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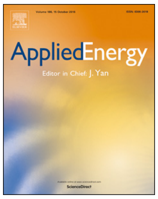

# A financial model for lithium-ion storage in a photovoltaic and biogas energy system

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## HIGHLIGHTS

- A novel cash flow model was created for Li-ion battery storage in an energy system.
- The financial study considers Li-ion battery degradation.
- Frequently using Li-ion (thus reducing lifetime) can be financially attractive.
- Using Li-ion is unprofitable unless it participates in grid services.

## ARTICLE INFO

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## ABSTRACT

Electrical energy storage (EES) such as lithium-ion (Li-ion) batteries can reduce curtailment of renewables, maximizing renewable utilization by storing surplus electricity. Several techno-economic analyses have been performed on EES, but few have investigated the financial performance. This paper presents a state-of-the-art financial model obtaining novel and significative financial and economics results when applied to Li-ion EES. This work is a significant step forward since traditional analysis on EES are based on oversimplified and unrealistic economic models. A discounted cash flow model for the Li-ion EES is introduced and applied to examine the financial performance of three EES operating scenarios. Real-life solar irradiance, load, and retail electricity price data from Kenya are used to develop a set of case studies. The EES is coupled with photovoltaics and an anaerobic digestion biogas power plant. The results show the impact of capital cost: the Li-ion project is unprofitable in Kenya with a capital cost of 1500 $/kWh, but is profitable at 200 $/kWh. The study shows that the EES will generate a higher profit if it is cycled more frequently (hence a higher lifetime electricity output) although the lifetime is reduced due to degradation.

## 1. Introduction

To achieve the goal of decarbonizing the energy sector, more and more energy systems are heavily reliant on non-dispatchable intermittent renewables, such as solar photovoltaics (PV) and wind energy. Electrical energy storage (EES) can store the surplus generation produced by renewables until a time when it is needed, thus smoothing the energy system operation by acting as an additional generator or load and reducing curtailment of renewables [1].

EES comprises a wide range of technologies, covering mechanical, electrical, electrochemical, chemical and thermal storage systems [2]. By discharging or charging, EES systems can release or absorb electricity to/from a power system. Electrochemical storage with rapid response times (on the order of milliseconds) can avoid short-term abnormal phenomena such as voltage and frequency deviations. State of charge (SOC) and depth of discharge (DOD) are parameters considered for hybrid energy system planning and operation [3,4]. While there is an abundance of studies about the economics of EES, financial studies are remarkably rare. This paper focuses on the financial analysis of EES, with a case study on graphite/$LiCoO_2$ batteries.

Precise financial analysis of EES must deal with uncertainties surrounding technical and economic performance. As such, various models

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have been developed to examine EES economics (reviewed in Section 2.2), with many studies emphasizing the levelized cost of electricity (LCOE) in particular [5–10]. However, these works have focused on the economic aspects of EES such as costing. A key to successfully deploying EES is an in-depth understanding of the financial aspects, i.e., the quantification of assets and liabilities and their allocation over the project lifetime.

The financing of EES is studied in [11,12] and a review of the literature is given in [13]. However, these works do not provide all the key indicators, e.g., net present value (NPV), internal rate of return (IRR), and levelized cost of electricity (LCOE). In addition, the modeling of EES in many techno-economic studies (such as [11,14–16]) does not consider EES degradation. This work aims to address the research gap in EES by building and presenting a more realistic financial model. The novelty of the work is described as follows:

- A comprehensive cash flow model is developed for Li-ion EES. The model includes detailed technical (e.g., degradation), financing (e.g., cost of debt), and economic (e.g., capital cost) parameters;
- The detailed techno-economic and financial study are conducted using two-stage simulation. The technical aspect includes the hybrid energy system operation, with the results used as input for the cash flow model; and
- A case study for a hybrid energy system composing of PV/biogas generator/Li-ion EES in Gorge Dam, Kenya is conducted with real-life solar, load, and electricity price data.

Specifically, the aims are to:

- Identify the research gaps in techno-economic analyses of PV/biogas generator/Li-ion EES hybrid energy systems, with a particular focus on EES;
- Examine the financial performance of EES;
- Describe how EES economics relate to key financial parameters e.g., the weighted average cost of capital (WACC);
- Provide a research agenda for financial and economic analysis of low-carbon energy storage.

The rest of this paper is organized as follows: Section 2 provides a review of the literature on the techno-economic analysis and financing of EES and biogas/PV/EES hybrid energy systems. Section 3 presents the energy system context and a case study on the LCOE of EES given in Section 4. To examine the financing of EES, Sections 5 and 6 present the cash flow model and case studies respectively. A sensitivity analysis of the effect on the NPV of various technical and economic parameters is provided in Section 7. Finally, discussion and conclusions are given in Sections 8 and 9 respectively.

## 2. Literature review

This work is concerned with the financing and economics of hybrid energy systems under a range of EES capital costs and operating conditions. EES degradation is also considered, which can affect the system lifetime. The first part of this literature review covers the techno-economic analysis of biogas, PV, and EES hybrid energy systems. Next, a review of previous work on EES degradation is presented, followed by a review of the literature on techno-economic studies of EES. Finally, financial studies of EES and renewable energy systems are reviewed.

### 2.1. Techno-economic studies of biogas, PV, and EES hybrid energy systems

Das et al. [17] presented a techno-economic analysis of an off-grid PV/biogas generator/pumped hydro energy storage/battery hybrid renewable energy system for a radio transmitter station, using metaheuristic optimization approaches. Metaheuristic algorithms can outperform genetic algorithms in techno-economic optimization. The total net present cost and LCOE are examined. The LCOE from the hybrid energy system is found to be 0.4864 $/kWh, but the effect of storage on LCOE is not discussed.

Biomass for electricity is gaining popularity in rural areas of Pakistan. Ahmad et al. [18] used HOMER to conduct a techno-economic analysis of a wind/PV/biogas generator hybrid energy system for rural electrification. The cost of energy, net present cost, and LCOE are examined. For a 50 MW system, the LCOE of the hybrid energy system is 0.058 $/kWh. A grid-connected PV/biomass/wind system can have a lower LCOE than a grid-connected PV/biomass system, showing wind to be an important component of hybrid energy systems in Pakistan. However, this work has not examined EES. Similarly, Shahzad et al. [19] used HOMER to perform a techno-economic analysis of a PV/biomass off-grid system for rural areas in Pakistan. The economic indicators examined are cost of energy, net present cost and payback period. For the hybrid system, the capital cost has the highest share of net present cost, followed by the replacement, and finally the operating cost. Batteries are included in this work but there is no information on the LCOE for storage or the consideration of battery degradation. Das et al. [20] presented a techno-economic study for an off-grid biogas generator/PV/diesel/battery EES hybrid renewable energy system for application in remote areas of Bangladesh, where cow dung is a commonly-accessible resource for biogas production [20]. The cost of energy, net present cost, payback period and emissions are studied. The optimal system has PV, diesel generation, and biogas generation with capacity shares of 49%, 36%, and 15% respectively.

In summary, a large number of studies use the HOMER software, showing it to be a comprehensive and powerful tool for microgrid planning and techno-economic analysis of energy systems. However, it is a black-box model and not open source, and it is difficult to modify the optimization algorithm and cost calculation methodologies [5].

### 2.2. EES degradation

Electrochemical EES has been used extensively in many electronic and electrical applications, such as mobile phones, laptops, and uninterruptible power supplies [21,22]. In recent decades, EES has been extended to grid applications and applications requiring high energy and power densities, such as electric vehicles (EVs).

There are numerous parameters that may affect the state of health of an EES system, and for an electrochemical system, the most prominent of these are temperature, charge/discharge rate (C-rate), and change in the state of charge (SOC). Therefore the development of a comprehensive model that quantifies the capacity and power fade is challenging [23]. Ref. [23] provides a technical discussion of the mechanisms that cause Li-ion cell degradation, affecting the electrolyte, electrodes, separator, and current collectors.

Both power systems and EVs require high EES energy (kWh) and power (kW) capacities to meet the energy demand. Since the electrochemical EES technologies used for EVs and power systems are the same, the issue of degradation is present in both research areas. In the area of EVs, one of the main barriers to their wide-scale adoption is the degradation of battery packs [24], leading to reductions in range and power output. EES degradation is affected by the dynamic battery temperature (influenced by solar irradiance), ambient temperature, the heat generated from chemical reactions in battery cycling, electrical resistance, and wear of mechanical components. The work in Ref. [24] provided a methodology to quantify EV battery degradation with different vehicle-to-grid services. The trade-off for the vehicle to provide grid services with maximum value with minimal impact on vehicle battery life was identified.

Degradation has a significant impact on the performance of electrochemical storage systems. It affects storage and power capacities, and hence the ability of the storage to meet electrical demands [23]. Li-ion cells degrade due to operation and environmental conditions. The degradation can be classified as cycling-induced degradation and calendar aging as follows [24]:

**Cycling-induced degradation:** This is caused by the operation of the EES system, C-rate, temperature, and energy throughput. The degradation is caused by mechanical strains in the lithium plating or electrodes' active materials and is promoted by deep discharge, high C-rate, temperature, and energy throughput. As such, $LiFePO_4$ storage can potentially achieve 3200 cycles at 20% DOD (depth of discharge) or 760 cycles at 80% DOD [10].

To determine the rated cycle-life of a Li-ion EES under cycling from different SOC levels, Saxena et al. [25] determined that the capacity loss is affected by the mean SOC, change in SOC (ΔSOC), and C-rate. A power law model for the capacity loss was also developed based on the experimental results. The mean SOC is calculated with Eq. (1) during a discharge event.

$$\mathrm{SOC}_{\mathrm{Mean}} = \frac{\mathrm{SOC}_{\mathrm{Upper}} + \mathrm{SOC}_{\mathrm{Lower}}}{2} \tag{1}$$

$\mathrm{SOC}_{\mathrm{Lower}}$ is the SOC when the charging starts for each partial cycle and $\mathrm{SOC}_{\mathrm{Upper}}$ is the SOC when the discharge starts. The change in SOC is given in Eq. (2) as follows:

$$\Delta\mathrm{SOC} = \mathrm{SOC}_{\mathrm{Upper}} - \mathrm{SOC}_{\mathrm{Lower}} \tag{2}$$

Subsequently, the rated cycle-life is calculated with Eqs. (3) and (4) [25] where NDC is the normalized discharge capacity at 80% depth of discharge.

$$\mathrm{Ratedcycle}_{\mathrm{SOC}_{\mathrm{Upper}},\mathrm{SOC}_{\mathrm{Lower}}} = e^{\frac{\ln\left(\frac{100^{0.453} * (100-\mathrm{NDC})}{a_{\mathrm{EES}}}\right)}{0.453}} \tag{3}$$

$$a_{\mathrm{EES}} = 3.25 * \mathrm{SOC}_{\mathrm{Mean}} * (1 + 3.25 * \Delta\mathrm{SOC} - 2.25 * \Delta\mathrm{SOC}^2) \tag{4}$$

For year $n$ and discharge cycle $k$, the cost of EES degradation in each cycle ($) is calculated with Eq. (5) [10]. $C_{\mathrm{Cap}_{\mathrm{EES}}}$ is the EES capital cost ($/kWh) and $E_{\mathrm{EES}_{\mathrm{Rated}}}$ is the rated energy capacity (kWh).

$$C_{\mathrm{EES}_{\mathrm{Degcycle}}}(n, k) = \frac{C_{\mathrm{Cap}_{\mathrm{EES}}} E_{\mathrm{EES}_{\mathrm{Rated}}}}{\mathrm{Ratedcycle}_{\mathrm{SOC}_{\mathrm{Upper}},\mathrm{SOC}_{\mathrm{Lower}}}(n, k)} \tag{5}$$

The EES system will reach end-of-life when the accumulated cost of degradation reaches the EES capital cost [10,26] (i.e., when $W_{\mathrm{EES}}$ equals to one), as provided in Eq. (6) below:

$$W_{\mathrm{EES}} = \frac{\sum_n^N \sum_k^K C_{\mathrm{EES}_{\mathrm{Degcycle}}}(n, k)}{C_{\mathrm{Cap}_{\mathrm{EES}}} E_{\mathrm{EES}_{\mathrm{Rated}}}} \tag{6}$$

**Calendar aging**: This class of degradation is independent of charge-discharge cycling. Calendar aging is mainly caused by time and temperature exposure. This is due to the change in passivation layers at the electrode-electrolyte interfaces.

