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Techno-economic evaluation of a battery system integrated into a residential grid-connected PV system considering battery degradation

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ABSTRACT

Stationary battery storages become a promising solution for improving flexibility of renewable energy system to balance the fluctuating of power production and demand. However, each application has a specific operational strategy, consequently a specific dynamic operational profile which leads to a different estimated battery lifetime due to the degradation of battery capacity over its operation in the application. An accurate knowledge about battery lifetime, and battery state of health at different operational conditions is important to ensure a feasible techno-economic assessment. This paper deals with the techno-economic evaluation of a battery system integrated into a residential grid-connected PV system considering two battery models with and without battery degradation. The battery life cycle cost, the self-sufficiency ratio and battery lifetime are analyzed for techno-economic assessment of a residential grid-connected hybrid PV-battery system. The results show that the simulation without battery degradation gives 31.43% lower life cycle cost and 7.4% higher self-sufficiency ratio, compared to the modeling with battery degradation. This proves the importance of battery aging model for assessing a battery integrated into a renewable PV system.

Keywords: Battery storage, battery aging models, techno-economic assessment, residential grid-connected Photovoltaic system, distributed renewable energy

1. INTRODUCTION

A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several increasing threats to human civilization [1]. With growing the intermittent renewable resources such as solar, stationary energy storage systems play indispensable role in boosting power quality and reliability, to improve the flexibility of renewable energy system to balance the fluctuating of power production and demand [2]. Compared to other types of battery technologies, lithium-ion batteries are a helpful technology for grid-applications due to the cost reduction potential and characterized with features of high round trip efficiency, high cycle lifetime and flexibility for charging and discharging. [3, and 4]. The achievable lifetime and also capacity degradation of batteries are among of the most important parameters for analyzing the operation and techno-economic profitability of stationary battery systems integrated into renewable system applications [5-7]. However, each application has a specific operational strategy, consequently a specific dynamic operational profile which leads to a different estimated battery lifetime due to the degradation of battery capacity over its operation in the application. An accurate knowledge about battery lifetime, and battery state of health at different operational conditions is important to ensure a feasible techno-economic assessment. Therefore, battery lifetime models are indispensable to predict the degradation behavior and to estimate the corresponding lifetime when a battery is operated under a wide range of possible loads in different applications [8]. In order to assess the impact of battery degradation on the profitability of stationary battery applications,

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superposition model which is a combination of calendar and cycle aging should be accurately estimated.

This paper deals with the techno-economic evaluation of a battery system integrated into a residential grid-connected PV system considering two battery models with and without battery degradation. Model 1 does not consider the impact of the degradation of battery capacity in modelling of a battery integrated into residential PV system and uses the data provided by the battery manufacturer. By contrast, Model 2 considers a realistic battery aging model, which is able to accurately estimate battery lifetime and total capacity fade. A straightforward operational strategy is employed for the simulation and techno-economic assessment of a residential grid-connected hybrid PV-battery system. The battery life cycle cost, the self-sufficiency ratio and battery lifetime are analyzed in the paper.

2. METHODS

Section 2.1 describes the studied system. Sections 2.2 and Section 2.3 introduce the battery modelling and problem definition, respectively. Section 2.4 presents case study.

2.1. System description

The schematic view of the studied hybrid energy system is shown in Fig.1. This system is composed of PV panels, a battery bank, an energy management system; a grid, a load, and DC/AC inverter. In brief, the system is supposed to electrochemically store the extra power electricity produced by the PV system through charging battery bank. During high demand hours when the PV power cannot meet loads, power is taken from the battery to meet the load, and in case of unmet load, electricity is purchased from the grid to satisfy the unmet load.

2.2. Battery modelling

In this study, Lithium-ion battery with specification listed in [9] is considered. Two battery models with and without degradation are considered for techno-economic evaluation of a battery system integrated into a residential grid-connected PV system.

2.2.1. Battery performance model

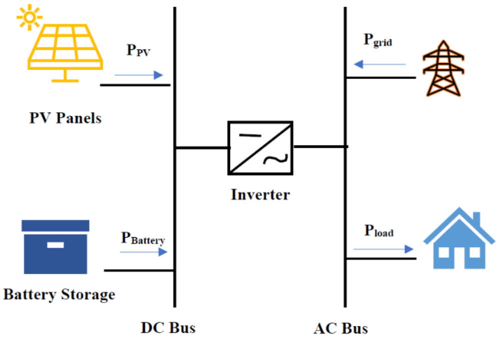


Fig 1. Schematic of the studied hybrid PV-battery system.

