

Optimal Home Battery Sizing and Dispatch in EU Countries Taking Into Account Battery Degradation and Self-Consumption Incentives

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Abstract

Solar home battery systems are becoming popular to final consumers driven by substantial price reduction. The use of batteries couples solar energy generation and demand patterns increasing the use of the installation and the self-consumption rates. However, the feasibility of batteries is still under discussion especially when referring to reliability along its lifetime. In this sense and to guarantee positive revenues to end-users, long-term battery models should be investigated. To this end, this study presents a simplified battery ageing model to assess the impact of battery degradation in a comprehensive solar home battery system. This work demonstrates that, if battery ageing mechanisms are considered, revenues derived from the installation decrease by half. In addition, feasible unitary battery price cost is limited up to EUR 400/kWh.

Key words: solar home battery systems, battery ageing, techno-economics, battery lifetime

1. Introduction

In recent years, PV installations have become more attractive driven by a significant price reduction of PV technologies [1]. Although, more commonly deployed at high scale where the electricity production is directly injected in the grid, PV installations come to an alternative solution at local level [2] especially when supported by policy measures, such as feed-in-tariffs [3]. To improve competitiveness of residential PV installation, where PV's electricity costs competes with electricity retail prices [4], self-consumption has to be maximised under no supporting scheme scenarios requiring storage solutions to couple demand and solar energy availability. Although still not economically viable in most of the EU countries [5], solar home battery storage appears as a feasible solution especially under the assumption that technology prices will evolve as in the last years.

When assessing the effectiveness and feasibility of battery storage, long term battery performance should be considered. Literature review reveals that many works, dedicated to assess battery storage options to increase self-consumption, limit the timeframe of the analysis to a typical year [6],[7], in which battery storage is modelled by two main parameters, capacity and efficiency.

However if we expand the analysis to cover the installation lifetime, battery storage models become more complex driven mainly by long-term degradation processes that alter battery performance. From this long-term approach, battery ageing mechanisms play a significant role in the assessment of the solar home battery storage viability.

Battery ageing mechanisms are driven by different processes including, mechanical, chemical and electromechanical processes [8]. Accelerated ageing tests developed in laboratories have been used to obtain battery ageing models [8], [9], [10]. However, the high number of parameters that may affect battery performances and the difficulties on their characterisation are hindering the development of generic battery lifetime models [11] required to perform techno-economic assessments.

The objective of this paper is to assess the effect of battery ageing in the performance of a solar home battery system expanding the analysis to the lifetime of the installation. To this end, a simplified battery ageing model is implemented and incorporated to a dispatch model that will be optimised to maximise the economic benefit. Then, outputs will be compared with the non-battery-

ageing assumption to assess the impact of battery ageing mechanism in the performance of the solar home battery system.

This paper is structured as follows: Section 2 presents the simplified battery ageing model and its integration in the dispatch model. Section 3 introduces the study case. Section 4 covers results and in Section 5 conclusions are discussed.

2. Proposed dispatch and battery ageing model

2.1. Dispatch model

The study is based on a dispatch model, which was previously implemented by authors [5]. The model was designed to maximize self-consumption. This strategy prioritises the use of the battery with disregard of potential positive revenues derived from surplus electricity sold to the grid. Only when the battery is fully charged and the electric demand satisfied, electricity produced is injected in the grid. Therefore, this strategy offers valuable information about the battery reliability and the performance of the comprehensive solar home battery system when affected by battery ageing processes.

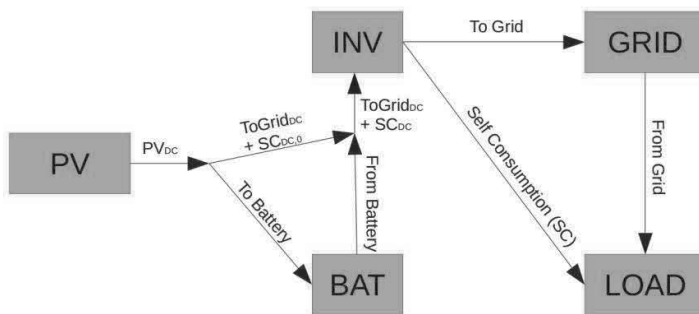


Figure 1: Dispatch model layout

Although detailed explained in [5], some general features assumed for the dispatch model are introduced to facilitate the understanding of the study:

- PV model is simplified assuming a south orientation and a tilt angle of 35°
- Household generation profile is computed using the typical meteorological year (TMY3 files) for the capital of the country under study [12].
- To ensure realistic PV production, yearly generation is scaled to match average capacity factor for each country according to the JRC PVGIS information system [13].