### 2.3. Techno-economic analysis for EES

The techno-economic analysis examines research, development, and deployment areas with a focus on benefits, costs, risks, timeframes, and uncertainties [27]. LCOE is widely used to compare generation cost for an asset or energy system [28,29]. An energy system typically operates over a long lifetime; a PV system, for example, may last for 25 years [30]. As such, LCOE includes a discount rate that converts future cash flows into their present value. A classical formulation of LCOE is given in Eq. (7) below [5]:

$$\mathrm{LCOE} = \frac{\sum_{n=0}^{N} C_{\mathrm{cap}_n} + \frac{C_{\mathrm{O\,\&\,M}_n}}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+d)^n}} \tag{7}$$

where $C_{\mathrm{cap}}$ – capital cost ($), $C_{O\,\&\,M}$ – operation and maintenance (O&M) cost ($), $E$ – energy output (kWh), $N$ – system lifetime in years, and $d$ – discount rate. One of the key challenges in estimating the LCOE is to identify the costs (fixed, variable, direct, and indirect) and energy produced (accounting for round-trip efficiency).

In the techno-economic analysis of EES, the costs can be separated into two types, namely direct and indirect costs [31]. Direct costs can be traced in an economically viable manner, whereas indirect costs cannot. The costs and revenues can be broken down into four categories [32]:

- Monetary savings and profits: Revenues or savings are accumulated based on power, energy or reliability related applications;
- Investment cost: Direct storage cost such as a battery, casing, and electrolyte. In addition, there is the grid coupling cost such as the transformers and power electronics;
- Operation and maintenance cost: Indirect cost such as conversion losses due to component efficiencies, auxiliary consumptions such as thermal management systems, and direct operating costs such as labor and insurance;
- Degradation and replacement cost: Battery performance degradation due to increased resistance and capacity fade, and fatigued materials replacement cost for battery and power electronics. Replacement cost needs to be considered if the unit of analysis is the hybrid system. Many studies consider degradation as an indirect cost [16,17,21].

The cost of EES can be evaluated via the levelized cost of storage (LCOS). The LCOS metric is derived from LCOE. The LCOS is given in Eq. (8) as follows [5,8]:

$$\mathrm{LCOS} = \frac{\sum_{n=0}^{N} C_{\mathrm{capEES}_n} + \frac{C_{\mathrm{O\,\&\,MEES}_n}}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_{\mathrm{out}}}{(1+d)^n}} \tag{8}$$

$C_{\mathrm{capEES}}$ and $C_{\mathrm{O\,\&\,}MEES}$ are the capital and O&M costs of EES respectively. $E_{\mathrm{out}}$ is the EES energy discharge.

Having summarized the components (cost and revenue) of EES economics, the following section provides a literature review on the recent works in EES techno-economics.

Obi et al. [9] proposed a methodology to calculate the LCOE for utility-scale storage systems. The purpose is to provide financiers, policy makers, and engineers a way by which to evaluate different EES systems with a common economic metric. Zakeri and Syri [21] examined life cycle costs and LCOS, using the Monte Carlo method to consider uncertainties. The study presents the economy of different EES for three main applications, i.e., frequency regulation, transmission and distribution support services, and bulk energy storage. Jülch [8] examined the LCOS for electrochemical EES, pumped hydro storage, and compressed air energy storage. The LCOS depends on the cost data, plant design, and annual operation hours. Belderbos et al. [33] proposed three different LCOS metrics and their application to EES for electricity price arbitrage. These metrics are known as "required average price spread", "required average discharge price", and "required average operational profit". Lai and McCulloch [5] studied the LCOS for vanadium redox flow batteries and Li-ion batteries for a PV system. The lifetime, costs, and efficiency can affect the LCOS. The works reviewed in this paragraph have not considered storage degradation.

Having reviewed the LCOS metric, the rest of this review covers the general techno-economic analysis of EES. Shaw-Williams et al. [34] conducted a techno-economic analysis to evaluate the economic impacts on distribution networks of PV and EES investments. PV-only installations achieve the largest return, and the economic viability of a combined EES and PV system is based on the current EES capital cost.

Kaldellis et al. [35] presented a mathematical model to maximize the contribution of a PV generator and to minimize the life-cycle electricity generation cost for remote island networks containing one or more PV generators and an EES system. It is determined that for islands with abundant solar resources, it is more cost effective to use a PV-EES system than thermal power stations. Xia et al. [16] proposed a stochastic cost-benefit analysis model. The energy system consists of wind generation and conventional generators. The model considers both the generation fuel cost expectation and the EES's amortized daily capital cost. Based on the cost-benefit analyses, it is indicated that the EES charging/discharging efficiency, capital cost, and lifetime are critical factors for optimizing the EES size, whilst it is not always economically viable to use EES in power systems. However, the degradation cost is not examined in either work. Bordin et al. [26] presented linear programming models for the optimal management of off-grid systems. Battery degradation is included in the optimization model and the terms "cost per cycle" and "cost per kWh" for batteries were presented.

In summary, there is an increasing importance of and interest in studying the EES economics. As such, LCOS is a widely examined metric due to the simplicity of calculation and the ability to compare different EES costs "at a glance". Due to the complexities of battery degradation and its effect on cycle-life, as discussed in Section 2.1, battery degradation is only considered at a primitive level or not considered at all.

### 2.4. *Financing for renewable energy systems and EES*

Due to high capital cost and uncertainties, financing is a key aspect for renewables power plants [36,37]. Financing decentralized renewable energy infrastructures is a complicated task. Private investors are commonly reluctant to invest due to risk-return-concerns and high transaction costs [38–41]. For many renewable energy projects, start-ups rely on their own capital, government support (grants and seed funds) or private funding sources (angel investor and venture capital) [39,42].

The merit of a specific investment in a renewable energy technology can be examined by calculating indicators such as PP, NPV, and IRR [43]. The selection of financing structures, e.g., corporate financing, sales before construction, and leveraged lease for renewable energy projects, depends on technical maturity, financial viability of renewable energy technologies, and the availability of natural resources, in addition to the supported regulatory environment and government policies [39]. In simple terms, projects can be financed through debt and equity [37]. The financing cost is a crucial input for the calculations since it changes the rate by which both electricity output and costs are discounted [44]. The WACC is used to determine a realistic discount rate to be used in a financial project appraisal and can be calculated using Eq. (9) as follows [44–46]:

$$\mathrm{WACC} = D.\ K_{\mathrm{d}}.\ (1-t) + E.\ K_{\mathrm{e}} \tag{9}$$

$D$ and $E$ are the percentage of debt (%) and percentage of equity (%) respectively, and sum to 100%. $K_{\mathrm{d}}$ and $K_{\mathrm{e}}$ are cost of debt (%) and cost of equity (%) respectively. $t$ is the corporate tax rate (%).

There are several categories of technology-related risk which need to be scrutinized for an investment decision. These risks are major determinants of the financing cost and structure and can be broken down into six categories [36,46]: Construction, Technological, O&M, Supply, Market, and Political.

For new technologies, many of the above risks are often judged to be high, and this is reflected in a higher cost of financing (i.e., $K_{\mathrm{d}}$ and $K_{\mathrm{e}}$ increase with the perceived investment risk). For instance, loans can be obtained from banks and usually guarantees are required; these guarantees and the cost of the loan increase with the risk of the project [39].

Cucchiella et al. [47] used a discounted cash flow (DCF) model to examine the financial feasibility and NPV of PV integrated lead acid battery systems. It is found that subsidies are needed for the energy system to be profitable. Avendano-Mora and Camm [15] used the DCF model to examine the benefit-cost ratio, NPV, IRR, and PP of battery storage systems, for market-based frequency regulation service in a regional transmission organization. It shows that systems greater than 5 MW with minimal battery replacements are expected to have the best financial performance. Jones et al. [48] combined life cycle assessment and DCF analysis to find the carbon dioxide and financial impact of adding battery storage to a PV system. Battery costs need to be reduced rapidly, or extra revenue from delivering electricity system services is required to make batteries financially attractive in areas with reduced insolation. Financial studies of EES considering EES degradation are not examined.

Krupa and Harvey [46] examined the current and future financing of renewable electricity options. Over the past ten years, private equity has contributed to the growth of the U.S. renewable electricity industry. Part of the capital came from commercial banks [49] and large investment banks, which exercised private equity funds to create public companies. Venture capital and private equity funds are pooled investment vehicles that raise money from large investors (such as pension funds) and wealthy individuals for targeted investments.

As reported by Yildiz [38], financial citizen participation is a financing approach that is increasingly popular in Germany, where private individuals can invest in renewable energy projects. The two main equity-based financial citizen participation business models are "The energy cooperative" and "Closed-end funds". Karltorp [36] studied the challenges of financing the development of offshore wind power and biomass gasification in Europe. Renewable energy tends to have high risks and low return. Therefore, it needs support from public and private finance. Energy bonds can be used to promote energy system investment.

To summarize, Table 1 presents an overview of the recent works in the techno-economic and financing studies of EES. It can be observed that many financial and economic indicators have been examined for different EES technologies. However, EES degradation is seldom taken into account, and the consideration of both financial and economic metrics for EES is missing.

Another emerging financing method for renewables projects is crowdfunding [39,50–53]. It is the practice of project funding by securing small amounts of cash from many people, typically via the Internet. Compared with traditional financing, crowdfunding has the advantage of low search and transaction costs, and savings can be passed on to investors [52]. It is possible to obtain project feedback via comment features on the crowdfunding page. However, due to the viral nature of this financing method, the project is prone to public failure if the funding campaign's goals are not achieved. Cybersecurity is also an issue as the funding is conducted via the internet. At present, there is no literature on financing EES with crowdfunding.

In summary, the deployment of EES in renewable energy systems is limited more by economics and financing than by the technology itself [13]. These include high capital costs and a lack of financing incentives and options. Similar to renewable energy, regulations and market rules can impact strongly on whether EES is economically viable. As such, Miller and Carriveau [13] evaluated the factors and mechanisms of renewable energy financing that could be adapted for the EES industry. Compared to renewable energy, EES financing is more difficult to comprehend due to multifunctional capabilities and services.

