Levelized cost of electricity for solar photovoltaic and electrical energy storage

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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 stand-alone 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 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 (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.**

***Index Terms*-- PV, LCOE, Electrical Energy Storage**

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].

Industrial and digital economy firms are collectively losing \$45.7 billion a year due to outages. These data suggest that across all business industries, the US economy is losing between \$104 billion to \$164 billion a year due to outages and another \$15 billion to \$24 billion due to poor power quality [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 many ways to calculate the economic viability of distributed generation and energy efficiency projects. The capital cost of equipment, the operation and maintenance costs, and the fuel costs must be combined in some ways so that a comparison may 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 II. Section III will provide a survey in the recent trend of large-scale PV systems and the LCOE for renewable systems with storage devices. Section IV provides the derivation for the LCOD for EES and the $\mathrm{LCOE_{system}}$, the LCOE for the combined assets, PV and EES. Section V 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 Section VI and Section VII respectively.

2. Levelized cost of electricity for solar PV

LCOE is a measure of costs which attempts to compare different methods of electricity generation on a comparable basis. It is an economic assessment of the average 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 aim of LCOE is to give comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities.

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

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

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 Equation (2), the stream of real future costs and electrical outputs identified as $\mathrm{C_t}$ and $\mathrm{E_t}$ 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 ''discounting'' method, $\mathrm{LCOE_{Discount}}$, is given in Equation (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 Equation (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 Equation (2) is the same as that used in calculating the annuity factor in Equation (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. Reference [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 Equation (4) below:

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

It is worth noting that the initial investment $\mathrm{I_t}$ 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 energy generated in a given year $\mathrm{E_t}$ is the rated energy output per year $\mathrm{S_t}$ multiplied by the degradation factor $(1-\mathrm{d})$ which decreases the energy with time. The maintenance costs, operation costs and interest expenditures for time year t are denoted as $\mathrm{M_t}$, $\mathrm{O_t}$ and $\mathrm{F_t}$ 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]. Reference [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 technologies in 2010 and 2020 for different locations is provided in [18]. Also mentioned in [19], it concludes that at present these technologies cannot yet compete with conventional forms of power generation, but will approach competitiveness around 2020 in favorable locations. In order to further refine policy recommendations, policymakers are in the need for more precise advice on which policy mixes are most workable to improve the usage of different technologies. Future research should assist policymakers in exploiting this potential by evaluating in more detail the needs for accompanying measures in the areas of storage and grid management. An economic analysis of the investment in grid-connected PV systems installed on the building's rooftops located in densely urbanized contexts is provided in [20]. The LCOE was calculated as an indicator of the competitiveness of the PV technology. Although the competitiveness of the PV LCOE with retail electricity prices is an appealing goal, the trajectory towards the grid parity is still slow in Italy.

A comparison of LCOE across PV systems with equal installation areas but with modules of different efficiencies installed with fixed tilt, 1-axis tracking or 2-axis tracking is provided in [21]. The first finding was that at a given module price in $/W, more efficient PV modules lead to lower LCOE systems. The second finding was that when meeting a LCOE goal, the PV module efficiency has a lower limit that cannot be offset by module price; and the third and final finding was that both 1-axis and 2-axis tracking installations provide lower LCOEs than fixed tilt installations. To summarize, the LCOE will decrease with the increase in energy production of the system. The LCOE for PV systems in 143 countries is provided in [22]. The differences in both the solar resource and the financing cost were considered. The findings show that the LCOE values are highly dependent on the location, due to regional cost differences and variation of irradiance strength, which has a direct effect to the energy output [23].

The LCOE of commercial scale PV systems were investigated in [24, 25] with the System Advisor Model (SAM) developed by National Renewable Energy Laboratory. SAM [26] is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. At present, SAM does not model isolated or off-grid power systems.

3. Review on cost benefit analysis for PV and energy storage system

3.1. PV system

An investigation on PV surplus generation and storage requirements in Germany is provided in [5]. Surplus energies are generally low, but there are high surplus power peaks. It states that there are several questions remain for future research, in particular regarding the optimal mix of storage, curtailment and other flexibility options. The study of different energy storage technologies interaction with network expansion, power-to-heat, and thermal plants appears to be a particularly promising field of research. Additionally, the full system value of storage technologies should be investigated, including their capacity value and the provisions of ancillary services.

The benefits of deploying storage into a power network is provided in [6]. A simulation environment was developed with multiple types of network event to be monitored simultaneously. Historical data were used to recreate the network conditions with load flow analysis and an assessment was made with the participation of EES. The simulations have shown that operating an EES in the distribution network has a positive effect on the tasks of power flow management and voltage control. It is learnt that a higher power rating and energy capacity EES could solve a greater number of problems, but there is a balance of cost/benefit to be achieved. As progress is made in the transition to future electricity networks, electrical energy storage embedded at distribution level is set to become an integral part of the Smart Grid.

The techno-economic feasibility study of different PV hybrid systems for a typical household in Urumqi, China using the RETScreen is presented in [27]. The energy production and economical assessment for a grid-connected 5 MW PV power plant in Saudi Arabia were studied with RETScreen is provided in [28]. RETScreen [29] is a clean energy management software in the form of excel spreadsheet, with the purpose for calculating a large number of valuable financial indicators. The issue with the program is that the input solar isolation for the study does not include the daily load and renewable sources fluctuation into account, and the computation costs will be exponential for detail analysis due to the size of database.

The economic performance of a residential PV system in Queensland, Australia was investigated with the software package HOMER in [30]. It aimed to optimize the size and slope of PV array in the system. A PV-diesel hybrid system with battery backup for a village was studied with HOMER [31]. HOMER [32] is an optimization software package which simulates different renewable energy sources system layouts and sized them on the basis of net present cost. It uses sensitive analysis to consider different generation capacities and battery storage capacity to determine the optimal size of the system. The issue with this program is the high computational requirement, due to the large number of cases needed to be computed. As an example, the study in [30] required a total of 448,000 runs based on 28 sensitivities, where sensitivities are defined as the sizing control parameters such as size of PV and storage. In addition, the software is of "Black Box" code utilization, where the optimization algorithm and cost calculating methodologies are unknown [33]. Reference [34] presents a method for technical-economic optimization of a PV system with energy storage. The system aims to meet the energy requirements of a given load distribution for a specific site. The storage unit characteristics and requirements were determined. The cost of storage has not been investigated.

A stand-alone PV system for electrification of a single residential household in the city of Faisalabad, Pakistan was studied in [35]. Lifecycle cost analysis was used to provide economic analysis of the system. It concluded that it is more economical to become an off-grid PV system than being grid-connected. It is noted that the cost of generation and storage sources were not separated and evaluated, where the electrical load requirement is used as the total system energy output. A simulation model was developed in [36] that studies the economics of EES for residential PV in Germany under eight different electricity price scenarios, in the years between 2013 to 2022. Investments in storage solutions were economically viable for small PV systems in 2013.

