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Techno-economic assessment of 10 MW centralised grid-tied solar photovoltaic system in Uganda

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ABSTRACT

There is increasing interest in solar PV installations in Uganda, however, there is little or no information available on performance of solar PV systems in Uganda. Since solar PV performance is site specific, there is need to provide stakeholders with information that could help them in making informed decision. Therefore, this paper presents a performance analysis of a 10 MW solar-photovoltaic plant installed in Soroti City, in Eastern Uganda (latitude 1°N, longitude 33°E). Energy production data for this solar power plant over a 3-year period between January 2017 and December 2019 were collected and analysed using IEC standard 61724–1. It was found that the average annual energy generation by the plant is 16702 MWh and specific energy output of 1670.2 kWh/kW. Furthermore, the daily final yield, annual performance ratio, annual capacity factor and energy yield per unit area are found as 4.58 h/day, 75.84%, 19.07%, and 121.4 kWh/m^2. respectively. Based on the assumption used in this study and approved feed-in tariff, the estimated discounted payback period (9.28 years), profitability index (1.51), and internal rate of return (10.55%) showed that it is economically viable. The estimated levelized cost of energy of US$ 0.1087/kWh, is within range of values reported for similar projects.

1. Introduction

The technical performance of solar PV installation depends on factors that include; the installation's location and its associated weather and meteorological conditions, efficiencies of the main components of the system and their responses to environmental conditions, as well as installation angles (tilt angle and orientation angle). Furthermore, the economic viability of a solar PV system is a function of the main components' costs, labour, and land costs (which depend on site locations), other related operation and maintenance costs, and the site's macroeconomic issues. Therefore, to assess economic viability of solar PV-grid connected energy systems, both economic and environmental parameters of the location of the installation should be taken into consideration.

Even though, both technical and economic performance of any solar PV can be assessed using simulation tools, the best way is to carry out performance assessment under actual operating conditions. Several performance evaluation studies of PV installations have been carried in Africa (see for examples [2–11]; and worldwide [16–31,43]). As shown in Table 1 as well as in recent comprehensive review on solar PV performance reported by Ref. [1], all these studies indicate that solar PV performance indicators (such as final yield, performance ratio, capacity factor and specific energy) varies and depends on site's environmental conditions.

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Nomenclature

A_r	Annual revenue ($)
A_s	Annual saving ($)
BCR	Benefit-cost ratio (−)
C_o	Investment cost ($)
$C_{O\&M}$	Operation and maintenance cost ($)
DPP	Discounted payback period (year)
E_{AC}	Daily final alternating current (AC) energy output (kWh)
E_d	Daily energy output (kWh)
f_d	Average daily derate factor or performance ratio (−)
G_{STC}	Reference solar radiance (1000 W/m2)
H_c	Solar radiation on inclined plane (kWh/m2/day)
i	Discounted rate (%)
IRR	Internal rate of return (%)
LCC	Life cycle cost ($)
LCOE	Levelised cost of energy ($/kWh)
n	Project economic life (year)
N	Number of data point
NCF_t	Net cash flow in year t ($)
NPV	Net present value ($)
P_{IC}	Solar PV installed capacity (kW)
PR	Performance ratio (−) or (%)
S_h	Peak sun hour (h/day)
SPP	Simple payback period (year)
t	Year
T_h	Time (h)
Y_f	Daily final energy yield (h/day)
Y_r	Daily reference yield (h/day)

While there are couple of small-scale and utility-scale solar PV installations in Uganda (see Table 2), and as well increasing interest from households, commercial and industrial consumers in the development of system solar PV installations in the country, to the authors' knowledge, there is little or no information available (in open literature) on performance of solar PV systems in Uganda. Furthermore, Ref. [1] and information presented in Table 1 shows that there is lack of information on the performance of solar PV in the Eastern Africa region. Therefore, in order to fill this knowledge gap of lack of information on performance of solar PV installation in this country, this study aims to provide a techno-economic performance analysis of a 10 MW solar PV plant located in Soroti City, in the eastern region of Uganda. The Soroti solar power plant is the first grid-connected solar plant in Uganda and, at the time of its commissioning in December 2016, it was the largest solar power plant in East Africa. Results obtained from this study are intended to provide helpful information to policy makers, interested individuals and organizations about the actual performance of grid-connected PV systems in Uganda.

