function of the developed HEM system. It responds to the benchmark off-grid smart home layout described in Section 2 and encompasses the monetary expenditures due to fuel consumption besides penalty terms referred to thermal demands and non-satisfied demand. This way, flexible and non-flexible operation of the thermostatically controlled appliances can be controlled and quantified, enabling their analysis.

4.1.- Assumptions

In the mathematical HEM model presented in sections 4 and 5, several assumptions have been considered. Firstly, degradation and maintenance costs of the BES and PV array are not taken into account. This simplification is assumable in most cases as the fuel cost is typically much more significant [29]. In addition, the inclusion of additional costs in the objective function of the HEM program may provoke undesirable behaviours as the DEG may be priority operated even when PV generation is available. Secondly, rectangular geometry is assumed for the building. Thirdly, when hot water is drawn from the EWH, then it is completely replenished by cold water. Finally, all the considered thermostatically controlled loads are assumed to be installed inside the house.

4.2.- Objective function

The developed HEM system is formulated as a scenario-based optimization approach. Several requirements are included in the objective function. On the one hand, the minimization of the fuel cost in which the system incurs due to DEG generation. Secondly, the possible drawbacks induced by non-satisfied demand are penalized. Last, some thermal needs and comfort requirements are quantitatively included. Mathematically, these objectives are jointly encompassed in a single-objective function with controllable penalty terms, which are devoted on weighting the importance of the different terms involved. The different c's functions in (1) are the costs terms which compose the objective function. Firstly, c^{DEG} denotes the monetary expenditures due to fuel consumption. Secondly, c^{HVAC}, c^{EWH} and c^{Fr} are cost functions that aim at penalizing the non-compliance of thermal needs. The penalty term γ^{Th} in (1) serves to tune the importance given to thermal comfort. This way, the larger value of γ^{Th}, the more thermal comfort-oriented the HEM system is. Similarly, the term c^{app} penalizes the non-satisfied appliances demand. Assuming that the DEG is properly sized to satisfy the peak home demand, the penalty term γ^{app} in (1) can be fixed arbitrarily large if one desires that home demand was fully covered. With these considerations, the objective function for our proposal is given by:

$$\min_{\Phi} \sum_{\forall s \in \mathcal{S}} \left\{ \pi_s \cdot \left(c_s^{\mathrm{DEG}} + \frac{\gamma^{\mathrm{Th}}}{3} \cdot [c_s^{\mathrm{HVAC}} + c_s^{\mathrm{EWH}} + c_s^{\mathrm{Fr}}] + \gamma^{\mathrm{app}} \cdot c_s^{\mathrm{app}} \right) \right\} \quad (1)$$

where $s(\mathcal{S})$ is the index(set) for scenarios; π indicates the probability of each scenario; γ^{Th} and γ^{app} are penalty terms for thermal requirements and appliances non-satisfied demand, respectively; and Φ is the vector of decision variables which is defined in this case as follows:

$$\Phi = \left\{ \begin{matrix} p_{s|t}^{\mathrm{PV}}, p_{s|t}^{\mathrm{BES,dch}}, p_{s|t}^{\mathrm{BES,ch}}, p_{s|t}^{\mathrm{HVAC,h}}, p_{s|t}^{\mathrm{Fr}}, p_{s|t}^{\mathrm{EWH}}, \\ p_{s|t}^{\mathrm{HVAC,c}}, y_{s|t}^{\mathrm{BES,d}}, y_{s|t}^{\mathrm{BES,c}}, y_{s|t}^{\mathrm{HVAC,h}}, y_{s|t}^{\mathrm{HVAC,c}}, \\ y_{s|t}^{\mathrm{DEG}}, \kappa_{s|t}, \theta_{s|t}^{\mathrm{HVAC,db}}, \theta_{s|t}^{\mathrm{EWH,db,u}}, \theta_{s|t}^{\mathrm{EWH,db,l}}, \\ \theta_{s|t}^{\mathrm{EWH,db,u}}, \theta_{s|t}^{\mathrm{EWH,db,l}}, \theta_{s|t}^{\mathrm{w,h}}, \theta_{s|t}^{\mathrm{Fr}}, \theta_{s|t}^{\mathrm{air,in}} \end{matrix} \right\}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (2)$$

where $t(\mathcal{T})$ is the index(set) for time intervals; p indicates power; y is the commitment status of assets; κ indicates the portion of the actual appliances demand that is satisfied; θ is temperature; 'PV' and 'DEG' make mention to PV array and DEG unit, respectively; 'BES, dch' and 'BES, ch' refer to the BES in discharging and charging modes, respectively; 'HVAC, h' and 'HVAC, c' stands for the HVAC system in heating and cooling modes, respectively; 'Fr' and 'EWH' indicate the variables and parameters related to the freezer and EWH, respectively; 'db' means dead-band while 'u' and 'l' stand for 'upper' and 'lower', respectively; 'w, h' makes mention to the hot water; while 'air, in' is referred to the indoor air. The different terms that compose the objective function are presented and explained below.

For small-scale devices, the fuel consumption (in litres) of DEG units can be calculated as a function of the rated and delivered powers [5], as follows:

$$F_s^{\text{DEG}} = \sum_{\forall t \in \mathcal{T}} \left\{ a^{\text{DEG}} \cdot p_{s|t}^{\text{DEG}} \right\} + b^{\text{DEG}} \cdot \overline{p}^{\text{DEG}}; \ \forall s \in \mathcal{S} \tag{3}$$

where a^{DEG} and b^{DEG} are the fuel coefficients; and $\overline{p}^{\text{DEG}}$ is the rated power of the DEG unit. The expression (3) allows to calculate the daily monetary expenditures due to fuel consumption for the scenario s by simply including the fuel cost σ^{DEG}, as follows:

$$c_s^{\text{DEG}} = \sigma^{\text{DEG}} \cdot F_s^{\text{DEG}}; \ \forall s \in \mathcal{S} \tag{4}$$

Such cost functions which take into account thermal premises (e.g. ambient comfort and required temperature for proper conservation of frozen food) in the objective function are respectively formulated for the HVAC system, EWH and freezer, as follows.

$$c_s^{\text{HVAC}} = \frac{\sum_{\forall t \in \mathcal{T}} \left\{ \theta_{s|t}^{\text{HVAC,db}} \right\}}{\mathcal{T} \cdot \overline{\theta}^{\text{HVAC,db}}}; \ \forall s \in \mathcal{S} \tag{5}$$

$$c_s^{\text{EWH}} = \frac{1}{\mathcal{T}} \cdot \left(\frac{\sum_{\forall t \in \mathcal{T}} \left\{ \theta_{s|t}^{\text{EWH,db,l}} \right\}}{\theta^{\text{w,h,sp}} - \underline{\theta}^{\text{w,h}}} + \frac{\sum_{\forall t \in \mathcal{T}} \left\{ \theta_{s|t}^{\text{EWH,db,u}} \right\}}{\overline{\theta}^{\text{w,h}} - \theta^{\text{w,h,sp}}} \right); \ \forall s \in \mathcal{S} \tag{6}$$

$$c_s^{\text{Fr}} = \frac{1}{\mathcal{T}} \cdot \left(\frac{\sum_{\forall t \in \mathcal{T}} \left\{ \theta_{s|t}^{\text{Fr,db,l}} \right\}}{\theta^{\text{Fr,sp}} - \underline{\theta}^{\text{Fr}}} + \frac{\sum_{\forall t \in \mathcal{T}} \left\{ \theta_{s|t}^{\text{Fr,db,u}} \right\}}{\overline{\theta}^{\text{Fr}} - \theta^{\text{Fr,sp}}} \right); \ \forall s \in \mathcal{S} \tag{7}$$

where 'sp' refers to set-point; whereas $\overline{(\cdot)}$ and $\underline{(\cdot)}$ indicate the maximum and minimum value of a variable or parameter, respectively. Rightly, the equations (5)-(7) aim at quantifying how far the observed indoor, hot water and freezer temperature are from their respective set-points over the time horizon $\mathcal{T}$. Therefore, by the costs above, it is assumed that home users would desire that the thermostatically controlled appliances were able to maintain the temperature as close to the established set-points as possible. In fact, the equations (5)-(7) would be equal to zero if the temperatures are equal to their respective set-points $\forall t \in \mathcal{T}$. This way, if the thermal requirements are perfectly compliance, the cost functions (5)-(7) do not have any impact on the objective function.