The LCOE for a system with PV, concentrate solar power plant and thermal energy storage on the Atacama Solar Platform is presented in [37]. The study uses monthly solar irradiance to calculate the annual energy production from PV system. Reference [38] presents a technical and economic model for the design of a grid-connected PV plant with EES. The aim is to determine the PV system rated power and the EES capacity being able to minimize the LCOE. In the study, total energy demand was used for cost analysis instead of the energy output from the generation assets. Reference [39] presents the LCOE study of renewable energy in China with an emphasis on feed-in-tariffs and discount rates. Energy storage was not considered in the study.

The modification to the electric power system required to incorporate high penetration of variable wind and solar electricity generation in a transmission constrained grid is presented in [7]. The main concerns with combining the use of these sources at large-scale are the restricted flexibility of thermal generators to reduce output, in additional with the relative short time coincidence of the renewable resource with the instantaneous electricity demand. This would result in unusable renewable generation and increased system direct and opportunity costs. A highly flexible system, with must-run base-load generators virtually eliminated, allows for penetrations of up to about 50% variable generation with curtailment rates of less than 10%. For renewable penetration levels up to 80%, keeping curtailments to less than 10% requires the use of load shifting and storage capacity with the size equal to approximately one day of average demand.

It is impractical to install an EES that is capable of providing a solution to all events at all times; either the events would have to be very modest and the EES will be very large. The EES operates to make a contribution to improve network performance in cooperation with other Smart Grid control actions such as active generator curtailment or demand side management. The contribution significance made by EES depends upon the event schedule and the dynamic behavior of the network on both short and long-term time-scale.

Reference [40] suggested that energy storage and generation must be separated. There is an increasing acceptance that energy storage will play a major role in future electricity systems to provide at least a partial replacement for the flexibility naturally present in fossil-fueled generating stations. It mentioned that if all UK power come from PV with storage, 57.1% of all energy consumed would have passed through storage. As a result, if future electricity systems are powered largely from inflexible sources, substantial fractions of all electrical energy consumed may pass through storage.

An overview of the Spanish power generation sector is given in [41]. The sector is surrounded with number of challenges, with generation overcapacity as one of the factors [42]. Appropriate energy planning could have reduced investments in the Spanish power sector by 28.6 billion euro by 2010, without the conflict on performance in terms of energy security or sustainability. The main causes of these surplus investments were partly due to solar technologies. EES could potentially improve the situation by reducing the required generation capacity by providing flexibility to the system.

3.2. Electrical energy storage

Turning to EES, a cost analysis for various EES in grid-connected system is presented in [8]. It calculates the cost of electricity added by storing electricity for different storage technologies. It has made comparisons solely for storage technologies and renewable energy system which have not been considered in the paper. The economic implications of EES technologies are obscured for the power grid stakeholders [9]. If the cost of charging electricity would be deducted from the LCOE delivered by EES, the net Levelized cost of storage (LCOS) is presented in Equation (5) [9].

$$\mathrm{LCOS} = \mathrm{LCOE} - \frac{\text{price of charging power}}{\text{overall efficiency}} \tag{5}$$

Equation (5) states that LCOS will be less than LCOE. The cost of storage should be higher than the cost of the system, since the storage cost needs to include the cost of electricity generation to be stored in EES. The storage will have an efficiency factor; hence the storage output energy will be lower than the energy generates by source. It is noted that the generation source in the calculation of LCOS or LCOE for the system has not been considered. The energy stored in storage system is affected by the energy production of renewable source.

In general, the future perspective is promising for Lithium-ion (Li-ion) batteries in power system applications as the retail price is declining and the technical specifications are reaching new heights with reducing manufacturing costs, extending the lifetime, using new materials, and improving the safety parameters. Li-ion and lead-acid batteries are suitable for short duration services, whereas Sodium-sulfur and vanadium redox-flow batteries (VRB) are suitable for long duration services [10].

A study of the LCOE for hydrogen-bromine flow battery is provided in [11]. It mentioned that although the capital cost of storage is of critical, the most important metric is the levelized cost of electricity and it should be the value to be minimized, rather than minimizing capital cost. At 0.40 $/kWh, the hydrogen-bromine flow battery system is too expensive for grid-level application. It is explained that the high cost is due to hydrogen storage. The costs of the hydrogen-bromine system can be significantly lowered if the costs of the battery stack and power electronics can be reduced.

Li-ion batteries are the most common storage technology and the VRB are emerging as another storage option for grid applications [43]. The World Energy Council [44] has proposed a formula as shown in Equation (6), known as the Levelized Cost of Storage. It enables the comparisons between different types of storage technologies in terms of average cost per produced and stored kWh.

$$\mathrm{LCOS} = \frac{\mathrm{I_o} + \sum_{t=1}^{n} \frac{\mathrm{C_{EES_t}}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\mathrm{E_{EES_t}}}{(1+r)^t}} \tag{6}$$

$\mathrm{I_o}$ is the initial investment cost. $\mathrm{C_{EES_t}}$ and $\mathrm{E_{EES_t}}$ are the total costs and energy output at year t respectively. It is mentioned that the LCOS formula only summarizes the general LCOS of each technology, i.e. without applying the application cases to a specific context such as for a PV system. It shows that the renewables industry faces two main challenges when applying the LCOS metric:

1. Arbitrariness: The application case varies widely and dependent on the type of service provide;
2. Incompleteness: The cost calculation does not reflect the characteristics of storage. Traditionally, LCOE is reflected on by the applied discount factor. Since it neglects higher potential revenues, e.g., from providing flexibility, it is a simplified approach for the actual value of storage.

Policymakers should examine storage through holistic case studies in context, rather than only emphasis in generic cost estimations. Lazard [45] modeled 10 different use cases for storage including frequency regulation, grid balancing and micro-grid support with the possibility of eight different storage technologies, ranging from compressed-air energy storage to Li-ion batteries. The required energy output for different storage applications are predetermined. Because of the operating and physical conditions, some electrical energy storages would need to be overrated. This oversizing results in depth of discharge (DOD) over a single cycle less than 100%. While energy storage is a beneficiary of and sensitive to various tax subsidies, the report presents the LCOS on an unsubsidized basis in order to isolate and compare the technological and operational components of energy storage systems and use cases.

The LCOS provided by Lazard is an optimistic estimation and in practice, the storage system will not be used to 100% of its capacity. In the case of PV integration, the energy stored in the storage system depends on the PV system output and this is highly arbitrary as it depends on the nature of solar irradiance. Therefore, the LCOS will be different in real-life situation and is expected to be higher. The values provided by Lazard can be used as a comparison for different storage technologies and applications, but cannot be used for system resource planning and decision making. The operational parameters used in Lazard's LCOS study for PV integration are presented in Table 1.

