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Levelized cost of electricity for solar photovoltaic and electrical energy storage

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HIGHLIGHTS

- Levelized cost of delivery (LCOD) for electrical energy storage (EES) is proposed.
- Marginal levelized cost of energy (LCOE) shows that EES can reduce the system LCOE.
- LCODs for Lithium-ion and Vanadium redox flow battery in PV system were compared.
- The EES lifetime, costs, and efficiency can affect the LCOD significantly.

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ABSTRACT

With the increasing technological maturity and economies of scale for solar photovoltaic (PV) and electrical energy storage (EES), there is a potential for mass-scale deployment of both technologies in standalone and grid-connected power systems. The challenge arises in analyzing the economic projections on complex hybrid systems utilizing PV and EES. It is well known that PV power is of diurnal and stochastic nature, and surplus electrical energy is generally available in midday during high irradiance levels. EES does not produce energy as it is not a conventional generator source. Commonly, the cost of a generating asset or the power system is evaluated by using levelized cost of electricity (LCOE). In this paper, a new metric levelized cost of delivery (LCOD) is proposed to calculate the LCOE for the EES. A review on definitions in LCOE for PV hybrid energy systems is provided. Four years of solar irradiance data from Johannesburg and the national load data from Kenya are obtained for case studies. The proposed cost calculation methods are evaluated with two types of EES, namely Vanadium redox flow battery (VRB) and Lithium-ion (Li-ion) battery. It shows that the marginal LCOE and LCOD indices can be used to assist policymakers to consider the discount rate, the type of storage technology and sizing of components in a PV-EES hybrid system.

1. Introduction

As solar photovoltaic (PV) takes a larger share of generation capacity and where electrical systems cannot keep up with the increasing demand, increasing system flexibility should thus become a priority for policy and decision makers. Electrical energy storage (EES) could provide services and improvements to the power systems, so storage may one day be ubiquitous [1]. It is believed that energy storage will be a key asset in the evolving smart grid.

The use of energy storage is increasing as EES options become increasingly available and countries around the globe continue to enrich their portfolios of renewable energy. For example, increased deployment of EES in the distribution grid could make this process more effective and could improve system performance. Mainly, EES mediates between variable sources and variable loads; works by moving energy through time. Essentially, EES can smooth out this variability and allow electricity to be dispatched at a later time. EES are highly adaptable and can meet the needs of various users including renewable energy generators, grid equipment, and end users [2]. Energy storage system may assist in achieving the aim to reduce emission reduction targets and lower the needs for PV output curtailments, which is a major issue with high penetration of PV [3].

The digital economy and industrial firms in combine are losing \$45.7 billion annually due to system outages. This indicates that across all business industries, the economy in US is annually losing between \$104 billion and \$164 billion due to outages and another

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$15 billion to $24 billion due to power quality issues [4]. By using EES, the security of supply and power quality issue could potentially be minimized, and consequently with a reduction in outages.

There are several methods to evaluate the economic viability of distributed generation projects. The capital cost of assets, the operation and maintenance costs, and the fuel costs must be considered in a systematic way so that a comparison can be made. One of the most commonly used metrics is the levelized cost of electricity (LCOE).

In this paper, the concepts of marginal LCOE and levelized cost of delivery (LCOD) are provided for a PV system with EES. Variable renewable generators such as solar PV are unlike conventional generators; they cannot be dispatched (except by curtailing output) and their output varies depending on local weather conditions, which are not well predictable. Existing papers have given reasons for deployment of EES in the future power system [5–7]. Many literatures analyzed the lifecycle or levelized cost solely for storage component, without considering the cost at a system level and energy exchange between generation source and storage [8–11]. LCOE analyses for renewable systems are also already well established and presented in many literatures, such as [12]. However, cost analysis for PV-EES system, and particularly for the analysis of levelized cost of storage has not been given a proper treatment and have not been clearly justified.

A detailed review on recent LCOE calculation methods for PV and EES systems has been given and possible shortcomings of existing methods have been highlighted. The marginal LCOE and LCOD have been derived from first principles. Real-life solar irradiance, load, and the most recent system components cost data from literatures have been collected for the analysis in this paper. The results have been compared with different sources to understand the implication of the proposed methods.

The paper proceeds as follows, the definition of LCOE will be reviewed in Section 2. Section 3 will provide a survey in the recent trend of large-scale PV systems and the LCOE for renewable systems with storage devices. Section 4 provides the derivation for the LCOD for EES and the $LCOE_{system}$, the LCOE for the combined assets, PV and EES. Section 5 provides the case studies for calculations of marginal LCOE and LCOD. A real-life case study with the daily national load data of Kenya and four years of collected solar irradiance data from Johannesburg is given. Discussions and conclusions are given in Sections 6 and 7 respectively.

