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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 the photovoltaic (PV) system design to allow the further penetration of PV into the grid. This study 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 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 renewable energy sources in the energy mix is the geographical scattering of PV installations, which raise 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 utilisation of battery ESS (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 study 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 maximisation of the self-consumed energy and more importantly the reduction of the excess energy that is injected to the grid are examined by coupling battery energy storage to the system. The required size of the BESS was studied based on the energy efficiency class (EEC) of the WB [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 the lithium-ion battery, which is very promising due to its high energy density.

In this study, a simulation-based approach deals with the maximisation 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 EEC of the house and the WB.

2 Methodology

As already mentioned in the introduction, the battery sizing was done based on the local energy consumption and the EEC of the house and the WB. The local energy consumption profile was calculated from data recorded from smart meters installed in 300 houses in Cyprus. The data were recorded for one year with a sampling rate of 15 min. 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.

The total load of the house was the base load plus the house AC system and the 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 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...
The local energy consumption and the EEC of the house and the WB. In order to simulate the heat loss of the house and the WB, 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 WB thermal model

The thermal model of the WB is shown in Fig. 2. In the simulation, only the boiler-ambient thermal resistance ($R_{bo,a}$) 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.

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

\[ Q_{ambient} = \frac{T_{water} - T_{ambient}}{R_{bo,a}} \]  
\[ Q_{water} = P_{boiler} - Q_{ambient} \]  
\[ \Delta T_{water} = \frac{Q_{water}}{C_{water}} \times t_{step} \]

The equations above were iterated in the simulation in order to calculate the water temperature ($T_{water}$) and the heat loss ($Q_{boiler} = Q_{ambient}$) 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 WB model parameters are summarised in Table 1. A 200 L boiler was assumed since it is widely used in Cyprus.

### Table 1 WB modelling parameters

| Property                      | Value                          |
|-------------------------------|--------------------------------|
| Water specific heat capacity  | 4185.5 J/kg K                  |
| Boiler water capacity         | 200 L                          |
| Boiler-ambient thermal resistance | 837.5 kJ/K                   |
| Boiler-ambient thermal resistance $(R_{bo,a})$ | 0.15 (low EEC) – 0.55 (high EEC) KWM$^2$ |

$^2$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 ($R_{ac,a}$) 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 ($R_{h,a}$), 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-h and hence there is not enough time for the structure ($C_h > 25 \times 10^3$ 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.

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

\[ Q_{floor} = \frac{T_{room} - T_{soil}}{R_{floor} + R_{wall}} \]  
\[ Q_{wall} = \frac{T_{room} - T_{ambient}}{R_{wall}} \]  
\[ Q_{air} = P_{ac} - Q_{floor} - Q_{root} - Q_{wall} \]  
\[ \Delta T_{room} = \frac{Q_{air}}{C_{air}} \times t_{step} \]

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 WB was turned off.

The house model parameters are summarised in Table 2. A 150 m$^2$ (15 x 10 x 3 m, L x W x H) house was assumed since it is common in Cyprus.

![Fig. 1 Average daily local load consumption profile per month taken from 300 houses in Cyprus](image1)

![Fig. 2 Thermal model of the WB. $P_{boiler}$ represents the power input to the electrical heater of the boiler](image2)

![Fig. 3 Thermal model of the house. $P_{ac}$ represents the power input to the AC system of the house](image3)
In order to understand and interpret the results better, the monthly average ambient temperature \( T_{\text{amb}} \) and the PV energy production that were used in the simulation are shown in Fig. 4. The data were calculated from one-year measurement 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 \( (27.6^\circ \text{C}) \) occurs in July and August while the peak PV energy production \( (22 \text{ kWh}) \) 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 WB and house AC system load) is presented since it will be useful for the comparison of the results later when the WB 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.

### 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 WB or the house AC system is done separately in order to investigate the influence each system has on the battery size for different EEC under different ambient temperatures. As a consequence, the battery size can be obtained for different EEC. 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 \( T_{\text{amb}} \) and the PV energy production that were used in the simulation are shown in Fig. 4. The data were calculated from one-year measurement 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 \( (27.6^\circ \text{C}) \) occurs in July and August while the peak PV energy production \( (22 \text{ kWh}) \) 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 WB and house AC system load) is presented since it will be useful for the comparison of the results later when the WB 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.

### 3.2 Battery size versus WB 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 WB on the battery size. The aim of this simulation was to investigate the WB heat loss for different ambient temperature variations and more importantly how the EEC can affect the 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 WB consumption, the typical house load profile (Fig. 1) was used as an additional load.

The plots in Figs. 5 and 6 illustrate the daily PV exported power to the grid for different WB EEC per month and the parameters in Table 1 to study the influence of the WB on the battery size. The aim of this simulation was to investigate the WB heat loss for different ambient temperature variations and more importantly how the EEC can affect the 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 WB consumption, the typical house load profile (Fig. 1) was used as an additional load.

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In this work, a series of simulations were performed for studying the influence of two home appliances, namely the WB and the house 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. Furthermore, a range of suitable thermal resistance values was chosen to examine the battery size for different 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 WB, it was found that the maximum direct PV consumption is 1.7 kWh for a low EEC WB. This affects the battery size but it is not that significant as the house AC system. However, for high EEC, the WB direct PV consumption is small and can be neglected.

4 Conclusions

The daily PV exported grid power and energy for different house energy classes per month is shown in Figs. 8 and 9, respectively. It can be observed that during 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, and hence the required maximum 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.

A summary of the results is shown in Table 3. For the 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 WB and the house EEC on the minimum battery size is presented in Table 4.

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 WB 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.
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 WB 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 WB 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.

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