Table 1
Parameters used for LCOS study for PV integration [45].

Parameters	
Project lifetime (Year)	20
Discount rate (%)	8
Storage power capacity (MW)	2
Storage energy capacity (MWh)	4
Cycles per day (100% DOD)	1.25
Days of operation per year	350
Annual energy production (MWh)	1750
System's total generated energy (GWh)	35

The report did not provide the method for the LCOS calculation. It is assumed that the results are calculated with Equation (6). The results of LCOS for PV integration with the lower and upper bound range for different storage technology are provided in Table 2. The results from Table 2 will be useful to provide a comparison of the results in the case study in this paper. Table 3 presents a comparison on the levelized cost analysis features for the three prominent hybrid renewable energy system software packages. It is learnt that LCOS are currently not included at present.

Table 2
Current LCOS for PV integration [45].

	LCOS ($/kWh)	
Storage Type	Lower bound	Upper bound
Zinc	0.245	0.345
VRB	0.373	0.950
Li-ion	0.355	0.686
Lead	0.402	1.068
Sodium	0.379	0.957

A new methodology for the calculation of levelized cost of stored energy was proposed in [46]. New terms have been proposed such as price increase factor and internal transfer cost to calculate the LCOE of the hybrid system. These two terms are currently not well defined in the industry and no literature has discussed them, hence these values are not practical to use for

Table 3
Comparison of levelized cost analysis features for the prominent hybrid renewable energy system software packages.

	HOMER Pro	RETScreen Expert	System Advisor Model (SAM)
Developer	HOMER Energy LLC	Natural Resources Canada	National Renewable Energy Laboratory
Availability	Priced	Free	Free
Description	The software can provide hourly interval data analysis, hence better modelling of the intermittency of renewables. It is capable of performing brute-force system optimization such as for components sizing purposes. The software may generate synthetic hourly solar data from monthly average clearness index or daily radiation data if real-data is unavailable.	The software evaluates the performance of systems based on statistical monthly average data. One of the major advantages of the software is that it has an abundant amount of geographical data built-in, which is obtained from NASA's climate database.	The software is used for studying grid-connected systems only, and currently does not support stand-alone system analysis. Shading and snow data can be included in the analysis to model the reduced PV output. A database of hourly solar irradiance data is provided from NREL database.
Supported energy storage model	Flywheel, customizable batteries, flow batteries and hydrogen	Thermal storage tank	Lead-acid and Li-ion
Provide LCOE?	Yes	No	Yes
Provide LCOS?	No	No	No
Reference	[49]	[50]	[51, 52]

calculations. As stated in [47], the economic estimation on hybrid systems utilizing a combination of PV, EES and cogeneration is difficult and at present, no comprehensive method exists for guiding decision makers. The proposed LCOE for the hybrid system is given in Equation (7) [47]:

$$\mathrm{LCOE} = \frac{\mathrm{I} + \sum_{t=1}^{n} \frac{(\mathrm{I} * \mathrm{i} + \mathrm{O} + \mathrm{F_{chp}})}{(1+\mathrm{r})^{t}}}{\sum_{t=1}^{n} \mathrm{E_{tpv}}(1-\mathrm{d_1})^{t} + \frac{\mathrm{E_{tchp}}(1-\mathrm{d_2})^{t}}{(1+\mathrm{r})^{t}}} \quad (7)$$

I is the total installation cost which includes the cost of PV, battery and the combined heat and power (CHP) module, i is the interest rate on the hybrid system for 100% debt financing. O is the total operation and maintenance cost. $\mathrm{F_{chp}}$ is the annual fuel cost of the CHP unit. $\mathrm{E_{tpv}}$ and $\mathrm{E_{tchp}}$ are the rated annual energy production from PV and CHP unit respectively. $\mathrm{d_1}$ and $\mathrm{d_2}$ are the degradation rates for PV and CHP unit respectively. The energy produced by PV system is not discounted. It does not reflect the actual value of the PV energy in the future. The equation for the hybrid system LCOE does not discount the energy lost from using the storage system due to round-trip efficiency, where the total energy output from the system is the energy produced by PV and the CHP unit.

Reference [48] has discussed and proposed the LCOE metric for energy storage. The authors claimed that large-scale storage is becoming a significant issue for utilities, therefore it justifies the development of a levelized costing algorithm which accommodates storage systems. In the LCOE equation for energy storage, the energy output from the energy storage is assumed to be the annual energy production of the system. This may not be the case as not all energy produced by the system will be delivered by energy storage.

4. Cost calculation methodology

The literature review has shown that many LCOE work considers the cost of storage and renewable energy systems as a whole rather than being separated. Also, it is learnt that the daily average global solar irradiance or capacity factor are commonly used to calculate the total energy generation from of the hybrid system. This will provide a less accurate study due to the absence in the consideration of variability of renewable sources. This section aims to provide the methodology to better represent the LCOE for a PV-EES hybrid system.

It is common to store the excess energy generated by PV in storage systems to be used later on. The PV energy at an available time instance should be used directly to support the load and to avoid the losses due to round-trip efficiency, η. In splitting the total energy produced by the PV system into two types, known as the surplus and the direct energy. Surplus energy, $\mathrm{E_{pvsurplus}}$, is the extra energy generated by PV system and not consumed by the load. Direct energy, $\mathrm{E_{pvdirect}}$, is the energy that consumed by the load directly. $\mathrm{C_{pvsurplus}}$ and $\mathrm{C_{pvdirect}}$ are the costs for generate surplus energy and direct energy respectively.

Equation (8) gives the LCOE for a PV system which has both the direct and surplus energy component. The surplus energy can be stored in EES. To fully utilize the PV energy, since the surplus energy cannot be used when load demand is less than the generation output, therefore there is a need to have energy storage to store the energy. It is noted that the energy delivered by EES will be reduced due to the round-trip efficiency. $\mathrm{LCOE_{PV}}$ will be reduced when storage is included in the system by utilizing the surplus energy.

As energy storage is not an energy generating source, however, in the definition of LCOE, it is defined that only energy generation is considered [53]. As a result, the definition of LCOE for PV system with EES needs further consideration in order to provide a more accurate representation of the LCOE. Equations (9) shows the LCOE with two partitions, namely, direct and surplus energy from the conventional LCOE as shown in Equation (4).

$$\mathrm{LCOE_{PV}} = \frac{\sum_{t=0}^{n} \frac{(C_{pvsurplus} + C_{pvdirect})_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{(E_{pvsurplus} + E_{pvdirect})_t}{(1+r)^t}} \quad (8)$$

$$\mathrm{LCOE_{PV}} = \frac{\sum_{t=0}^{n} \frac{C_{pvsurplus_t}}{(1+r)^t}}{\sum_{t=0}^{n} \frac{(E_{pvsurplus} + E_{pvdirect})_t}{(1+r)^t}} + \frac{\sum_{t=0}^{n} \frac{C_{pvdirect_t}}{(1+r)^t}}{\sum_{t=0}^{n} \frac{(E_{pvsurplus} + E_{pvdirect})_t}{(1+r)^t}} \quad (9)$$

Figure 1 shows the energy flow diagram of the renewable energy and storage system. The PV array in the system are separated into two sets. The net energy output of the EES needs to take account of η. The EES experiences the electrical energy flowing in and flowing out.