In this study, the battery current-voltage characteristics is estimated under various operating conditions such as state of charge (SOC), load current, charge and discharge modes as described in Eqs. (1) and (2). More information about the battery performance model employed in this study is found in the authors previous publication [6].

$$V_{ch,k}(SOC_k, T, I_k) = OCV_{ch}(SOC_k, T, I_k) + I_{ch,k} \times R_{ch}(SOC_k, T, I_k) \quad (1)$$

$$V_{dch,k}(SOC_k, T, I_k) = OCV_{dch}(SOC_k, T, I_k) + I_{dch,k} \times R_{dch,k}(SOC_k, T, I_k) \quad (2)$$

2.2.2. Battery model without capacity degradation

Battery model without capacity degradation, which is further referred to Model 1, does not consider the impact of the degradation of battery capacity in the simulation of a battery integrated into residential PV system and only uses the lifetime data provided by the battery manufacturer.

2.2.3. Battery model with capacity degradation

Battery model with capacity degradation, which is further referred to Model 2, considers a realistic battery aging model which is able to accurately estimate battery lifetime and capacity fade. The model is a combination of calendar and cycle aging under dynamic operational conditions. Calendar aging and cycle aging in this study are modeled through Eqs. (3) and (4). The influencing parameters on calendar aging are the temperature T, storage SOC, and passed time t since beginning of life. Moreover, the possible influence factors on cycle aging are the cell temperature T, C-rate, depth of cycle (DOC) and the average SOC of cycle. The parameters

$\alpha_{temp,C_{fade,Cal}}$, $\alpha_{SOC,C_{fade,Cal}}$, $\alpha_{C-rate,C_{fade,Cyc}}$ and $\alpha_{DOC,C_{fade,Cyc}}$ in Eqs. (3) and (4) are calculated through methods in ref. [8].

$$C_{fade,Cal}(T,SOC,t) = \alpha_{temp,C_{fade,Cal}}(T).\,\alpha_{SOC,C_{fade,Cal}}(SOC).\,t^{0.5} \tag{3}$$

$$\begin{aligned} C_{fade,Cyc}(C-rate,DOC,FEC) \\ = \alpha_{C-rate,C_{fade,Cyc}}(C \\ - rate).\,\alpha_{DOC,C_{fade,Cyc}}(T).\,FEC^{0.5} \end{aligned} \tag{4}$$

To evaluate the aging effects of battery cells under operation, a superposition of calendar and cycle aging is calculated to estimate total aging.

$$\begin{aligned} C_{fade,total}(T,SOC,t,C-rate,DOC,FEC) \\ = C_{fade,Cal} + C_{fade,Cyc} \end{aligned} \tag{5}$$

2.3. Problem definition

Battery life cycle cost (LCC), the battery system's self-sufficiency ratio (SSR)_ as shown in Eqs. (6) and (7) _and battery lifetime are analyzed for techno-economic assessment of a battery system integrated into residential grid-connected PV system. In this study, according to the current loan rate in Sweden, a 2% discount rate is considered in this study. It is considered that project lifetime is 30 years.

$$SSR_{battery} = \left(1 - \frac{\sum_{t=1}^{8760}(P_{grid,im,t} + P_{PV,supply,t}}{\sum_{t=1}^{8760} P_{load,t}}\right).\,100 \tag{6}$$

$$\begin{aligned} LCC_{battery} = ICC + \sum_{n=1}^{N} \frac{a_n}{(1+i)^n} \\ + \sum_{r=1}^{R} \frac{ICC_c}{(1+i)^{rl_c}} - \frac{salvage}{(1+i)^N} \end{aligned} \tag{7}$$

2.4. Case study

The study implemented for a single-family house in Västerås (N59.62◦, E16.53◦). The building is equipped with 12 kW$_p$ PV panels. The hourly PV power production and hourly electricity consumption are recorded from the building owner. It is worth mentioning that the annual self-sufficiency with PV system is 11.9%.