2.2. Battery ageing model

As mentioned in the introduction section, battery ageing characterisation is at an experimental stage. Ageing mechanism characterisation is highly dependent on the particular conditions of the experiments and battery cell design. In addition, reproducing real battery life in laboratories requires long periods.

From a general approach, different ageing mechanisms can be grouped into calendar and cycle ageing. Calendar ageing is associated with storage periods while cycle ageing is linked to battery use periods – charging and discharging modes [14].

In the proposed model only cycle ageing was considered. The reasons to neglect calendar ageing are the following:

- it is not easy to decouple both mechanisms when testing batteries. Then, even when focused on the characterisation of cycle ageing, the experiment is affected by the passing of the time during the test;
- unlike in electric vehicle application where 95% of the time the battery is in parking mode [15], for domestic applications and according to authors' dispatch model, battery is used 65% of time throughout the year. Then, it is assumed that for PV applications cycle ageing is more important than calendar ageing. Therefore, the impact of calendar ageing is not as critical as for electric vehicles applications;
- calendar ageing is highly dependent with time and temperature. Concerning time dependency there is no consensus about a linear or square root dependency [16], [10]. Regarding temperature, calendar ageing is highly dependent on the surrounded temperature [11], which is difficult to foresee in advance for general analysis purposes.

Simplified model for battery ageing

Although battery lifetime prediction models are based on experimental analysis, it is widely accepted cycle ageing depends on the depth of discharge (DOD) defined as the difference between initial and final state of charge for a discharge cycle [17].

To implement the proposed model, we have considered the DOD vs. number of cycles correlation proposed by [18]. This correlation provides the maximum number of cycles that a battery can perform for a given DOD (Figure 2).

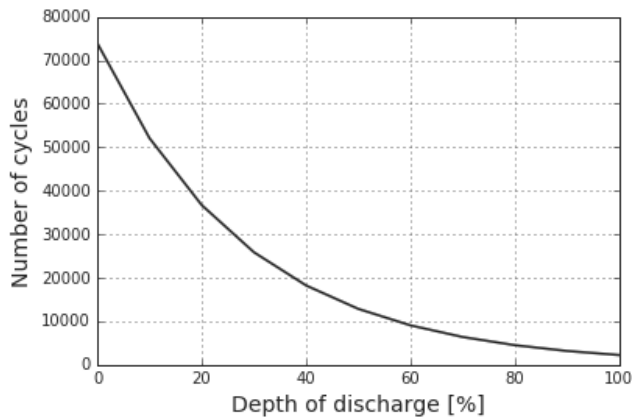


Figure 2: Number of cycles before battery end of life with depth of discharge [18]

Based on this correlation, the impact of a cycle with a given ΔDOD in the battery life is inverse proportional to the maximum number of cycles that the battery may perform for this DOD level (Eq.1). Accordingly, a cycle with a ΔDOD of 60% will decrease battery life in 0.01% (1/10 000 maximum number of cycles).

$$[1] \Delta life = \frac{1}{Max\ number\ of\ cycles(DOD)}$$

Finally, to determine battery capacity fade, a linear relation is assumed between the remaining battery life and remaining battery capacity (Figure 3). To do so, an end-of life-criterion has to be set.