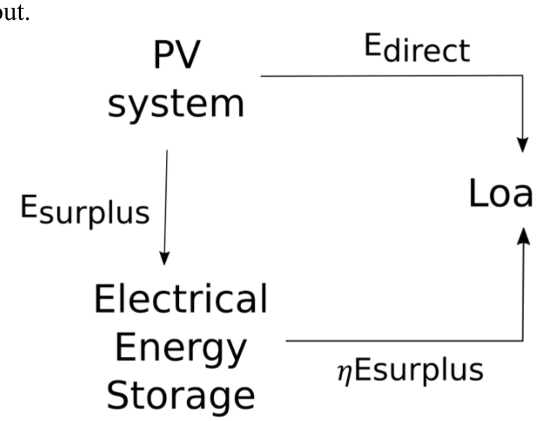

Figure 1: Energy flow diagram of the PV system

To simplify the derivation process, Equations (10) to (14) are used for the LCOE calculations in the upcoming derivations.

$$C_{EES} = C_{Cap\_EES} + \sum_{t=0}^{n} \frac{C_{O\&M\_EES_t}}{(1+r)^t} \quad (10)$$

$$E_{EES} = \eta \sum_{t=0}^{n} \frac{E_{surplus_t}(1 - D_{EES})^t}{(1+r)^t} \quad (11)$$

$$C_{pvsurplus} = \left(C_{Cap_{pv}} + C_{Inst_{pv}}\right) N_{surplus\_ave} + \sum_{t=0}^{n} \frac{\sum_{h}^{m} C_{O\&M\_pv} N_{surplus_h}}{(1+r)^t} \quad (12)$$

$$C_{pvdirect} = (C_{Cap_{pv}} + C_{Inst_{pv}}) N_{direct\_ave} + \sum_{t=0}^{n} \frac{\sum_{h}^{m} C_{O\&M\_pv} N_{direct_h}}{(1+r)^t} \quad (13)$$

$$E_{pvdirect} = \sum_{t=0}^{n} \frac{E_{direct_t}(1 - D_{pv})^t}{(1+r)^t} \quad (14)$$

D_{EES} and D_{PV} are the annual performance degradation rates for storage and the PV array respectively. N_{direct_ave} and $N_{surplus\_ave}$ are the fraction of PV array for generating energy for direct consumption and surplus energy for storage respectively. N_{direct_h} and $N_{surplus_h}$ are the fraction of PV array at hour h for generating energy for direct consumption and surplus energy for storage respectively. E_{direct} is the energy generated from PV and directly supplied to the load without going through storage. $C_{pvsurplus}$ and $C_{pvdirect}$ are the total lifetime costs of PV generation that produce the surplus and direct consumption of energy for the system respectively.

4.1. Electrical energy storage

The derivation of the LCOE for the EES is given in Equations (15) to (18). The LCOE of the energy into the system is given in Equation (15).

$$\mathrm{LCOE}(E_{in}) = \frac{\sum_{t=0}^{n} \frac{C_{in_t}}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_{in_t}}{(1+r)^t}} \quad (15)$$

C_{in_t} is the total cost for delivering the PV energy into EES at year t. $E_{in_t}$is the input energy to the EES at year t. The LCOE for EES in a renewable energy system is more complicated to comprehend. It is necessary to take the cost of the solar array to generate the surplus energy to be stored into the EES into account. This is due to the fact the energy stored in the EES is produced by the solar array. The LCOE of the energy delivered by the EES is given in Equations (16) and (18):

$$\mathrm{LCOE}(E_{out}) = \frac{\sum_{t=0}^{n} \frac{C_{in_t}}{(1+r)^t} + \sum_{t=0}^{n} \frac{C_{storage_t}}{(1+r)^t}}{\eta \sum_{t=0}^{n} \frac{E_{in_t}}{(1+r)^t}} \quad (16)$$

$$\mathrm{LCOE}(E_{out}) = \frac{\sum_{t=0}^{n} \frac{C_{in_t}}{(1+r)^t}}{\eta \sum_{t=0}^{n} \frac{E_{in_t}}{(1+r)^t}} + \frac{\sum_{t=0}^{n} \frac{C_{storage_t}}{(1+r)^t}}{\eta \sum_{t=0}^{n} \frac{E_{in_t}}{(1+r)^t}} \quad (17)$$

$$\mathrm{LCOE}(E_{out}) = \frac{C_{pvsurplus}}{\eta E_{PVdirect}} + \frac{C_{EES}}{E_{EES}} \quad (18)$$

By splitting Equation (11) into two individual components, the final form of the LCOE for the EES is given in Equation (19).

$$\mathrm{LCOE}(E_{out}) = \mathrm{LCOD} = \frac{1}{\eta}\mathrm{LCOE}\left(E_{surplus}\right) + \mathrm{LCOS} \quad (19)$$

In practice, E_{in} will be the surplus energy, $E_{surplus}$ flowing into the storage to be a dispatchable source of power. Therefore, C_{in} will be $C_{PVsurplus}$, the fraction of PV array that produced the surplus energy for the system. The surplus energy may be generated in some hours of a day by the same panels producing directly-used energy in some other hours. Therefore, a panel can produce both excess and direct electricity, depending on time of the day, and/or seasonal conditions. As proposed in Equation (16), the cost of the electricity delivered by storage needs to take into account of the fraction of solar array for producing the surplus energy. To calculate the fixed costs (capital and installation costs) for the PV system, the fraction of PV arrays generates the surplus and direct energy needs to be fixed. The operation and maintenance costs varies throughout the lifetime of the system. Equations (20) and (21) present the average of fraction for direct and surplus energy respectively for the PV array. The fractions of array for direct and surplus energy at a particular time instance h is presented in Equations (22) and (23) respectively. The fractions of array should make up the PV array for the system, N_{Total}, in the PV system as given in Equations (24) and (25).

$$N_{direct\_ave} = \frac{\int_{h=0}^{m} P_{direct}(h)}{\sigma \int_{h=0}^{m} \varepsilon(h)} \tag{20}$$

$$N_{surplus\_ave} = \frac{\int_{h=0}^{m} P_{surplus}(h)}{\sigma \int_{h=0}^{m} \varepsilon(h)} \tag{21}$$

$$N_{direct_h} = \frac{P_{direct}(h)}{\sigma\varepsilon(h)} \tag{22}$$

$$N_{surplus_h} = \frac{P_{surplus}(h)}{\sigma\varepsilon(h)} \tag{23}$$

$$N_{Total} = N_{direct\_ave} + N_{surplus\_ave} \tag{24}$$

$$N_{Total} = N_{direct_h} + N_{surplus_h} \tag{25}$$

σ is the PV array efficiency, ε is the solar irradiance at Wm^{-2}, h is the time interval of the system operation. When solar irradiance is zero, then there will be zero power output, that is $P_{surplus}$ is also zero. The situation will be 0/0, that is mathematically, it is an undefined solution. However, in real-life situation, these cases should not be taken into account but rather just in considering the situation when there is a PV output. Therefore, the authors limit the study to cases in which $P_{surplus}$ or P_{direct} is not zero. There will be situations such that there is a P_{direct} but no $P_{surplus}$ as the generated power is fully supplied to the load fully.

