# Techno-economic Feasibility Analysis and Levelized Cost of Solar Photovoltaic Electricity

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**Summary:** There is a possibility for mass-scale deployment of Photovoltaic (PV) technology in stand-alone and grid-connected power systems. To deal with technical constraints of PV, 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. The challenge arises in analyzing the economic projections on PV and EES systems. Commonly, the cost of a generating asset or the power system is evaluated by using Levelized Cost of Electricity (LCOE). From the investment perspective, the economics of energy systems with EES can be challenging to appraise due to EES not being an electrical generator. Here, a Kenyan energy system consisting of PV, Anaerobic Digestion biogas power plant (AD) and EES is used as a case study with EES energy capital cost at 200 $/kWh. Sensitivity analysis is conducted for various PV and EES capacity to examine the system's LCOE with and without energy storage degradation cost. Degradation cost needs to be accounted for in techno-economic analysis to inform system investors. Finally, the chapter introduced an ongoing standard development for PV system techno-economic appraisal: IEEE P2814 Recommended Practice on Techno-economic Metrics for Hybrid Energy and Storage System.

**Keywords:** Technical standard, energy storage, storage degradation cost, levelized cost of electricity, solar photovoltaic, anaerobic digestion

## 1. Introduction

The installation capacity of solar Photovoltaic (PV) energy systems is growing globally in order to decarbonize energy [1]. PV systems are particularly attractive for locations where an abundance of solar insolation is available. At the same time, the composition of energy supply is transforming at an ever-increasing rate. This is due to the availability of novel energy generation and storage technologies, information and communications technology, novel business models and supporting energy policies [2].

The techno-economic viability is a fundamental question to be examined for any energy generation project, in particular to compare energy production methods (e.g. wind and nuclear). An energy system typically operates for a long lifetime, such as a PV system that may last for 25 years [3]. The techno-economic feasibility analysis and levelized cost of solar PV electricity are not simply the concern of a PV system, but needs to consider other energy system assets which supports the PV system, including relevant power converters and Electrochemical Energy Storage (EES) [3]. The auxiliary assets ensure that the energy system is operating in a reliable and cost-effective manner.

This chapter aims to examine the LCOE for a PV system when connected with an EES and Anaerobic Digestion biogas power plant (AD) biogas power plant. The context will be based on a stand-alone energy system in Kenya. Several research works have provided a strong motivation for hybrid energy systems (with diverse energy sources) in particular to offset the negative impact from intermittent PV power generation and increase energy security [4, 5]. In particular, the cost of EES degradation is not well considered in present techno-economic appraisals of PV energy systems with EES. To make techno-economic results meaningful, the appraisal techniques should incorporate the cost of EES degradation. This chapter reports the on-going work of the Institute of Electrical and Electronics Engineers (IEEE) P2814

Recommended Practice on Techno-economic Metrics for Hybrid Energy and Storage Systems which aims to provide a generic framework for energy system techno-economic appraisal. Section 2 provides a literature review on the works conducted to examine the LCOE for PV systems. The precise terminology of LCOE for PV systems and how LCOE is considered for the PV system with EES is given in Section 3. Based on real-life solar irradiance and load demand data obtained from Kenya, case studies are presented in Section 4 to examine the LCOE for a PV-AD-EES hybrid energy system considering the impact of EES degradation. Section 5 presents a new technical standard, IEEE P2814 Recommended Practice, to address the need for technical standards in techno-economic appraisal. Finally, the conclusion is provided in Section 6.

## 2. Literature Review

There are several research projects that were conducted to examine the Levelized Cost of Electricity (LCOE) for PV systems. Wang et al. [6] benchmarked the LCOE for several PV systems considering same installation areas but with dissimilar efficiencies for modules. In addition, the panels were considered to be fixed tilt, 1-axis tracking or 2-axis tracking. A key discovery is that at a specific module price ($/W), higher efficient PV modules reduced the LCOE of the system. Another discovery was that to achieve an LCOE target, the PV module efficiency presents a lower bound that cannot be counterbalance by the module price. The final discovery was that the 1-axis and 2-axis tracking installations give reduced LCOEs than fixed tilt installations. In summary, the LCOE reduces with additional electricity production such observation satisfies Equation (1) presented in this chapter. Ondraczek et al. [7] presented the LCOE calculations for PV systems in 143 countries. The dissimilarities in both the financing cost and solar resource were accounted for. The authors identified that the LCOE values are largely affected by geographical location, as a result of regional cost discrepancies and changes of irradiance resources, which directly affects the electricity production [8].

Commercial and free software packages are available to compute the LCOE for solar PV systems. The LCOE of PV systems were studied in [9, 10] with the System Advisor Model (SAM) created by National Renewable Energy Laboratory. SAM [11] works as a financial model developed to aid decision making for stakeholders working in the low-carbon energy sector. Presently, SAM does not support the modelling of stand-alone or off-grid power systems. Table 1 presents the comparison of LCOE studies features of well-known hybrid low-carbon energy system software packages.