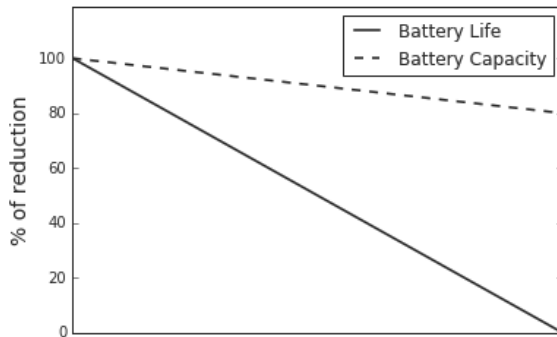


Figure 3: Linear relation between Battery life and battery capacity. End-of-life criterion of 80% of the nominal battery capacity [18]

Mathematically,

$$RC = 1 - (1 - RL) \cdot (1 - ELC)$$

Where,

$RC \equiv$ remaining capacity

$RL \equiv$ remaining life

$ELC \equiv$ end of life criteria (% of original capacity)

In summary, the parameters that describe the battery are:

- battery capacity
- end-of- life criterion as a share of nominal battery capacity
- cycle ageing correlation (Figure 2).

Some additional hypotheses are assumed:

- Round trip efficiency and discharge power is assumed constant.
- It has been assumed the cycle ageing effect is no dependent with specific SOC, meaning that a cycle with a ΔDOD of 70% will have the same effect whether this cycle goes between 100 and 30% of SOC or between 80 and 10%.

2.3. Dispatch algorithm

Instead of calculating the remaining battery capacity at every simulation time step, to maximize the performance of the algorithm, battery ageing is computed on an annual basis. Therefore, effective battery capacity is updated not at every time step simulation but at the end of each year. Therefore for every year the dispatch model is executed and then with the level of charge of the battery processed for every time step, the battery ageing is calculated. For the following year, the battery capacity is updated and used to calculate the dispatch model. (Figure 4)

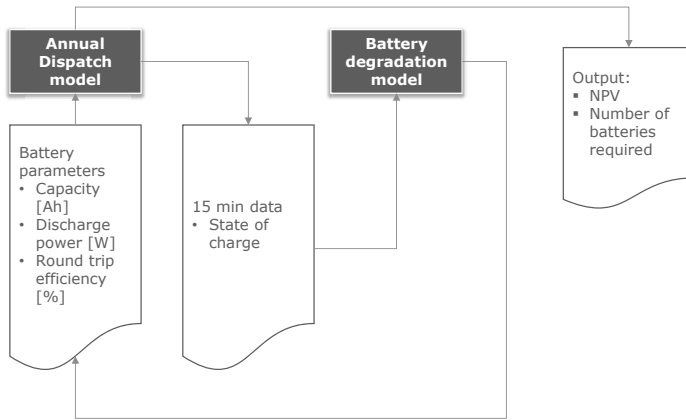


Figure 4: Algorithm resolution

2.4 Optimisation

With the structure defined in previous section (Figure 4), the optimisation problems can be formulated and solved. It should be mentioned that the introduction of the battery ageing model makes the optimisation problem non-linear, which makes difficult the resolution of the problem and increases the computation time.

Concerning the optimisation problem (Figure 5), the decision variables are:

- PV size (kW_p)
- Battery size (kWh)

Objective variable: net present value of the investment. The net present value is defined considering that with no solar home battery system; user pays the electricity to satisfy its demand. Therefore, to calculate annual cash-flows, both the electricity locally consumed and the one injected in the grid are considered as positive terms.

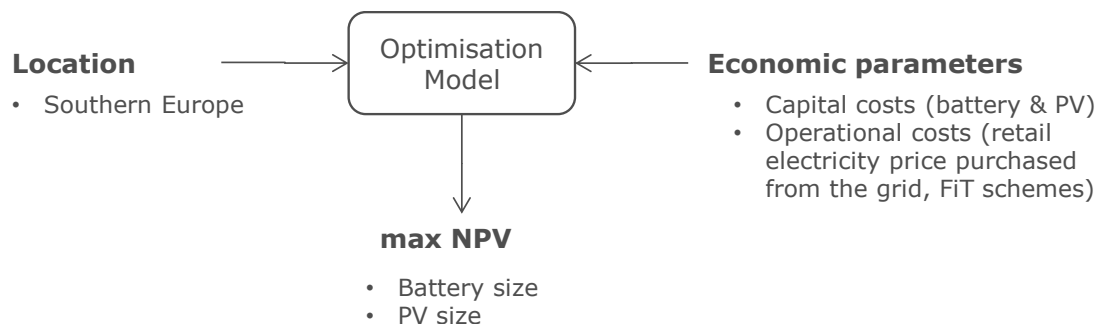


Figure 5: Optimisation problem

3. Case study

As mentioned in the introduction, the goal of this work is to assess the impact of the battery ageing mechanism in the solar home battery system. Therefore, we want to compare the performance of the system with and without considering battery ageing mechanism.