4.2. Solar PV and storage system

For the PV and EES storage system, the following LCOE relationship will hold:

$$LCOE_{system} = \frac{\sum_{t=0}^{n} \frac{C_{system_t}}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_{system_t}}{(1+r)^t}} \tag{26}$$

C_{system_t} and E_{system_t} are the total cost and total energy production from the system at time t respectively. The total cost of the renewable system is the sum of PV generation and storage costs. The total energy produced by the system is the energy output of EES and the energy directly delivered to the load by PV. In this paper, the term $LCOE_{system}$ is denoted for the LCOE for the generating and energy delivering assets PV and EES system. It does not consider the context of standalone or on-grid system. The purpose of $LCOE_{system}$ is to provide the understanding of the cost implications to the renewable and storage assets. Therefore, the LCOE for the system is given in Equation (27).

$$LCOE_{system} = \frac{C_{pvsurplus} + C_{EES} + C_{pvdirect}}{E_{EES} + E_{pvdirect}} \tag{27}$$

5. Case studies

5.1. Data acquisition

Solar irradiance and load data were obtained for the studies in this paper. The SKS 1110 pyranometer device manufactured by Skye Instruments [54] was used to collect the irradiance data. Four years of complete solar irradiance data in 2009-2012 were collected in Johannesburg. The sampling rate is at a sample/30min. Due to the restricted space to present the hourly annual solar irradiance, Figure 2 shows the solar irradiance collected for the first six days in 2009-2011.

The national load curve of Kenya is presented in Figure 3. As explained in [55], the national peak starts rising at 18:30 and reaches its peak at 20:30. The shape of the national load profile for South Africa and Kenya are very similar [56, 57]. It is therefore safe to have the assumption that the load curve for Johannesburg is similar to that for Kenya.

PV projects are currently favorable in Kenya. Kenya has an abundant source of solar irradiance and it is capable to generate several times more electricity from PV than the national grid annual consumption. The economic value of PV has already exceeded the potential projects costs in 2012 [58] and grid-connected PV systems may already be more economical than the most expensive conventional power plants, such as gas turbines and medium-speed diesel generators. They are currently the largest share of Kenya's current power generation mix [59].

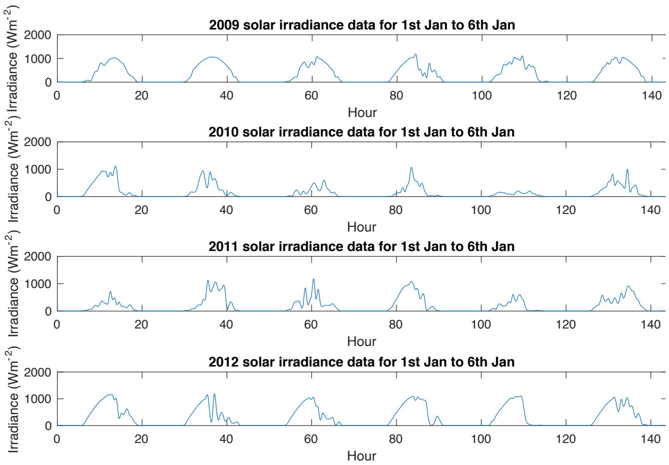

Figure 2: Solar irradiance between 1st Jan to 6th Jan for 2009-2012

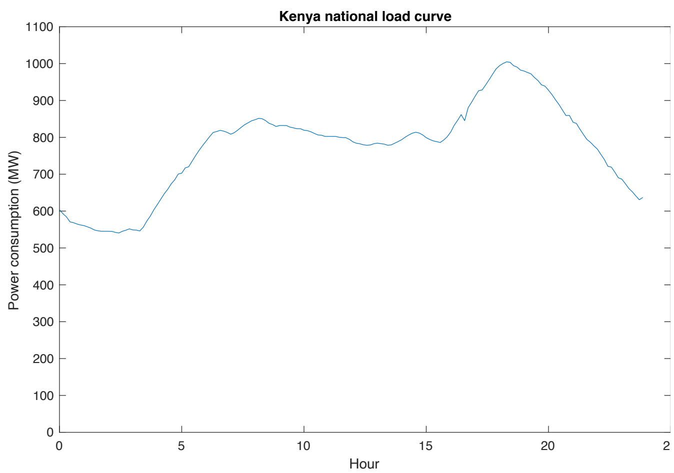

Figure 3: Daily national load curve in Kenya

5.2. *Cost and asset specification*

The cost and asset specification is presented in Table 4. The solar panel to be used for the system is the Sharp ND-250QCS. It has an efficiency of 15.3% and has a rated power of 250 W [60]. The lifetime of PV panels can be up to 25 years [61], which exceeds the lifetime of EES. In the case studies, the lifetime of PV panels is assumed to be the same as the storage system and the project lifetime.

Table 4
Cost and technical specification of the system components for case study.

		EES	
	PV	VRB	Li-ion battery
Capital cost (C_{Cap})	120 ($/unit) [60, 62]	760-1600 ($/kWh) [45, 63]	715-1640 ($/kWh) [45, 63]
Installation cost (C_{Inst})	108 ($/unit) [60]	N/A	N/A
O&M cost ($C_{O\&M}$)	6 ($/unit/year) [60]	100-140 ($/kWh) [63]	80-95 ($/kWh) [63]
System Lifetime (n)	N/A	20 years [45, 63]	15 years [45, 63]
Round-trip efficiency (η)	N/A	70% [45, 63]	90% [10, 45, 63]
Degradation rate	0.5 %/year [64, 65]	0.01 %/year [46]	2 %/year [46]

5.3. *Marginal levelized cost of electricity*

The concept of marginal LCOE is proposed in this paper. By definition, marginal cost is the cost of producing one more unit of output. In this paper, the authors proposed the marginal LCOE to examine the long-term investment by adding additional PV capacity and storage into the system. This will be useful to understand the costs implication with respect to the system investment.

