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Energy Procedia 158 (2019) 3308–3313

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Levelized cost of electricity considering electrochemical energy storage cycle-life degradations

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Abstract

Electrochemical Energy Storage (EES) will be a crucial asset to support the increasing high penetrations of intermittent renewables and to provide means for energy arbitrage. From the investment perspective, the economics for energy systems with EES can be challenging to appraise due to not being an electrical generator. This work examines the system's Levelized Cost of Electricity (LCOE) for a Photovoltaic (PV), Anaerobic Digestion biogas power plant (AD) and EES hybrid energy system in Kenya. By excluding degradation costs at scenarios with high EES capital costs, it is learned that the lowest LCOE can be achieved when EES is given dispatch priority over AD. This appears to be the opposite when degradation cost is included. For more accurate economic analysis, the future research areas are identified as follows: techno-economic analysis needs to consider storage degradation at different operating conditions; and storage degradation models that consider various temperature, C-rate, and state of charge, calendar ageing are required. When comparing energy storage options, cell degradation for EES is an important factor to be addressed in a techno-economic analysis for Generation Integrated Energy Storage (GIES) and non-GIES systems.

Keywords: Levelized cost of electricity; hybrid energy system; electrochemical storage degradation; solar photovoltaic

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10.1016/j.egypro.2019.01.975

1. Introduction

More and more energy systems heavily rely on non-dispatchable intermittent renewables, such as solar photovoltaic and wind energy. Electrochemical Energy Storage (EES) can possibly store the surplus generation that produced by renewables and to be dispatched at a later time. This effectively smooths the energy system operation by acting as an additional generator or load; to better utilize the surplus generation and reducing power curtailment [1]. Due to the quick response time, e.g., milliseconds with EES, the short-term negative phenomena such as over/under frequency and voltage dip/surge that appears in a power system can be relieved by releasing or absorbing energy from a storage system. With the inclusion of EES, State of Charge (SOC) and Depth of Discharge (DOD) have been considered in hybrid energy system's optimal planning and operation [2, 3].

It is crucial to fully comprehend the amount of energy that can be stored and called upon at any time instance when storage is included in an energy system. Due to numerous parameters with the most prominent ones such as temperature, C-rate, and change in state of charge that may affect the storage's state of health, e.g., normalized discharge capacity; a comprehensive model that quantifies the capacity and power fade is challenging [4]. Reference [4] provides a technical discussion on the mechanisms that cause cell degradations for Li-ion, affecting the electrolyte, electrodes, separator and the current collectors. It is worth mentioning that our work is not intended to provide a deep technical discussion on the battery degradation process and its chemistry. The techno-economic analysis for a hybrid energy system with battery degradation is the focus of this work.

Several storage options are available ranging from mechanical, electrical, electrochemical, chemical and thermal storage systems [5]. Unlike EES, storage degradation may be negligible in certain types of energy storage such as molten salt or gravel thermal storage. These thermal storages can store thermal energy without causing permanent material structure and properties changes. When connecting energy storage with electricity generators, storage systems can be classified as Generation Integrated Energy Storage (GIES) and non-GIES systems [6]. GIES 'combines' energy storage with the electricity generator by storing energy in primary form. An example of GIES system is storing thermal energy produced by concentrating solar power in thermal storage. This class of system may increase the overall conversion efficiency and reduces costs. As such, it may be a better option than using EES. However, thermal storage may not have a response time that matches EES. Therefore, when comparing storage options, technical and economic properties need to be compared and accounted for in a non-bias approach.

In techno-economic analysis, Levelized Cost of Electricity (LCOE) is widely used to compare generation cost for an asset or system [7]. However, the context and parameters that compute the LCOE need to be clearly clarified otherwise an unfair comparison will be made. In light of this, this paper examines the LCOE for a hybrid energy system with accounting the storage degradation costs. Section 2 provides an overview of the techno-economic analysis with EES for energy systems and Electric Vehicles (EVs), with an emphasis on Li-ion. Section 3 presents the context of hybrid energy system operation, with case studies including and excluding degradation cost on LCOE analysis. Conclusions will be given in Section 4 with the inclusion of the future works.

2. Techno-economic analysis with energy storage degradation

EES has been used extensively in many electronic and electrical applications such as mobile phones, laptops, and uninterrupted power supply systems. In the recent decades, EES has been extended to the high energy and power density applications such as EVs and electricity grids.