Similar to (5)-(7), the cost function that measures the satisfaction due to appliances demand satisfied is given by:

$$c_s^{\text{app}} = \frac{\sum_{\forall t \in \mathcal{T}} \{1 - \kappa_{s|t}\}}{\mathcal{T}}; \ \forall s \in \mathcal{S} \quad (8)$$

It is worth noting that (5)-(8) range from 0 to 1. Thereby, they can be straightforward quantified, making easier their qualitative evaluation. This is the reason why the three terms devoted on thermal demands are divided by 3 in (1). Thereupon, both the second and third terms in the objective function are ranged from 0 to γ^{Th} and γ^{app}, respectively, facilitating their tuning settings.

5.- Modelling the home components

While the previous section was devoted on defining the objective function of the developed HEM system, the component models are described throughout this section. These mathematical models are incorporated within the developed HEM framework as inequality/equality constraints. The developed flexible and non-flexible operational modes of the thermostatically controlled appliances are similarly described in Section 5.5.

5.1.- Thermostatic model of the building

Assuming rectangular geometry, both the equivalent thermal resistance of the house and the mass of air inside it can be calculated by using the equations (9) and (10), respectively [29].

$$R^{\text{build}} = \frac{1}{\mathcal{N}} \cdot \sum_{\forall i \in \mathcal{N}} \left\{ \frac{l_i}{\varphi_i \cdot A_i} \right\} \quad (9)$$

$$m^{\text{air,in}} = \rho^{\text{air}} \cdot (L_1 + L_2 + L_3 + \tan(\beta) \cdot L_1 \cdot L_2) \quad (10)$$

where $i(\mathcal{N})$ is the index(set) for building elements (walls, windows…); l, A and φ are the thickness, area and thermal coefficient of each building element; ρ^{air} is the density of air; L's are the dimension of the building; and β is the roof angle.

5.2.- Modelling the PV array

The expected available solar generation is influenced by some weather parameters such as outdoor temperature and solar irradiation. Once these parameters are available in some manner, the maximum instantaneous power that a PV array could deliver can be calculated as follows [31]:

$$\phi_{s|t}^{\mathrm{PV}} = \overline{p}^{\mathrm{PV}} \cdot \vartheta_{s|t} \cdot \left\{0.8 + 0.024 \cdot \left(\theta_{s|t}^{\mathrm{air,out}} + \vartheta_{s|t} \cdot [33.8 - 37.5 \cdot \eta^{\mathrm{PV}}] - 25\right)\right\};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (11)$$

where $\overline{p}^{\mathrm{PV}}$ is the rated power of the PV array; ϑ is the solar irradiance; 'air, out' refers to the outdoor air; and η means efficiency. However, the equation (11) does not impose limits over the PV generation. In other words, the value of (11) may be higher than $\overline{p}^{\mathrm{PV}}$. This issue can be clearly checked since the term that multiplies the rated power of the PV array in (11) may be occasionally higher than 1. In practise, solar inverters typically impose limits on the power that a PV array can give in order to avoid fast degradations or failure of components. This restriction is modelled by the constraint (12).

$$0 \leq p_{s|t}^{\mathrm{PV}} \leq \begin{cases} \phi_{s|t}^{\mathrm{PV}}, & \text{if } \phi_{s|t}^{\mathrm{PV}} \leq \overline{p}^{\mathrm{PV}} \\ \overline{p}^{\mathrm{PV}}, & \text{o.w.} \end{cases};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (12)$$

In (12), the power given by the PV array may vary from zero to its rated value. This is possible since this value is included as a decision variable in the HEM framework rather than a bound parameter. This approach aims at modelling a real-life situation, in which the delivered power of a solar panel may be fixed lower than the expected one ($\phi_{s|t}^{\mathrm{PV}}$) if needed. Indeed, during hours with high PV production, may occur that solar generation cannot be totally exploited due to low demand and fully charged status of the storage facilities. In such circumstances, surplus energy has to be dissipated in dump loads [32].

5.3.- Modelling the DEG

Typically, DEGs work within a specific range which is facilitated by manufacturers [33]. This principle is imposed by the constraint (13).

$$y_{s|t}^{\mathrm{DEG}} \cdot \underline{p}^{\mathrm{DEG}} \leq p_{s|t}^{\mathrm{DEG}} \leq y_{s|t}^{\mathrm{DEG}} \cdot \overline{p}^{\mathrm{DEG}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (13)$$

where $\underline{p}^{\mathrm{DEG}}$ is the minimum dispatchable power of the DEG unit.

5.4.- Modelling the BES

In this work, a conventional model for the BES is considered [31]. The maximum power that the BES can exchange with the home is limited by its capacity and energy-to-power ratio [34], as said by the equation (14). The equation (15) models the state of charge of the BES, which is bounded by its capacity and the specified depth of discharge, as imposed by the constraint (16). It is assumed that charging and discharging processes of the BES are complementary, as forced by the equation (17). As customary (e.g. see [35]), the initial and final state of charge of the BES are forced to be equal to the total capacity of the battery bank by the constraint (18).

$$0 \leq p_{s|t}^{\mathrm{BES},i} \leq y_{s|t}^{\mathrm{BES},j} \cdot \frac{\overline{\varepsilon}^{\mathrm{BES}}}{\mathrm{e2P^{BES}}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T}, \forall j \in \{\mathrm{ch}, \mathrm{dch}\} \tag{14}$$

$$\varepsilon_{s|t}^{\mathrm{BES}} = \varepsilon_{s|t-1}^{\mathrm{BES}} + \Delta\tau \cdot \left(p_{s|t-1}^{\mathrm{BES,ch}} \cdot \eta^{\mathrm{BES,ch}} - \frac{p_{s|t-1}^{\mathrm{BES,dch}}}{\eta^{\mathrm{BES,dch}}} \right);\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \backslash t > 1 \tag{15}$$

$$\overline{\varepsilon}^{\mathrm{BES}} \cdot (1 - \mathrm{DOD^{BES}}) \leq \varepsilon_{s|t}^{\mathrm{BES}} \leq \overline{\varepsilon}^{\mathrm{BES}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{16}$$

$$\sum\nolimits_{\forall j \in \{\mathrm{ch,dch}\}} \left\{ y_{s|t}^{\mathrm{BES},j} \right\} \leq 1;\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{17}$$

$$\varepsilon_{s|1}^{\mathrm{BES}} = \varepsilon_{s|\mathcal{T}}^{\mathrm{BES}} = \overline{\varepsilon}^{\mathrm{BES}};\ \forall s \in \mathcal{S} \tag{18}$$

where ε denotes the energy stored; $\Delta\tau$ is the time step; and DOD is the depth-of-discharge setting.