**Table 1**
LCOE features for the well-known low-carbon energy system software packages [12].

| | HOMER Pro | RETScreen Expert | System Advisor Model (SAM) |
|---|---|---|---|
| Creator | HOMER Energy LLC | Natural Resources Canada | National Renewable Energy Laboratory |
| Licence | Priced | Free | Free |
| Overview | • Performs hourly interval data analysis for enhanced modelling and accounting intermittency of renewables<br>• Runs brute-force system optimization for assets sizing<br>• Simulates hourly solar data based on monthly average clearness index or daily radiation data if real-data is inaccessible | • Studies systems performance based on statistical monthly average data<br>• Provides prolific quantity of geographical data linked to the NASA's climate database | • Works for grid-connected systems only and does not work with stand-alone system analysis<br>• Snow and shading data can be accounted for in the study to simulate the reduced PV energy production<br>• A database of hourly solar irradiance data is available from NREL database |
| Energy storage model available | Customizable batteries, Flywheel, hydrogen, and flow batteries | Thermal storage tank | Li-ion and Lead-acid |
| Is LCOE calculation available? | Yes | No | Yes |

## 3. Methods for Levelized Cost of Electricity and Techno-economic

### 3.1 Levelized Cost of Electricity

The LCOE is a measure of costs with the purpose to benchmark alternative electricity generation methods on an equivalent basis. An LCOE analysis is an economic appraisal of the average accumulated cost to construct and operate a power-generating asset throughout its lifetime, divided by the accumulated energy production of the asset during lifetime. The LCOE is the minimum cost that the electricity generated can be sold for in order to break even across the project lifetime. LCOE study can provide benchmark of dissimilar technologies (e.g., natural gas, solar, wind) of different life spans, installed capacity, capital cost, risk, and return. The common equation for LCOE [13, 14] is given in Equation (1) and is the ratio of the system lifecycle cost to the system lifetime energy production.

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

The two typical levelized costs calculation methods are namely the "discounting" method, and the "annuitizing" method [12, 15]. With the discounting approach, the stream of electricity productions and real future costs are denoted as $E_t$ and $C_t$, in year *t*, and are discounted with discount rate *r* to reflect the present value (*PrV*). The costs in the present value are then divided by the present cost of lifetime electricity production. The levelized costs computed with the ''discounting'' approach, $\mathrm{LCOE}_{\mathrm{Discount}}$, is given in Equation (2).

$$\mathrm{LCOE}_{\mathrm{Discount}} = \frac{PrV(\mathrm{Costs})}{PrV(\mathrm{Production})} = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \qquad (2)$$

For the ''annuitizing'' approach as depicted in Equation (3), the present value of the series of costs during asset's lifetime is first computed. Consequently, the present value is transformed to a comparable annual cost with a standard annuity formula. The comparable annual cost is then divided by the average yearly electricity production over the lifetime of the plant.

$$\mathrm{LCOE}_{\mathrm{Annuitizing}} = \frac{\mathrm{Ann(Costs)}}{\mathrm{Ave(Production)}}$$

$$= \frac{\left(\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}\right)\left(\frac{r}{1-(1+r)^{-n}}\right)}{\left(\sum_{t=1}^{n} E_t\right)/n} \qquad (3)$$

Both approaches provide the same levelized costs, under the condition that the discount rate adopted for discounting electricity production and costs in Equation (2) is identical as that utilized in computing the annuity factor in Equation (3). Both equations will give identical levelized costs when the yearly energy production is fixed across the lifetime of the asset. The annuity approach transforms the costs to a consistent flow across time. Such method is suitable where the rate of electricity production is fixed over time. Many researchers assume that the yearly electricity production is fixed in LCOE calculations. Such calculation is useful to provide a rough indication of techno-economic feasibility. In reality, the yearly energy production of renewable technologies including PV would be different, as the energy production changes from minute-to-minute largely caused by changes in the renewable resources' availability. As such, it is more suitable to adopt the discounting approach when computing the LCOE for renewable sources.

It is worth noting that when computing the LCOE, the summation does not begin from $t = 0$ to include the project cost in year one [12, 16]. The cost in the first year should not be discounted to reflect the present value and there is no system electricity production to be reduced due to system degradation. Branker et al. [16] reviewed the methodologies of computing the LCOE for solar PV and presented the equation for computing the LCOE for a PV system, as depicted in Equation (4).

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

The initial investment $I_t$ is a single cost and should not be discounted, hence it is factored out from the summation. The LCOE also accounts for the degradation factor of PV modules. The electricity produced in a particular year $E_t$ is the rated electricity production per year $S_t$ multiplied by the degradation factor (1 − d), which reduces the electricity production with time. The operation costs, maintenance costs, and interest expenditures are denoted as $O_t$, $M_t$, and $F_t$ respectively.

