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Levelized cost of electricity for photovoltaic/biogas power plant hybrid system with electrical energy storage degradation costs

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ABSTRACT

Off-grid renewable energy system is a critical infrastructure in providing electrical power for small communities, especially in remote and rural areas where grid connection points are not available. Due to the diurnal and intermittent nature of solar irradiance, the photovoltaic (PV) power plant can introduce generation and load power imbalance issue. Anaerobic digestion biogas power plant (AD) also has a part-load operation constraint that needs to be met. To overcome these issues, electrical energy storage (EES) such as Graphite/$LiCoO_2$ needs to be employed to provide generation flexibility. The research work provided in this paper is twofold. An optimal operating regime is devised for the PV-AD-EES hybrid system, followed by a study on the levelized cost of electricity (LCOE). Degradation cost per kWh and degradation cost per cycle for EES are considered. 22 years (1994–2015) of irradiance data for Turkwel Gorge Dam, Kenya (1.90°N, 35.34°E) and the Kenya national load are used for the study. With the current technology costs and a discount rate at 8%, it is shown that the capital cost for $LiCoO_2$ needs to be reduced to 200 $/kWh to be economically competitive with dispatchable source such as AD biogas power plant by considering the EES degradation costs.

1. Introduction

Electrical energy storage (EES) plays an increasingly important role in electrical power systems, especially for energy balancing in off-grid systems. With the escalation of energy demand and the pressure to reduce environmental pollution, renewable energy source such as solar photovoltaic (PV) needs to be adopted [1,2]. For countries located in Africa at the equator, e.g. Kenya, there is an abundant amount of solar insolation throughout the year. In addition, the waste product generated from the large agricultural industry in Kenya makes electrical power generation from biogas power plant via anaerobic digestion (AD) a desirable option [1]. Hence, the optimal hybrid energy system for a rural community in Kenya should consists of solar PV and AD biogas power plant. In this paper, the term AD represents the combination of the anaerobic digester and the biogas power plant.

In general, off-grid hybrid renewable energy systems perform better with multiple energy sources compared to a single energy source [3]. This can be explained by the fact that different energy sources have different technical constraints, and may be used to complement each other and to maximise the security of supply. The generation costs could also be potentially reduced. However, the control, design, and optimization of such systems is a complicated matter. In general, many of these systems were designed to with the aim to minimize the total generation cost such as the levelized cost of electricity (LCOE) [3,4].

The operation strategy for a system with an EES and PV generator is relatively simple. Surplus energy is stored in EES and discharges if the load is greater than generation. The interesting questions arise for systems with multiple energy sources. For the case where a dispatchable source such as AD is included, it is required to determine how the EES is charged and which dispatchable source (AD or EES) to use when the load demand is greater than the generation. As mentioned in [4], there are three basic control strategies for a PV-Diesel-EES system. These are known as zero-charge strategy, full cycle-charge strategy and the predictive control strategy. The EES is never charged with the diesel generator in the zero-charge strategy. Diesel generator is used to charge the EES to 100% state of charge (SOC) when the generator is on for the full cycle-charge strategy. Predictive control strategy requires the forecast of renewable generation and load demand to charge the EES.