5.5.- Thermostatically controlled appliances

In this head, the flexible and non-flexible operational modes for the HVAC system, EWH and freezer are presented. It is assumed the power consumption of these devices may vary from zero (off) to their rated power in order to continuously control the corresponding temperatures. This is possible by means of modulating controllers which, contrarily to on/off control mechanisms, allow a smooth control of the energetic consumption [36]. Nowadays, this task may be effectively performed through smart thermostats/plugs [37, 38], which can be scheduled so that the necessity of manually operating the temperature-controlled devices is avoided.

5.5.1.- Modelling the HVAC system

In this research, a thermal resistance-based model of the building is used to determine the air indoor temperature at any time instant. This model, is naturally based on differential equations. Nevertheless, it can be linearized under some plausible assumptions [29, 39] in order to simplify the overall formulation. Thus, the indoor temperature is included as a variable in the problem and determined by the equation (19). Equation (19) yields the indoor air temperature as a function of the value at the previous time slot and a series of heat transfer effects (q's functions). Indeed, the second term in (19) stands for the temperature variation due to heat transfer from indoor to outdoor through home walls; similarly, the third term in (19) yields the temperature variation due to heat gain from outdoor to indoor; last, the fourth term indicates the variation of indoor temperature due to the action of the HVAC system.

$$\theta_{s|t}^{\text{air,in}} = \theta_{s|t-1}^{\text{air,in}} - q_{s|t-1}^{\text{in}\rightarrow\text{out}} + q_{s|t-1}^{\text{out}\rightarrow\text{in}} + q_{s|t-1}^{\text{HVAC}} = \theta_{s|t-1}^{\text{air,in}} - \frac{\Delta\tau}{10^3 \cdot m^{\text{air,in}} \cdot C^{\text{air,in}} \cdot R^{\text{build}}} \cdot \theta_{s|t-1}^{\text{air,in}} + \frac{\Delta\tau}{10^3 \cdot m^{\text{air,in}} \cdot C^{\text{air,in}} \cdot R^{\text{build}}} \cdot \theta_{s|t-1}^{\text{air,out}} + \frac{\Delta\tau \cdot \left(p_{s|t-1}^{\text{HVAC,h}} - p_{s|t-1}^{\text{HVAC,c}}\right)}{0.000277 \cdot m^{\text{air,in}} \cdot C^{\text{air,in}}} \cdot \text{COP}^{\text{HVAC}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \backslash t > 1 \quad (19)$$

where $C^{\text{air,in}}$ is the heat capacity of the air; and COP^{HVAC} is the coefficient of performance of the HVAC system.

As commented, the HVAC is devoted on keeping the temperature inside the building within comfortable limits. The equation (20) imposes that consumption of the HVAC appliances cannot be higher than its rated power. On the other hand, the constraint (21) forces heating and cooling modes of the HVAC system to be complementary processes.

$$0 \leq p_{s|t}^{\text{HVAC},j} \leq y_{s|t}^{\text{HVAC},j} \cdot \overline{p}^{\text{HVAC}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T}, \forall j \in \{\text{h}, \text{c}\} \quad (20)$$

$$\sum_{\forall j \in \{\text{h,c}\}} \{y_{s|t}^{\text{HVAC},j}\} \leq 1;\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (21)$$

As commented, a dead-band is typically included in order to avoid frequent operation of the HVAC system, nevertheless, it is realistic to assume that the dead-band is upper bounded in order to avoid the indoor temperature takes unacceptable values. These conditions are modelled by the constraints (22) and (23), respectively.

$$\theta^{\mathrm{HVAC,sp}} - \theta_{s|t}^{\mathrm{HVAC,db}} \leq \theta_{s|t}^{\mathrm{air,in}} \leq \theta^{\mathrm{HVAC,sp}} + \theta_{s|t}^{\mathrm{HVAC,db}}; \ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (22)$$

$$0 \leq \theta_{s|t}^{\mathrm{HVAC,db}} \leq \overline{\theta}^{\mathrm{HVAC,db}}; \ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (23)$$

The model (19) requires the initial indoor temperature to be fixed. In this paper, it is assumed that the HVAC system is normally operated in a non-flexible manner. This way, indoor temperature can be maintained reasonably near to the desired set-point. Under these assumptions, the initial indoor temperature is forced to be equal to the HVAC set-point as indicated the constraint (24).

$$\theta_{s|1}^{\mathrm{air,in}} = \theta^{\mathrm{HVAC,sp}}; \ \forall s \in \mathcal{S} \quad (24)$$

If the HVAC system is operated under the flexible mode described in Section 2, it is assumed that the home users are willing to let the indoor temperature varies according to (22) over the considered time horizon. In contrast, if the non-flexible mode is activated, the overall model should be consistent with (24) and, similar to the BES, the constraint (25) has to be imposed.

$$\theta_{s|\mathcal{T}}^{\mathrm{air,in}} = \theta^{\mathrm{HVAC,sp}}; \ \forall s \in \mathcal{S} \quad (25)$$

5.5.2.- Modelling the EWH

As in the case of the HVAC system, the hot water temperature can be modelled by linearized differential equations. According to [29, 40], when the hot water consumption is zero, the hot water temperature inside the EWH may be determined by (26). Equation (26) is similar to (19) as the hot water temperature is modelled as a function of the value at the previous time step and a series of heat transfer effects. Thus, the second term in (26) reflects the temperature variation due to EWH operation; while the third term above stands for the heat transfer effect from the water tank to the home.

$$\theta_{s|t+1}^{\mathrm{w,h}} = \theta_{s|t}^{\mathrm{w,h}} + q_{s|t}^{\mathrm{EWH}} - q_{s|t}^{\mathrm{EWH}\rightarrow\mathrm{in}} = \theta_{s|t}^{\mathrm{w,h}} + p_{s|t}^{\mathrm{EWH}} \cdot \eta^{\mathrm{EWH}} \cdot C^{\mathrm{w,h}} - \left(\theta_{s|t}^{\mathrm{air,in}} - \theta_{s|t}^{\mathrm{w,h}}\right) e^{\left(\frac{-\Delta\tau}{R^{\mathrm{w,h}} \cdot C^{\mathrm{w,h}}}\right)}; \ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \backslash t < \mathcal{T}, v_{s|t}^{\mathrm{w,h}} = 0 \quad (26)$$

where $C^{\mathrm{w,h}}$ and $R^{\mathrm{w,h}}$ are the thermal capacitance and resistance of the water, respectively; and $v^{\mathrm{w,h}}$ stands for the volume of hot water consumption.

During those time steps in which the hot water consumption is greater than zero, the hot water temperature is calculated by (27).

$$\theta_{s|t+1}^{\mathrm{w,h}} = \frac{\theta_{s|t}^{\mathrm{w,h}} \cdot \left(\overline{v}^{\mathrm{EWH}} - v_{s|t}^{\mathrm{w,h}}\right) + \theta^{\mathrm{w,c}} \cdot v_{s|t}^{\mathrm{w,h}}}{\overline{v}^{\mathrm{EWH}}}; \; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \backslash t < \mathcal{T}, v_{s|t}^{\mathrm{w,h}} > 0 \quad (27)$$

where 'w, c' refers to the cold water; and $\overline{v}^{\mathrm{EWH}}$ is the capacity of the EWH. Rightly, the equation (27) takes into account the temperature variation due to the volume of cold water that refills the tank.