3. Results and discussion

In this section, the simulation results of the hybrid PV-battery storage system, which are obtained considering two battery lifetime scenarios i.e., scenarios considering battery degradation model and without battery degradation, are compared and discussed on techno-economic performances.

Table 1 compares the obtained self-sufficiency, life cycle cost and battery lifetime related to two different battery lifetime models for a specific battery capacity of 12 kWh. From economic point of view, Table 2 shows that simulation considering battery capacity degradation (Model 2) results in a 45.9% higher LCC compared to the simulation without degradation (Model 1). The reason is that the estimated battery lifetime through the simulation with Model 2 is 9.7 years which means more

Table 1. Comparison of the simulation results under two lifetime models

	Model 1 (Without degradation)	Model 2 (with degradation)	Change to Model 1(%)
PV size	12 kW$_p$	12 kW$_p$	-
Battery pack size	12 KWh	12 kWh	-
Predicted battery lifetime until 20% capacity fade	15 years	9.7 years	-35.3%
SSR$_{battery}$	19.54%	18.19 %	-7 %
LCC$_{battery}$ (€)	11,135 €	16,240 €	+45.9%
Contribution of calendar aging until 20% capacity fade	-	12.2 %	
Contribution of cycle aging until 20% capacity fade	-	7.8 %	

replacements are required during project lifetime compared to Model 1, in which battery lifetime is 15 years without any changes with operational condition. From technical point of view, as shown in Table 1, the simulation considering battery capacity fade (Model 2) leads to 7% lower self-sufficiency ratio in comparison with Model 1 (without degradation). This is because that Model 2 considers a capacity fade model, which is able to accurately estimate both calendar and cycle aging and respective lifetime under dynamic operating condition, in contrast to Model 1, which ignores the impact of battery degradation and uses manufacturer data which is valid only for specific battery operational condition.

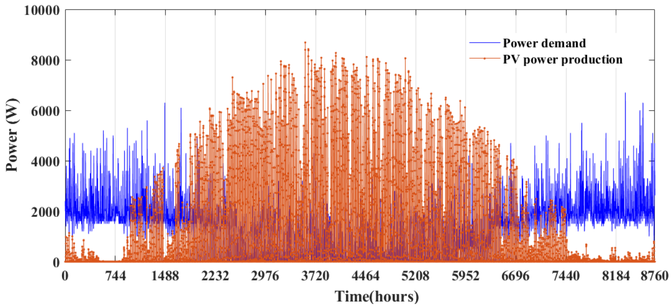


Fig. 2. PV power production along with the electricity consumption power over one-year

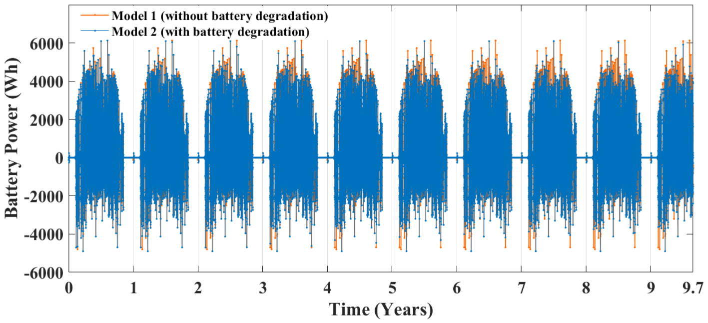
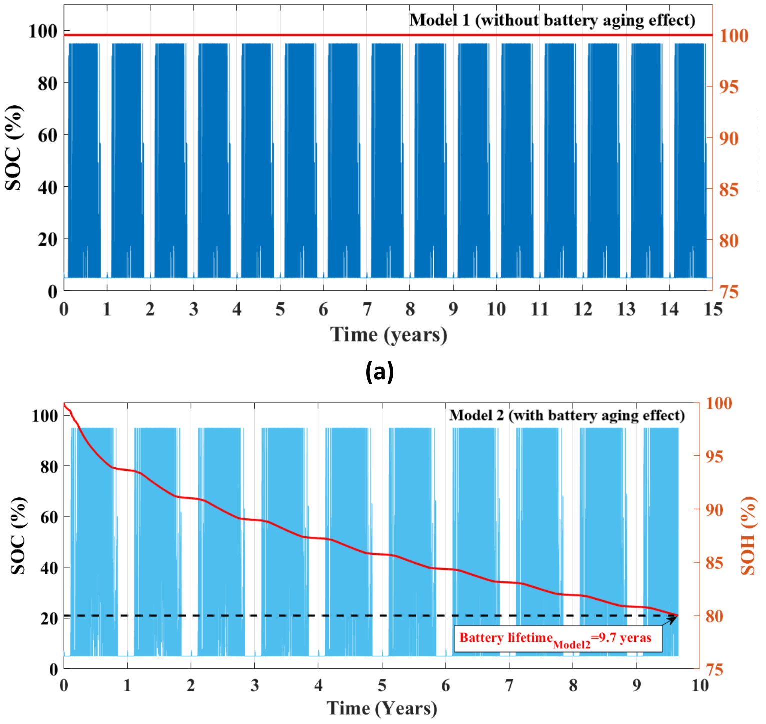