## 3. Research background: Hybrid energy system in Kenya

The government in Kenya aims to provide energy access for all by 2020 [55]. Rural electrification in remote areas faces multiple challenges including the inability to extend the national grid to provide electricity in rural areas.

The Nationally Determined Contribution in Kenya has pledged to reduce its greenhouse gas emissions by 30% in 2030 from the emissions level in 2016 [56]. This is achievable with a timely deployment of renewable technology, and strict climate change policies in the transport and residential sectors [56].

Nowadays, businesses can take advantage of the opportunities presented by the changing regulatory environment and the abundant natural solar resource in Kenya [10,57,58]. Solar PV is becoming increasingly attractive as a grid electricity source. As commented by Ondraczek [57], previous studies suggest that solar PV in developing countries should 'forever' only be used in off-grid applications, due to

**Table 1**
Comparison of recent techno-economic and financing studies for EES.

| | This work | Berrada et al. [11] | Shaw-Williams et al. [34] | Locatelli et al. [12] | Guinot et al. [54] | Xia et al. [16] | Avendano-Mora and Camm [15] | Cucchiella et al. [47] | Jones et al. [48] |
|---|---|---|---|---|---|---|---|---|---|
| Country considered | Kenya | Spain | Australia | U.K. | Ilorin, Nigeria | Unspecified | U.S.A. | Italy | U.K. |
| Research context | Presenting a financial model for EES coupled with PV and AD biogas power plant. A DCF model for the Li-ion storage is introduced | A cost-benefit analysis is performed to determine the economic viability of energy storage used in residential and large-scale applications | Evaluating the scope for promoting distributed generation and storage from within existing network spending | Examining the value of real options valuation on the development of the ESS project | The techno-economic feasibility of a hybrid solar energy system, including lithium batteries and a hydrogen chain for an off-grid application | Using a stochastic model to size the ESS for power grid planning with intermittent wind generation | Examining the expected financial performance of battery storage systems by providing market-based frequency regulation service | A DCF analysis is conducted to evaluate the financial feasibility of photovoltaic-integrated lead acid battery systems | Combining a life cycle assessment approach and DCF analysis to assess the carbon dioxide and financial impact, of adding battery storage to a PV system |
| Financial and economic indicators examined | NPV, IRR, Debt duration, LCOE, and LCOS | NPV | NPV, IRR, LCOE, value of deferred augmentation, value of customer reliability | NPV | LCOE | Present value | NPV, PP, IRR, benefit-cost ratio, simple payback | NPV | NPV |
| Types of storage | Li-ion | Gravity storage | Batteries | Compressed air energy storage and pumped hydro storage | Li-ion | Lead acid, superconducting magnet, zinc bromine, and sodium-sulphur | Li-ion | Lead-acid | Li-ion |
| Storage degradation | Yes (cycle degradation considers the change in SOC) | No | Yes (as a percentage per year) | No | Yes, (cycle degradation and calendar degradation) DOD only | No | No | No | No |
| Findings | The existing market is unprofitable to use Li-ion when the capital cost is at 1500 $/kWh, unless participating in grid services with high payments | Storage is unprofitable for residential applications except if it is used as a stand-alone system | There are power network benefits with a more rapid adoption of distributed generation and residential battery storage | Real option analysis increases the economic performance of ESS | Not considering battery degradation leads to significant difference in estimating system size and LCOE values | The ESS charging/ discharging efficiency, amortized daily capital cost, and lifetime are crucial to affect the system cost-benefits | The finance can be affected by the system size, regulation market capability clearing prices, and EES replacements | The profitability of PV-integrated battery system is affected by the EES energy self-consumption and the presence of subsidies | The battery storage costs would have to drop significantly to contribute positively to the financial performance of PV systems in current U.K. market conditions |

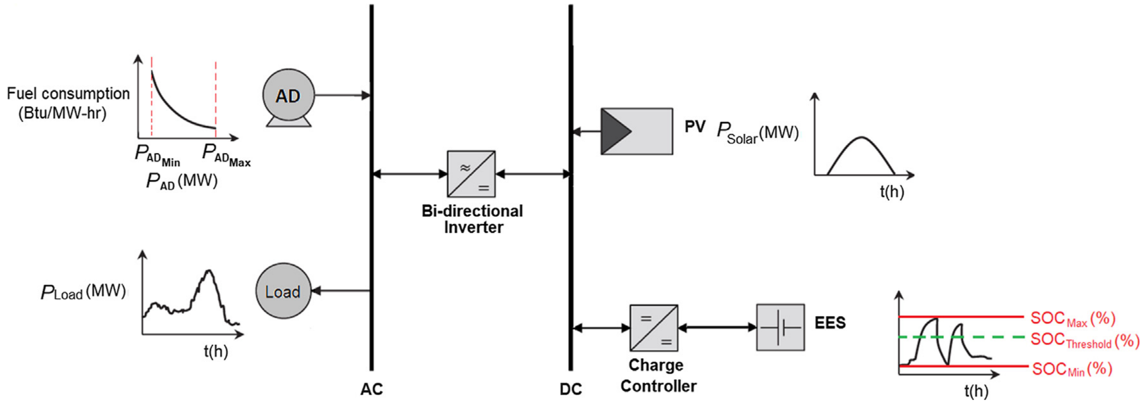

**Fig. 1.** Diagram of the hybrid energy system [59].

its high LCOE. Nevertheless, solar PV can be less expensive than the most expensive conventional generation technologies, e.g., emergency power plants running on heavy fuel oil [57].

In addition to the abundant solar resources, electricity generation can be achieved via biogas power plants with anaerobic digestion (AD). The large agricultural industry in Kenya produces significant animal and crop waste [10,30].

Having discussed energy in Kenya in a wider context, the following section provides the hybrid system sizing and operating methodologies, to examine the EES finance.

### 3.1. Hybrid system sizing and operation

Fig. 1 presents the layout of a hybrid PV-AD-EES energy system. The EES can be charged from the PV and from the AD biogas power plant. The AD plant has a minimum and maximum output power, denoted as $P_{AD_{Min}}$ and $P_{AD_{Max}}$ respectively. The load is met by the electricity output from the PV, biogas power plant, and EES. The solar charge controller is used to constrain the rate at which electric current is drawn from or added to the EES. The bi-directional inverter converts DC electricity to AC electricity and vice versa, to charge the EES from the AD. According to the sizing methodology proposed in [30], the EES is sized with a power capacity and energy capacity of 2 MW and 5 MWh respectively.

The optimal generator/EES dispatch or scheduling is challenging for the hybrid renewable energy system, due to the intermittent nature of solar power and the unpredictability of demand. Hence, this paper adopts the operating regime proposed by Lai et al. [10], a deterministic rule-based approach. Since the biogas generator and EES are the dispatchable sources in the system, during times when PV is unavailable, the load can be met by biogas power or electricity stored in the EES. Hence in this regime, a state of charge (SOC) threshold, $SOC_{Threshold}$, has been defined for the EES to discharge its energy content to meet the demand before operating the biogas generator. A lower $SOC_{Threshold}$ reduces the solar curtailment (storing surplus energy) by cycling the EES more frequently.

Having presented the system operating method and optimal sizing, the following section presents the real-life solar and electricity price data to conduct the research.

### 3.2. Solar and retail electricity price data

This model considers an isolated community. There is no “opportunity cost” in the financial analysis because the assumption is that the community already receives the electricity it needs. The EES stores the surplus of electricity when is produced and not needed.

This research employs real-life data to examine the effectiveness of the proposed cash flow model for Kenya. These are solar irradiance data and national retail electricity market data, discussed as follows:

**Solar irradiance data:** Solar irradiance data is crucial for solar energy studies [30]. In this study, the location for the solar irradiance is Turkwel Gorge Dam, Kenya, with longitude 35.34°, latitude 1.90°, and elevation at 1170 m above sea level. The solar irradiance data is obtained from SOLARGIS [60]. The sampling period is from 01 January 2012 to 31 December 2012 with a sampling interval of one sample every 15 min. Fig. 2 displays the solar irradiance intensity for the location in 2012. The sunrise and sunset hours are consistent throughout the year and as expected the peak irradiance is at noon. The intermittency of solar irradiance can be seen in the figure during the daytime, shaded in blue.

**Retail electricity market data:** In Kenya as of Jan. 2018, power distribution was maintained by a monopoly, Kenya Power and Lighting Company (Kenya Power). However, the government has recently introduced new companies for electricity retail [61]. Fig. 3 shows the CI3 customer’s peak and off-peak retail electricity prices for Kenya, set by Kenya Power. Currently, there are seven core tariffs. These are known as DC (Domestic, 240 V), SC (Small Commercial, 240 V), CI1 (Commercial, 415 V), CI2 (Commercial, 11 kV), CI3 (Commercial, 33 kV), CI4 (Commercial, 66 kV), and CI5 (Commercial, 132 kV) [62]. The CI3 tariff is adopted based on the size of the hybrid energy system under consideration. The Government of Kenya has announced special off-peak rates for commercial customers with effect from December 2017. For CI3 customers, the average peak and off-peak electricity prices from December 2017 to Oct. 2018 were 0.1632 $/kWh and 0.1129 $/kWh respectively [62].

Having described the research background in Kenya, i.e., hybrid energy system and data, the following section begins to examine the

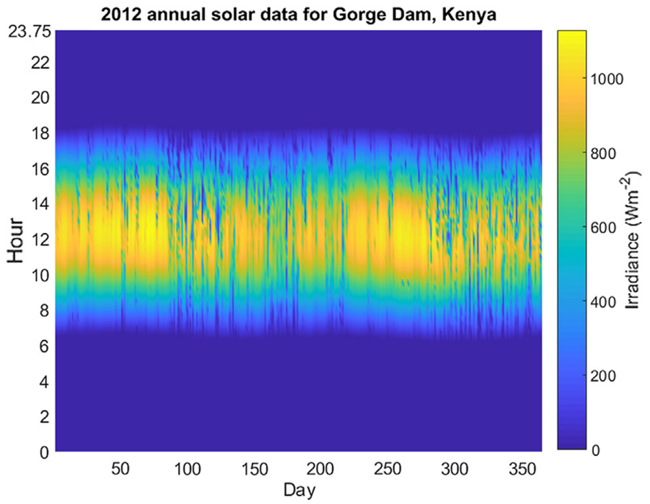

**Fig. 2.** Kenya solar irradiance data [60].

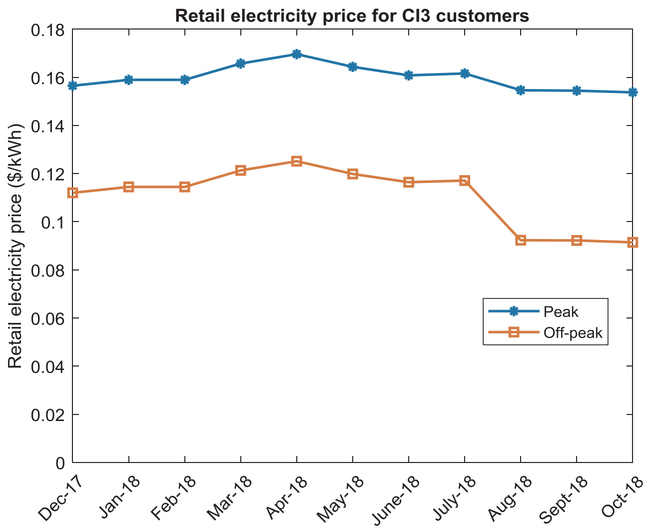

**Fig. 3.** Retail electricity price in Kenya for CI3 customers [62].

economics of the hybrid energy system with EES.