The EWH model is completed by upper bounding its power consumption to its rated value, as said the constraint (28).

$$0 \leq p_{s|t}^{\mathrm{EWH}} \leq \overline{p}^{\mathrm{EWH}}; \; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (28)$$

According to the non-flexible mode described in Section 2 for the EWH, the hot water temperature may vary from the EWH set-point to a specified upper bound. On the other hand, under flexible operability conditions, this constraint is relaxed and the EWH temperature may be eventually lower than the desired set-point but higher than a lower threshold yet. In this study, this operational principle is modelled by fictitious dead-bands. Thus, the equations (29) and (30) define the limits imposed over the hot water temperature under non-flexible and flexible operational modes, respectively. In order to be coherent to the premises described in Section 2, the modelled fictitious dead-bands have to be upper bounded by the constraints (31) and (32). Finally, similar to the HVAC system, the initial EWH temperature is set by the constraint (33) while (34) is only imposed under non-flexible operational principles.

$$\theta^{\mathrm{w,h,sp}} \leq \theta_{s|t}^{\mathrm{w,h}} \leq \theta^{\mathrm{w,h,sp}} + \theta_{s|t}^{\mathrm{EWH,db,u}}; \; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (29)$$

$$\theta^{\mathrm{w,h,sp}} - \theta_{s|t}^{\mathrm{EWH,db,l}} \leq \theta_{s|t}^{\mathrm{w,h}} \leq \theta^{\mathrm{w,h,sp}} + \theta_{s|t}^{\mathrm{EWH,db,u}}; \; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (30)$$

$$0 \leq \theta_{s|t}^{\mathrm{EWH,db,u}} \leq \left(\overline{\theta}^{\mathrm{EWH}} - \theta^{\mathrm{w,h,sp}}\right); \; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (31)$$

$$0 \leq \theta_{s|t}^{\mathrm{EWH,db,l}} \leq \left(\theta^{\mathrm{w,h,sp}} - \underline{\theta}^{\mathrm{EWH}}\right);\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{32}$$

$$\theta_{s|1}^{\mathrm{w,h}} = \theta^{\mathrm{EWH,sp}};\ \forall s \in \mathcal{S} \tag{33}$$

$$\theta_{s|\mathcal{T}}^{\mathrm{w,h}} = \theta^{\mathrm{EWH,sp}};\ \forall s \in \mathcal{S} \tag{34}$$

5.5.3.- Modelling the freezer

Similar to the other thermostatically controlled loads, the temperature inside the freezer can be modelled by linearized differential equations as in (36) [41]. In (36), the second term indicates the effect of the freezer operation; the second term yields the temperature variation due to the mass of flood that is extracted from the freezer; while the fourth term stands for the heat transfer from the freezer to the home.

$$\theta_{s|t+1}^{\mathrm{Fr}} = \theta_{s|t}^{\mathrm{Fr}} - q_{s|t}^{\mathrm{Fr}} - q_{s|t}^{\mathrm{food}} - q_{s|t}^{\mathrm{Fr}\to\mathrm{in}} = \theta_{s|t}^{\mathrm{Fr}} - \frac{1}{C^{\mathrm{Fr}}} \cdot \Delta\tau \cdot p_{s|t}^{\mathrm{Fr}} \cdot \mathrm{COP}^{\mathrm{Fr}} - \frac{m_{s|t}^{\mathrm{food}}}{\overline{m}^{\mathrm{Fr}}} \cdot \left(\theta_{s|t}^{\mathrm{Fr}} - \theta^{\mathrm{food}}\right) - \frac{1}{C^{\mathrm{Fr}}} \cdot \xi^{\mathrm{Fr}} \cdot \Delta\tau \cdot \left(\theta_{s|t}^{\mathrm{Fr}} - \theta_{s|t}^{\mathrm{air,in}}\right);\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \backslash t < \mathcal{T} \tag{36}$$

where $\mathrm{COP}^{\mathrm{Fr}}$ is the coefficient of performance of the freezer; m^{food} stands for the mass of food consumption; C^{Fr} and ξ^{Fr} are the heat capacity and thermal dispersion of the freezer, respectively; and $\overline{m}^{\mathrm{Fr}}$ is the total mass capacity of the freezer. On the other hand, the constraint (37) upper bounds the power consumption of the freezer.

$$0 \leq p_{s|t}^{\mathrm{Fr}} \leq \overline{p}^{\mathrm{Fr}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{37}$$

Similar to the EWH, fictitious dead-bands strategy is used to model the operational modes of the freezer. This way, the constraint (38) is imposed for the non-flexible operational mode while (39) is contemplated under flexible operational principles. For remainder of the freezer model (40)-(43), the same principles explained for the EWH can be extended to this case.

$$\theta^{\mathrm{Fr,sp}} - \theta_{s|t}^{\mathrm{Fr,db,l}} \leq \theta_{s|t}^{\mathrm{Fr}} \leq \theta^{\mathrm{Fr,sp}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{38}$$

$$\theta^{\mathrm{Fr,sp}} - \theta_{s|t}^{\mathrm{Fr,db,l}} \leq \theta_{s|t}^{\mathrm{Fr}} \leq \theta^{\mathrm{Fr,sp}} + \theta_{s|t}^{\mathrm{Fr,db,u}};\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{39}$$

$$0 \leq \theta_{s|t}^{\mathrm{Fr,db,u}} \leq \left(\overline{\theta}^{\mathrm{Fr}} - \theta^{\mathrm{Fr,sp}}\right);\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{40}$$

$$0 \leq \theta_{s|t}^{\mathrm{Fr,db,l}} \leq \left(\theta^{\mathrm{Fr,sp}} - \underline{\theta}^{\mathrm{Fr}}\right);\ \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \tag{41}$$

$$\theta_{s|1}^{\mathrm{Fr}} = \theta^{\mathrm{Fr,sp}};\ \forall s \in \mathcal{S} \tag{42}$$

$$\theta_{s|\mathcal{T}}^{\mathrm{Fr}} = \theta^{\mathrm{Fr,sp}};\ \forall s \in \mathcal{S} \tag{43}$$

5.6.- Home balance

To complete the HEM model, a home energy balance contemplating non-satisfied demand is established as follows:

$$p_{s|t}^{\mathrm{DEG}} + p_{s|t}^{\mathrm{BES,dch}} + p_{s|t}^{\mathrm{PV}} = p_{s|t}^{\mathrm{BES,ch}} + p_{s|t}^{\mathrm{HVAC,h}} + p_{s|t}^{\mathrm{HVAC,c}} + p_{s|t}^{\mathrm{Fr}} + p_{s|t}^{\mathrm{EWH}} + \kappa_{s|t} \cdot p_t^{\mathrm{app}}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T} \quad (44)$$

6.- Case study

Throughout this section, various results are presented and commented in order to illustrate the behaviour of the considered thermostatically controlled loads under the flexible and non-flexible modes described in Section 2, and analyse how these operational principles affect to the home operation. To that end, the HEM model developed in Section 4 has been coded under Matlab R2019a environment, and solved with 30-min time resolution over a 24 h time horizon using Gurobi [42] on an Intel® Core™ i5-9400F 2.90 GHz 8.00 GB RAM personal computer.

6.1.- Input data

The different parameters considered for simulations have been extracted from different references [5, 29, 35, 41] and are collected in Tables 1-7. Three scenarios (optimist, average, pessimist) with same probability are considered for PV generation which are plotted in Fig. 3. As seem, the scenario 1 can be considered optimist while the scenario 3 is the most unfavourable. The home appliances demand is shown in Fig. 4 which is based on typical home demand profiles such as those reported in [43]. Fig. 5 shows the hot water and food demand over the time horizon. To build these profiles, it has been taken into account that 10 and 3 litres are consumed on average in each shower and dish washing event, respectively [41]. On the other hand, it is assumed that breakfast, lunch, snack and dinner are the most significant 'food events' during a day. According to

[41], 5 kg of food are consumed on average each lunch and dinner, while only 2 kg are ingested during breakfast and snack.