Fig. 3. Time variation of battery charge power (negative power) and discharge power (positive power) relating to battery capacity of 12 kWh, under two different battery aging models

Fig. 2 presents the time variation of PV power production and demanded power over one-year period. Fig. 3 shows the battery power during both charge (negative power) and discharge (positive power) processes under two battery lifetime models. Fig. 4 gives battery SOC and state of health (SOH) over battery lifetime under two battery lifetime models with and without degradation. It is observed from Fig. 3 that although the electricity consumption and PV power production data are the same for both models (as depicted in Fig. 2), battery power output/input are decreasing each year because battery SOH is steadily decreased over the operational conditions in contrast to Model 1, as shown in Fig. 4a, which battery SOH is assumed to be 100%.



(b)

Fig. 4. Time variation of battery state of charge (SOC) and state of health (SOH) until EOL (a) without considering battery degradation model (Model 1); (b) with considering realistic battery degradation model (Model 2), relating to the 12-kWh battery operated in PV system

4. Conclusion

The results showed that the simulation without degradation leads to an unrealistic and too optimistic results which gives 31.43% lower life cycle cost and 7.4 % higher self-sufficiency ratio in comparison with the modelling with battery degradation.

This study proves that battery capacity fade plays important role in operation of battery and is a key parameter in assessing techno-economic profitability of a stationary battery integrated into renewable PV system.

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REFERENCE

[1]. Zhao N, You F. New York State's 100% renewable electricity transition planning under uncertainty using a data-driven multistage adaptive robust optimization approach with machine-learning. Adv Appl Energy. 2021 May 26; 2:100019.

[2]. Victoria M, Zhu K, Brown T, Andresen G. B, Greiner M. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Convers Manage 2019; 201: 111977.

[3]. Huggins RA. Energy storage. New York: Springer; 2010 Aug 12.

[4]. Schleifer AH, Murphy CA, Cole WJ, Denholm PL. The evolving energy and capacity values of utility-scale PV-plus-battery hybrid system architectures. Adv Appl Energy. 2021 May 26; 2:100015.

[5]. Dhundhara S, Verma YP, Williams A. Techno-economic analysis of the lithium-ion and lead-acid battery in microgrid systems. Energy Convers Manage. 2018 Dec 1; 177:122-42.

[6]. Kocer M. C, Cengiz C, Gezer M, Gunes D, Cinar M. A, Alboyaci B, Onen A. Assessment of battery storage technologies for a Turkish power network. Sustainability 2019; 11(13): 3669.

[7]. Wei M, Lee SH, Hong T, Conlon B, McKenzie L, Hendron B, German A. Approaches to cost-effective near-net zero energy new homes with time-of-use value of energy and battery storage. Adv Appl Energy. 2021 May 26; 2:100018.

[8]. Swierczynski M, Stroe DI, Stan AI, Teodorescu R, Kær SK. Lifetime Estimation of the Nanophosphate $LiFePO_4$/C Battery Chemistry Used in Fully Electric Vehicles. IEEE Transactions on industry Applications. 2015 Feb 19;51(4):3453-61.

[9]. Shabani M, Dahlquist E, Wallin F, Yan J. Techno-economic impacts of battery performance models and control strategies on optimal design of a grid-connected PV system. Energy Conversion and Management. 2021 Oct 1; 245:114617.