Energy Class Dependent Residential Battery Storage Sizing for PV Systems in Cyprus

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Abstract

Battery energy storage systems (BESS) have started to be part of photovoltaic (PV) system design to allow the further penetration of PV into the grid. This paper deals with the sizing (power and energy capacity) of a BESS for residential households which are represented by a typical load consumption profile, they have electrical air conditioning (AC) and electrical water heating (water boiler) resembling a common residential house in Cyprus. The BESS sizing is done considering the local energy consumption profile and the energy efficiency class of the house and the water boiler. The BESS is sized in order to achieve zero PV grid export and to increase self-consumption.

1 Introduction

The recent price reduction of Photovoltaic (PV) systems has brought the technology to the forefront rendering it as a very attractive alternative to fossil fuel generation. However, the increasing share of PV generation in the total installed capacity and energy production poses numerous challenges to the energy network. One of the issues concerning the further penetration of RES in the energy mix is the geographical scattering of PV installations, which raises significant concerns regarding grid operation and are mainly connected to power quality and security of supply. In order to resolve the aforementioned issues and pave the way towards a greener energy network, new technologies will have to be adopted in the existing energy system. Amongst various solutions to support further PV deployment, the combination of Energy Storage Systems (ESS) and demand response (DR) is a potential solution to support future smart grids and provide the desired flexibility. This combination and in particular the utilization of Battery Energy Storage Systems (BESS), is considered as a viable and potentially sustainable option which can offer numerous services to support grid operation. Also, the coupling of BESS with DR flexibility can increase prosumer self-consumed electricity, in a way to alleviate grid issues that are associated with surplus energy injection to the grid.

This paper describes a case study of a household which consists of an existing solar PV system and two flexible loads that strongly depend on the season, namely a water boiler (WB) and a house Air Conditioning (AC) system. Initially, a custom energy management algorithm was implemented to control the flexible loads based on the PV generated electricity and keep the house and water temperature within a predefined (known) comfort zone. The main objective of this study is to investigate the degree of solar PV utilization for every month of a benchmark year by calculating the amount of surplus electricity that is injected to the grid. After that, the maximization of the self-consumed energy and more importantly the reduction of the excess energy that is injected to the grid is examined by coupling a battery energy storage to the system. The required size of the BESS was studied based on the energy efficiency class (EEC) of the water boiler [1] and the house itself [2]. Finding the optimum BESS size is important since chemical batteries have considerably high unit cost, especially after the recent introduction of Lithium-Ion battery which is very promising due to its high energy density.

In this study, a simulation-based approach deals with the maximization of self-consumed electricity by taking into consideration solar PV production along with the flexible loads and battery. Additionally, the methodology accounts for the sizing of the BESS in terms of power and energy capacity and takes into consideration the local energy consumption profile and the energy efficiency class (EEC) of the house and the water boiler.

2 Methodology

As already mentioned in the introduction, the battery sizing was done based on the local energy consumption and the energy efficiency class (EEC) of the house and the water boiler. The local energy consumption profile was calculated from data recorded from Smart Meters (SMs) installed in 300 houses in Cyprus. The data was recorded for one year with a sampling rate of 15-mins. Then, based on these data, the daily average energy consumption profile of all 300 houses was calculated for every month. The monthly average energy profile was considered as the base load of the house used in this study as illustrated in Fig. 1 below.

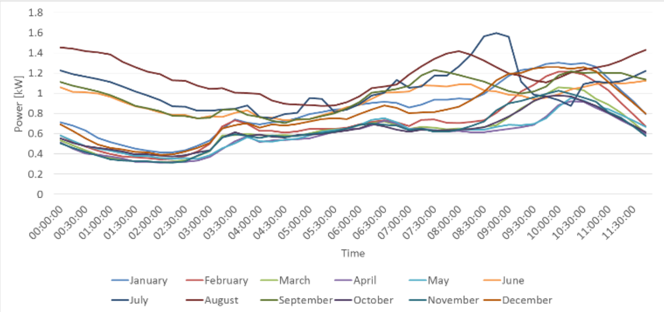

Figure 1. Average daily local load consumption profile per month taken from 300 houses in Cyprus.