Table 1 - Parameters of the PV array

Parameter	**Value**
Peak power	1 kWp
Efficiency	16.7%

Table 2 - Parameters of the BES

Parameter	**Value**
Capacity	2 kWh
Energy-to-power ratio	4 h
Charging/discharging efficiency	98%
Depth of discharge	60%

Table 3 - Parameters of the DEG

Parameter	**Value**
Rated power	3 kW
Minimum power	100 W
a^{DEG}	0.08415 litre/kW
b^{DEG}	0.246 litre/kW
Fuel cost	2 $/litre
CO2 emiss. factor	2.4 kg/litre

Table 4 - Structural parameters of the building

Parameter	**Value**	**Parameter**	**Value**
Length (L_1)	30 m	Area of windows	1 m²
Width (L_2)	10 m	Wall thermal coeff.	$136.8\ \text{J}/(\text{h} \cdot \text{m} \cdot {}^\circ\text{C})$
Height (L_3)	4 m	Window thermal coeff.	$2{,}808\ \text{J}/(\text{h} \cdot \text{m} \cdot {}^\circ\text{C})$
Roof angle	40º	Thickness of walls	0.15 m
Nº of windows	6	Thickness of windows	0.05 m

Table 5 - Characteristics of the HVAC system

Parameter	**Value**
Rated power	2 kW
Coeff. of performance	2
Set-point	23 ºC
Heat capacity of the air	$1.01\ \text{kJ}/(\text{kg} \cdot {}^\circ\text{C})$
Max. dead-band	3 ºC
Min. dead-band	0.5 ºC

Table 6 - Characteristics of the EWH

Parameter	**Value**	**Parameter**	**Value**
Rated power	2.1 kW	Min. Temperature	40 ºC
Efficiency	90%	Cold water temperature	10 ºC
Capacity	50 gallons	Equivalent thermal resistance	1.52 kW/ºC
Set-point	45 ºC	Heat capacity of the water	863.4 kWh/ºC
Max. Temperature	60 ºC		

Table 7 - Characteristics of the freezer

Parameter	**Value**	**Parameter**	**Value**
Rated power	120 W	Set-point	-18 ºC
Coeff. of performance	2	Max. Temperature	-15 ºC
Capacity	170 kg	Min. Temperature	-22 ºC
Thermal dispersion	0.000531 kW/ºC	Heat capacity of the freezer	0.000453 kWh/ºC
Food temperature	-1 ºC		

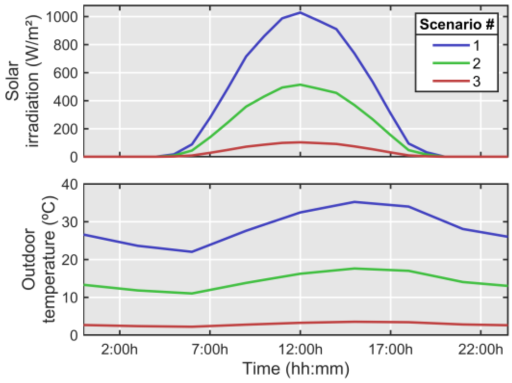

Fig. 3 Solar irradiation (upper) and outdoor temperature (bottom) considered in simulations

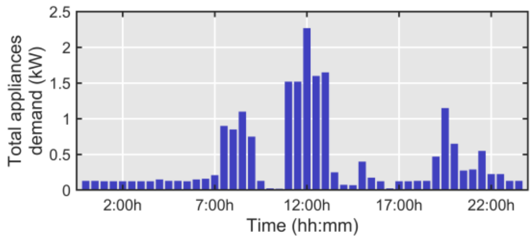

Fig. 4 Appliances demand considered in simulations

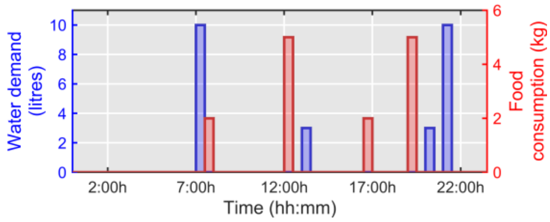

Fig. 5 Hot water demand and food consumption considered in simulations

6.2.- Indicators

To evaluate the impact of flexibility brought by thermostatically controlled appliances, some helpful indicators are considered. On the one hand, DEG energy generated, fuel consumption, fuel cost and CO_2 emissions are respectively defined by (45)-(48).

$$\text{DEG energy} = \sum_{\forall s \in \mathcal{S}} \left\{ \Delta\tau \cdot \pi_s \cdot \left[\sum_{\forall t \in \mathcal{T}} \left(p_{s|t}^{\text{DEG}} \right) \right] \right\} \quad (45)$$

$$\text{Fuel consumption (litres)} = \sum_{\forall s \in \mathcal{S}} \left\{ \pi_s \cdot F_s^{\text{DEG}} \right\} \quad (46)$$

$$\text{Fuel cost (\$)} = \sum_{\forall s \in \mathcal{S}} \{\pi_s \cdot \sigma^{\text{DEG}} \cdot F_s^{\text{DEG}}\} \tag{47}$$

$$\text{CO}_2 \text{ emissions (kg)} = \sum_{\forall s \in \mathcal{S}} \{\pi_s \cdot \mu^{\text{DEG}} \cdot F_s^{\text{DEG}}\} \tag{48}$$

On the other hand, it is well-known that lifecycle of a BES is strongly influenced by the total charging-discharging cycles completed through a year [34, 35]. For our case, this factor can be calculated as follows:

$$\text{Char/Dis BES cycles} = \sum_{\forall s \in \mathcal{S}} \left\{ \frac{\pi_s \cdot \Delta\tau}{2 \cdot \overline{\varepsilon}^{\text{BES}}} \left(\sum_{\forall t \in \mathcal{T}} \left[p_{s|t}^{\text{BES,ch}} \cdot \eta^{\text{BES,ch}} - \frac{p_{s|t}^{\text{BES,dch}}}{\eta^{\text{BES,dch}}} \right] \right) \right\} \tag{49}$$

6.3.- Results

6.3.1.- Influence of thermal requirements

Firstly, it is analysed the impact of users' thermal requirements (considered in the objective function by the penalty term γ^{Th}) on the flexible modes proposed for thermostatically controlled loads. To that end, it is considered that home inhabitants consider essential to fully satisfy the home demand. This way, let us assume that the penalty term γ^{app} has been set equal to 10^3 (it has been empirically observed that 100% demand is satisfied with these settings), while the thermal penalty term freely varies to study its influence.

Thereby, Fig. 6 shows the total energy generated by the DEG considering flexibility on different thermal appliances. A base case in which all temperature-based devices are operated in a non-flexible way is also shown for comparison ('None'). As expected, greater energy savings are observed for low values of γ^{Th}, since in this way the thermal requirements are very relaxed. The HVAC system provides the highest degree of flexibility, achieving an energy saving up to 15% w.r.t. the base case. The EWH also provides a certain degree of flexibility, achieving an energy saving of 10%. In contrast, the freezer hardly brought any benefit w.r.t. the base case.