LCOE is considered as an objective function in several studies concern with low-carbon stand-alone (not grid-connected) systems. Alternative costs are included in LCOE studies, including the value of lost load-related costs in LCOE was examined in [17]. Díaz et al. [18] examined the optimal installment time of PV system in the LCOE to address the challenge with the stationary nature of classic LCOE, i.e., the installment is performed today. The LCOE calculation framework proposed by Díaz et al. [18] dynamically explores for a future time where the LCOE would be the least. The research projects have made contributions to LCOE calculation. It is identified that the energy storage has not been accounted for in the PV system.

### 3.2 Techno-economic studies for PV systems with electrical energy storage

Electrochemical Energy Storage (EES) provides additional controllability to balance energy supply with demand, by storing surplus electricity produced by renewables and is discharged in the future. This essentially smooths the energy system operation by working as an supplementary generator or load and to make greater use of surplus generation and minimizing power curtailment [19]. Due to the rapid response time, e.g. milliseconds with EES, the short-term negative events including voltage dip/surge and over/under frequency that emerge in a power system can be overcome by absorbing or releasing energy from the EES system. State of Charge (SOC) and Depth of Discharge (DOD) need to be considered for EES in hybrid energy systems optimal planning and operation.

It is necessary to compute the energy amount that could be stored and to be dispatched at any moment when EES is included in an energy system. With several parameters including important ones such as C-rate, temperature, and change in SOC that may affect the EES' state of health and normalized discharge capacity; a generic model that calculates the capacity and power fade is difficult [20].

Several EES technologies are available including electrical, mechanical, electrochemical, thermal, and chemical EES systems [21]. As such, when benchmarking EES options, technical and economic factors need to be compared and considered in a non-bias perspective.

For PV and EES systems, the context and parameters that calculate the LCOE need to be strictly clarified otherwise an unfair comparison will be made. As such, the following section examines the LCOE for a hybrid energy system with accounting the EES degradation costs. EES degradation has a great impact on the storage performance. It affects the cell's capability to hold energy and meet electrical demands [20]. Lithium-ion (Li-ion) cells degrade from operation, i.e. charging and discharging and environmental conditions exposure. The degradation can be described as cycle-life degradation and calendar aging, describes as follows [22]:

- Cycle-life degradation: Cycle-life loss is created by storage operation, which is affected by charge/discharge rate, i.e. C-rate, temperature, and energy throughput. The degradation is created by mechanical strain in the lithium plating or electrode active materials. Degradation is increased by deep discharges, high C-rate, temperature, and energy throughput, For example, $LiFePO_4$ storage can typically achieve 2100 cycles at 30% DOD or 670 cycles at 90% DOD [4]
- Calendar aging: This category of degradation is not affected by the charge-discharge cycling. Calendar aging is generally caused by time and temperature exposure. This is caused by the variation in passivation layers at the electrode-electrolyte interfaces.

In a techno-economic analysis for grid applications EES systems, the revenue and cost can be divided into four classes [23], known as:

- Monetary profits and savings: Revenues or savings gathered according to power, energy or reliability relevant applications;

- Investment cost: Direct storage cost including a battery, casing, and electrolyte. Also, the grid coupling cost such as the transformers and power electronics;
- Operational cost: Indirect cost including conversion losses due to component's efficiency, auxiliary consumptions including thermal management systems, and direct operational cost including insurance and labor; and
- Degradation and replacement cost: Battery performance degradation due to greater resistance and capacity fade, and aging materials replacement cost for power electronics and the battery. Replacement cost should 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 [24]. Recently, HOMER Energy has provided the Advanced Storage Module which can personalize a storage system and takes the changes in storage capacity with temperature and variable DOD for cycle-life [25]. The prominent energy system packages HOMER Energy and RETScreen do not provide Levelized cost of storage studies, which may be useful in comparing storage options particularly the "energy delivery" lifetime cost in $/kWh [12, 26]. LCOE allows comparing electricity generation sources and systems.

## 4. Case Study: LCOE for PV Hybrid Energy System with Storage Degradation

The hybrid system adopted for the case studies is a hybrid energy system consisting of an Anaerobic Digestion biogas power plant (AD), EES, and a PV system. 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 depicted in Fig. 1 uses a threshold indicator that will prioritize the dispatch of EES when the battery is above a predefined SOC, namely $SOC_{\text{Threshold}}$. The study interval is at 15min/sample for 22 years of Kenya Turkwel Gorge Dam irradiance data [4].

In this case study, the discount rate is at 6 % [3, 12] and the PV capital cost is at 0.36 $/W [27]. Due to the maturity of EES, the capital cost can reach 200 $/kWh within 2025 [1]. The system considered has an AD biogas generator, rated capacity at 2.4 MW with a Kenyan load curve at 2 MW peak [4]. A $SOC_{\mathrm{Threshold}}$ of 30% is set to frequently cycle the EES system. The number of charge cycles available for $LiCoO_2$ at various depth of discharge can be identified in [4, 28]. All cost assumptions are given in Table 2 in [4] unless predefined in this chapter.