In the realm of EVs, one of the key issues arose in wide adoption over the traditional diesel and petrol vehicles is the degradation, e.g., capacity loss, performance reduction and timely replacements of battery packs [8]. Reduced mileage range and impedance raise from battery's accessible power output will be the consequence of battery degradation in EVs. The quantitative analysis of costs and risks associated with accelerated EV battery degradation needs additional efforts, such as for vehicle-to-grid applications [8]. The challenge is on the variability working conditions of EV batteries, which is directly related to the driver's behavior. This is also accompanied by the dynamic battery temperature influenced by solar radiation, ambient temperature, heat generated from chemical reactions in battery cycling, electrical resistance and friction of mechanical components. The work in [8] has provided a methodology to quantify the EV battery degradation with different vehicle-to-grid services. In addition to the detailed EV powertrain model and battery thermal model, it adopted a semi-empirical Li-ion cell capacity fade model for the degradation analysis. The trade-off for the vehicle to provide grid services with maximum value with minimal impact on vehicle battery life was identified.

Storage degradation has a significant impact on the storage performance. It affects the cell's capability to hold energy and meet electrical demands [4]. Lithium-ion (Li-ion) cells degrade due to the operation, i.e., charging and discharging and environmental conditions exposure. The degradation can be classified as cycle-life degradation and calendar aging, describes as follows [8]:

- Cycle-life degradation: Cycle-life loss is caused by storage operation, which is a function of charge/discharge rate, i.e., C-rate, temperature, and energy throughput. The degradation is caused by mechanical strain in the lithium plating or electrode active materials. This is promoted by deep discharges, high C-rate, temperature, and energy throughput, As such, $\mathrm{LiFePO_4}$ storage can potentially achieve 3200 cycles at 20% DOD or 760 cycles at 80% DOD [9].
- Calendar aging: This class of degradation is independent of charge-discharge cycling. Calendar aging is largely caused by time and temperature exposure. This is due to the change in passivation layers at the electrode-electrolyte interfaces.

In a techno-economic analysis for grid applications storage systems, the cost and revenue can be broken down into four categories [10], namely:

- Monetary savings and profits: Revenues or savings accumulated based on power, energy or reliability related applications;
- Investment cost: Direct storage cost such as a battery, casing, and electrolyte. In addition, the grid coupling cost such as the transformers and power electronics;
- Operational cost: Indirect cost such as conversion losses due to component's efficiency, auxiliary consumptions such as thermal management systems, and direct operating costs such as labor and insurance;
- Degradation and replacement cost: Battery performance degradation due to increased resistance and capacity fade, and fatigued materials replacement cost for battery and power electronics. Replacement cost needs to be taken into account as the unit of analysis is the hybrid system.

Due to the complex chemical and physical mechanisms of battery degradation, this phenomenon is considered as a restricted level in the techno-economic analysis [11]. LCOE allows comparing electricity generation sources and systems. An energy system typically operates for a long lifetime, such as a PV system may last for 25 years [12]. As such, LCOE includes a discount rate that converts the future cash flows into the present value. A classical formulation of LCOE is [13]:

$$\mathrm{LCOE} = \frac{C_{\mathrm{cap}} + \sum_{n=0}^{N} \frac{C_{\mathrm{O\&M}_n}}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+d)^n}} \tag{1}$$

Where C_{cap} is the capital cost ($), assumed all spent at year zero, $C_{\mathrm{O\&M}}$ is the operational and maintenance cost ($), E is the energy output (kWh), N is the system lifetime in years, and d is the discount rate. The cost of an asset typically consists of fixed capital cost and variable operational and maintenance cost. The energy output of an asset is typically calculated with an annual average value in kWh or capacity factor at %. As depicted in Eq. (1), one of the key challenges in calculating the LCOE will be to identify the costs and energy produced.

3. Case studies for System LCOE with storage degradation

The hybrid system adopted for the case studies is a hybrid energy system consisting of AD, EES, and PV in [9]. Since the dispatchable sources are AD and EES, there is an option to meet the energy demand by operating AD or to discharge EES. The operating regime proposed in [9] uses a threshold indicator that will prioritize the dispatch of EES when a battery is above a predefined SOC, namely $\mathrm{SOC_{Threshold}}$. Same as [9], the study interval is at 15min/sample for 22 years of Kenya Turkwel Gorge Dam irradiance data.

In this case study, the discount rate is at 6 % [12, 13], PV capital cost at 0.36 $/W [14]. The AD rated capacity is at 2.4 MW with a Kenyan load curve at 2 MW peak [9]. The cost and technical parameters for the system can be found in [9]. To frequently cycle the storage system a $\mathrm{SOC_{Threshold}}$ of 30% is used.