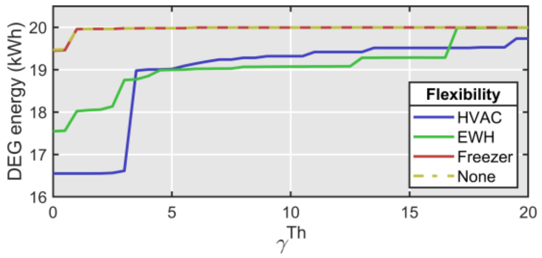

Fig. 6 Total energy generated by the DEG considering various thermal comfort levels and flexible modes of the different thermostatically controlled appliances ($\gamma^{\text{app}} = 10^3$)

In order to show how the flexibility of thermostatically controlled appliances affects to the diesel generation, Fig. 7 compares the scheduling result considering non-flexible and flexible operational modes of the HVAC system with $\gamma^{\text{Th}} = 0$. As seen in this figure, when thermal comfort requirements are relaxed, the HVAC system is largely operated from midday to evening, whereas this appliance is also scheduled during night and early morning for higher values of γ^{Th}. This circumstance forces to usually set the DEG at higher power values.

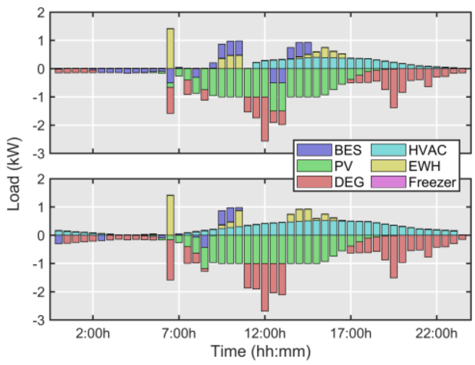

Fig. 7 Scheduling result considering flexibility (upper) and non-flexibility (bottom) of the HVAC system with $\gamma^{\text{Th}} = 0$ in scenario 1 with $\gamma^{\text{app}} = 10^3$. In this figure, negative power means 'to-home' flow direction (generation)

The other relevant aspects related with the DEG operation refer to the fuel consumption, fuel cost and CO_2 emissions. Fig. 8 plots the value of these three variables for different levels of thermal comfort. As seen, these variables follow the same trending as all of them are proportional to the fuel consumption. The conclusions extracted for the results shown in Fig. 6 can be also drawn in this case. Indeed, notable benefits are observed when both the HVAC system and the EWH are operated in a flexible manner (up to 12% and 8% of reduction of all indexes w.r.t. the base case, respectively). On the other hand, the flexible operation of the Freezer seems not to offer any substantial benefit.

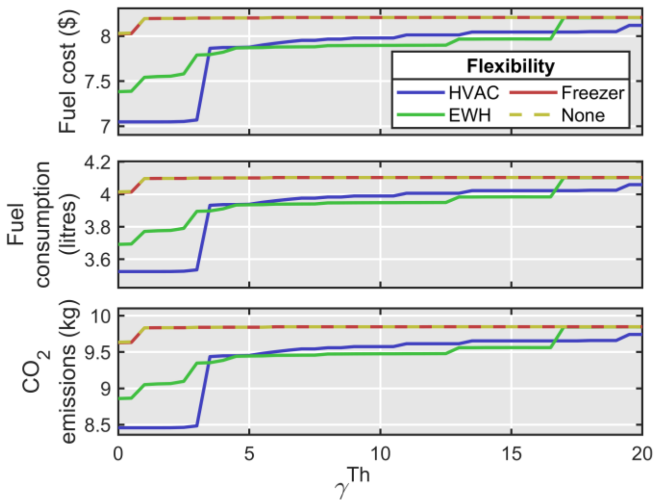

Fig. 8 Total fuel cost (upper), fuel consumption (middle) and CO_2 emissions (bottom) considering various thermal comfort levels and flexible modes of the different thermostatically controlled appliances ($\gamma^{\text{app}} = 10^3$)

Lastly, Fig. 9 analyses the total charging/discharging cycles completed by the BES. In this case, few differences are observed among the different studied cases. Thus, only 0.1 cycles were completed in the base case or flexible operation of the freezer; while ~0.25 cycles were demanded from the BES in the case of flexible operation of the EWH or flexible operation of the HVAC system with lax thermal requirements.

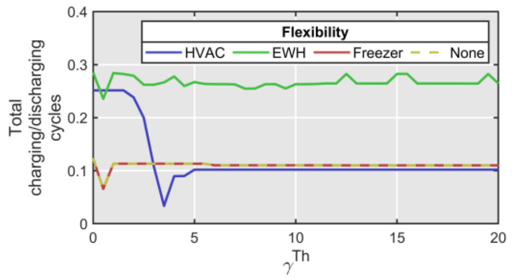

Fig. 9 Total charging/discharging cycles required from the BES through a day considering various thermal comfort levels and flexible modes of the different thermostatically controlled appliances ($\gamma^{\text{app}} = 10^3$)

6.3.2.- Influence of the PV array sizing

In this section, it is analysed how the peak power of the PV array impacts on the benefits brought by flexible operation of temperature-controlled appliances. To perform this study, it is assumed that thermal comfort is disregarded ($\gamma^{\text{Th}} = 0$) as it supposes the most favourable scenario for energy management, while the home users are not willing to dissatisfy any demand ($\gamma^{\mathrm{app}} = 10^3$).

Fig. 10 shows the value of some indicators for different PV array sizing. Regarding those indexes related with the operation of the DEG, same conclusions drawn in previous experiments can be also extended for this analysis. In other words, the benefits brought by the flexible operation of thermostatically controlled loads are kept regardless the PV array size. Nevertheless, it is worth mentioning that all the indexes are improved as the size of the PV array is increased. Indeed, the energy generated by the DEG is reduced up to 28% while the other indicators can be enhanced up to 24% by increasing the PV system peak power from 100 to 2,000 Wp. On the other hand, it is observed as the BES is further operated as the PV sizing grows. Rightly, up to ~0.5 cycles/day may be completed considering flexible operation of the EWH and a PV array peak power > 1.4 kWp.

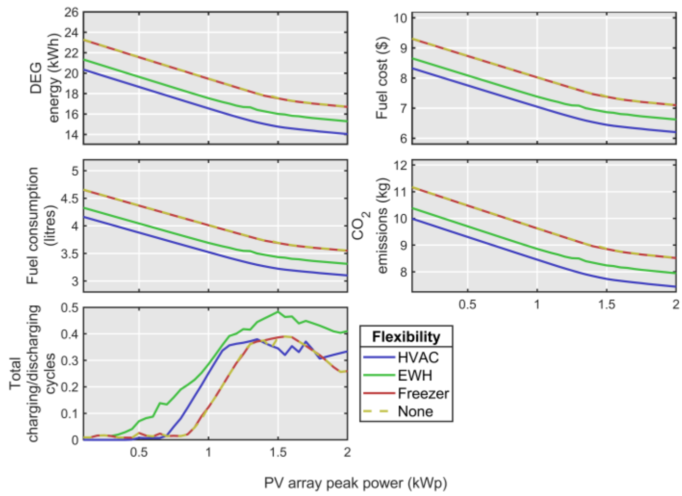

Fig. 10 Value of different indicators for different PV array sizing considering flexible modes of the different thermostatically controlled appliances ($\gamma^{\mathrm{app}} = 10^3$, $\gamma^{\mathrm{Th}} = 0$)

6.3.3.- Influence of the BES capacity

Similar to the previous section, various experiments are carried out to analyse the impact of the total BES capacity. Same conditions are also considered in the experiments performed in this Section ($\gamma^{\mathrm{app}} = 10^3$, $\gamma^{\mathrm{Th}} = 0$). Thus, Fig. 11 shows the value of various indicators for different BES sizing. As observed, those indicators related with the operation of the DEG scarcely vary with the BES sizing. Only in the case of flexible operation of the EWH, the different indexes are slightly improved (all indicators can be reduced by ~2% by increasing the BES capacity from 100 to 3,000 Wh). On the other hand, the total charging-discharging cycles completed by the BES is normally reduced as the capacity of the storage system grows. This is due to the BES presents the same charging-discharging operational cycle disregarding the storage capacity. Indeed, Fig. 12 plots the scheduling result with a BES of 1 and 3 kWh. As seen, the BES is in both cases discharged during dawn while PV generation during central hours is exploited for charging the batteries. The main difference between the two analysed cases is the rated charging/discharging power, which according to (14) is proportional to the BES total capacity.