The SOC constraints are imposed and the power balance is attained with the operating regime. For the scenario where the degradation cost is not considered, $C_{\mathrm{EES}_{\mathrm{DegkWh}}}$ is excluded in the LCOE calculation. The mathematical formulation for computing the degradation cost with a capacity fade model is available in [4]. A fixed 'operational cost' is considered for EES system energy discharge at 0.42 $/MWh [4]. System LCOE signifies the LCOE for the hybrid system which includes the lifetime system, i.e. AD, EES, PV, inverters and charge controllers costs and energy productions that fulfil the energy demand. The mathematical modeling for the cost and energy calculations can be found in [4].

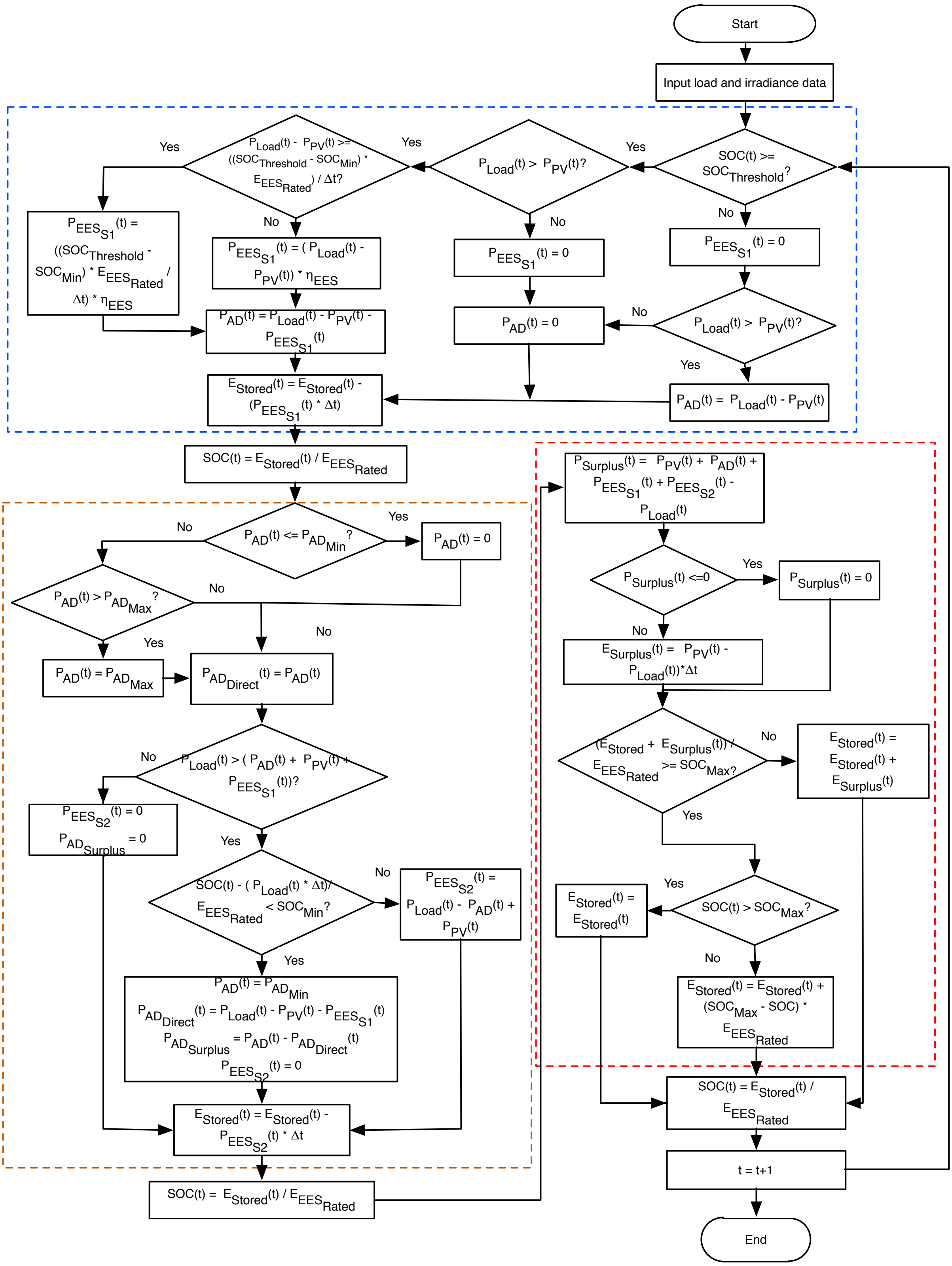


Fig. 1. PV-AD-EES hybrid energy system operating regime [4]