The total load of the house was the base load plus the house air conditioning (AC) system and the water boiler (WB). In order to increase self-consumption, the energy management strategy adopted was to reduce the exported PV power to zero. The average daily PV production per month was also calculated from 15-min samples over the course of one year. This, together with the total house load, were the inputs to the energy management algorithm which was targeting increased self-consumption.

The method chosen to increase self-consumption was the battery storage. Self-consumption could be increased by consuming PV energy to heat/cool the house and/or the boiler within the allowable comfort zone, however, this method is not optimal. In order to demonstrate this, consider the following example. If the excess PV production is used to increase the temperature of the house to 27 °C (e.g. maximum of the comfort zone) instead of keeping it at 23 °C (e.g. average of the comfort zone), self-consumption will theoretically increase, however, the house will cool down after a few hours and will need power from the grid to maintain 23 °C when there is no sunshine at night. The power used to heat the house to 27 °C could have been stored in a battery and used later to maintain the house at 23 °C during night time. As can be seen, in this example, self-consumption increases theoretically but it has no practical meaning. The same applies for the water boiler.

In light of the above, it is better to store the excess PV energy in a battery for later use. The battery sizing is affected by the local PV production, the local energy consumption and the energy efficiency class (EEC) of the house and the water boiler. In order to simulate the heat loss of the house and the water boiler, thermal models have been developed. The models were kept simple since the intent of this work is to show how the energy class affects the battery size and not to calculate the accurate temperature of the studied systems.

2.1 Water Boiler Thermal Model

The thermal model of the water boiler (WB) is shown in Fig. 2. In the simulation, only the boiler-ambient thermal resistance (R_{b-a}) was considered since the heater-water thermal resistance (R_{h-w}) does not affect the amount of heat transferred into the water. Also, only the water heat capacity (C_{water}) was taken into account since the boiler metallic structure heat capacity is not significant.

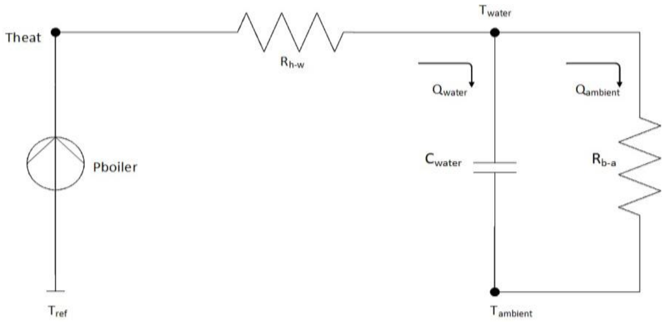

Figure 2. Thermal model of the water boiler (WB). P_{boiler} represents the power input to the electrical heater of the boiler.

The thermal model of the water boiler in Fig. 2 is described by the following equations:

$$Q_{ambient} = \frac{T_{water} - T_{ambient}}{R_{b-a}} \quad (1)$$

$$Q_{water} = P_{boiler} - Q_{ambient} \quad (2)$$

$$\Delta T_{water} = \frac{Q_{water}}{C_{water}} * t_{step} \quad (3)$$

The equations above were iterated in the simulation in order to calculate the water temperature (T_{water}) and the heat loss ($Q_{loss} = Q_{ambient}$) of the boiler. During the boiler simulation, only the local load profile (Fig. 1) was used as an additional load, the house AC system was turned off.

The water boiler (WB) model parameters are summarised in Table 1. A 200 L boiler was assumed since it is widely used in Cyprus.