In doing so, other parameters that directly affect the whole system including performance and economic parameters have to be defined for both scenarios. The set of economic parameters

includes; unitary battery and PV prices (capital costs) and the energy prices and potential supporting schemes (operational costs).

To provide a comprehensive comparison framework for the two scenarios, a sensitivity analysis is carried out for the mentioned parameters. This sensitivity analysis provides valuable information in terms of marginal prices.

Concerning potential incentives, it has been assumed that there are no incentives in place as well as no limitations when exchanging electricity with the grid. To developed detailed analysis per country, the assessment of particular policies in place is needed to set economic operational costs.

4. Base case scenario results

Before solving the optimization problem and taking into account its potential complexity, a simplified case is presented to illustrate the battery degradation effect in the battery performance and in the dispatch model. This base case scenario is defined by the parameters included in (Table 1).

Table 1: Parameters considered. Battery degradation effect

Variable	Unit	Value
PV size	kW	10
Battery size	kWh	10
End of Life criterion	% of nominal battery capacity	60
Lower limit DOD	% of nominal battery capacity	20
Lifetime	yr	20
Round trip efficiency	%	0.9
Inverter efficiency	%	0.95

4.1. Analysis of battery degradation effect

The battery capacity is the most influential parameter in the system. As presented in Figure 6, battery capacity becomes lower throughout the years requiring a replacement before the end of life of the installation according to the battery end-of-life criterion. Battery replacement reduces considerably economic revenues of the installation, as a result not only of the additional battery investment cost but also of the higher operational costs derived from the battery capacity reduction.

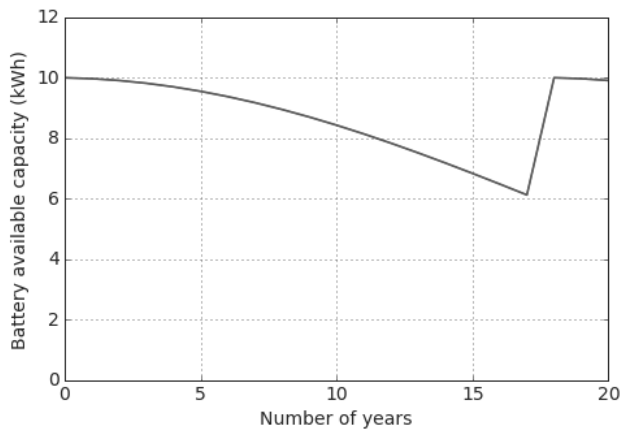


Figure 6: Battery capacity evolution for a base case scenario

For the presented base case scenario, if the battery size is modified the available capacity evolves differently. As expected, the battery degrades faster when the capacity is limited as the battery is charged and discharged in deeper cycles. Thus, for the base case scenario a battery of 5 kWh of

capacity degrades by a 23.1% almost double as in the case of the 20 kWh of capacity, 12.96% (Figure 7.a). If we perform similar analysis for different PV capacities, the effect is depreciated as the different amount of energy produced by the photovoltaic systems is driven directly to either the local demand or the grid. Only in the cases where the installed PV capacity is not sufficient to charge the battery, the ageing will be affected, extending the life of the battery.