### 4.1 Case Study 1: Sensitivity Analysis on PV and EES Rated Capacities

This case study determines how the System LCOE at various EES capacity (MWh), and PV rated capacity (MW) when degradation cost is included. EES energy capital cost is at 200 $/kWh. Figures 2 and 3 depict the results for the System LCOE when degradation is considered and not considered respectively. Intuitively, the System LCOE is higher when degradation cost is considered. For both cases, the minimal LCOE is attained when no EES is installed and have a 1.5 MW to 2.5 MW of PV rated capacity. The little capital cost and negligible marginal cost for PV can offset the biogas fuel cost. Storing the surplus energy produced by PV for future consumption is not the most economic solution as the capital cost and degradation cost for EES. The maximal LCOE appears when the PV rated capacity is at 9.5 MW with EES at rated energy capacity at 0.5 MWh. This may be caused by the waste of surplus energy produced by PV that is not consumed but the high capital cost exists. When degradation cost is not considered as shown in Fig. 3, the nonlinear mathematical relationship between cycle-life degradation (cycles) and cost ($) is excluded in the techno-economic analysis. When the degradation cost is considered, the high EES rated capacity can provide a high LCOE which is not shown in the case when degradation cost is excluded.

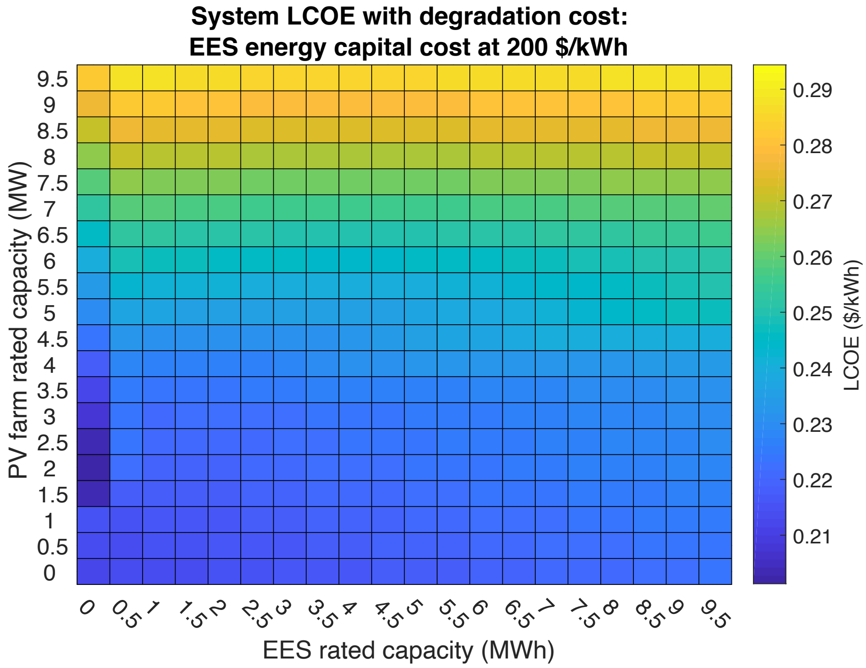


Fig. 2. System LCOE with degradation cost considered

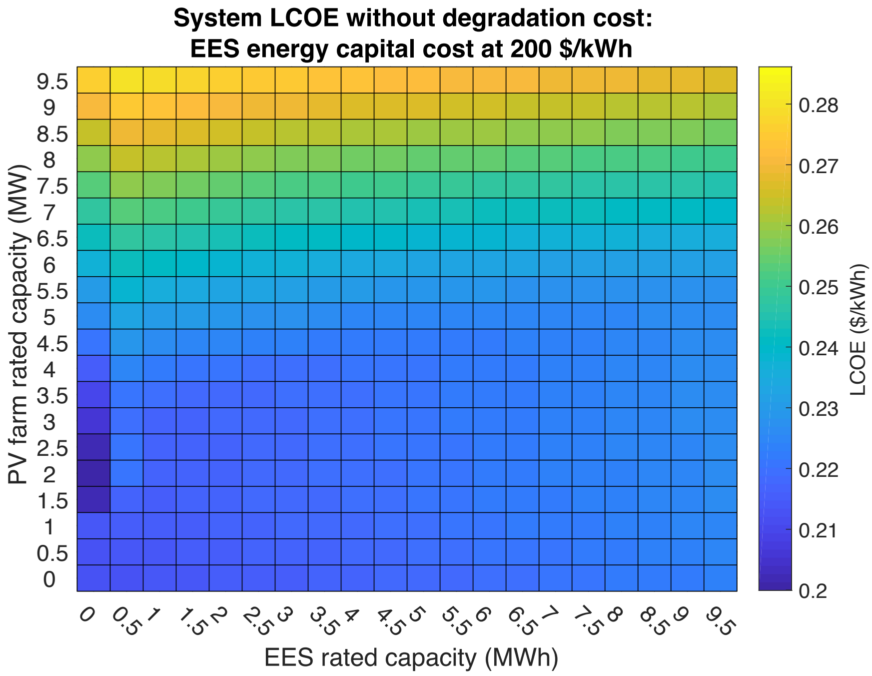


Fig. 3. System LCOE with degradation cost not considered

### 4.2 Case study 2: Sensitivity Analysis on SOC Threshold

This case study shows how the dispatch priority for EES will impact on the System LCOE when degradation cost is considered. The PV rated capacity is at 5 MW and the EES energy capacity is at 5 MWh [4]. Fig. 4 presents the results for the sensitivity analysis with difference values of $SOC_{\text{Threshold}}$. The diamond and circle symbols represent the maximum and minimum LCOE, respectively.