## 4. A case study on the degradation effect on LCOE

As degradation is an important aspect for EES cost-benefit analysis, this section examines how the degradation cost affects the LCOE of the hybrid energy system (by including and excluding the degradation cost in the LCOE calculation).

The key assumptions are:

- Operating life: 22 years [10];
- Discount rate: 6% [5,30];
- PV capital cost: 0.36 $/W [63];
- AD rated capacity: 2.4 MW [10];
- Kenya load curve at 2 MW peak [10]; and
- Fixed 'operational cost' to EES energy discharge: 0.42 $/MWh [10].

The cost and technical parameters for the system can be found in [10].

The LCOE for the hybrid energy system can be calculated by Eq. (10) as follows [10]:

$$\mathrm{LCOE}_{\mathrm{System}} = \frac{C_{\mathrm{PV}} + C_{\mathrm{Con}} + C_{\mathrm{EES}} + C_{\mathrm{AD}} + C_{\mathrm{Inv}}}{E_{\mathrm{ADDirect}} + E_{\mathrm{EES}} + E_{\mathrm{PVDirect}}} \tag{10}$$

$C_{\mathrm{PV}}$, $C_{\mathrm{Con}}$, $C_{\mathrm{EES}}$, $C_{\mathrm{AD}}$, and $C_{\mathrm{Inv}}$ are the lifetime PV panels, solar charge controller, EES, AD biogas plant, and inverter costs (in NPV) respectively. $E_{\mathrm{EES}}$ is the lifetime energy output (discounted) from EES. $E_{\mathrm{ADDirect}}$ and $E_{\mathrm{PVDirect}}$ are the lifetime energy outputs that are used to meet the load directly (i.e., no storage) from AD and PV respectively. Due to the length of the derivation and the scope of this paper, the details for calculating the cost and energy output for the system (consist of each generation type and storage) can be found in [10].

The SOC constraints are enforced by the operating regime and the power balance (between generation and demand) is achieved. For the case with no degradation cost, $C_{\mathrm{EESDegkWh}}$ is not included in the LCOE. The degradation cost equation obtained from a capacity fade model can be found in Section 2.1. In this work, System LCOE refers to the LCOE for the hybrid system which considers the lifetime system, i.e., PV, AD, EES, inverters and solar charge controller costs and energy productions that meet the energy demand. The details of the mathematical modeling for the cost and energy calculations can be found in [10].

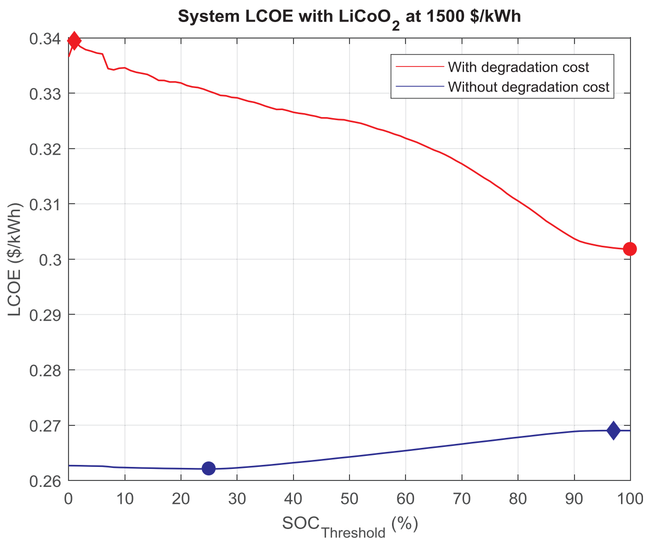

**Fig. 4.** System LCOE studies with various.SOC$_{\mathrm{Threshold}}$.

### 4.1. Sensitivity analysis on the SOC$_{\mathrm{Threshold}}$

This case study analyses how the dispatch priority for EES will affect the LCOE with respect to the degradation cost. The PV rated capacity is at 5 MW and the EES energy capacity is at 5 MWh [10]. Fig. 4 presents the results for the sensitivity analysis with various values of SOC$_{\mathrm{Threshold}}$. The diamond and circle symbols denote the maximum and minimum LCOE respectively.

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

The EES degradation can affect the energy system's LCOE. By excluding degradation costs at scenarios with high EES capital costs, it is learned that the lowest LCOE can be achieved when EES is given dispatch priority over AD. This appears to be the opposite when degradation cost is included. Hence, degradation is an important aspect of EES techno-economic studies.

As the rated capacities of PV systems and EES can affect the LCOE for the energy system, the next section examines the LCOE based on different EES and PV farm capacities, with and without EES degradation.

### 4.2. Sensitivity analysis on PV and EES rated capacities

This case study investigates the energy system's LCOE at different energy storage capacity (MWh), and PV rated capacity (MW) when degradation cost is studied with EES at 1500 $/kWh energy capital costs [22]. Different results with the EES at 200 $/kWh energy capital costs were reported in [64]. Here, a SOC$_{\mathrm{Threshold}}$ of 30% is used to frequently cycle the EES. Figs. 5 and 6 depict the results for the System LCOE when degradation cost is considered and not considered respectively.

The energy system's LCOE increases proportionally to the degradation cost. The minimal LCOE is achieved when no EES is installed and has a 1.5 MW to 2.5 MW of PV rated capacity. The reduced capital cost and negligible marginal cost for PV can produce less expensive

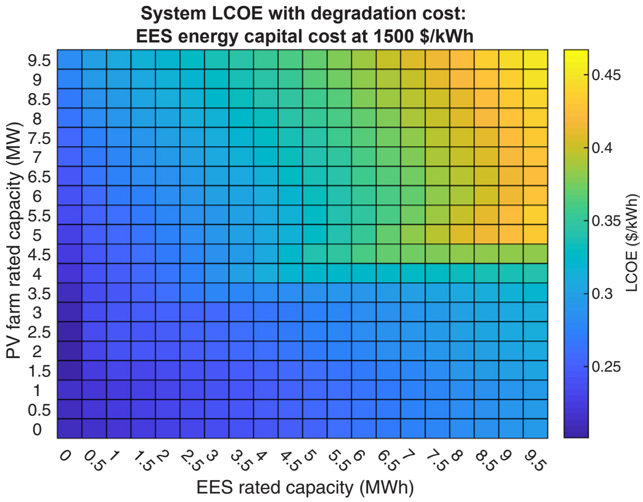

**Fig. 5.** System LCOE with the degradation cost considered.

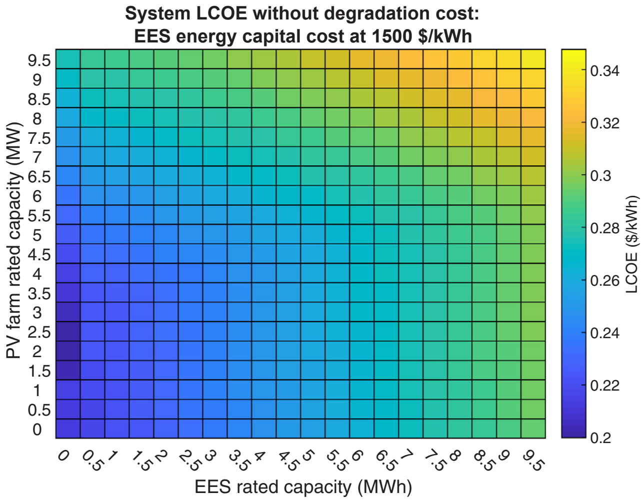

**Fig. 6.** System LCOE with the degradation cost not considered.

electricity than the biogas. In this case with no import electricity, storing the surplus energy produced by PV for later use is not the most economic choice, due to the high capital cost for EES. When degradation cost is considered with the PV capacity below 3.5 MW, the change in LCOE is insignificant due to the battery cycling is reduced. This can be explained by the insignificant presence of PV power. The LCOE escalates when EES rated capacity is larger than 6.5 MWh and PV rated capacity is above 4.5 MW. This is the contribution of significant storage degradation. When degradation cost is not considered, the nonlinear mathematical relationship between cycle-life degradation (cycles) and this cost is excluded in the techno-economic analysis. Due to a fixed O&M cost is applied to EES discharge, it could be observed that the LCOE increases as the EES capacity increases. Similar to the case where degradation cost is considered, the maximum LCOE is located at PV is at 9.5 MW and EES is at 9.5 MWh.

This section concludes that the inclusion of an EES cannot be justified only by the economic merit, at least with the actual market in Kenya. However, as discussed in the Introduction, there are political reasons to support the deployment of EES (and renewable). Hence, the next section will examine EES from the financial perspective.

## 5. Financial modeling for EES

The NPV is an important concept for economic and financial studies alike. The NPV is the summation of the present value of a series of present and future cash flows (outbound and inbound) generated by an investment (in this case the EES) with discount [12]. Fig. 7 summarized how different types of cash flow are considered in the financial model. In the construction of infrastructure, the capital can be provided in several ways with the most relevant are debt and equity.

Ideally, the investment has to create a value sufficient enough to gain support from the debt holders and to provide adequate remuneration to the equity. Realistic financial models consider three types of NPV as follows [45,65]:

- **NPV for economic studies**: This is the “traditional” NPV used in economic studies as it does not consider taxes or how the finance is divided between equity and debt. The cash flow is discounted at WACC calculated with Eq. (9). The finance and economic data is presented in Section 5.2. The WACC is at 3.55%, which is viable as examined by Sidhu et al. [66]. This indicator only considers the cost aspect or the outbound cash flow. This NPV is useful for engineers and policymakers to calculate the LCOE and electricity price to break-even, since the LCOE is the average minimum price at which the electricity must be sold (at lifetime) for the project to break-even. The point of cash flow used for examining the LCOE is ① in Fig. 7.
- **NPV to the firm:** This is the “free cash flow to the firm” or the sum of the unlevered cash flows discounted with the WACC. Debt holders may consider financing the EES project if the NPV is larger than zero. This signifies the investment generates enough value to pay off the debt. With respect to the “NPV for economic studies”, this NPV considers the taxes and the financial structure of the investment. The point of cash flow used for examining the free cash flow to the firm (FCFF) is displayed as ② in Fig. 7.
- **NPV to equity holders:** This is the sum of the levered cash flows. Specifically, the equity can be determined by discounting the “free