Material Properties	
Water Specific Heat Capacity	4185.5 J/kgK
Mechanical Parameters	
Boiler Water Capacity	200 L
Thermal Parameters (calculated)	
Water Heat Capacity (C_{water})	837.5 kJ/K
Boiler-Ambient Thermal Resistance (R_{b-a})	0.15 (low EEC) – 0.55 (high EEC) K/W (1)

Table 1. Water boiler modelling parameters.

(1) The boiler thermal resistance to ambient was varied between 0.15 and 0.55 °C/W in order to simulate the various energy classes according to the EU Directive 2010/30/EU on the energy labelling of water heaters [3]. Only classes from G to C were simulated since higher classes have little effect in this study.

2.2 House Thermal Model

The thermal model of the house is shown in Fig. 3. In the simulation, the air conditioner (AC) thermal resistance to the internal house air ($R_{ac\text{-}a}$) was ignored since it does not affect the amount of heat power transferred into the air. In order to calculate the total thermal resistance of the house to ambient ($R_{h\text{-}a}$), the wall, roof and floor thermal resistance were considered. The thermal resistances were calculated by considering both the convection and conduction mechanisms for heat transfer [4], [5]. The heat capacitance of the whole structure ($C_{structure}$) was ignored deliberately because the simulation time is 24-hours and hence there is not enough time for the structure ($C_h > 25*10^6$ J/K) to change temperature since several days are required. The room heat capacitance (C_{room}) due to the air inside the house was considered though since the air temperature can change within a few hours.

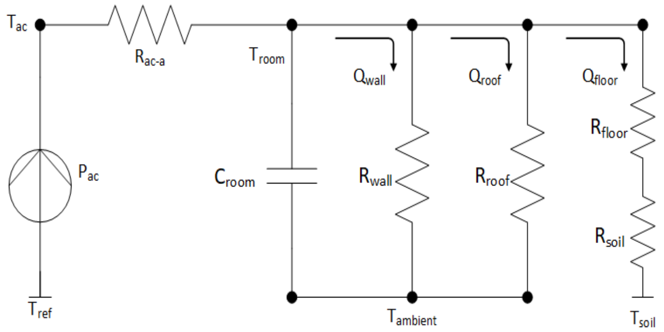

Figure 3. Thermal model of the house. P_{ac} represents the power input to the air conditioning system of the house.

The thermal model of the house in Fig. 3 is described by the following equations:

$$Q_{floor} = \frac{T_{room} - T_{soil}}{R_{floor} + R_{soil}} \quad (4)$$

$$Q_{roof} = \frac{T_{room} - T_{ambient}}{R_{roof}} \quad (5)$$

$$Q_{wall} = \frac{T_{room} - T_{ambient}}{R_{wall}} \quad (6)$$

$$Q_{air} = P_{ac} - Q_{floor} - Q_{roof} - Q_{wall} \quad (7)$$

$$\Delta T_{room} = \frac{Q_{air}}{C_{air}} * t_{step} \quad (8)$$

The equations above were iterated in the simulation in order to calculate the room temperature and the heat loss of the house. During the house AC system simulation, only the local load profile (Fig. 1) was used as an additional load, the water boiler (WB) was turned off.

The house model parameters are summarised in Table 2. A 150 m^2 (15x10x3 m, LxWxH) house was assumed since it is common in Cyprus.

Material Properties		
Air Specific Heat Capacity	1000 J/kgK	
Wall Bricks Thermal Resistivity	2.5 mK/W	
Wall Insulation Thermal Resistivity	33.33 mK/W	
Roof Tiles Thermal Resistivity	1 mK/W	
Roof Insulation Thermal Resistivity	24.39 mK/W	
Floor Cement Thermal Resistivity	0.4 mK/W	
Soil Thermal Resistivity (1)	1 mK/W	
Mechanical Parameters		
	Low EEC	High EEC
Wall Thickness	0.2 m	0.2 m
Wall Insulation Thickness	0 m	0.08 m
Roof Tiles Thickness	0.02 m	0.02 m
Roof Insulation Thickness	0 m	0.1 m
Floor Thickness	0.02 m	0.02 m
Floor Insulation Thickness (2)	0 m	0 m
Soil Thickness (3)	10 m	10 m
Thermal Parameters (calculated) (4)		
Wall Thermal Resistance (R_{wall})	4.47 mΩ	22.24 mΩ
Roof Thermal Resistance (R_{roof})	1.07 mΩ	17.32 mΩ
Floor Thermal Resistance (R_{floor})	1.8 mΩ	1.8 mΩ
Soil Thermal Resistance (R_{soil})	66.67 mΩ	66.67 mΩ