In this paper, three different cases of the marginal LCOE are studied with the following assumptions.

Case 1: The peak of solar power meets the peak load demand with no surplus energy available;

Case 2: Extra PV capacity is added to the system and additional solar power will be generated. However, the surplus energy will be discarded because of no storage;

Case 3: Storage will be used to store the surplus energy. The size of PV capacity is the same as that in Case 2.

To provide the visual illustrational for the concepts of marginal LCOE, a constant linear load curve and clear sky irradiance are used as shown in Figures 4 to 6. The total cost and energy to calculate the LCOE for the system in the case studies are given in Equations (28) and (29), with $C_{case(k)}$ is the annual cost for the PV array and $E_{pv(k)}$ is the annual energy production from the PV array in case k.

$$C_{total\_case(k)} = \sum_{t=0}^{n} \frac{C_{case(k)_t}}{(1+r)^t} \tag{28}$$

$$E_{total\_case(k)} = \sum_{t=0}^{n} \frac{E_{pv(k)_t}}{(1+r)^t} \tag{29}$$

In Case 1, the load uses all the produced solar energy. LCOE is then calculated. Figure 4 shows the visual representation of Case 1.

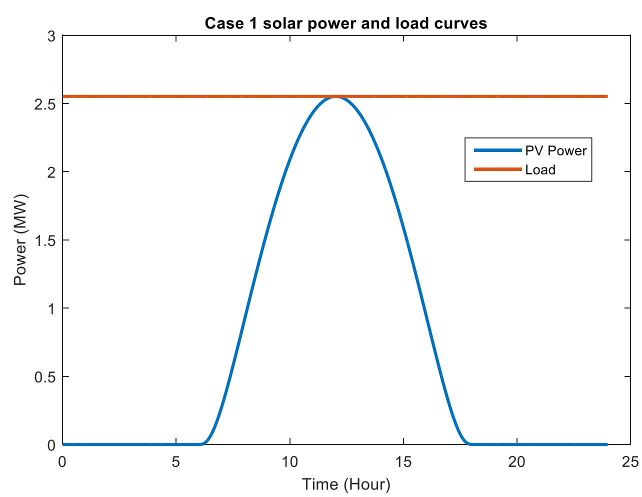

Figure 4: Solar and load curve for Case 1

The load power is assumed to be at the maximum point of the solar power curve for the default case. The LCOE for the default case is:

$$LCOE_{basecase} = \frac{C_{total\_case1}}{E_{total\_case1}} = \frac{C_{PVdirect}}{E_{PVdirect}} \quad (30)$$

In Case 2, additional PV capacity is invested into the system. However, there is no storage device. Therefore, the surplus energy will be wasted. The shaded area is the extra solar energy produced in the system that consumed by the load compared to Case 1. Figure 5 shows the visual representation of Case 2. E_{total_case2} is obtained by taking away $E_{surplus}$ from the total energy production from PV, E_{PV2} due to no energy storage present in the system.

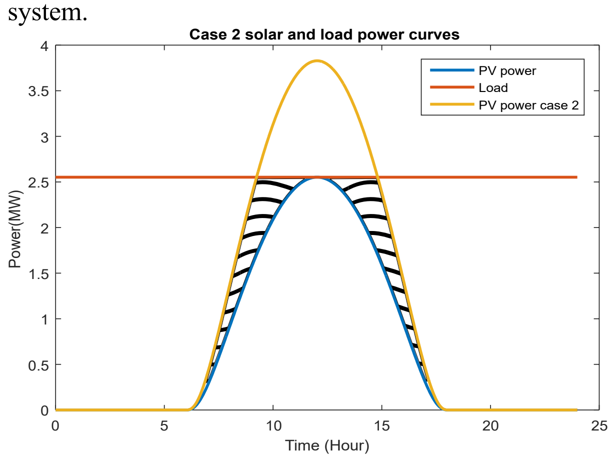

Figure 5: Solar and load curve for Case 2

The marginal LCOE from Case 1 to Case 2 is:

$$LCOE_{marginal(1-2)} = \frac{\Delta C}{\Delta E} = \frac{C_{total\_case2} - C_{total\_case1}}{E_{total\_case2} - E_{total\_case1}} \quad (31)$$

$$\text{where } E_{total\_case2} = E_{PV2} - E_{surplus} \quad (32)$$

In Case 3, further investment is put into the system as compared to Case 2 by including EES. The surplus energy will be stored in the EES and consumed by the load. Figure 6 shows the visual representation of Case 3. The marginal LCOE from Case 2 to Case 3 is:

$$LCOE_{marginal(2-3)} = \frac{\Delta C}{\Delta E} = \frac{C_{total\_case3} - C_{total\_case2}}{E_{total\_case3} - E_{total\_case2}} = \frac{(C_{EES} + C_{total\_case2}) - C_{total\_case2}}{E_{total\_case3} - E_{total\_case2}} = \frac{C_{EES}}{E_{EES}} = LCOS \quad (33)$$

The marginal LCOE from Case 2 to 3 can be deduced into LCOS as given in Equation (6).

A single combination investment of additional PV capacity and storage can be applied to Case 1. The marginal LCOE from Case 1 to Case 3 is provided in Equation (34).

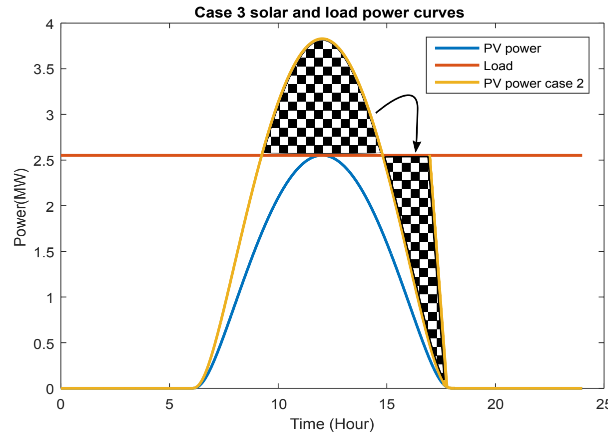

Figure 6: Solar and load curve for Case 3

$$LCOE_{marginal(1-3)} = \frac{\Delta C}{\Delta E} = \frac{(C_{total\_case2} - C_{total\_case1}) + C_{EES}}{(E_{total\_case2} - E_{total\_case1}) + E_{EES}} \quad (34)$$

A sensitivity analysis has been conducted by varying the PV rated capacity. Case 1 consists of a solar farm with rated capacity of 2.5 MW, an arbitrary size used for the initial rated capacity of the solar farm. The calculated peak output power from the PV farm is 1.9 MW. As no surplus energy is available for case 1, the load curve will have a peak of 1.9 MW. This real-life load profile will be fixed throughout the sensitivity analysis for the study. The storage system used is VRB with storage capacity of 3 MWh. The storage capacity is determined by calculating the maximum surplus power for the system. As reported in [66], the current discount rate for PV is 6-9%. The discount rate could be as much as 2-3% lower over the next decade, and could fall by a further 1-2% by 2040. A discount rate at 5% is used to be in line with the best discount rate for PV systems in Kenya [59]. The resultant $LCOE_{basecase}$ for the system is \$0.093/kWh. The results from the sensitivity analysis on marginal LCOE, $LCOE_{system}$ and LCOD are presented in Figure 7.