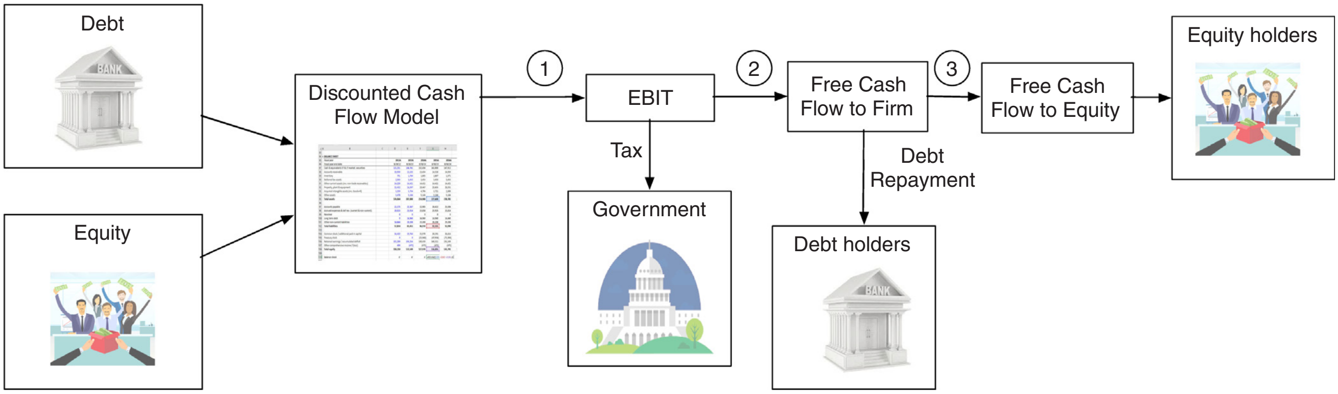

**Fig. 7.** Exemplification of the financial model for EES.

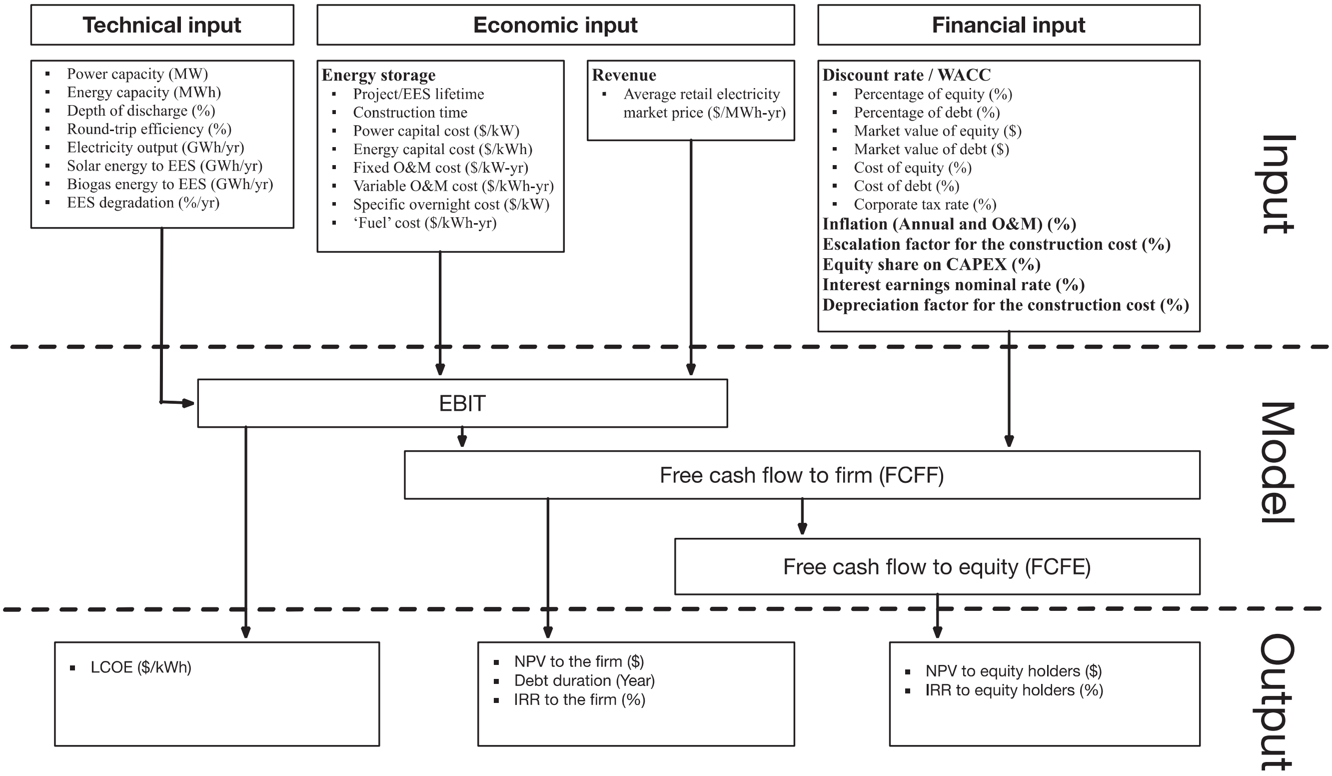

**Fig. 8.** Technical, financial, and economic inputs for EES financial assessments.

cash flow to the equity” at equity cost. It is the NPV from the perspective of the equity holders, e.g., consider the payment of taxes and the repayment of debt to debt holders. The equity holders receive a remuneration equal to the cost of equity if the NPV is zero. The point of cash flow used for examining the free cash flow to equity (FCFE) is displayed as ③ in Fig. 7.

### 5.1. Model description

The inputs for the EES financial model can be separated into three major categories, namely, technical, economic, and financial as detailed in Fig. 8. Fig. 8 presents the financial modeling process for the EES with the model inputs and outputs. Remarkably the EES variable O&M cost also includes the biogas labor and fuel cost, when the biogas energy is stored in EES.

The model calculates the NPVs, debt durations, and IRRs with FCFF and FCFE. The LCOE is calculated with the EBIT cash flow. Eqs. (11) and (12) present the NPV and IRR to the firm. This is similar for “to the equity” calculations by changing the cash flow to the equity. The NPV to equity needs to be discounted at the cost of equity and not the WACC.

$$\text{NPV to the firm} = \sum_{t=0}^{n} \frac{\text{Cash flow to the firm}_t}{(1 + \text{WACC})^t} \tag{11}$$

$$\sum_{t=0}^{n} \frac{\text{Cash flow to the firm}_t}{(1 + \text{IRR}_{\text{firm}})^t} = 0 \tag{12}$$

The debt duration is the amount of time for the project to repay the debt to the debt holders. This is calculated as $\sum_t^n \text{Debt}_{\text{Duration}}(t)$. Let $D_{\text{Cum}_t}$ and $E_{\text{Cum}_t}$ be the debt cumulated in million dollars (M$) and equity cumulated (M$) respectively, the debt duration is calculated with Eqs. (13) and (14) as follows:

$$\text{Debt}_{\text{Duration}}(t) = \begin{cases} 1, \ if\, \text{Debt}_{\text{Percentage}}(t) > 0 \\ \quad 0, \ otherwise \end{cases} \tag{13}$$

$$\text{Debt}_{\text{Percentage}}(t) = \begin{cases} \frac{D_{\text{Cum}_t}}{D_{\text{Cum}_t} + E_{\text{Cum}_t}}, \ ifD_{\text{Cum}_t} > 0andE_{\text{Cum}_t} > 0 \\ \quad 1, \ ifE_{\text{Cum}_t} \leq 0 \\ \quad 0, \ otherwise \end{cases} \tag{14}$$

### 5.2. Case studies context

Technical, economic, and financing factors affect the financial and economic viability of EES. In this research, the focus will be on the financing studies based on the change in EES capital costs and operating conditions. The $\text{SOC}_{\text{Threshold}}$ affects how the electricity demand is met by generators and storage.

This work considers six scenarios based on three operating methods and two EES capital costs as presented in Table 2. The names “High-PV”, “Balanced”, and “High-AD” represent different $\text{SOC}_{\text{Threshold}}$ values at 20%, 50%, and 100%, respectively. Table 2 also presents the technical data for the financial modeling. Given the nature of the project, we assumed, that the investment is subsidized lowering the cost of both equity and debt in Kenya. These numbers may be representative also for Organisation for Economic Co-operation and Development (OECD) countries. The sensitivity analysis provides a comprehensive perspective. The energy input and output of storage are calculated according to [10], relevant inputs are:

- Construction time: 1 year
- Annual inflation (%): 5.50 (2005–2018 average) [67]
- O&M inflation (%): 5.50 (2005–2018 average) [67]
- Escalation factor for the construction cost (%): 5.50 (2005–2018 average) [67]
- Depreciation factor for the construction cost (%): 10.00
- Equity share on capital expenditure (CAPEX) (%): 50.00
- $k_d$ (%): 3.00
- $k_e$ (%): 5.00
- Tax rate (%): 30.00 [68]
- Interest earnings nominal rate (%): 5.00 [69]

**Table 2**
Technical and economic specifications.

| Index | Input | Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| A1 | $\text{SOC}_{\text{Threshold}}$ (%) | 20 | 50 | 100 | 20 | 50 | 100 |
| A2 | EES capital cost ($/kWh) | 1500 | | | 200 | | |
| A3 | Energy capacity $E_{\text{EES}_{\text{Rated}}}$ (MWh) | 5 [30] | | | | | |
| A4 | Power capacity $P_{\text{EES}_{\text{Rated}}}$ (MW) | 2 [30] | | | | | |
| A5 | Construction time (Year) | 1 | | | | | |
| A6 | EES operating lifetime (Years) | 8 | 9 | 18 | 8 | 9 | 18 |
| A7 | EES energy output during the first year of operation (GWh) | 1.56 | 1.14 | 0.61 | 1.56 | 1.14 | 0.61 |
| A8 | Equivalent EES degradation cost (M$/yr) | 0.86 | 0.75 | 0.40 | 0.114 | 0.10 | 0.05 |
| A9 | Round-trip efficiency (%) | 95 [22] | | | | | |
| A10 | EES fixed O&M costs ($/kW-yr) | 2.12 [10] | | | | | |
| A11 | Specific overnight cost ($/kWh) | 1500 | | | 200 | | |
| A12 | Total overnight cost (M$) | 7.5 | | | 1 | | |
| A13 | Biogas energy to storage (GWh/yr) | 0.12 | 0.014 | 0.005 | 0.12 | 0.014 | 0.005 |
| A14 | Solar PV energy to EES (GWh/yr) | 1.53 | 1.18 | 0.64 | 1.53 | 1.18 | 0.64 |
| A15 | Biogas labour and fuel cost for EES (M$/yr, fuel at 6.97 $/mcf+ labour at 0.05 $/kWh [10]) | 0.014 | 0.0018 | 0.0006 | 0.014 | 0.0018 | 0.0006 |
| A16 | EES's NDC losses $E_{\text{Deg}}$ (%/yr) | 2.29 | 2.01 | 1.08 | 2.29 | 2.01 | 1.08 |
| A17 | Average retail electricity price ($/MWh) | 138.10 | | | | | |

- Average retail electricity price ($/MWh): 138.10

The O&M inflation rate and the escalation factor for construction costs are assumed to be the same as the annual inflation rate. The average retail electricity price is calculated by taking the average of the peak and off-peak electricity prices, as discussed in Section 3.2. The EES will be "grid parity" if the project breaks even or makes a profit from the revenue based on the average retail electricity price.