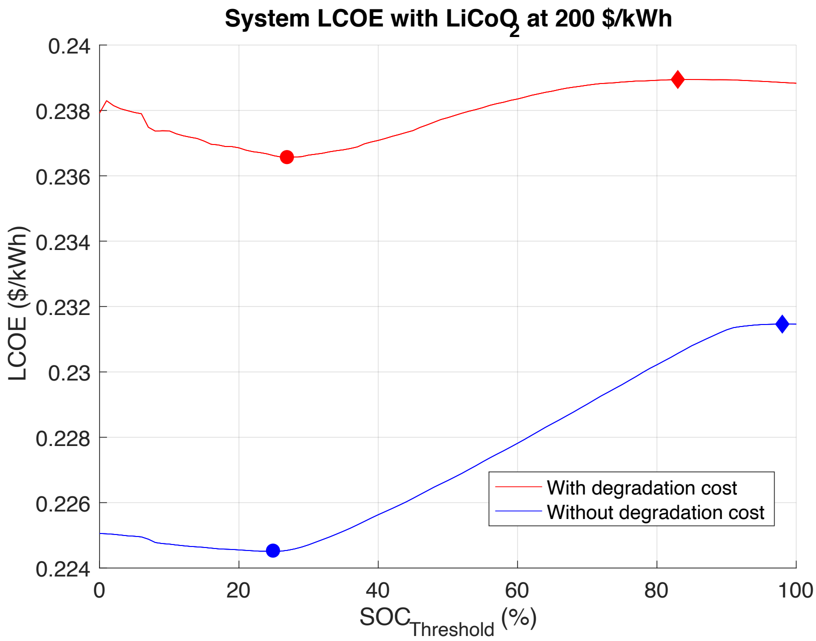


Fig. 4. System LCOE studies with various $SOC_{\text{Threshold}}$

The maximal and minimal LCOEs appear at comparable $SOC_{\text{Threshold}}$ for the two studies. It is identified that the minimal LCOE is attained when the $SOC_{\text{Threshold}}$ is at 20-30%, indicating the frequent use of EES ideal. The LCOE increases when the $SOC_{\text{Threshold}}$ value further reduces, this may be due to the cost accumulated with AD dispatch when the EES SOC is too low. It is impossible to discharge the EES when system energy deficit occurs. If the degradation is not considered, the frequent usage of EES is ideal since it maximizes the asset usage and the "fuel cost" for EES is minimal as benchmarked to other energy sources, since the marginal cost for PV is negligible.

## 5. Standardization of Techno-economic Methodologies for Solar PV Energy Systems

To address emerging energy challenges and to accommodate new technologies and practices, many technical standards are in development for sustainable energy technologies including fuel cells, photovoltaics, dispersed generation, and ES [2]. Technical standards help users to verify that the service or produce is performing as intended. They also promote interoperability, create uniform design, installation and validation techniques, help protect users and their environment, and increase the quality of life of numerous communities and individuals worldwide [2].

The IEEE P2814 Recommended Practice on Techno-economic Metrics for Hybrid Energy and Storage Systems fills a critical gap in the current energy sector landscape by developing a techno-economic framework to benchmark various ES technologies considering different energy generation and service scenarios [29]. The practical aspect of the standard includes the application of techno-economic terminologies to assist a range of stakeholders in assessing possible economic viabilities, constraints, processes for enhancement, and additional research and development needs for various low-carbon power generation and energy storage technologies. The scope and purpose of the standards project are as follows [29]:

**Scope:** This standard defines techno-economic terminologies used in the development, construction, and operation of renewable energy and electrical energy storage systems.

**Purpose:**

- There is no consistent definition of techno-economic terms that have arisen in the evolution of renewable energy and ES systems
- There is a need to define techno-economic terminology so that stakeholders can use a common language when planning standards and for understanding published industrial and technical reports
- This standard is intended to serve as a basic reference for policymakers, developers, and users of such systems, for planning industry standards, and the interpretation of published technical and industrial reports
- The envisioned stakeholders for the standard include financial advisors, engineers, policy-makers, entrepreneurs, academics, researchers and those with a general interest in energy systems and ES systems

Identifying the power flows for various timescales and technologies is necessary to study low-carbon electricity systems with energy balancing technologies (e.g., EES and demand-side response) [30]. EES may enhance not only the economics of real-time system operation by minimizing costs, but also reduce the investment into generation and network capacity in the long-term.

