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OPTIMAL HYBRID PV-BATTERY RESIDENTIAL SYSTEM MANAGEMENT AND SIZING TAKING INTO ACCOUNT BATTERY THERMAL BEHAVIOR AND AGEING

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Abstract (200 w)

The fall in price for PV systems and the democratisation of electricity storage technology there is an increased interest in hybrid photovoltaic and battery systems. In interconnected applications, their operating cost must be competitive concerning the power supplied by the grid when no additional services are considered. This work presents the findings of a study on the optimal sizing of residential HPVB systems in Europe, considering the climatic and financial characteristics of each country. The study analyses also the temperature impact on battery ageing and its importance on system sizing.

1 Introduction

This paper presents the results on a study on the optimal sizing of hybrid PV-battery (HPVB) residential systems and it is based on the following assumptions:

Recent improvement in the PV industry allowed for dramatic cost reduction bringing PV-based electricity production close and below grid parity cost in different regions [1].

We are witnessing a similar phenomenon with Li-ion battery cost reduction which is unlocking new use cases for storage technology [2]

Feed-in tariffs for renewables are gradually being phased out leaving renewable power producers to look after new sources of revenue.

There is a growing interest in flexibility, also from electric vehicles, and its valorisation to solve network problems and to deal with renewables variability [3]

These aspects suggest that distributed energy storage systems (DESS) may become valid support to residential PV systems also in grid-connected areas. This can happen only if HPVB can offer a cost-effective solution for users' needs for example by lowering energy purchase costs or lowering peak power or reliability cost. This can be achieved by the democratisation of these energy technologies and by optimising PV and battery size for maximising the benefit for the final user.

In this framework, it is necessary to define optimal storage control strategies able not only to solve the aforementioned problems but also to guarantee an optimal balance between extended battery life and reduce HPVB systems CAPEX and OPEX. Among the several challenges linked to this, the present work aims at 1) quantifying the importance of battery

thermal behaviour in accelerating its ageing and hence increasing its operation cost and 2) analysing the importance of local climatic conditions, both climatic and economic, in the definition of the optimal sizing.

2 Methodology

This study can be divided into 4 main steps:

- 1) Defining a simple management strategy for the DESS
- 2) Modelling the impact of temperature on battery ageing
- 3) Optimising PV and battery size
- 4) Testing the model for different climatic and economic conditions.

A detailed description of the steps above can be found below.

2.1 DESS management strategy

For this task, a simple tree-based control algorithm has been devised. The objective is twofold: 1) to approximate the control algorithm that can effectively be installed in residential HPVB systems and 2) to avoid a more computationally intensive optimisation which would have increased considerably the computational time for the sizing described in Section 12.3.

The approach followed, divided into three main actions, can be described as below:

Action 1: reduce peaks above the contractual power subscribed

Action 2: minimise the cost of electricity

Action 3: maximise the available flexibility

The first Action can be summarised as follow: If the net flow in above the maximal contractual consumption or below the maximum contractual injection, the battery is called to

respectively discharge or charge to alleviate the problem. This action has priority over the others.

The second action can be summarised as follow: If the net flow is within the contractual boundaries, the battery is called to minimise the electricity purchase cost. If the cost of storing energy, from PV when the net flow is negative or from the grid when it is positive is lower, once the battery ageing is considered, than the expected energy price in the next 24h, then the battery is called to charge. Similarly, if the expected cost of purchased energy over the next 24h is lower than the current electricity cost, once battery ageing has been considered, the battery is called to discharge.

The third action can be summarised as follows: Finally, when no action is required to maintain net flow within contractual limits and to minimise electricity cost, the battery is slowly charged or discharged to reach the 50% storage capacity. This will help to have flexibility when necessary.

2.2 Ageing dependence on temperature

Battery ageing is strongly influenced by cycling and temperature. In this work, ageing due to cycling is considered linear (in some battery technology is non-linear with the depth of discharge). On the contrary, ageing due to battery temperature is interpolated from datasheet data and modelled as in Equation 1, where $r_{T,t}$ is the relative ageing, T is the temperature of the battery and a_i are coefficients obtained from interpolation. The temperature of the battery is considered equal to the ambient temperature, this corresponds to an outdoor installation cooled with natural or forced convection but not cooling.