Table 2. House modelling parameters.

(1) The soil thermal resistivity value is an average value since it depends on the soil humidity [6].
(2) The house floor was assumed to have no insulation in all simulation cases.
(3) The soil thickness below the house floor was taken as 10 m since beyond this depth, the soil temperature is constant at 22 °C [7].
(4) In order to simulate the various energy efficiency classes of the house, these values were varied from the low energy class to the high energy class during the simulation in even steps forming five EEC test cases.

The low energy efficiency class (EEC) house is made of a single row brick walls, a tile roof and cement floor (not considering the floor tiles). No insulation was assumed for this house at all. For the high energy efficiency class house, the same materials were used, however, the walls were insulated with extruded polystyrene and the roof with glass wool. The floor was assumed to have no thermal insulation for all energy efficiency class cases.

3 Results

This section presents the results which are based on the methodology described previously. For all simulation cases, the hot water demand and the room temperature were set constant at 60 °C and 23 °C respectively. The simulation of either the water boiler (WB) or the house air conditioning (AC) system is done separately in order to investigate the influence each system has on the battery size for different energy efficiency classes (EEC) under different ambient temperatures. As a consequence, the battery size can be obtained for different energy efficiency classes. Finally, a typical residential load consumption profile (Fig. 1) representing a typical house was used for each simulation case.

3.1 Environmental Conditions

In order to understand and interpret the results better, the monthly average ambient temperature (T_{amb}) and the PV energy production that were used in the simulation are shown in Fig. 4. The data were calculated from one year measurements with a sampling rate of 15-min at the University of Cyprus. From the data, it is observed that the maximum monthly average ambient temperature (27.6 °C) occurs in July and August while the peak PV energy production (22 kWh) occurs in June. It can be verified that both PV energy production and ambient temperature remain high during the spring and summer months. Further to this, the PV grid export electricity for each month with only the typical house load (without the water boiler and house AC system load) is presented since it will be useful for the comparison of the results later when the water boiler and house AC system load are included in the simulation. The highest daily exported electricity reaches up to 12.37 kWh in spring while the lowest is 2.13 kWh and occurs in winter.

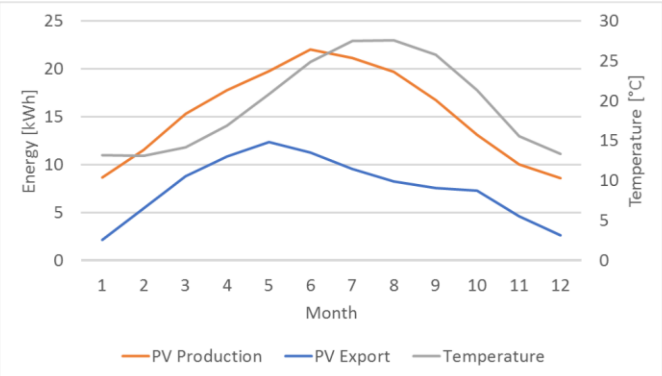

Figure 4. Monthly average ambient temperature, PV energy production and PV export for a 3 kWp PV system at the University of Cyprus.