The ongoing work for the IEEE P2814 Recommended Practice includes [29]:

1. To continue with the techno-economic framework development: The Working Group has determined some necessary inputs for the techno-economic framework including the EES degradation cost presented in this chapter. The Working Group will be continuing to determine and create data lists by considering availability and relevance of various emerging energy technologies, including novel solar PV panels.
2. To determine the recommended practices for power flow analysis with "new" energy technologies including energy storage. The framework will emphasise on the importance of power flow studies to provide credible techno-economic feasibility analysis and levelized cost of solar photovoltaic electricity studies, by considering the short-term system dynamics.
3. To conduct case studies (e.g., grid and off-grid) with the proposed framework. At present, some relevant case studies to show the practicality of the framework including techno-economic studies for microgrid with demand response and PV systems.
4. To propose or revise techno-economic metrics for the comparison of different energy technologies. It is evident that the traditional LCOE metric widely used for dispatchable sources needs to be revisited.

The Project Authorization Request was submitted on 14th Feb. 2019, approved on 21st May 2019, and with an expiration date on 31st Dec. 2023 [29]. As of Sept. 2020, the Working Group has approximately 20 active members from academic institutions and industries, from global including the USA, UK, Australia, and China.

## 6. Conclusion

The techno-economic feasibility analyses and levelized cost of solar photovoltaic electricity studies are challenging to perform and give accurate results. The power availability from solar PV is inherently uncertain, as such, EES could act as an energy buffer to supply power to the system and absorb power from the system. This chapter firstly present an overview of the LCOE metric for PV systems. LCOE is crucial to evaluate the electricity generation (e.g., wind, solar PV, and concentrate solar power), and defined as the minimum cost that the electricity generated can be sold for in order to break even across the project lifetime. At present, the technical features of energy storage such as batteries are not well examined in techno-economic studies for hybrid energy systems. In this chapter, the LCOE is examined for a hybrid energy system (PV, AD and EES) in a community in Kenya. Based on a case study with real-life data, the minimum LCOE for the hybrid system is achieved when the operating regime has a threshold SOC at 25% when the degradation cost is not accounted for, and 27% when the degradation cost is accounted for. This signifies that the charge and discharge occasions for energy storage should be kept minimal. Therefore, the AD biogas generator should be used to meet energy demand. It is determined that the maximum LCOE for the system can increase from 0.232 $/kWh to 0.239 $/kWh when the degradation cost is considered in the techno-economic analysis. By not accounting the realistic operating costs including the degradation cost for energy storage, energy planners will be unable to identify the actual cost of electricity delivery. For electrification in rural areas including remote communities in Kenya, it is crucial to evaluate the available electricity generation and storage options.

It is evident that additional effort is needed to research and standardize the techno-economic appraisals for complex energy systems. Hence, the chapter introduced an ongoing standard development: IEEE P2814 Recommended Practice on Techno-economic Metrics for Hybrid Energy and Storage System. This standard defines techno-economic terminologies used in the development, construction, and operation of renewable energy and electrical energy storage systems. This standard is intended to serve as a basic reference for policymakers, developers, and users of such systems, for planning industry standards, and the interpretation of published technical and industrial reports. It is necessary to have a unified techno-economic framework so that stakeholders could make meaningful techno-economic comparisons.

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**References**

[1] C. S. Lai, Y. Jia, L. L. Lai, Z. Xu, M. D. McCulloch, and K. P. Wong, "A comprehensive review on large-scale photovoltaic system with applications of electrical energy storage," *Renewable and Sustainable Energy Reviews,* vol. 78, pp. 439-451, 2017.

[2] C. S. Lai *et al.*, "A review of technical standards for smart cities," *Clean Technologies,* vol. 2, no. 3, pp. 290-310, 2020.

[3] C. S. Lai and M. D. McCulloch, "Sizing of stand-alone solar PV and storage system with anaerobic digestion biogas power plants," *IEEE Transactions on Industrial Electronics,* vol. 64, no. 3, pp. 2112-2121, 2017.

[4] C. S. Lai *et al.*, "Levelized cost of electricity for photovoltaic/biogas power plant hybrid system with electrical energy storage degradation costs," *Energy Conversion and Management,* vol. 153, pp. 34-47, 2017.