The ageing due to cycling $r_{c,t}$ is calculated as shown in Equation 2, where P_t is the power charged or discharged from the battery during the period dt , n_{cic} is the lifetime of the battery expressed as the maximum number of cycles and E_B is the energy rating of the battery. The cost linked to the ageing of the battery at time t can then be calculated as in Equation 3, where $A_{B,t}$ [€] is the loss of value due to ageing at time t and C_B [€] is the purchase cost of the battery.

$$r_{T,t} = a_1 + a_2 \cdot T_t + a_3 \cdot T_t^2 \quad (1)$$

$$r_{c,t} = \frac{P_t \cdot dt}{n_{cic} \cdot E_B} \quad (2)$$

$$A_{B,t} = C_B (r_{T,t} + r_{c,t}) \quad (3)$$

2.3 HPVB optimal sizing

The sizing of the HPVB system can be seen as an optimisation problem where an optimisation function must be maximised by defining the optimal combination of the optimisation variables. The optimisation problem is presented in Equation 4, whilst the optimisation function is reported in Equation 5.

$$\begin{aligned} & \min_{P_{PV}, E_B} f(P_{PV}, E_B) \\ & \text{s. t.} \\ & \begin{cases} 0 < P_{PV} < P_{PV,max} \\ 0 < E_B < E_{B,max} \end{cases} \end{aligned} \quad (4)$$

$$f(P_{PV}, E_B) = -\alpha \cdot ROI \cdot (1 - \alpha) \cdot NR \quad (5)$$

Where: P_{PV} [kW] is the rating of the PV system, E_B [kWh] is the energy rating of the battery, ROI [%] is the return on investment of the HPVB system, NR [€] is the net revenue of the system and α [0,1], (equal to 0.5 in this case). The last two terms are calculated as described in Equation 6 and 7 respectively, where: $L_{0,t}$ [kW] is the original load of the residence without PV or battery, $NL_{>0,t}$ [kW] is the positive (meaning that the residence is consuming power from the grid) netload after that the effect of PV and battery has been considered, $\pi_{L,t}$ [€/kWh] is the price of the energy consumed at time t , $P_{PV,t}$ [kW] is the power produced by the PV system, $LCOE_{PV}$ [€/kWh] is the Levelized Cost of Energy of the PV system, taking into account both of the cycling and the temperature, $NL_{>0,t}$ [kW] is the negative net power flow from the residence corresponding to hours when the PV is exporting power to the grid, π_{PV} [€/kWh] is the resale price for PV.

$$NR = \sum_t (L_{0,t} - NL_{>0,t}) \cdot \pi_{L,t} - P_{PV,t} \cdot LCOE_{PV} - A_{B,t} - NL_{>0,t} \cdot \pi_{PV} \quad (6)$$

$$ROI = \frac{NR}{\sum_t (P_{PV,t} \cdot LCOE_{PV} - A_{B,t})} \quad (7)$$

It must be noted that this formulation doesn't consider the PV and battery as an initial expenditure to be recovered during time as usually seen in such problems, but these costs have been spread over the energy use. This is made necessary by the fact that the lifetime of the battery changes considerably during the simulations from a few years to decades according to the numbers of cycles. It is equivalent to consider PV and battery as 'consumables' replaced when arrived at the end of their lifetime, or resold on the market after a limited period of use.

2.4 Data

Two datasets have been used in this work, corresponding to two use cases.

Case A is based on the use of a simulated dataset for residential consumption and PV production in several European countries (DE, ES, FI, FR, PT, UK) already presented in [4] and based on a bottom-up simulation considering weather reanalysis and residential consumption modelling. These are coupled with historical retail and wholesale energy prices in these countries and with PV LCOE estimation from [1]. The objective of this case study is to have an overview of the combined impact of climatic conditions (influencing PV production) and retail energy prices.

Case B, on the contrary, is based on a single monitored building in Liverpool (UK) characterised by low consumption, solar rooftop and electric vehicle. The yearly energy consumption of the household is roughly of 700kWh, increased to 2700kWh when the electric car, a 24kWh Nissan Leaf, is considered. The PV system is a 4kW south faced plant with a yearly production of roughly 3500kWh when losses are considered. The advantage of this case is that it is based on real measurements and not on modelling.

A summary of the financial data used is presented in Table 1 and 2.

Table 1: Summary of financial data per case and geographical location

Case	Town	LCOE PV [€/kWh]	Electricity av. price [€/kWh]
A	DE, Nuremberg	0.15	0.267
A	ES, Seville	0.1	0.227
A	FI, Helsinki	0.2	0.156
A	FR, Nice	0.12	0.145
A	PT, Evora	0.1	0.206
A	UK, Nottingham	0.17	0.178
B	UK, Liverpool	0.01*	

* specific installation and incentives considered day-night tariff.