3.2 Battery Size vs Water Boiler EEC

A simulation was performed based on the thermal model in Fig. 2 and the parameters in Table 1 to study the influence of the water boiler (WB) on the battery size. The aim of this simulation was to investigate the water boiler heat loss for different ambient temperature variations and more importantly how the energy efficiency class (EEC) can affect battery size. For that reason, the water temperature set-point was chosen to be at 60 °C, representing a typical temperature for domestic hot water. Apart from the water boiler consumption, the typical house load profile (Fig. 1) was used as an additional load.

The plots in Fig. 5 and Fig. 6 illustrate the daily PV exported grid power and energy for different boiler EEC per month respectively. It is observed that although the PV grid export changes with the season, the export is not affected by the boiler EEC significantly. From the results, if the water boiler and the typical house load are considered, the maximum battery size required to achieve zero-grid export is 1.8 kW/12 kWh for all boiler EEC (EEC in Table 1) in spring and summer when the PV production is at maximum (22 kWh). During the winter time, the PV production is at its minimum (8.5 kWh) and hence the required maximum battery size to achieve zero-grid export is 1.2 kW/4 kWh.

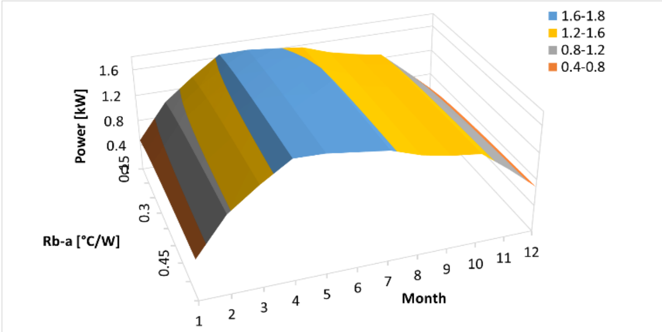

Figure 5. Average daily PV exported power to the grid for different water boiler energy efficiency classes per month.

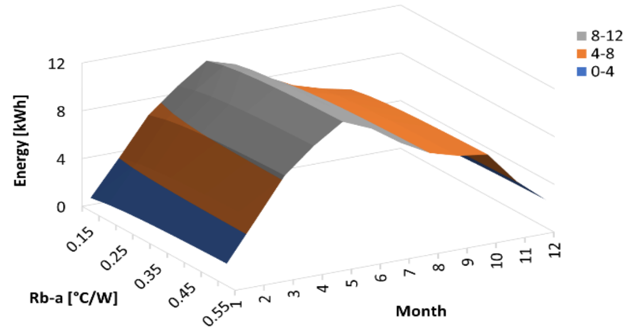

Figure 6. Average daily PV exported energy to the grid for different water boiler energy efficiency classes per month.

Next the direct PV consumption (influence) of the water boiler EEC on the PV grid export was examined. The PV grid export with the water boiler was subtracted from the PV grid export without the water boiler (only the typical house load) as shown in Fig. 7. It is seen that the maximum direct PV consumption for all months is 1.7 kWh at the low EEC and 0.48 kWh at the high EEC. This means that for a high EEC boiler the direct PV consumption and hence the battery capacity is not affected significantly.

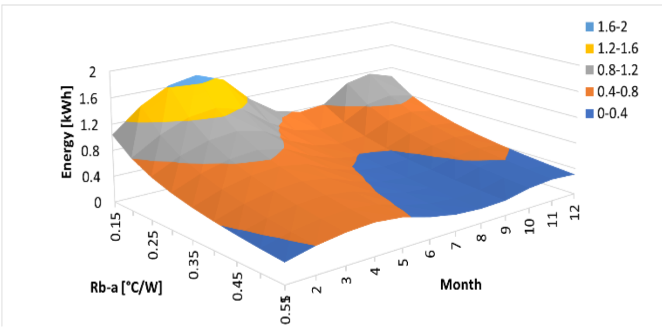

Figure 7. Direct PV energy consumption (influence) of the

water boiler from the PV exported energy for different boiler energy classes per month ($PV_{export\text{-}no\ boiler} - PV_{export\text{-}with\ boiler}$).