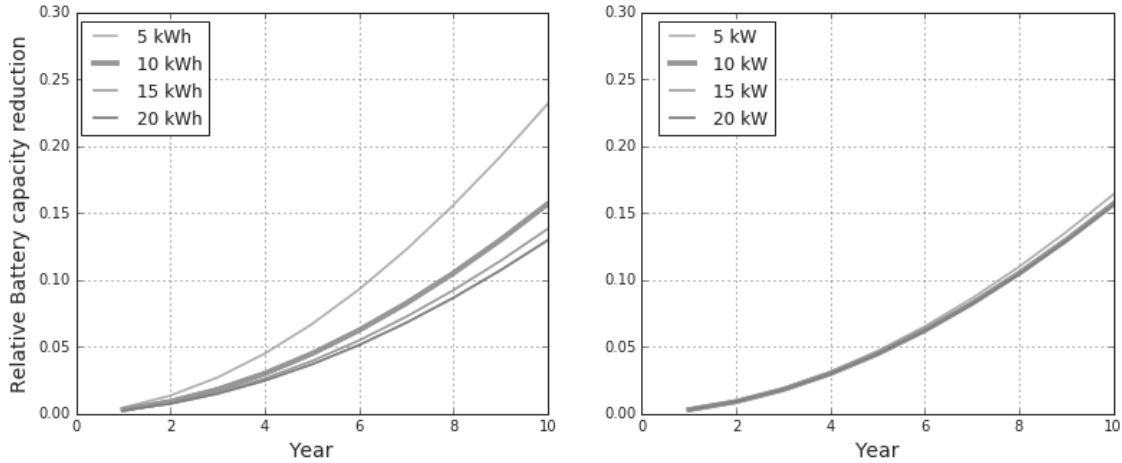


Figure 7: Battery capacity reduction for different battery capacities (left) and different photovoltaic capacities (right)

4.2. The effect of considering battery ageing in the dispatch problem

One of the most interesting aspects of this study is the comparison of the same system considering both battery ageing and no-battery ageing scenarios to assess the real impact in the whole system. To do this, same parameters as for the base case scenario have been considered. The Net present value of the investment has been selected as the parameter to compare and different unitary prices for the battery and PV have been also investigated. It has also been assumed that the energy injected in the grid is given the same price as the retail electricity cost purchased from the grid (net-metering incentive). Results are shown in Figure 8.

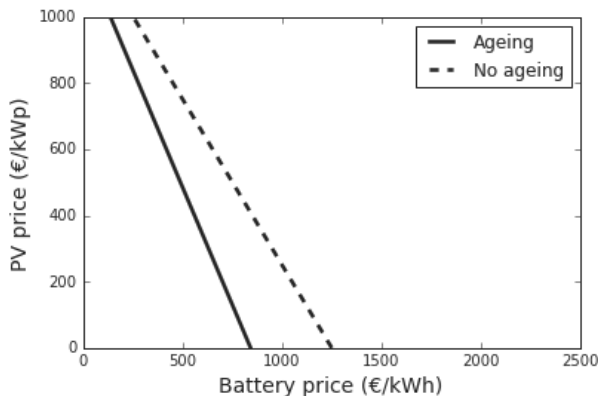


Figure 8: Zero-NPV lines for the case study for the scenarios considering/not considering ageing mechanisms

In the figure, NPV is positive in the areas below the lines. As expected, in the ageing scenario breakeven point is ranges from EUR 844/kWh down to EUR 137/kWh for the unitary battery cost for unitary PV costs ranging from 0 to EUR 1 000/kWp. In the non-ageing scenario, battery price ranges from 1 250 to EUR 252/kWh. Therefore, battery prices have to be between 33% (PV price = EUR 0/kWp) and 46% (PV price = EUR 1000/kWp) lower than in the scenario with no ageing mechanism considered to achieve similar economic revenues. It is also important to mention that

as long as the unitary PV price increases, the weight of the battery investment in the capital costs is lower and therefore the zero-NPV lines converge for high PV prices and low battery prices.

As mentioned, the comparison of both scenarios considers net meeting supporting mechanism. The potential existence of feed-in-tariff schemes, which is defined as an added price to the retail electricity price purchased from the grid and set at EUR 0.2/kWh, contributes to increase marginal investment prices (Figure 9).

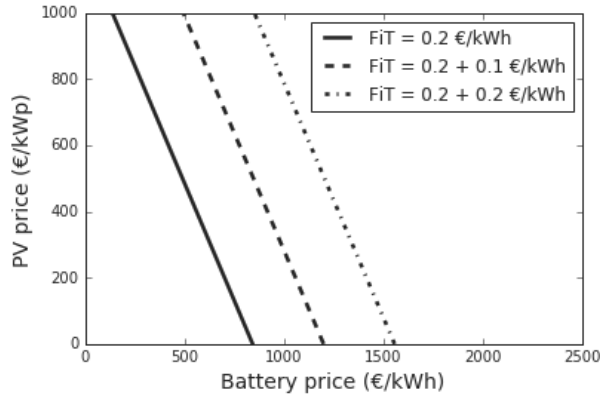


Figure 9: Zero-NPV lines for different FIT schemes. Battery ageing mechanisms considered.