Table 2: Data about the battery system.

Parameter	Value
Battery cost [€/kWh]	1000
Battery max cycles	5000

3 Results and discussion

The model described above has been simulated using the datasets presented for one year. Results are given relative to the size of the load, therefore are referred to each kW of contractual power. When not stated otherwise, illustrations are referred to the Nuremberg case.

3.1 Impact of PV size on profit and ROI

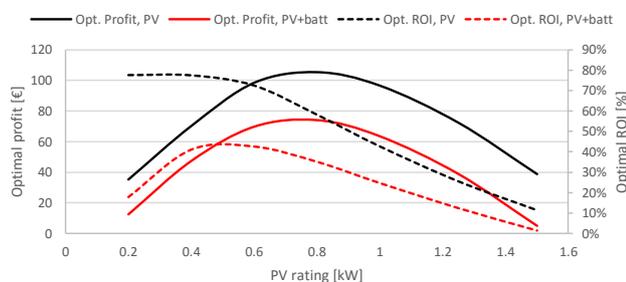


Figure 1: Influence of PV rating on profit and ROI for optimal solutions

A first analysis concerns the impact of PV size on profit and ROI as seen in Figure 1. This is ideal to show the reason why and how the optimisation function described in Equation 5 has been chosen. In general, the LCOE of the PV is lower than the retail cost for electricity but higher than the resale price for energy injection in the grid. Therefore, a little PV system will maximise the share of self-consumed energy maximising its ROI (dashed line) with or without battery. But the absolute financial benefit will be negligible due to the little volume of self-consumed energy. Increasing the size of the PV plant will increase the total profit but with reducing returns. At a certain point, the highest share of reinjected power will start to decrease also the total profit. Furthermore, there may be two configurations returning the same profit but with different values of ROI.

The presence of a battery reduced both ROI and profit since the ageing add cost to the LCOE of the PV and the purchase cost of electricity.

3.2 Impact of battery size

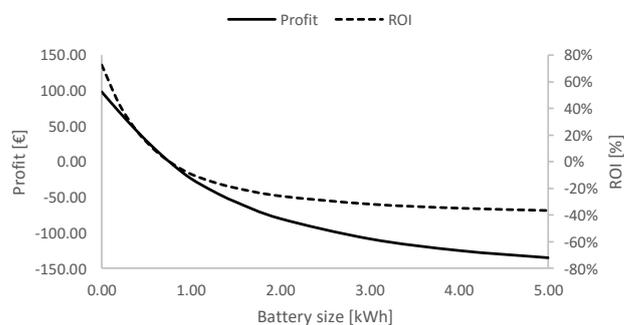


Figure 2: Influence of battery energy rating on profit and ROI for optimal solutions

Similar considerations are possible for the impact of battery size on profit and ROI, shown in Figure 2. Both the indicators decrease with the size of the battery. This is because in general, the ageing cost of the battery is higher than the daily spread of electricity process and the difference between purchased energy and PV LCOE. It must be remembered that in this simulation battery ageing cost due to cycling is in the region of 0.2€/kWh, PV LCOE is in the region between 0.1 and 0.2 €/kWh and retail electricity price is between 0.14 and 0.26 €/kWh. Unless stated otherwise, the analysis below is conducted considering a battery with an energy rating equivalent to at least 200Wh per KW of contractual power.

3.3 Optimal sizing for rural, suburban and urban loads, Germany

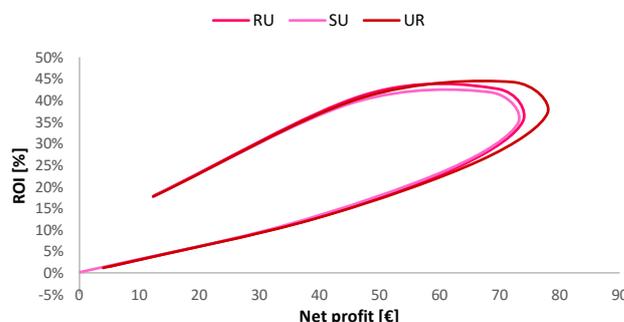


Figure 3: Optimal sizing solutions for rural, suburban and urban loads, Pareto front

Another way to present the result is to observe at the Pareto front of the optimal solutions for the two objectives of the optimisation problem. Figure 3 represents this for three types of load (rural, suburban and urban) in the region of Nuremberg, DE. The chart shows that there is little difference between the optimal results of different loads, meaning that climate (influencing the LCOE of the PV) and retail electricity prices are the main drivers. This is an important information because it makes the results obtained generalised and not depending on the specific load profile used.