The unit of analysis is the single EES project. Hence, the EES operating lifetime (years) and the NDC degradation per year needs to be determined with the equivalent degradation cost as discussed in Section 2.1, as follows:

**EES operating lifetime:** The number of years for the EES to operate can be calculated with Eq. (6). The lifetime $N$ needs to be an integer with $W_{\text{EES}}$ to be less than and close to one.

**NDC loss:** The EES will reach the end-of-life when the NDC reaches 80% [10,25]. The equivalent EES degradation cost ($) for the year can be calculated with $\sum_k^K C_{\text{EES}_{\text{Degcycle}}}(k)$ for $k$ cycles. Based on the assumption that the perfect EES (i.e., NDC at 100%) is equal to the EES capital cost ($), Eq. (15) calculates the NDC degradation per year.

$$E_{\text{Deg}}(\%/\text{yr}) = \frac{(100 - \text{NDC}) \sum_k^K C_{\text{EES}_{\text{Degcycle}}}(k)}{C_{\text{Cap}_{\text{EES}}} E_{\text{EES}_{\text{Rated}}}} \tag{15}$$

The equivalent EES degradation cost per year, NDC losses per year, and the operating lifetime are presented in Table 2.

A Li-ion loss of NDC is approx. 2% per year [5]. The operating lifetime for the scenarios can be different. The "High-AD" scenario has a longer EES lifetime due to the reduced cycling and less energy input and output of EES. The NDC losses increase as more cycling occurs.

The biogas energy and costs for EES reduces as the $\text{SOC}_{\text{Threshold}}$ increases (see Table 2). "High-AD" refers to the operating strategy for the hybrid energy system to utilize more biogas. Hence, the total biogas energy output increases with a higher $\text{SOC}_{\text{Threshold}}$, as presented in [10]. However, the amount of biogas energy stored in EES may not necessarily increase with a higher $\text{SOC}_{\text{Threshold}}$. Biogas is a form of stored energy (i.e., in an anaerobic digester) and is inefficient to store the energy in EES in electricity form, due to conversion cost and energy losses. A low $\text{SOC}_{\text{Threshold}}$ causes the EES to be at a low SOC more often. To avoid energy deficits in the energy system, the biogas power plant needs to charge the EES to the $\text{SOC}_{\text{Threshold}}$ [10].

This section has presented the model description and the financial, economic and technical input data to conduct the study. The case studies to be examined are described. The next section presents the case study results for the EES financial feasibility in Kenya.

## 6. Case studies on financing EES in Kenya

This section presents a financial appraisal of Li-ion EES using the Kenyan scenario.

### 6.1. Influence of WACC

WACC is a key input for financial models, especially for capital intensive infrastructure. Hence, this section performs a sensitivity analysis on the WACC. The WACC is considered as an overall combined effect of the cost of debt, cost of equity, share of CAPEX, and the corporate tax rate.

International Renewable Energy Agency (IRENA) [70] mentioned that the WACC for six low carbon generation technologies (i.e., wind, PV, concentrating solar power, hydro, biomass, and geothermal) is 10% for countries excluding OECD and China. A 10% WACC is also used by the Institute of Development Studies, U.K. for renewable energy projects in Kenya [71].

The WACC values are between 8% and 32% for 46 African countries and nine power generation technologies (i.e., concentrating solar power, PV, onshore wind, small hydro, geothermal, large hydro, coal, natural gas, and diesel) [72]. In the african context, Sweerts et al. [72] reported that PV electricity needs a WACC of 6% to be cost competitive with natural gas. Similarly, Rose et al. [58] examined the prospects for grid-connected solar PV systems in Kenya with a 5% WACC. Grant Thornton [73] suggested that the WACC for ground mount solar PV for Kenya is between 11.8% and 16.25%.

Considering the literature, this paper analyses a WACC between 0% and 20%.

Due to the importance and uncertainty in WACC, Figs. 9 and 10 show the LCOS and NPV to the firm for the EES, respectively, under different WACCs. The EES capital cost is at 200 $/kWh. In Fig. 9, compared to the other two scenarios, the LCOS has a higher rate of change with respect to the WACC for "High-AD". "High-AD" contributes to a higher life-cycle cost (i.e., LCOS) due to lower annual energy output. The increased rate of change can be explained by the non-linearity of LCOS in Eq. (8). The LCOS is reasonable by considering the order of magnitude, compared to the Lazard's LCOS analysis [74] and the works in [5,8–10]. In addition, Jülch [8] claimed that battery technologies can achieve 0.22 $/kWh in the future. From this study, the LCOS can be reduced if the system operates in "High-PV" scenario. The range of WACC required for the LCOS to be greater than the retail

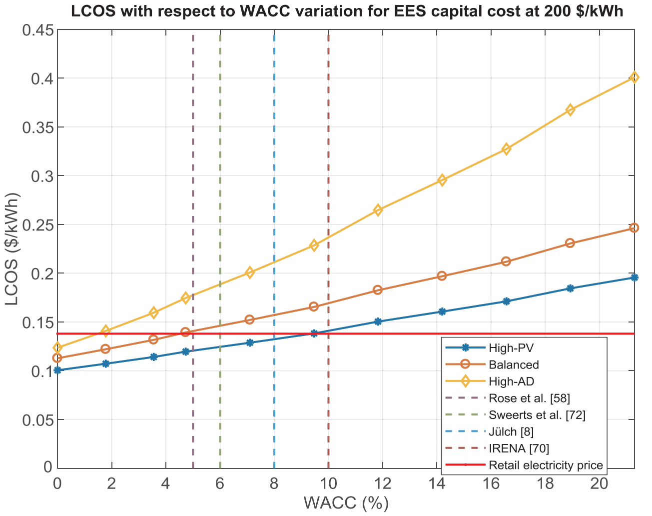

**Fig. 9.** LCOS with respect to various WACCs. The vertical dashed lines are the references from the literature, while the horizontal continuous line is the retail price of electricity.

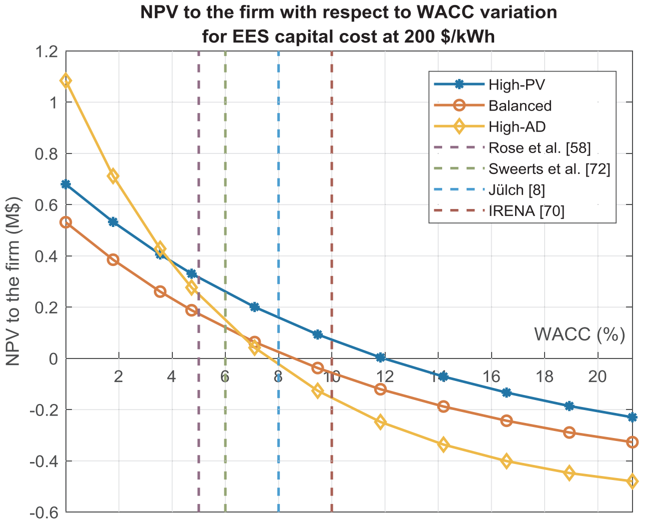

**Fig. 10.** NPV to the firm with respect to various WACCs. The vertical dashed lines are the references from the literature.

electricity price is between 2% (High-AD) to 10% (High-PV). This is an important indicator as the EES can be economic if the cost of electricity per kWh (LCOS) is less than the revenue generated per kWh (retail electricity price).

The following examines the value of EES (NPV to the firm) with respect to the WACC.

Rose et al. [58] claimed that a one percent increase in the discount rate results in a 6% decrease in the value of solar ($/W). For the case of EES, the relationship between NPV to the firm and WACC is quadratic as depicted in Fig. 10. Compared to other scenarios, “High-AD” can have a higher rate of change in the NPV at low WACCs because of the higher LCOS (Fig. 9). It is profitable to invest in EES (i.e., NPV $>$ 0) when the WACC is larger than 7.6%, 8.8%, and 11.8% for “High-AD”, “Balanced”, and “High-PV” operating scenarios respectively. With reference to the WACC from IRENA, EES can be profitable in “High-PV” scenario. ESS can be profitable for all scenarios with the WACC used by Rose et al. [58] and Sweerts et al. [72]. However, the NPV for the “High-AD” scenario is below zero with the WACC discussed by Julch [8]. This analysis concludes that the WACC to make the EES profitable depends on the energy system operating strategy, and has not been examined and discussed in other studies.

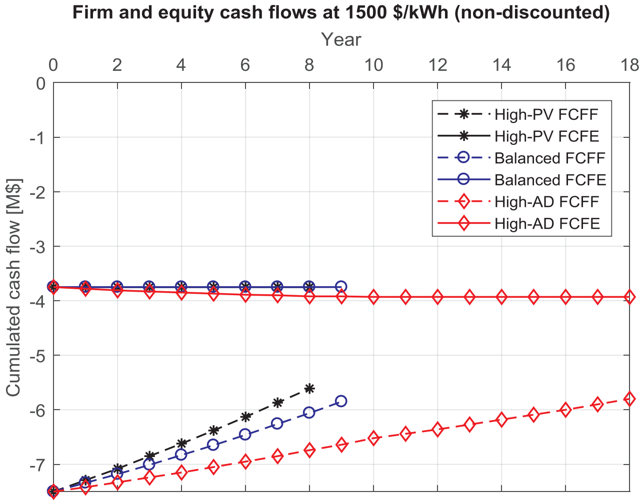

**Fig. 11.** Cumulated cash flow to the firm and cumulated cash to the equity for three operating scenarios with EES capital cost at 1500 $/kWh.

## 6.2. Equity and firm cash flows

(a) Cash flows for EES capital cost at 1500 $/kWh

Fig. 11 displays the non-discounted annual cash flows (firm and equity) for the three operating scenarios based on an EES capital cost at 1500 $/kWh. It can be observed that none of the scenarios is profitable with the EES, as the cash flow at the end of project life is negative. Usually, for a project, the cash flow repays the debt first (as depicted in Fig. 7). Hence, the cash flow to the equity is less than the cash flow to the firm. The FCFE for “High-PV” and “Balanced” scenarios are constant with no profit to the equity. However, the project is making a profit overall and the debt gradually decreases. For “High-AD” scenario, the FCFF is decreasing, this means that the equity is losing money as the EES revenue does not even cover operating cost and debt repayment. Consequently, it is better to use the EES more frequently with a reduced lifetime to avoid extra capital loss.

(b) Cash flows for EES capital cost at 200 $/kWh

Fig. 12 displays the non-discounted annual cash flows (firm and equity) for the three operating scenarios based on an EES capital cost at 200 $/kWh. The EES is financially viable under the three operating

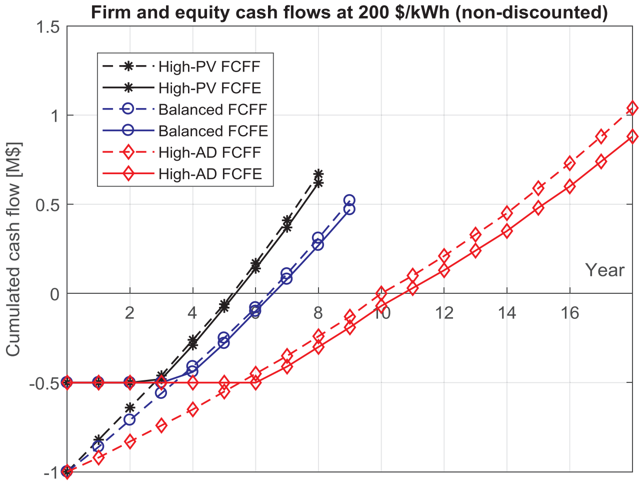

**Fig. 12.** Cumulated cash flow to the firm and cumulated cash to equity for three operating scenarios with EES capital cost at 200 $/kWh.