The SOC constraints are enforced and the power balance is achieved in the operating regime. For the case where degradation cost is not considered, $C_{\mathrm{EES}_{\mathrm{DegkWh}}}$ is not included in the LCOE. The mathematical formulation for obtaining the degradation cost via a capacity fade model can be found in [9]. A fixed 'operational cost' is assigned for storage energy discharge at 0.42 $/MWh [9]. In this work, System LCOE refers to the LCOE for the hybrid system which considers the lifetime system, i.e., PV, AD, EES, inverters and charge controllers costs and energy productions that meets the energy demand. The mathematical modeling for the cost and energy calculations can be found in [9].

3.1. Sensitivity analysis on PV and EES rated capacities

This case study aims to understand the System LCOE at different energy storage capacity in MWh, and PV rated capacity in MW when degradation cost is studied with EES at 1500 $/kWh energy capital costs [15]. Different results with EES at 200 $/kWh energy capital costs were reported in [16]. Figures 1 and 2 depict the results for the System LCOE when degradation is considered and not considered respectively.

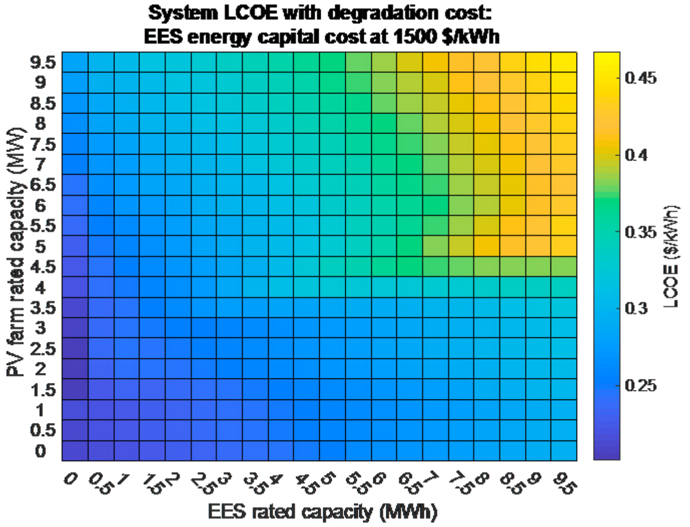

Fig. 1. System LCOE with degradation cost considered.

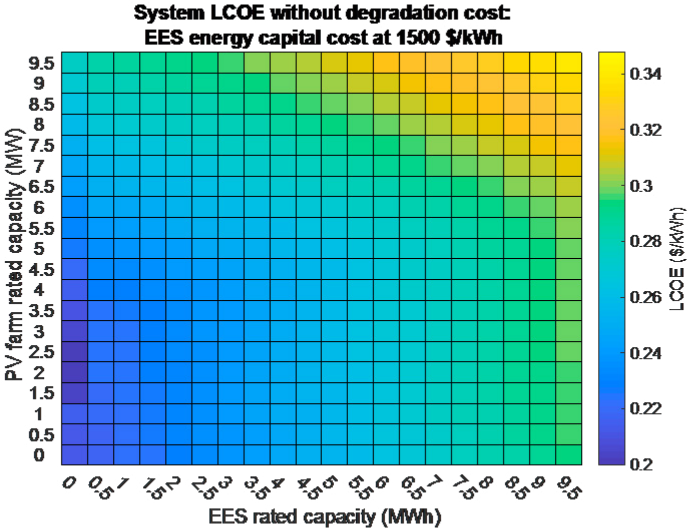

Fig. 2. System LCOE with degradation cost not considered.

The System LCOE in higher when degradation cost is included. The minimal LCOE is achieved when no storage is installed and have a 1.5 MW to 2.5 MW of PV rated capacity. The low capital cost and negligible marginal cost for PV can offset the biogas fuel cost. Storing the surplus energy produced by PV for later use is not the most economic choice, this may be due to the high capital cost for EES. When degradation cost is considered with the PV capacity below 3.5 MW, the change in LCOE is insignificant due to the battery cycling is reduced. This can be explained by the insignificant presence of PV power. The LCOE escalates when EES rated capacity is larger than 6.5 MWh and PV rated capacity above 4.5 MW. This is the contribution of significant storage degradation. When degradation cost is not considered, the nonlinear mathematical relationship between cycle-life degradation (cycles) and cost ($) is excluded in the techno-economic analysis. Due to a fixed operational and maintenance cost is applied to EES discharge, it could be observed that the LCOE increases as the EES capacity increases. Similar to the case where degradation cost is taken into account, the maximum LCOE is located at when PV is at 9.5 MW and EES is at 9.5 MWh.