3.4 Optimal sizing in different countries

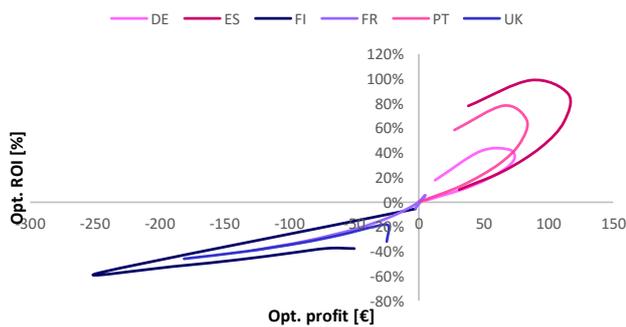


Figure 4: Optimal sizing solutions for the six countries considered, Pareto front

The analysis of the results for different countries shows that, without subsidies, the HPVB system is competitive only in Germany, because of the higher retail cost of electricity, Spain and Portugal, because of the lower LCOE for the PV. The HPVB system results not competitive in France, because of the lower cost of electricity, the UK and Finland, because of the higher LCOE for PV.

3.5 Impact of ageing and temperature modelling

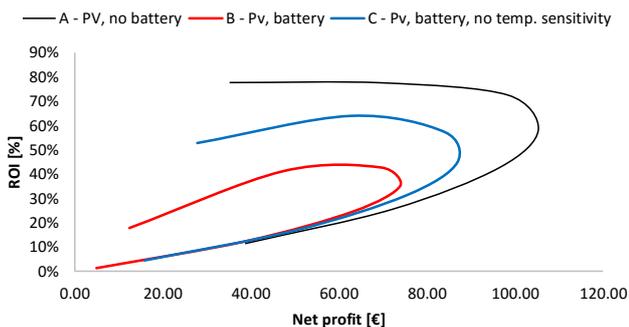


Figure 5: Optimal sizing solutions for HPVB systems, the importance of the impact of temperature on ageing, Pareto front

A central aspect of this work was to analyse the impact of temperature adjusted ageing on the optimal sizing of HPVB systems. This can be seen in Figure 5, where the three curves represent the Pareto front for a system without battery (black line), one with battery with an average constant ageing which doesn't consider the effect of temperature (blue line) and finally the results of simulations taking into account the temperature led degradation into the model. It is clear that this effect is not negligible and can lead to an overestimation of the benefits (or underestimation, according to the local climatic conditions).

3.6 Optimal sizing in Case B

The same analysis is carried out for Case B, where incentives for PV are considered along with day-night tariff and measured load and PV production. The results are quite different if compared to the other simulation for the UK and the other countries. In particular incentives, by reducing considerably the LCOE of the PV system make the investment positive also with high shares of exported power, becoming even profitable in the case of a little load. In any case, the values are lower

than for the other countries where HPVB systems are profitable.

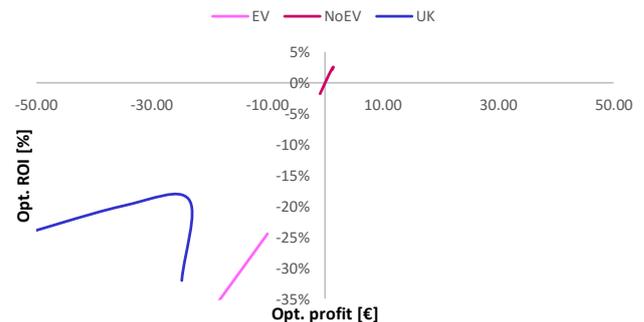


Figure 6: Optimal sizing solutions for the six countries considered, Pareto front

4 Conclusion

In this document, the optimal sizing of hybrid photovoltaic-battery systems is presented. It is proposed a simplified control methodology and sizing is conceived as an optimisation problem. Also, the effect of temperature on battery ageing is considered. This model is simulated over seven test cases relative to six European countries characterised by different climatic conditions and retail electricity prices. The first six cases are simulated whilst the last one consists of measured load and PV production data. The main conclusions can be summarised as follows: 1) with the cost for storage considered, the use of a battery in the system does not allow batteries to give positive contributions to the system, 2) in absence of subsidies, with the LCOE tested, HPVB systems are profitable in half of the countries considered, 3) optimal PV size is in the region of 40% of the load contractual power. This work opens the door to further investigation, such as the benefit of HPVB for frequent peaks mitigation and sensitivity analysis of the sizing according to projected values of PV and storage cost.

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