**Table 3**
Financial modeling results for the six scenarios.

| | Scenarios | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Electricity price – LCOE ($/kWh) | −0.62 | −0.80 | −0.96 | 0.02 | 0.01 | −0.02 |
| LCOS ($/kWh) | 0.76 | 0.94 | 1.10 | 0.11 | 0.13 | 0.16 |
| NPV (cash flow for LCOE) (M$) | −6.01 | −6.21 | −6.38 | 0.27 | 0.06 | −0.10 |
| IRR (cash flow for LCOE) (%) | 0.00 | 0.00 | 0.00 | 9.95 | 4.99 | 2.13 |
| NPV to the firm (M$) | −5.68 | −5.91 | −6.05 | 0.41 | 0.26 | 0.43 |
| IRR to the firm (%) | 0.00 | 0.00 | 0.00 | 12.11 | 8.66 | 7.89 |
| NPV to equity (M$) | −5.20 | −5.35 | −5.17 | 0.32 | 0.18 | 0.24 |
| IRR to equity (%) | 0.00 | 0.00 | 0.00 | 14.61 | 10.25 | 8.57 |
| Debt duration (year) | 9.00 | 10.00 | 19.00 | 3.00 | 4.00 | 7.00 |
| Max. exposition firm (M$) | −7.50 | −7.50 | −7.50 | −1.00 | −1.00 | −1.00 |
| Total exposition firm (M$) | −59.34 | −67.13 | −126.44 | −3.25 | −3.87 | −5.86 |
| Max. exposition equity (M$) | −3.75 | −3.75 | −3.93 | −0.50 | −0.50 | −0.50 |
| Total exposition equity (M$) | −33.75 | −37.50 | −73.90 | −2.34 | −2.82 | −4.46 |

scenarios. The debt duration for the firm for "High-PV", "Balanced", and "High-AD" are approximately 3, 4, and 7 years respectively.

Although the degradation is higher due to more energy input and output of the EES (and resulting in a shorter lifetime) this operating approach will be more financially attractive than "Balanced" or "High-AD" operating methods. To explain, the DD for the EES is shorter compared to the other scenarios with the highest cumulated cash flow by the end of the project life. Table 3 presents the financial modeling results for the six scenarios. The LCOS is the lowest amongst all scenarios when the EES discharges electricity more frequently with a capital cost at 200 $/kWh (Scenario 4), with the following observed phenomena:

- The NPV and the IRR to the equity holders are the highest;
- The maximum and total exposition for firm and equity are the smallest; and
- The retail electricity price in Kenya is greater than the LCOE.

Having examined the cash flows for the three operating scenarios at two different EES's capital costs, it can be concluded that the EES operation method can significantly affect the economic and finance of the EES. At 1500 $/kWh, Li-ion proves to be too expensive for investment. When the cost drops to 200 $/kWh, it is financially viable by using the EES more frequently although the EES lifetime will be shorter.

### 6.3. LCOS and project lifecycle cost composition

Since cost is an important aspect in finance, this section examines the LCOS and the lifecycle cost composition.

Fig. 13 presents the breakdown of the EES costs (variable O&M, fixed O&M, and capital) calculated from the cash flow for LCOE for the six scenarios. Capital is a major part of the cost, with the variable and fixed costs (e.g., servicing and import energy cost) constitute a small portion of the lifecycle cost. With reference to [19], this observation is reasonable as EES is a capital-intensive technology, similar to the cost of a hybrid energy system. At 200 $/kWh, it is seen that the percentage of capital cost reduces with the "High-PV" scenario at approx. 85% due to the project being less capital-intensive. The "Balanced" scenario has the highest percentage of capital cost. This is due to the similar percentage of variable O&M cost to "High-AD" (due to a comparable biogas consumption) and a similar percentage of fixed O&M cost to "High-PV" (due to a comparable lifetime), where both of them are low.

Since EES capital cost is uncertain with the economy of scale expansion and technology breakthrough, it is necessary to examine the LCOS based on different capital costs. Fig. 14 presents the LCOS for the three operating scenarios under different EES's capital costs. The relationship is linear for the three operating scenarios. The LCOS reduces as the EES cycles more frequently (with the "High-PV" scenario as most frequent), although the lifetime is also reduced. According to Eq. (8), this means that the energy output from EES is greater than the accumulated lifecycle cost.

This section shows the dependency of the capital cost, fixed O&M, and variable O&M cost on the lifecycle cost. Having examined the cost composition and the LCOS under different EES capital costs, the next section will study on the revenue aspect in the financing.

### 6.4. EES finance under different electricity prices

The electricity price affects the EES revenue. Due to intermittent generation, the electricity price can change in a low carbon electricity system [75]. EES has the ability to provide many grid services such as operating reserve and power quality improvement [22]. Hence, the electricity price for the EES energy is uncertain. As an example in the U.K., the electricity price to perform short-term operating reserve (STOR) is approximately three times the electricity market price [12].

This section examines the equity cash flow under different retail electricity price, for the EES with a capital cost at 1500 $/kWh. The "High-PV" scenario is adopted as it is the one to have the best chance to gain the highest profit, as shown in Section 6.1. Fig. 15 shows the cash flow for the EES under different retail electricity prices. As observed, a low price makes the project unprofitable. The equity will begin to have a positive cumulated cash flow when the electricity price is at 600 $/kWh. The cumulated cash flow to the equity increases with a higher electricity price and will take reduced years to break-even.

To examine the impact of different electricity prices on the EES financing in a more general context, Table 4 presents the NPV to equity for the three operating scenarios according to different retail electricity prices. Achieving a positive cumulated cash flow to the equity does not guarantee to give a positive NPV to equity. The NPV will begin to be positive when the electricity price is at 700 $/MWh for the "High-PV" scenario and EES capital cost at 1500 $/kWh. With the capital cost at 200 $/kWh, the EES can make a profit when the retail electricity price is at 100 $/MWh or above.

To summarize, this section examined the cash flow to equity under different retail electricity prices. The NPV to equity were also studied. It is identified that the EES profitability is affected by the retail electricity price and the EES operating conditions.

## 7. Sensitivity analysis of technical and economic parameters

Consider that there are many technical and economic uncertainties as presented in Table 2, this section presents a sensitivity analysis on the key parameters and to examine its effect on the NPV and LCOS.

Figs. 16–18 present the sensitivity analysis results for "High-AD", "Balanced", and "High-PV" scenarios. The description for the index at the x-axis can be referred to Table 2. For the sake of this analysis, the parameters are varied ± 10% independently from the others. The EES capital cost (where the sensitivity has been previously analyzed) is set here at 200 $/kWh.

The EES lifetime has the largest impact on the NPV for "High-PV" and "Balanced", since the lifetime is relatively short (e.g., 8 or 9 years of operation). This is not the case for "High-AD". Energy related parameters (e.g., PV energy to EES and round-trip efficiency) have a stronger influence on the NPV than economic parameters (e.g., fixed and operating costs). The fixed and operating costs are negligible on the NPV since EES is a capital-intensive project. The only economic parameter that affects the NPV is the average wholesale electricity price as it affects the revenue. There is a larger "swing" in the NPV with the

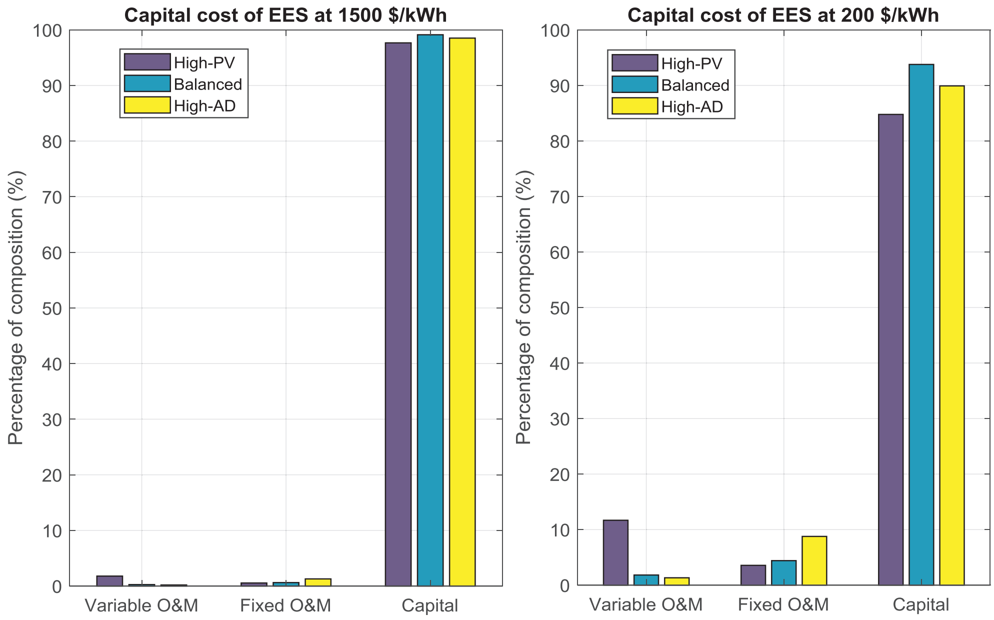

**Fig. 13.** Percentage of the costs for three operating scenarios with EES capital cost at 1500 $/kWh and 200 $/kWh.

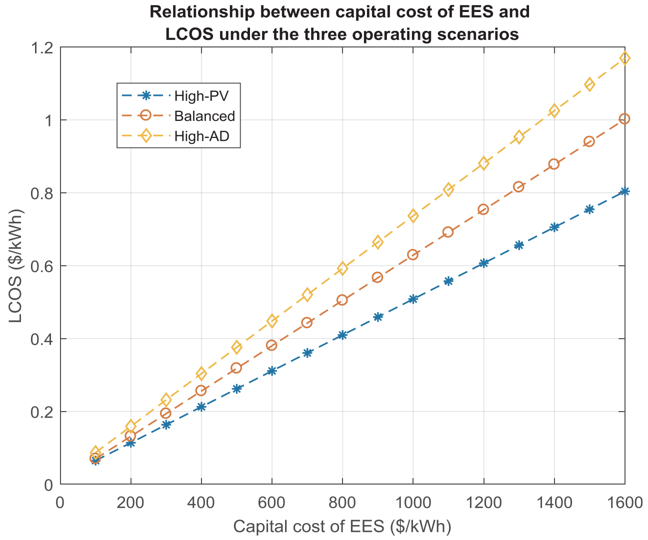

**Fig. 14.** Relationship between LCOS and EES's capital cost under the three operating scenarios.

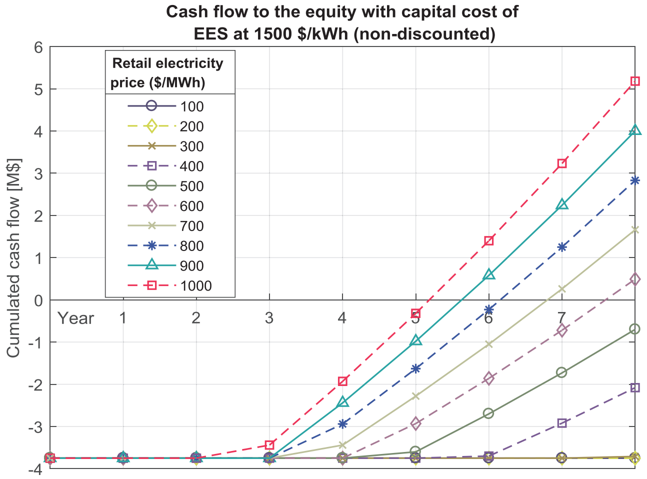

**Fig. 15.** The cumulated cash flow to the equity under different retail electricity prices for EES.

change of parameters value for "High-PV" compared to others, as the operating lifetime is shorter and the annual energy output is higher.