[5] D. Wang *et al.*, "Two-stage optimal scheduling of air conditioning resources with high photovoltaic penetrations," *Journal of Cleaner Production,* vol. 241, p. 118407, 2019.
[6] X. Wang, L. Kurdgelashvili, J. Byrne, and A. Barnett, "The value of module efficiency in lowering the levelized cost of energy of photovoltaic systems," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 9, pp. 4248-4254, 2011.
[7] J. Ondraczek, N. Komendantova, and A. Patt, "WACC the dog: The effect of financing costs on the levelized cost of solar PV power," *Renewable Energy,* vol. 75, pp. 888-898, 2015.
[8] J. Hernández-Moro and J. Martínez-Duart, "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution," *Renewable and Sustainable Energy Reviews,* vol. 20, pp. 119-132, 2013.
[9] M. H. Kang and A. Rohatgi, "Quantitative analysis of the levelized cost of electricity of commercial scale photovoltaics systems in the US," *Solar Energy Materials and Solar Cells,* vol. 154, pp. 71-77, 2016.
[10] M. Said, M. EL-Shimy, and M. Abdelraheem, "Photovoltaics energy: Improved modeling and analysis of the levelized cost of energy (LCOE) and grid parity–Egypt case study," *Sustainable Energy Technologies and Assessments,* vol. 9, pp. 37-48, 2015.
[11] System Advisor Model (SAM), National Renewable Energy Laboratory, [Online]. Available: https://sam.nrel.gov.
[12] C. S. Lai and M. D. McCulloch, "Levelized cost of electricity for solar photovoltaic and electrical energy storage," *Applied Energy,* vol. 190, pp. 191-203, 2017.
[13] S. B. Darling, F. You, T. Veselka, and A. Velosa, "Assumptions and the levelized cost of energy for photovoltaics," *Energy & Environmental Science,* vol. 4, no. 9, pp. 3133-3139, 2011.
[14] M. Jakob, "Energy policy: The fair cost of renewable energy," *Nature Climate Change,* vol. 2, no. 7, pp. 488-489, 2012.
[15] G. Allan, M. Gilmartin, P. McGregor, and K. Swales, "Levelised costs of wave and tidal energy in the UK: Cost competitiveness and the importance of “banded” Renewables Obligation Certificates," *Energy Policy,* vol. 39, no. 1, pp. 23-39, 2011.
[16] K. Branker, M. Pathak, and J. M. Pearce, "A review of solar photovoltaic levelized cost of electricity," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 9, pp. 4470-4482, 2011.
[17] S. Mandelli, C. Brivio, E. Colombo, and M. Merlo, "A sizing methodology based on Levelized Cost of Supplied and Lost Energy for off-grid rural electrification systems," *Renewable Energy,* vol. 89, pp. 475-488, 2016.
[18] G. Díaz, J. Gómez-Aleixandre, and J. Coto, "Dynamic evaluation of the levelized cost of wind power generation," *Energy Conversion and Management,* vol. 101, pp. 721-729, 2015.
[19] G. Locatelli, E. Palerma, and M. Mancini, "Assessing the economics of large Energy Storage Plants with an optimisation methodology," *Energy,* vol. 83, pp. 15-28, 2015.
[20] C. R. Birkl, M. R. Roberts, E. McTurk, P. G. Bruce, and D. A. Howey, "Degradation diagnostics for lithium ion cells," *Journal of Power Sources,* vol. 341, pp. 373-386, 2017.
[21] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy,* vol. 137, pp. 511-536, 2015.
[22] C. S. Lai, G. Locatelli, A. Pimm, Y. Tao, X. Li, and L. L. Lai, "A financial model for lithium-ion storage in a photovoltaic and biogas energy system," *Applied Energy,* vol. 251, p. 113179, 2019.

[23] H. C. Hesse, M. Schimpe, D. Kucevic, and A. Jossen, "Lithium-ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids," *Energies,* vol. 10, no. 12, p. 2107, 2017.
[24] C. Bordin, H. O. Anuta, A. Crossland, I. L. Gutierrez, C. J. Dent, and D. Vigo, "A linear programming approach for battery degradation analysis and optimization in offgrid power systems with solar energy integration," *Renewable Energy,* vol. 101, pp. 417-430, 2017.
[25] Advanced Storage Module, HOMER Energy, [Online]. Available: https://www.homerenergy.com/products/pro/modules/advanced-storage.html.
[26] V. Jülch, "Comparison of electricity storage options using levelized cost of storage (LCOS) method," *Applied Energy,* vol. 183, pp. 1594-1606, 2016.
[27] R. M. Swanson, "A vision for crystalline silicon photovoltaics," *Progress in Photovoltaics: Research and Applications,* vol. 14, no. 5, pp. 443-453, 2006.
[28] S. Saxena, C. Hendricks, and M. Pecht, "Cycle life testing and modeling of graphite/LiCoO2 cells under different state of charge ranges," *Journal of Power Sources,* vol. 327, pp. 394-400, 2016.
[29] "P2814 - Techno-economics metrics standard for hybrid energy and storage systems," IEEE Standards Association, [Online]. Available: https://standards.ieee.org/project/2814.html.
[30] "Strategic assessment of the role and value of energy storage systems in the UK low carbon energy future," Imperial College London and Carbon Trust, 2012. [Online]. Available: https://www.imperial.ac.uk/media/imperial-college/energy-futures-lab/research/Strategic-Assessment-of-the-Role-and-Value-of-Energy-Storage-in-the-UK.pdf.