3.2. Sensitivity analysis on SOC threshold

This case study analyses how the dispatch priority for EES will affect the LCOE when degradation cost is considered. The PV rated capacity is at 5 MW and the EES energy capacity is at 5 MWh [9]. Fig. 3 presents the results for the sensitivity analysis with various $\mathrm{SOC}_{\mathrm{Threshold}}$. The diamond and circle symbols denote the maximum and minimum LCOE respectively.

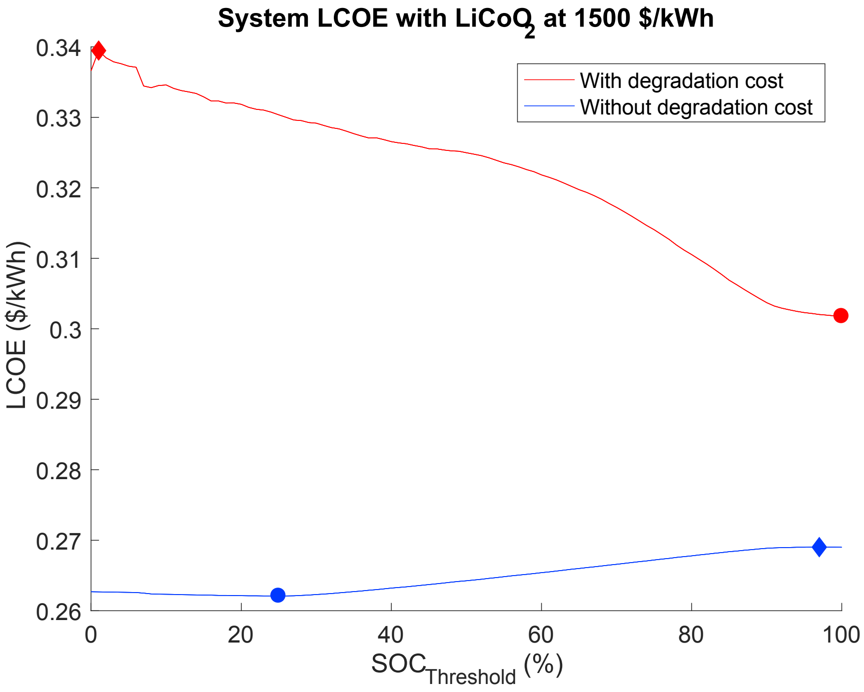

Fig. 3. System LCOE studies with various $SOC_{\mathrm{Threshold}}$.

Without degradation cost, it is identified that the least LCOE is achieved when storage is regularly discharged, i.e., $\mathrm{SOC}_{\mathrm{Threshold}}$ at 25% and the highest LCOE happens when storage is at minimal use. With degradation cost, the least LCOE is achieved when storage is at minimal use, i.e., $\mathrm{SOC}_{\mathrm{Threshold}}$ at 100% and the highest LCOE occurs when storage is used as much as possible. This can be explained due to degradation cost takes into account the cycle-life degradation, the cost for each cycle can contribute to the loss in capital value and life expectancy of storage. When degradation is not taken into account, the frequent use of storage is ideal since it maximizes the use of the asset and the "fuel cost" for storage is minimal, since the marginal cost for PV is approximately zero.

4. Conclusions

The accurate determination of energy system's cost, risk and energy production is a complicated task [17]. This challenge is elevated when energy storage is included. Comprehensive capacity fade models that include different temperature, C-rate and charge/discharge cycles, and calendar aging will increase techno-economic analysis accuracy when electrochemical storage is used. This work shows that degradation can affect the techno-economic analysis for electrochemical storages.

Future work will look into developing techno-economic models for each storage type, e.g., mechanical, electrochemical, thermal that takes the technical attributes into consideration, e.g., discharge rate and degradation. The energy system context, e.g., frequency regulation, load leveling will be highly relevant in deciding the storage type. As such, an area for future work would be a model for comparison on using thermal storage or EES for alleviating grid issues. How storage is integrated with generation will influence the overall economic due to energy efficiency.

Acknowledgments

This work is supported by EPSRC Grant "GIES: Generation Integrated Energy Storage: A Paradigm Shift" (EP/P022049/1); Department of Finance and Education of Guangdong Province 2016[202]: Key Discipline Construction Program, China; and Education Department of Guangdong Province: New and Integrated Energy System Theory and Technology Research Group [Project Number 2016KCXTD022]. Discussions with Dr. Daniel J. Rogers and Professor Richard McMahon are very much appreciated.

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