## 8. Discussion and future work

EES technologies such as Li-ion batteries are an increasingly important asset to support the rising penetrations of intermittent renewables and provide grid support (such as energy balancing). In regard to policy implications, this work has examined the impact of WACC (cost of debt and equity) on the LCOS and NPV to equity. Cost of debt and equity are reducing with respect to time due to lower risk and reduced borrowing costs promoted by governments [70]. For EES and low-carbon technology investments, the LCOE can be effectively reduced by reducing the WACC [70]. In Section 6.1, the LCOS has been studied and compared to values determined in previous studies. Apart from cost of debt and equity, the share of CAPEX and corporate tax rate also have an effect on the financing of EES.

From the investment perspective, financing the EES can be challenging due to the technical difference to a generator, i.e., EES is not an electrical generator that transforms primary energy to electricity. It is important to identify the flow of cash (inbound and outbound) and the stakeholders (debt and equity) clearly for a more in-depth cost-benefit study. In this study, it shows that the EES project financial feasibility and profitability depend on the retail electricity price, especially at high capital cost scenarios.

This work firstly examines the LCOE for a PV, AD biogas power plant, and EES hybrid energy system. Kenya is used for the case study. The research then focuses on the EES and a financial model is built to examine its financing and economics. The following phenomena are discovered in this research:

- The economics for EES with and without the degradation can be very different;
- The EES capital cost plays an important role in the financing. It constitutes the majority of the lifecycle cost. The EES is unprofitable under most operating situations when the capital cost is at 1500 $/kWh. When the capital cost drops to 200 $/kWh, the EES becomes profitable when it operates more frequently with a reduced lifetime;

**Table 4**

NPV to equity (M$) under different EES's capital costs and retail electricity prices.

| | | EES's capital cost ($/kWh) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1500 | | | 200 | | |
| | | High-PV | Balanced | High-AD | High-PV | Balanced | High-AD |
| Retail electricity price ($/MWh) | 100 | -5.59 | -5.66 | -5.84 | -0.01 | -0.03 | -0.06 |
| | 200 | -4.57 | -4.85 | -4.65 | 0.86 | 0.63 | 0.76 |
| | 300 | -3.55 | -4.03 | -4.04 | 1.75 | 1.35 | 1.57 |
| | 400 | -2.47 | -3.20 | -3.42 | 2.64 | 2.08 | 2.39 |
| | 500 | -1.50 | -2.29 | -2.67 | 3.53 | 2.80 | 3.21 |
| | 600 | -0.65 | -1.45 | -1.80 | 4.43 | 3.53 | 4.03 |
| | 700 | 0.20 | -0.70 | -0.86 | 5.33 | 4.27 | 4.86 |
| | 800 | 1.06 | 0.00 | 0.11 | 6.22 | 5.00 | 5.68 |
| | 900 | 1.91 | 0.69 | 1.07 | 7.12 | 5.74 | 6.51 |
| | 1000 | 2.79 | 1.39 | 2.00 | 8.02 | 6.47 | 7.33 |

Green: Profitable.
Red: Unprofitable.

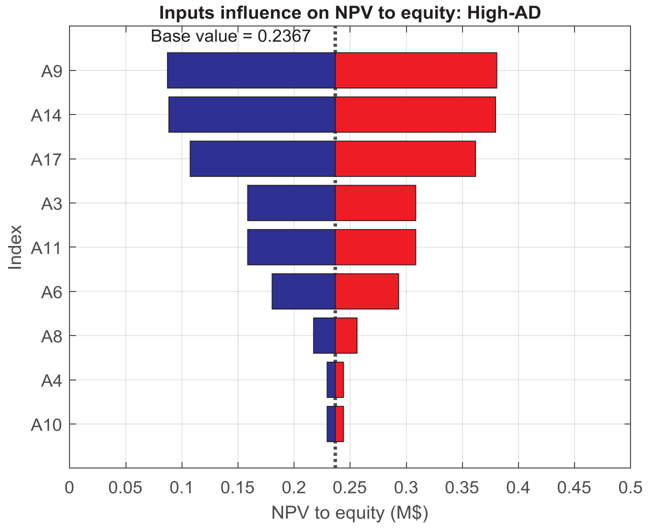

**Fig. 16.** Sensitivity analysis on parameters for "High-AD" scenario.

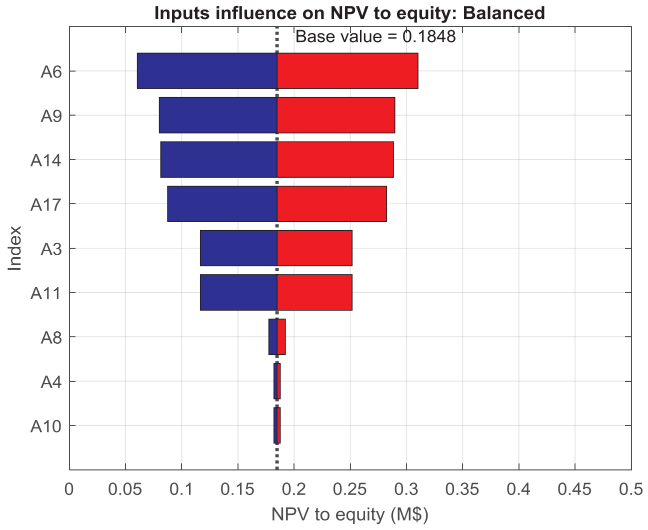

**Fig. 17.** Sensitivity analysis on parameters for "Balanced" scenario.

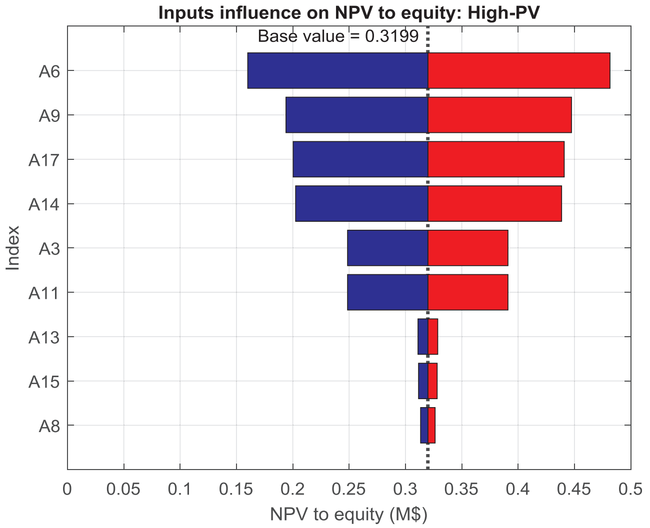

**Fig. 18.** Sensitivity analysis on parameters for "High-PV" scenario.

- A higher retail electricity price is needed to make the EES profitable at 1500 $/kWh. For the three operating scenarios namely "High-PV", "Balanced", "High-AD", the retail electricity prices required to make EES profitable are 700 $/MWh, 900 $/MWh, and 800 $/MWh respectively. Hence, the EES should participate in high revenue generating activities such as STOR; and
- With the EES's capital cost at 200 $/kWh, the EES can be used in regular discharging activities and will be profitable. The retail electricity price needs to be 200 $/MWh and above.

The following describes how the aims of this research are addressed:

- Section 2 has identified the research gaps in techno-economic analysis for PV/biogas generator/Li-ion EES hybrid energy system and EES. Subsequently, the EES degradation and financing are reviewed. It is identified that there is little work done in examining the finance of EES, in particular with storage degradation;
- Section 5 has presented an EES cash flow model that considers of storage degradation. The technical results (e.g., energy output and percentage of EES degradation per year) are used as inputs for the cash flow model. Section 6 presented the financial and economic analysis. In particular, the model has been verified, with the LCOS results compared to other works as presented in Section 6.1; and
- Section 6 studied the economics and financing of EES in detail.

Specifically, Section 6.1 examined how the WACC affects the NPV to the firm and LCOS for the EES. Section 6.2 investigated the cash flows for the three operating scenarios. Section 6.3 presented the breakdown of the cost of the EES by comparing how different operating strategies can affect the EES cost. Section 7 presented a sensitivity analysis on the economic and technical parameters, and identified the key parameters that affect the NPV to equity.

The present research has opened many future works. Future research directions on the financial and economic analysis for low-carbon energy storage are as follows:

- This work focuses on the development of a financial model for the EES. Future work will develop and study the financial model for the hybrid energy system;
- As reviewed in Section 2, there are other types of financing methods for renewable and EES (such as crowdfunding). Models based on other financing theories will be useful for EES financing;
- The degradation aspect could be enhanced by including other models (e.g., calendar aging) and additional data (e.g., operating and ambient temperatures) as these affect the cycle-life and lifetime of the EES. This will impact the financing results;
- In this work, the revenue for EES is based on the solar surplus energy and the biogas energy that are used to charge the EES to the predefined $\mathrm{SOC}_{\mathrm{Threshold}}$. An energy arbitrage algorithm can be included to maximize the revenue. This is particularly important for grid-connected systems;
- Real options valuation will be useful in the financial model to take the technical, economic, and financing uncertainties into account [12]; and
- The current financial model can be expanded by including additional EES technical details. It is particularly useful to examine generation integrated energy storage systems by taking the exergy and transmission efficiency into account [76].

## 9. Conclusions

The electrical energy storage (EES) profitability is difficult to establish due to uncertainties related to both key technical aspects such as the EES degradation, the operating lifetime and economic aspects such as EES capital cost and retail electricity price. Moreover, there is a need to integrate advanced EES technical models (e.g., accounting for EES degradation) to the cash flow model for the EES project financial appraisal. The literature in the energy storage field is mostly grounded in simplistic economic models. The key contribution of this paper is to detail a state-of-the-art financial model and apply it to the novel case of Li-ion EES. Three EES operating scenarios namely “High-PV”, “Balanced”, and “High-AD” were examined. It is identified that the project is unprofitable with the EES’s capital cost at 1500 $/kWh under current economic settings. The EES needs to participate in high revenue generating activities, e.g., short-term operating reserve for the EES to be profitable. For the case with the EES capital cost at 200 $/kWh, the project can be profitable when the EES is operated frequently (i.e., more energy discharge and a higher number of EES cycling) even if the lifetime is reduced due to the increase in EES degradation. The paper also shows the key importance of the weighted average cost of capital with respect to different system operating scenarios.

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