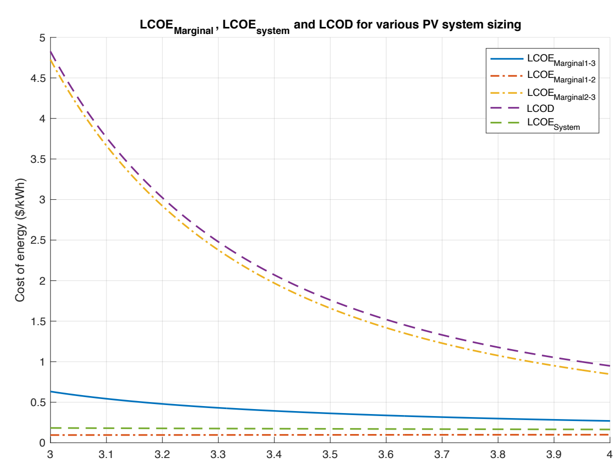

Figure 7: Marginal LCOE, LCOD and $LCOE_{system}$ with respect to PV capacity

It is noted that the value of $LCOE_{system}$ is different from the total of $LCOE_{basecase}$ and $LCOE_{marginal(1-3)}$, as the summation of Equations (30) and (34) does not equal to Equation (27). The LCOD and $LCOE_{marginal(2-3)}$ grows exponentially when the PV capacity is reduced. This is consistent with the LCOS for pumped storage provided in [67], where the LCOS will experience an exponential decrease with an increase in energy discharge from the storage system. This is due to the storage will store less energy with less surplus PV power. It is observed that the $LCOE_{marginal(2-3)}$ is less than LCOD, as LCOD takes account of the cost for the fraction of solar array used to provide energy for the EES. $LCOE_{marginal(1-2)}$ experiences an increase as the PV capacity increases, due to the energy wastage for not utilizing the surplus energy. $LCOE_{system}$ will decrease with an increase in PV capacity as the energy is stored and utilized. $LCOE_{marginal(1-3)}$ is less than $LCOE_{marginal(2-3)}$ and LCOD due to the inclusion of the additional PV capacity and surplus energy in system from Case 1 for non-storage. The $LCOE_{marginal(1-2)}$ is of higher value than the Lazard's result of LCOS in Table 2. As explained previously, Lazard has made an assumption that the storage system is used at full capacity at all times. In a PV hybrid system, the storage system will seldom be used to the maximum and the energy depends on surplus power. The following phenomenon can be observed.

1. System without storage attracts a small LCOE but naturally at a higher risk of security of supply and the marginal LCOE will increase with the increase of PV capacity. This signifies the cost of system will increase with additional PV capacity.
2. LCOD and $LCOE_{marginal(1-2)}$ can experience a decrease with the increase of PV capacity. The EES will deliver more energy as the surplus energy increases.
3. From investment point of view, it can be seen that it is important to add a battery as a component of the system rather than adding it in a later stage. The costs for separating the system can be high compared to considering the costs as a whole.

5.4. *LCOD and $LCOE_{system}$ for VRB and Li-ion battery*

A scenario has been developed with the load and generation data from two African countries. The national load curve has been down-sized with the peak load at 2 MW to represent a load demand for a typical community in Africa. The rated capacity of the PV farm is 5 MW. The calculated capacity factor for the PV system are 12.02%, 11.67%, 12.26% and 12.61% for years 2009, 2010, 2011 and 2012 respectively. The purpose of this study is to calculate the $LCOE_{system}$ and LCOD for a real-life renewable energy system with storage. $LCOE_{system}$ is the LCOE for the combined assets, PV and EES. Two types of dominant EES technologies, Li-ion and VRB are studied. In this study, three ranges of costs values are used to determine the cost of electricity for LCOD and $LCOE_{system}$. These are lower bound, upper bound and the medium bound cost. The cost calculation is performed for each year of the four years of data. Sensitivity analysis is conducted for a range of discount rates. One of the vital input parameters for LCOE calculations is the value of the discount rate. The discount rate essentially takes into account the time value of money, through monetary depreciation as well as the investments risks. PV systems are considered much higher risks when compared with traditional power plants, and therefore they will be at higher discount rates.

The results are summarized in a form of box plot in Figures 8 and 9. With a careful inspection in Figure 8, it can be seen that LCOD is higher with Li-ion than VRB for both the median and minimum value when the discount rate is less than 8%. The discount rate needs to be 10% or more when LCOD for VRB is higher than that for Li-ion.

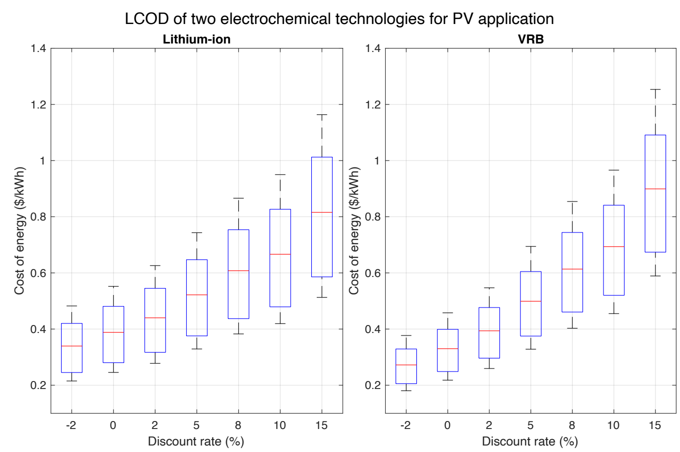

Figure 8: LCOD for Li-ion and VRB at various discount rates

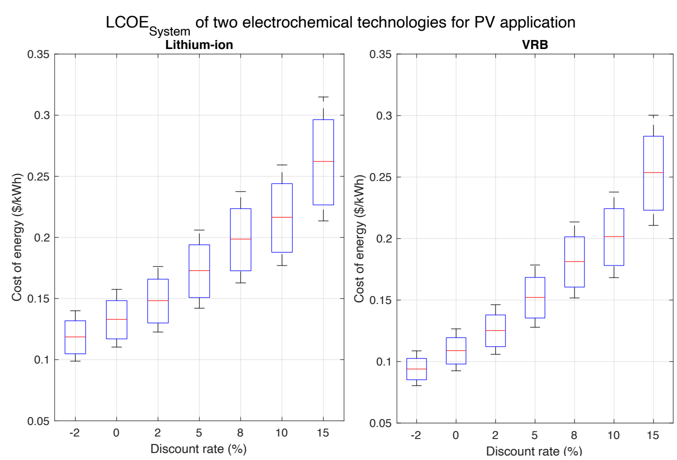

Figure 9: $LCOE_{system}$ for Li-ion and VRB at various discount rates

The results for $LCOE_{system}$ at various discount rates for the two EES technologies are given in Figure 9. Also with careful inspections, LCOE is lower for VRB in all the studied discount rates and price range consideration.