For an average European retail electricity price of EUR 0.2/kWh, if the electricity price for the energy injected in the grid increases, the area for NPV > 0 becomes larger. In particular, the marginal battery price increases by EUR 35.7/kWh for every additional c EUR/kWh. However, as presented in the next section dedicated to the optimisation of the system, an increase in the FIT conditions, via a high price for the electricity injected in the grid, complicates the penetration of batteries. In Figure 9 the battery investment is considered, therefore as long as the FIT price is higher than the retail electricity price with no limitation when injecting energy in the grid, the benefit of the installation increased and consequently marginal battery prices.

4.3. Optimisation and sensitivity analysis

To compare the effect of battery ageing mechanism in the optimal design of the solar home battery systems, optimal solutions, defined by the battery and PV sizes, are calculated for both cases with and without considering ageing mechanism. To determine the comparison framework, economic parameters have to be also defined (Figure 5). Instead of fixing values for these parameters, a sensitivity analysis has been carried out. Thus, optimal solution is calculated for different combination of economic inputs.

As before mentioned, economic parameters are divided in two different categories: capital costs, including PV and battery unitary prices and operational costs, including energy prices. For the parameters related to operational cost they have been modified taking EU market prices as reference. In particular electricity retail price has been set at EUR 0.2/kWh and then modifies up to EUR 0.3/kWh [19]. Neither FIT nor net-metering schemes have been considered as they discourage from investing in batteries.

Concerning parameters related to capital costs, PV prices including the inverters are ranged from 250 €/kW to 1 000 €/kW according to forecast prices evolution [20], [21]. For the battery unitary cost, it is varied from 200 to EUR 1 000/kWh.

In total 80 optimal solutions have been calculated, 40 for each scenario (non-battery ageing and battery ageing considered).

These different scenarios directly reveal that low retail electricity prices discourage from investing in batteries. To compare the effect of battery ageing, results are discussed for the scenario with no FiT schemes in place and a retail electricity price of EUR 0.3/kWh. (Figure 10) and (Figure 11).

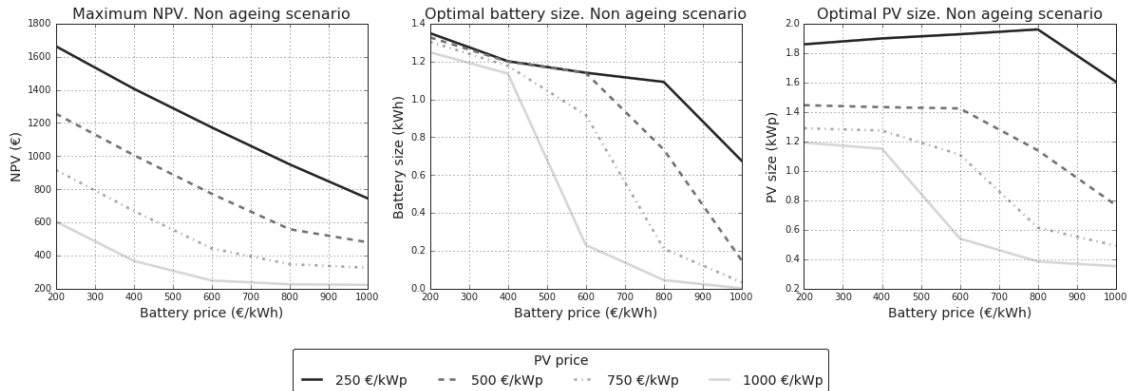


Figure 10: Optimisation results for the non-battery ageing scenario. $FiT = 0 \text{ €/kWh}$, $REP = 0.3 \text{ €/kWh}$