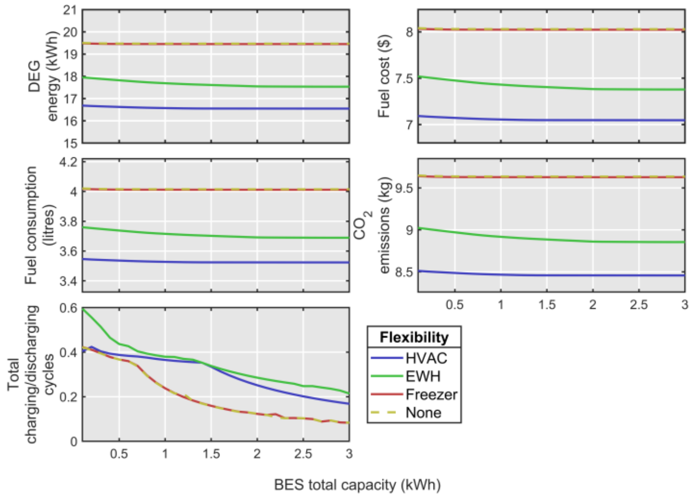

Fig. 11 Value of different indicators for different BES capacities considering flexible modes of the different thermostatically controlled appliances ($\gamma^{\mathrm{app}} = 10^3$, $\gamma^{\mathrm{Th}} = 0$)

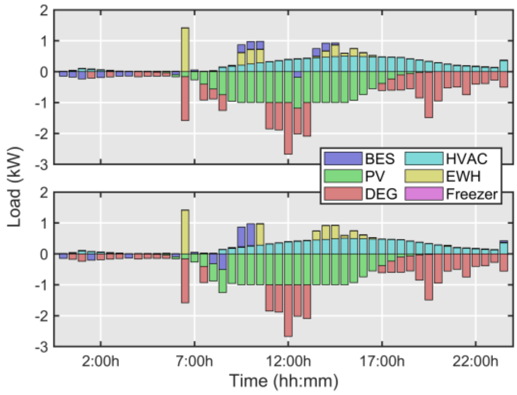

Fig. 12 Scheduling result for a total BES capacity of 1 kWh (upper) and 3 kWh (bottom) in scenario 1 under base case conditions (none flexibility, $\gamma^{\text{app}} = 10^3$, $\gamma^{\text{Th}} = 0$). In this figure, negative power means 'to-home' flow direction (generation)

7.- Conclusions

This work has analysed possible flexible operational modes for thermostatically controlled appliances in off-grid smart homes. Various experiments have been carried out on a benchmark building with different PV generation scenarios, in order to study how thermal comfort requirements, PV sizing and BES capacity influence on the benefits brought by flexible operation of temperature-based devices. More precisely we conclude that:

- Clearly, the HVAC system and EWH provided more flexibility than the freezer. Indeed, flexible operation of the former allow to reduce up to 15% and 10% the energy generated by the DEG per day, respectively. Other related indicators are also improved, thus, fuel consumption, fuel cost and CO_2 emissions may be reduced by 12% and 8% by operating the HVAC system and EWH in a flexible way. On the other hand, little benefits are obtained from the flexible operation of the freezer.
- PV array sizing has a much more remarkable impact on the daily operation of the studied home than the BES capacity. Thus, the different indicators may be improved up to 28% by increasing the PV system peak power from 100 to 2,000

Wp. In contrast, the impact of the BES capacity was just appreciable in the case of flexible operation of the EWH, improving the different indexes by ~2%.

- The impact of the proposed operational modes on batteries degradation was not significant. However, this aspect makes more notable as PV array size increases.

In conclusion, the authors believe that the operational modes proposed in this paper may help to reduce the monetary expenditures of home users' along to improve some environmental indicators. The benefits brought by the flexible operation of some appliances like HVAC systems or EWHs might be more remarkable in commercial or industrial buildings; and isolated communities, where a large number of appliances may be operated in a coordinated way. These points should be confirmed in future works.

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References

[1] International Energy Agency (IEA) - World Energy Outlook 2020. Available: https://www.iea.org/reports/world-energy-outlook-2020, 2020 (Accessed 5 Feb. 2021)

[2] R. Oki, et al. Renovating a house to aim for net-zero energy, thermal comfort, energy self-consumption and behavioural adaptation: A method proposed for ENEMANE HOUSE 2017. Energy Build 2019; 201: 183-193. https://doi.org/10.1016/j.enbuild.2019.06.041

[3] Q. Hassan. Evaluation and optimization of off-grid and on-grid photovoltaic power system for typical household electrification. Renew Energy 2021; 164: 365-390. https://doi.org/10.1016/j.renene.2020.09.008

[4] European Comission - Commission welcomes agreement on energy performance of buildings. Available: https://ec.europa.eu/energy/news/commission-welcomes-agreement-energy-performance-buildings_en?redir=1, 2017 (Accessed 5 Feb. 2021)

[5] C. Mokhtara, et al. Integrated supply–demand energy management for optimal design of off-grid hybrid renewable energy systems for residential electrification in arid climates. Energy Conv Manag 2020; 221: 113192. https://doi.org/10.1016/j.enconman.2020.113192

[6] H. Louie. Off-Grid Electrical Systems in Developing Countries. Springer; Gewerbestrasse, Switzerland: 2018. https://doi.org/10.1007/978-3-319-91890-7

[7] M. Rastegar, M. Fotuhi-Firuzabad, F. Aminifar. Load commitment in a smart home. Appl Energy 2012; 96: 45-54. https://doi.org/10.1016/j.apenergy.2012.01.056

[8] E. Rodríguez-Díaz, J.C. Vasquez, J.M. Guerrero. Intelligent DC Homes in Future Sustainable Energy Systems: When efficiency and intelligence work together. IEEE Consum Electron Mag 2016; 5(1): 74-80. https://doi.org/10.1109/MCE.2015.2484699

[9] A. Shewale, A. Mokhade, N. Funde, N.D. Bokde. An Overview of Demand Response in Smart Grid and Optimization Techniques for Efficient Residential Appliance Scheduling Problem. Energies 2020; 13: 4266. https://doi.org/10.3390/en13164266

[10] H. Hu, G. Augenbroe. A stochastic model based energy management system for off-grid solar houses. Build Environ 2021; 50: 90-103. https://doi.org/10.1016/j.buildenv.2011.10.011

[11] N. Tutkun, E.S. Şan. Optimal power scheduling of an off-grid renewable hybrid system used for heating and lighting in a typical residential house. In: 2013 13th International Conference on Environment and Electrical Engineering (EEEIC); Wroclaw, Poland, 2013: 352-355. https://doi.org/10.1109/EEEIC-2.2013.6737935

[12] N. Tuktun. Minimization of operational cost for an off-grid renewable hybrid system to generate electricity in residential buildings through the SVM and the BCGA methods. Energy Build 2014; 76: 470-475. https://doi.org/10.1016/j.enbuild.2014.03.003