Although Li-ion battery has a higher round-trip efficiency than VRB, the lifetime of the system is considerably shorter and this significantly affects the $\mathrm{LCOE}_{\mathrm{system}}$.

From Figures 8 and 9, it could be understood that adding EES to the system can increase the $\mathrm{LCOE}_{\mathrm{system}}$ at high discount rate. Also, the cost variation is wider. This is due to the capital and installation cost of the system being more dominant. At low discount rate, the value of energy will have less depreciation with respect to time.

6. Discussion

Successful operation of hybrid system requires continuous real-time balancing of supply and demand including losses. With the increasing amount of storage in the hybrid systems, it is crucial to analyze the economic values to determine the feasibility of such systems. The proposed methods could also be used to assess different EES technologies although in the paper, only VRB and Li-ion battery cases were given as examples. This method provides decision makers with a practical approach to consider the competitiveness of each technology for a given application with renewables in particular. From Figures 8 and 9, it can be seen that the results of LCOD and $\mathrm{LCOE}_{\mathrm{system}}$ are given in a range of values due to the uncertainty in the annual energy production from the PV system and the range of EES costs. Parameters such as round-trip efficiency, EES lifetime, discount rate have all been included in the studies and the functionality of the method has been shown with real-life data. It is noted that LCOS and LCOD will be higher than the $\mathrm{LCOE}_{\mathrm{system}}$.

For different types of EES, the state of charge will have a different impact on energy storage, as such the potential in using the battery fully will be different on each case. Therefore, the energy delivered and stored could affect the system performance as a whole, that is, the overall LCOE will be changed. State of charge and discharge and cycles could be considered in future work. This should also be studied even though energy balancing is not considered in the present paper.

Although the analyses show that the LCOD is cheaper for Li-ion than that for VRB at present, the $\mathrm{LCOE}_{\mathrm{system}}$ as a system could be lower for VRB compared to Li-ion. Since energy storage has many applications for power systems such as grid balancing and frequency regulation, the LCOS and LCOD will be significantly different due to the operating conditions of the EES. The future work would be to analyze the storage costs for different applications and services. With additional irradiance data, it will be possible to have a better determination of the cost in deployment of renewables system with integration of energy storage system. Table 5 presents the comparison of the technology and economic aspect of the two EESs. At present, the capital and variable O&M costs are higher for Li-ion battery. The lifetime is generally higher for VRB compared to Li-ion battery. There is a significant difference in the round trip-efficiency for the two batteries, where Li-ion can reach up to 95% and VRB can reach 85% at the best. Table 6 provides a comparison of the pros and cons and the maturity of the EES technologies. It is learnt that thermal management is a major issue in using Li-ion battery for grid scale systems. VRB is currently the most mature technology for grid scale storage application and is currently available for commercial use [43, 68]. Additional sensitivity analysis will be a future work by considering the extremes of costs, lifetime and round-trip efficiency in order to provide a more accurate representation of the levelized costs for the two EESs.

Demand response based on dynamic pricing such as time-of-use (TOU) tariff can be used in conjunction with EES to increase the usefulness of surplus PV generation [69]. However, TOU are not normally used for PV systems due to its lack of dispatchability and imperfect predictability. There are companies offering energy storage options to Hawaii customers that own PV systems, in order for the state to meet 100% renewable energy goal [70]. The study of optimal use of tariff structures and EES dispatch techniques to reduce the PV system and EES levelized costs may be of future significant interests and research work needs to be done in this area.

The proposed LCOD and $\mathrm{LCOE}_{\mathrm{System}}$ were used for studying an optimal sized stand-alone PV and EES with Anaerobic digestion biogas power plants presented in [71]. The techno-economic study of a grid-connected hybrid system will be a future work.

Table 5
A review on technology and economics based information for VRB and Li-ion battery in grid scale application.

	VRB	Li-ion battery
Capital cost	460-1600 ($/kWh) 600-1750 ($/kW) [9, 44, 45, 63, 72-74]	500-2500 ($/kWh) 900-3500 ($/kW) [9, 44, 45, 63, 72-74]
O&M cost	Fixed: 3.6-18.3 ($/kW-yr) Variable: 0.21-2.96 ($/MWh) [9, 44, 63, 72]	Fixed: 2.12-14.5 ($/kW-yr) Variable: 0.42-5.93 ($/MWh) [9, 44, 63, 72]
Lifetime	10-20 years [9, 10, 44, 45, 63, 72-75]	5-15 years [9, 10, 44, 45, 63, 72-75]
Round-trip efficiency	75-85% [9, 10, 44, 45, 63, 72-75]	85-95% [9, 10, 44, 45, 63, 72-75]

Table 6
A review on commercial-socio based information for VRB and Li-ion battery in grid scale application.

	VRB	Li-ion
Advantages	• Power and energy ratings are independent and highly scalable • No degradation in energy storage capacity • High cycle life, up to 10,000 cycles • Capable to achieve very deep cycle, i.e. 100% depth of discharge	• High energy and power density • Low self-discharge • High round-trip efficiency
Disadvantages	• High balance of system costs • Reduced efficiency due to rapid charge/discharge • Energy density and power density are generally lower compared to other EESs	• High capital cost • Requires battery management system for operation, management and against cell degradation • Limited thermal tolerance • Thermal run away due to electrolyte decomposition
Commercial maturity	Demonstration/early commercialized	Demonstration
Technological maturity	Development phase	Development phase
References	[9, 10, 43-45, 63, 68, 72-78]	[9, 10, 43-45, 63, 72-75]

7. Conclusions

This paper has provided a review on LCOE for PV and PV hybrid systems. From the basic principles, the LCOD and the LCOE for PV systems with storage have been proposed. A more accurate calculation of LCOE for VRB and Li-ion battery, known as the LCOD, is given in this paper by taking the cost for energy generation into account. The long-term economic impact for storage and PV system is provided and discussed with marginal LCOE. The findings reveal that with the present costs and technical specification, VRB has a lower LCOD in relation to Li-ion at low discount rate for the energy storage application in PV systems.

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