2. Levelized cost of electricity for solar PV

LCOE aims to provide comparisons of different technologies with different project size, life time, different capital cost, return, risk, and capacities. It is an economic assessment of the total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to achieve break-even over the lifetime of the project.

The general equation for LCOE [13,14] is given in Eq. (1). It is essentially the lifecycle cost of the system be divided by the lifetime energy production of the system.

$$\mathrm{LCOE} = \frac{\text{Lifecycle cost}(\$)}{\text{Lifetime energy production}(\mathrm{kW\,h})} \tag{1}$$

There are two methods commonly used to calculate the levelized costs, known as the "discounting" method, and the "annuitizing" method [15]. In the discounting method shown in Eq. (2), the stream of real future costs and electrical outputs identified as C_t and E_t in year t are discounted back with discount rate r, to a present value (PrV). The PrV of costs is then divided by the PrV of lifetime output. The levelized costs measured under the "dis counting" method, $LCOE_{Discount}$, is given in Eq. (2) below:

$$\mathrm{LCOE_{Discount}} = \frac{\mathrm{PrV(Costs)}}{\mathrm{PrV(Output)}} = \frac{\sum_{t=0}^{n}\frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n}\frac{E_t}{(1+r)^t}} \tag{2}$$

In the "annuitizing" method as shown in Eq. (3), the present value of the stream of costs over the device's lifetime is calculated and then converted to an equivalent annual cost, using a standard annuity formula. This equivalent annual cost is then divided by the average annual electrical output over the lifetime of the plant, where n is the lifetime of the system in years.

$$\mathrm{LCOE_{Annuitizing}} = \frac{\mathrm{Ann(Costs)}}{\mathrm{Ave(Output)}} = \frac{\left(\sum_{t=0}^{n}\frac{C_t}{(1+r)^t}\right)\left(\frac{r}{1-(1+r)^{-n}}\right)}{\left(\sum_{t=1}^{n}E_t\right)/n} \tag{3}$$

The two methods give the same levelized costs when the discount rate used for discounting costs and energy output in Eq. (2) is the same as that used in calculating the annuity factor in Eq. (3). However, for levelized costs to be the same under both measures, annual energy output must also be constant over the lifetime of the device. The annuity method converts the costs to a constant flow over time. This is appropriate where the flow of energy output is constant. It is commonly assumed in the literature on levelized cost estimates that annual energy output is constant. However, the annual energy output of renewable technologies would typically vary from day-to-day mainly due to variations in the renewable resources. Therefore, it is more appropriate to use the discounting method than the annuitizing method when calculating LCOE for renewable sources.

One of the misconceptions when calculating LCOE is that the summation does not start from $t = 0$ to include the project cost at the beginning of the first year [16]. The first year of the cost should not be discounted to reflect the present value and there is no system energy output to be degraded. Ref. [16] has also provided a review on the methodology of properly calculating the LCOE for solar PV. The equation for calculating the LCOE for a PV system is given in Eq. (4) below:

$$\begin{aligned}\mathrm{LCOE} &= \frac{\sum_{t=0}^{n}(I_t+O_t+M_t+F_t)/(1+r)^t}{\sum_{t=0}^{n}E_t/(1+r)^t}\\ &= \frac{\sum_{t=0}^{n}(I_t+O_t+M_t+F_t)/(1+r)^t}{\sum_{t=0}^{n}S_t(1-d)^t/(1+r)^t}\end{aligned} \tag{4}$$

It is worth noting that the initial investment I_t is a one-off payment. It should not be discounted and be taken out of the summation. The LCOE for PV systems given by the authors also considers the degradation factor of PV modules. The electricity generated in a given year E_t is the rated energy output per year S_t multiplied by the degradation factor $(1-d)$ which decreases the energy with time. The maintenance costs, operation costs and interest expenditures for time year t are denoted as M_t, O_t and F_t respectively.

LCOE has been employed as an objective function in many analyses that deal with renewable-based off-grid systems, and the value of lost load-related costs in LCOE was studied in [17]. Ref. [12] studied the time of installment of PV system in the LCOE, whereas the classic LCOE is static, i.e. the installment is done today, the proposed methodology dynamically searches a point in the future where LCOE would be optimum. The papers have made a contribution to re-modify the usage of LCOE, it is worth noting that the storage has not been considered in the system.

There are a number of reasons why large-scale PV system will be the future direction and in order to promote this, many researchers have considered different scenarios to achieve this. A comparative assessment of the three leading large-scale solar