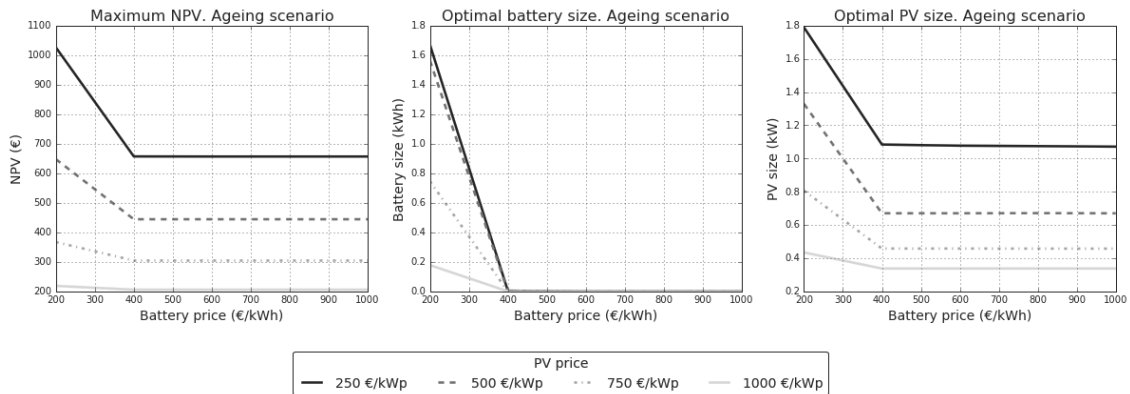


Figure 11: Optimisation results for the battery ageing scenario. $FiT = 0 \text{ €/kWh}$, $REP = 0.3 \text{ €/kWh}$

As expected, battery ageing reduces the marginal battery price which makes the battery part of the optimal solution. In the ageing scenario, marginal price is determined at EUR 400 €/kWh. Over this price, the battery size is zero (Figure 11). On the contrary, if battery ageing mechanisms are not considered, even for unitary battery prices of EUR 1000/kWh, certain battery capacity is included as a part of the optimal solution. Therefore, results reveals that batteries are economically feasible for prices below EUR 400/kWh. Over this breakeven battery price, NPV and PV remains constant varying only for different PV prices. Below this price, battery size increases with PV price reductions in an approximate ratio of about 1 kWh of storage capacity per kWp of PV installed capacity. For the non-ageing scenario, this ratio varies from 0.7 to 1 kWh/KWp, for battery prices below EUR 400/kWh.

Finally if we compare the effect on the economic revenues, battery ageing mechanisms and subsequent battery replacement, NPV is reduced by half on average for the battery price range between 200 and EUR 400/kWh.

5. Conclusions

This work demonstrates the importance of considering battery ageing effect in the battery model when assessing the feasibility of solar home battery systems. As presented in the results and based on a dispatch strategy that tries to maximise self-consumption, battery prices should be reduced if battery degradation is taken into account. In addition it is demonstrated that battery ageing reduces by half economic revenues for a timeframe of 20 years, when the battery is considered as a part of the optimal system.

Therefore, it is important to advance in developing robust and replicable battery ageing models that could provide realistic economic performance of Solar Home Battery Systems unless technology prices really shrink in the following years reducing the relative impact of degradation in the economic performance of the system. As also shown, appropriate supporting schemes may facilitate the penetration of these systems even if battery replacement is required.

6. Future work

As part of battery model improvement following activities are foreseen:

- Model calendar ageing mechanism including variable dependencies such as the state of charge (SOC) of the battery
- To assess the coupling of calendar and cycle ageing.
- Evaluate the impact of different dispatch strategies in the ageing mechanism of the battery.

Concerning the dispatch model, the optimisation problem may include in the future aspects such as the optimal end-of-life criterion as well as the optimal lowest accepted limit in the battery operation to prevent fast ageing mechanisms.

In addition, different dispatch strategies should also be assessed to analyse optimal strategies to prevent battery degradation.