3.3. Battery Size vs House EEC

The influence of the house air conditioning (AC) system on the battery size was studied as well. The simulation was performed based on the thermal model in Fig. 3 and the parameters in Table 2. The target was to investigate the house heat loss under different ambient temperatures and study how its energy efficiency class (EEC) affects the battery size. The EEC variation in this section is presented as different EEC test cases which are explained in Table 2. The house internal temperature set-point was set to 23 °C, which is the average of the comfort zone [8]. In addition, the typical house load consumption profile was added to the total load for a more realistic representation of the results.

The daily PV exported grid power and energy for different house energy classes per month is shown in Fig. 8 and Fig. 9 respectively. It can be observed that during the summer (27.6 °C, monthly average max) and winter (13.2 °C, monthly average min) times when the ambient temperature deviates much from the internal house comfort temperature (23 °C), the PV grid export is low (need more heating/cooling). The maximum PV grid export occurs in spring (Fig. 4) when the PV production is at its peak (22 kWh) and the ambient temperature is close to the internal house temperature (23 °C). In both cases, the house EEC affects the PV grid export, however, it is more significant in May when the exported power/energy varies from 0.4 kW/3 kWh to 1.6 kW/12 kWh maximum for a low EEC to a high EEC (EEC in Table 2) respectively. Therefore, for a low EEC house the maximum required battery size is 0.4 kW/3 kWh and for a high EEC house the maximum required battery size is 1.6 kW/12 kWh.

To examine the direct PV consumption (influence) of the house AC system on the PV grid export power, the PV grid export with the AC system was subtracted from the PV grid export without the AC system (only the typical house load) as shown in Fig. 10. It is observed that the maximum direct PV consumption at all months is 11.23 kWh for a low EEC house and 6.48 kWh for a high EEC house. Hence, the high EEC influences the direct PV consumption of the AC system (and hence energy which could be stored in the battery) by almost a factor of 2.

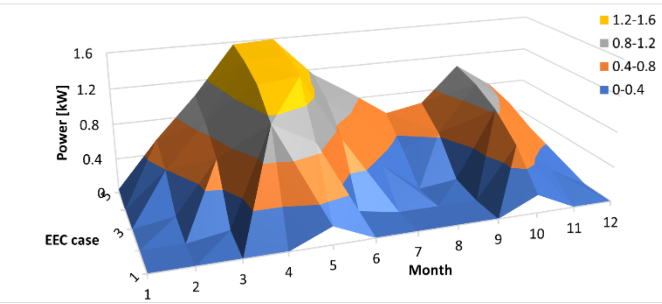

Figure 8. Average daily PV exported power to the grid for different house energy classes per month.

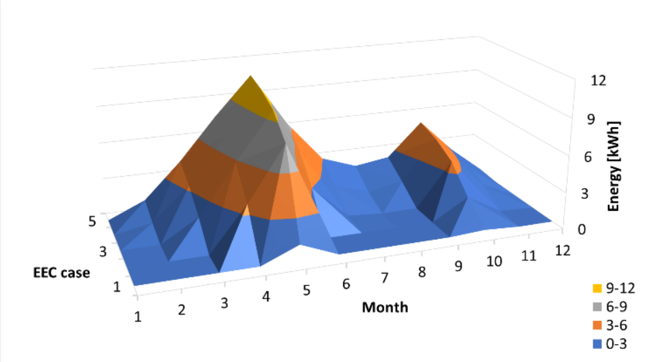

Figure 9. Average daily PV exported energy to the grid for different house energy classes per month.