[13] N. Tutkun, Ö. Can, E. S. Şan. Daily cost minimization for an off-grid renewable microhybrid system installed to a residential home. In: 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, Italy, 2015: 750-754. https://doi.org/10.1109/ICRERA.2015.7418511

[14] R. Kallel, G. Boukettaya, L. Krichen. Demand side management of an isolated hybrid energy production unit supplying domestic loads. In: 2014 IEEE 11th International Multi-Conference on Systems, Signals & Devices (SSD14); Barcelona, Spain, 2014: 1-5. https://doi.org/10.1109/SSD.2014.6808893

[15] A.S.O. Ogunjuyigbe, T.R. Ayodele, C.G. Monyei. An intelligent load manager for PV powered off-grid residential houses. Energy Sustain Dev 2015; 26: 34-42. https://doi.org/10.1016/j.esd.2015.02.003

[16] F.K. Arabul, A.Y. Arabul, C.F. Kumru, A.R. Boynuegri. Providing energy management of a fuel cell–battery–wind turbine–solar panel hybrid off grid smart home system. Int J Hydrogen Energy 2017; 42(43): 26906-26913. https://doi.org/10.1016/j.ijhydene.2017.02.204

[17] HOMER Software Optimization Tool. Available: https://www.homerenergy.com (Accessed 5 Feb. 2021)

[18] H. U. R. Habib, S. Wang, M. R. Elkadeem, M. F. Elmorshedy. Design Optimization and Model Predictive Control of a Standalone Hybrid Renewable Energy System: A Case Study on a Small Residential Load in Pakistan. IEEE Access 2019; 7: 117369-117390. https://doi.org/10.1109/ACCESS.2019.2936789

[19] H. O. Alwan, H. Sadeghian, S. Abdelwahed. Optimal Energy scheduling of an off-grid renewable system used for typical residential households. In: 2019 11th International Conference on Computational Intelligence and Communication

Networks (CICN); Honolulu, HI, USA, 2019: 103-109. https://doi.org/10.1109/CICN.2019.8902414
[20] A. Bouakkaz, S. Haddad, A. J. Gil Mena. Optimal Peak Power Shaving Through Household Appliance Scheduling in off-grid Renewable Energy System. In: 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe); Genova, Italy, 2019: 1-6. https://doi.org/10.1109/EEEIC.2019.8783662
[21] A. Bouakkaz, et al. Optimal Scheduling of Household Appliances in Off-Grid Hybrid Energy System using PSO Algorithm for Energy Saving. Int J Renew Energy Res 2019; 9(1): 427-436
[22] D. Cho, J. Valenzuela. Scheduling energy consumption for residential stand-alone photovoltaic systems. Solar Energy 2019; 187: 393-403. https://doi.org/10.1016/j.solener.2019.05.054
[23] D. Cho, J. Valenzuela. Optimization of residential off-grid PV-battery systems. Solar Energy 2020; 208: 766-777. https://doi.org/10.1016/j.solener.2020.08.023
[24] Eurostat - Energy consumption in households. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households, 2021 (Accessed 5 Feb. 2021)
[25] B. Sun, X. Su, D. Wang, et ál. Economic analysis of lithium-ion batteries recycled from electric vehicles for secondary use in power load peak shaving in China. Journal of Cleaner Production 2020; 276:123327 https//doi.org/10.1016/j.jclepro.2020.123327
[26] J. Persson, S. Gronkvist. Drivers for and barriers to low-energy buildings in Sweden. Journal of Cleaner Production 2015;109: 296-304 https//doi.org/10.1016/j.jclepro.2014.09.094
[27] T. Häring, A. Rosin, H. Biechl. Using common household thermal storages to support the PV- and battery system in nearly zero energy buildings in off-grid mode. Sustain Energy Technol Assess 2019; 35: 12-24. https://doi.org/10.1016/j.seta.2019.05.014
[28] M. Tostado-Véliz, P. Arévalo, F. Jurado. A Comprehensive Electrical-Gas-Hydrogen Microgrid Model for Energy Management Applications. Energy Conv Manag 2021; 228: 113726. https://doi.org/10.1016/j.enconman.2020.113726
[29] N.G. Paterakis, O. Erdinç, A.G. Bakirtzis, J.P.S. Catalão. Optimal Household Appliances Scheduling Under Day-Ahead Pricing and Load-Shaping Demand Response Strategies. IEEE Trans Ind Inform 2015; 11(6): 1509-1519. https://doi.org/10.1109/TII.2015.2438534
[30] Endesa - What is the ideal temperature for the freezer?. Available: https://www.endesa.com/en/discover-energy/blogs/the-ideal-temperature-for-a-freezer (Accessed 5 Feb. 2021)
[31] M. Tostado-Véliz, D. Icaza-Alvarez, F. Jurado. A Novel Methodology for Optimal Sizing Photovoltaic-Battery Systems in Smart Homes considering Grid Outages and Demand Response. Renew Energy 2021; 170: 884-896. https://doi.org/10.1016/j.renene.2021.02.006
[32] A. Chaib, D. Achour, M. Kesraoui. Control of a Solar PV/wind Hybrid Energy System. Energy Procedia 2016; 95: 89-97. https://doi.org/10.1016/j.egypro.2016.09.028

[33] L. Alvarado-Barrios, et al. Stochastic unit commitment in microgrids: Influence of the load forecasting error and the availability of energy storage. Renew Energy 2020; 146: 2060-2069. https://doi.org/10.1016/j.renene.2019.08.032

[34] I. Alsaidan, A. Khodaei, W. Gao. A Comprehensive Battery Energy Storage Optimal Sizing Model for Microgrid Applications. IEEE Trans Power Syst 2018; 33(4): 3968-3980. https://doi.org/10.1109/TPWRS.2017.2769639

[35] P. Arévalo, M. Tostado-Véliz, F. Jurado. A novel methodology for comprehensive planning of battery storage systems. J Energy Storage 2021; 37: 102456. https://doi.org/10.1016/j.est.2021.102456

[36] Z. Jiang, J. Cai, P.S. Moses. Smoothing control of solar photovoltaic generation using building thermal loads. Appl Energy 2020; 277: 115523. https://doi.org/10.1016/j.apenergy.2020.115523

[37] M. Collotta, G. Pau. An Innovative Approach for Forecasting of Energy Requirements to Improve a Smart Home Management System Based on BLE. IEEE Trans Green Commun Netw 2017; 33(12): 2988-96. https://doi.org/ 10.1109/TGCN.2017.2671407

[38] D. Schäuble, A. Marian, L. Cremonese. Conditions for a cost-effective application of smart thermostat systems in residential buildings. Appl Energy 2020; 262: 114526. https://doi.org/10.1016/j.apenergy.2020.114526

[39] H. Wang, et al. Demand response through smart home energy management using thermal inertia. In: Proc Australas Univ Power Eng Conf, Hobart, TAS, 2013: 1-6. https://doi.org/10.1109/AUPEC.2013.6725442

[40] P. Du, N. Lu. Appliance Commitment for Household Load Scheduling. IEEE Trans Smart Grid 2011; 2(2): 411-419. https://doi.org/10.1109/TSG.2011.2140344

[41] A. Rosin, et al. Performance and feasibility analysis of electricity price based control models for thermal storages in households. Sustain Cities Soc 2017; 32: 366-374. https://doi.org/10.1016/j.scs.2017.04.008

[42] Gurobi, the fastest solver. https://www.gurobi.com/, (Accessed 8 Feb. 2021)

[43] T. Singh. Smart Home Dataset with weather Information. Available: https://www.kaggle.com/taranvee/smart-home-dataset-with-weather-information (Accessed 8 Feb. 2021)