References

- [1] Luthander R, Widén J, Nilsson D, Palm J. Photovoltaic self-consumption in buildings: A review. *Appl Energy* 2015;142:80–94. doi:10.1016/j.apenergy.2014.12.028.
- [2] Weniger J, Tjaden T, Quaschnig V. Sizing of residential PV battery systems. *Energy Procedia* 2014;46:78–87. doi:10.1016/j.egypro.2014.01.160.
- [3] De Boeck L, Van Asch S, De Bruecker P, Audenaert A. Comparison of support policies for residential photovoltaic systems in the major EU markets through investment profitability. *Renew Energy* 2016;87:42–53. doi:10.1016/j.renene.2015.09.063.
- [4] Lang T, Ammann D, Girod B. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. *Renew Energy* 2016;87:77–87. doi:10.1016/j.renene.2015.09.059.
- [5] Quoilin S, Kavvadias K, Mercier A, Pappone I, Zucker A. Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Appl Energy* 2016;182:58–67. doi:10.1016/j.apenergy.2016.08.077.
- [6] Waffenschmidt E. Dimensioning of decentralized photovoltaic storages with limited feed-in power and their impact on the distribution grid. *Energy Procedia* 2014;46:88–97. doi:10.1016/j.egypro.2014.01.161.
- [7] Bruch M, Müller M. Calculation of the cost-effectiveness of a PV battery system. *Energy Procedia* 2014;46:262–70. doi:10.1016/j.egypro.2014.01.181.

- [8] Smith K, Shi Y, Santhanagopalan S. Degradation mechanisms and lifetime prediction for lithium - ion batteries – A control perspective. Am Control Conf 2015:728–30. doi:10.1109/ACC.2015.7170820.
- [9] Wang J, Liu P, Hicks-Garner J, Sherman E, Soukiazian S, Verbrugge M, et al. Cycle-life model for graphite-LiFePO₄ cells. J Power Sources 2011;196:3942–8. doi:10.1016/j.jpowsour.2010.11.134.
- [10] Ecker M, Gerschler JB, Vogel J, Käbitz S, Hust F, Dechent P, et al. Development of a lifetime prediction model for lithium-ion batteries based on extended accelerated aging test data. J Power Sources 2012;215:248–57. doi:10.1016/j.jpowsour.2012.05.012.
- [11] Ecker M, Nieto N, Käbitz S, Schmalstieg J, Blanke H, Warnecke A, et al. Calendar and cycle life study of Li(NiMnCo)O₂-based 18650 lithium-ion batteries. J Power Sources 2014;248:839–51. doi:10.1016/j.jpowsour.2013.09.143.
- [12] Department of Energy, weather data: typical meteorological years. n.d.
- [13] Amillo AG, Huld T, Müller R. A new database of global and direct solar radiation using the eastern meteosat satellite, models and validation. Remote Sens 2014;6:8165–89. doi:10.3390/rs6098165.
- [14] Barré A, Deguilhem B, Grolleau S, Gérard M, Suard F, Riu D. A review on lithium-ion battery ageing mechanisms and estimations for automotive applications. J Power Sources 2013;241:680–9. doi:10.1016/j.jpowsour.2013.05.040 Review.
- [15] Kassem M, Bernard J, Revel R, Pelissier S, Delacourt C. Calendar aging of a graphite / LiFePO₄ cell To cite this version : 2013.
- [16] Erdinc O, Vural B, Uzunoglu M. A dynamic lithium-ion battery model considering the effects of temperature and capacity fading. 2009 Int Conf Clean Electr Power, ICCEP 2009 2009:383–6. doi:10.1109/ICCEP.2009.5212025.
- [17] Sarasketa-Zabala E, Martinez-Laserna E, Berecibar M, Gandiaga I, Rodriguez-Martinez LM, Villarreal I. Realistic lifetime prediction approach for Li-ion batteries. Appl Energy 2016;162:839–52. doi:10.1016/j.apenergy.2015.10.115.
- [18] Omar N, Monem MA, Firouz Y, Salminen J, Smekens J, Hegazy O, et al. Lithium iron phosphate based battery - Assessment of the aging parameters and development of cycle life model. Appl Energy 2014;113:1575–85. doi:10.1016/j.apenergy.2013.09.003.
- [19] Eurostat. Electricity prices by type of user 2017.
- [20] Huld T, Waldau a J, Ossenbrink H, Szabo S, Dunlop E, Taylor N. Cost Maps for Unsubsidised Photovoltaic Electricity 2014.
- [21] International Energy Agency. Trends 2016 in photovoltaic applications. 2016.