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Nomenclature

ΔSOC	change in state of charge (%)
Δt	hour interval
η_{EES}	EES round-trip efficiency (%)
η_{PV}	PV array efficiency (%)
σ	degradation rate for PV (%)
ε	solar irradiance (Wm^{-2})
a, b and c	quadratic fuel cost function constants for biogas generator
AD	anaerobic digestion
$C_{AD_{Fuel}}$	Fuel cost for biogas generator ($)
$C_{AD_{Labour}}$	labour cost for operating the biogas power plant ($0.05/kWh)
C_{Asset}	net present value of asset, i.e. PV, AD, EES, controller or inverter ($)
$C_{Asset_{O\&M_{Fixed}}}$	fixed operation and maintenance cost for asset, i.e. AD, EES or PV ($/kW)
$C_{Asset_{O\&M_{Total}}}$	total O&M cost for asset, i.e. AD, EES or PV ($)
$C_{Asset_{O\&M_{Var}}}$	variable operation and maintenance cost for asset, i.e. AD, EES or PV ($/kWh)
$C_{Asset_{Storetotal}}$	net present value of electricity production from asset, i.e. AD or PV to be stored in EES ($)
$C_{Cap_{Asset}}$	capital cost for asset, i.e. AD, controller, EES, inverter or PV (Unit is asset dependent)
C_{EES}	net present value of electrical energy storage ($)
$C_{EES_{Replacement}}$	replacement cost per discharge cycle ($)
$C_{EES_{DegkWh}}$	EES degradation cost due to energy discharge ($)
C_{Gas}	AD gas cost (6.97 $/mcf)
$C_{Inst_{Asset}}$	installation cost for asset, i.e. AD, controller, EES, inverter or PV (Unit is asset dependent)
$C_{O\&M_{Asset}}$	operation and maintenance cost for asset, i.e. AD, controller, EES, inverter or PV (Unit is asset dependent)
$C_{O\&M_{PVint}}$	operation and maintenance cost for PV per hour ($)
CF	capacity factor (%)
d	discount rate (%)
d_{ees}, e_{ees} *and* f_{ees}	three-parameter equation constants for EES rated cycle life at deep discharges
DOD	depth of discharge (%)
$E_{Asset_{Directtotal}}$	net present value of electricity produced by asset, i.e. AD or PV for direct consumption (kWh)
E_{AD}	net present value of electricity production of biogas generator (kWh)
E_{EES}	net present value for EES electricity output (kWh)
$E_{EES_{Store}}$	electricity to be stored in EES (kWh)
$E_{EES_{Rated}}$	rated energy capacity of EES (kWh)
$E_{EES-S(X)}$	electricity discharge by EES at stage $X, X \in \{1,2\}$ (MW)
E_{PV}	net present value of electricity generated by PV farm (kWh)
$E_{Surplus}$	surplus electricity generated by PV system (kWh)
EES	electrical energy storage
EMS	energy management system
FiT	feed-in tariff
LCOD	levelized cost of delivery ($/kWh)
LCOE	levelized cost of electricity ($/kWh)
$LCOE_{Asset}$	levelized cost of electricity for generation asset, i.e. PV or AD ($/kWh)
$LCOE_{System}$	levelized cost of electricity for system ($/kWh)
LCOS	levelized cost of storage ($/kWh)
$LiCoO_2$	lithium cobalt oxide
LHV	lower heating value (905 btu/ft^3)
m	number of EES cycles (integer)
n	system lifetime (years)
N_{Con}	number of controllers (integer)
N_{EES}	number of EES replacements (integer)
N_{Inv}	number of inverters (integer)
N_{PV}	total number of PV panels (integer)
N_{Store}	number of PV panels for generating electricity for storage (integer)
NDC	normalized discharge capacity (%)
NaS	sodium-sulphur
NiMH	nickel-metal hydride
O&M	operation and maintenance
P_{AD}	output power of biogas power plant (MW)
$P_{AD_{Max}}$	rated power capacity of biogas power plant (MW)
$P_{AD_{Min}}$	minimum output power of biogas power plant (MW)
$P_{Asset_{Direct}}$	power generated with asset, i.e. AD or PV for direct consumption (MW)
$P_{Asset_{Store}}$	power generated with asset, i.e. AD or PV for storage (MW)
P_{Con}	rated power of controller (kW)
$P_{EES_{S(X)}}$	EES power discharge at stage X, $X \in \{1,2\}$ (MW)
$P_{Generation}$	power generation (MW)
P_{Load}	power demand (MW)
P_{Inv}	rated power of inverter (kW)
P_{PV}	output power of PV plant (kW)
$P_{PV_{Rated}}$	rated capacity of PV plant (kW)
$P_{Surplus}$	surplus power generated by PV farm (MW)
PV	photovoltaic
Ratedcycle	rated cycle life of EES (integer)
SOC	state of charge (%)
SOC_{Lower}	the minimum SOC value of a cycle (%)
SOC_{Max}	maximum state of charge (%)
SOC_{Mean}	mean state of charge (%)
SOC_{Min}	minimum state of charge (%)
$SOC_{Threshold}$	SOC threshold (%)
SOC_{Upper}	the maximum SOC value of a cycle (%)
SSR	self-sufficiency Ratio (unitless)
t	time (hour)

The advantage of this strategy is that energy wastage in surplus energy production from renewables is reduced. An interesting research question to be answered is to determine the optimal point for the SOC, between 0% to 100% to be charged with AD in order to provide a minimum operational cost [4]. In other words, the strategy will be less of an extreme and is between zero-charge and full cycle-charge.

Scheduling regimes such as rule-based strategies [5] have the advantages in avoiding the need of renewable and load forecasting for optimal operation. Additionally, complexity is further reduced when online optimization is not required. The work did not mention the degradation and costs of EES and have highlighted as a future work.

There are numerous amount of research works in cycle life studies and the costs due to EES degradation for hybrid renewable energy systems [6–9]. However, most do not consider partial charge-discharge cycles and uses depth of discharge (DOD), i.e. only accurate for initial SOC at 100% for EES cycle life calculations. Electrical energy delivered is also used to consider the DOD in some literatures such as [6] and the actual values of the two SOCs may be neglected. Theoretically as an example, the electrical energy output from EES at SOCs of 100% to 80% may be the same as a situation for 40% to 20%. Recent literatures [10,11] have confirmed that partial charge-discharge cycles at different SOC states have a profound effect to the State of Health, i.e. discharge capacity of the EES, and consequently affects the total available cycle life.

Due to irregular load demands and the PV power fluctuations induced from stochastic solar irradiance, the hybrid power system is