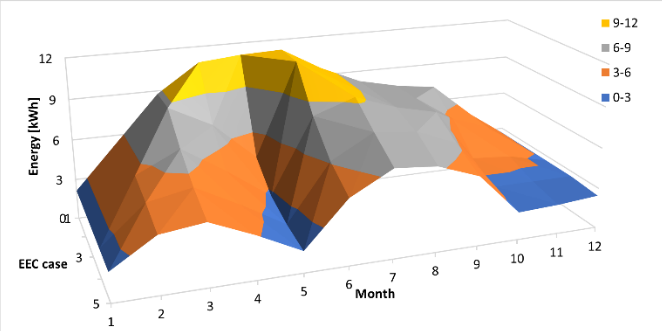

Figure 10. Direct PV energy consumption (influence) of the house AC system from the PV exported energy for different house energy classes per month ($PV_{export\text{-}no\ AC} - PV_{export\text{-}with\ AC}$).

A summary of the results is shown in Table 3. For the water boiler (WB), it is seen that the battery size remains within the same range independently of the EEC of the boiler. This means that the boiler energy class is not that important for sizing the battery. On the other hand, the house AC system affects the battery size by a factor of 4 from a low EEC house to a high EEC house (EEC in Table 2). The combined effect of the water boiler and the house EEC on the minimum battery size is presented in Table 4.

	Battery Power (kW)	**Battery Capacity (kWh)**	**Direct PV Consumption (kWh)**
Low EEC boiler	1.8	12	1.7
High EEC boiler	1.8	12	0.48
Low EEC house AC system	0.4	3	11.23
High EEC house AC system	1.6	12	6.48

Table 3. Battery size based on the water boiler and house energy efficiency class (EEC). The direct PV consumption of the water boiler and AC system are shown as well. The aim is to achieve zero PV energy export and the results are during seasons with maximum PV production.

From the results, it can be seen that the house EEC has the highest influence on the battery size (maximum variation of 1.4 kW/9 kWh) while the water boiler has the least influence (maximum variation of 0.2 kW/1.22 kWh). The battery capacity in Table 4 was calculated by subtracting the respective direct PV consumption from the battery capacity in Table 3.

Battery size (kW/kWh)	**Low EEC house**	**High EEC house**
Low EEC boiler	0.4/1.3	1.8/10.3
High EEC boiler	0.4/2.52	1.6/11.52

Table 4. Minimum battery size based on the combined energy efficiency class (EEC) of the water boiler and the house. The aim is to achieve zero PV energy export and the results are during seasons with maximum PV production.

4 Conclusions

In this work, a series of simulations were performed for studying the influence of two home appliances, namely the water boiler (WB) and the house air conditioning (AC) system on the battery size of a PV system. A thermal model was developed for each system and the temperature set-point for both systems was kept constant during the entire simulation. Further to this, a range of suitable thermal resistance values was chosen in order to examine the battery size for different energy efficiency classes (EEC) of the aforementioned appliances.

By coupling the system to a 3 kWp PV system and a typical residential load profile, different power and energy measures such as the average daily export power and electricity were studied in order to investigate the sizing of the battery system that is suitable for the different EEC. For the water boiler, it was found that the maximum direct PV consumption is 1.7 kWh for a low EEC water boiler. This affects the battery size but it is not that significant as the house AC system. However, for high EEC, the water boiler direct PV consumption is small and can be neglected.

On the other hand, the house AC system has a significant influence on the battery capacity since the average direct PV consumption is higher compared to the water boiler and strongly depends on the house volume and thermal insulation and also on the ambient temperature variation. From similar simulations performed for the AC system, it was found that the house AC system consumption has a very strong dependency on the house EEC. More specifically, for a low EEC house, the maximum direct PV consumption of the AC system is equal to 11.23 kWh, whereas by choosing a high EEC house, the consumption can drop down to 6.48 kWh.

Finally, it was found that the minimum required battery size to achieve zero PV export for a low EEC boiler and house is 0.4 kW/1.3 kWh while for both at a high EEC is 1.6 kW/11.52 kWh. This conclusion is a good approximation since the water boiler and house AC system were studied independently. In order to obtain more accurate results, further work needs to be conducted by simulating both of them at the same time.

Acknowledgements

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