2. Methods and materials

2.1. Study area

2.1.1. Energy situation in Uganda and solar PV development

Overall, the energy sector of Uganda is dominated by use of biomass of fuel wood, charcoal and agricultural residues, contributing 88% to national primary energy mix by mid-2019, while electricity and petroleum products contributed 2% and 10%, respectively [32]. This overdependence on wood fuel is mainly due to its accessibility and affordability. However, this has resulted into depletion of forest cover and land degradation [33]. Uganda is abundantly blessed by energy resources, especially hydrological and other renewable energy resources such as solar energy, biomass resource, wind energy and geothermal energy.

Historically, the generation capacity of Uganda's electricity sub-sector grew from 609.4 MW in 2011 to 1268.8 MW as of 2020 (Fig. 1), and it is dominated by hydropower, which accounted for 79.65% by 2020. The approved Government of Uganda Vision 2040 development plan anticipated an increase in the country's power generation from the 822 MW (in 2012) to about 41 800 MW (by 2040) and electricity consumption per capita to 3668 kWh/year [34]. The current installed power capacity and proposed distribution of installed capacity of power generation by 2040 are shown in Table 3. This table shows that renewable energy resources (hydropower, geothermal energy, solar energy, and biomass energy) are expected to contribute 12 700 MW to national grid by 2040. Furthermore, it can be deduced from this table that, solar energy resource is expected to provide about 12% of the Uganda's installed power capacity by 2040 and 39.4% of renewable-based power capacity.

2.1.2. Status of solar energy development in Uganda and government target

Given Uganda's total surface area of 236 040 km^2, and, on average, over 5 kWh/m^2/day global solar radiation on horizontal surface, Uganda has more than 400 000 TWh of solar energy potential, each year falling on its surface area. This is equivalent to over 15 000 times the total primary energy consumption in Uganda in 2017, which was 0.097 Million Quad (or 28.43 TWh) [36]. Due to a combination of this good resource and generous feed-in tariff (of US$0.1637/kWh), the utility-grid connected solar photovoltaic (PV) power plant capacity has increased from zero in 2015 to 60 MW by the end of 2020 Table 2 shows the list of commissioned solar PV installations in this country.

2.2. Description of the power plant

Access solar power plant, which was commissioned by the end of November 2016 and launched in December 2016 is located at Aliedi village in Soroti city and it occupies 34 acres (137 593 m^2) of land. Soroti city is in the Eastern region of Uganda (see shown in Fig. 2), approximately 300 km from the capital, Kampala. The city lies approximately on latitudes 1° 33′N and 2° 23′N, 30° 01′E and 34° 18′E and is over 2500 ft above sea level.

Being a grid-connected system, the access solar power comprises of the following major components: solar PV array, inverters, and transformers. The solar PV array comprises of 32680 CS6X–310P modules, with overall installed capacity of 10 MW. Table 4 shows selected specifications of the module CS6X–310P. Inverters, manufactured by SMA with model number SUNNY TRIPOWER STP 20000TL-30 (see Table 5 for selected specifications), eight (8) transformer equivalent to 10MVA (manufactured by ABB), each with capacity of 1.25MVA, 400 V generation voltage and 3 phase distribution. The plant was built at a cost of US$19 million (or US$1900/kW), which include the costs of modules, balance of system (BOS) components, construction, and operating licensing fees, and as well as installation costs. To minimize the effect of self-shading, two consecutive rows of PV modules are kept at spacing of 2 m apart. The

Table 1
Performance indicators for selected grid-connected solar PV installations.

Location	Installed capacity (kW)	Technology	Final yield (kWh/kW/year)	Performance ratio (%)	Capacity factor (%)	Refs.
Africa						
Navrongo, Ghana	2500	pc-Si	1419.1	70.6	16.20	[2]
Mauritania	15 000	Thin film	1558.6	67.9	16.14	[3]
Morocco	5	pc-Si	1624.3	79.0	14.83	[4]
Algeria	28	Mono-Si	1606.0	71.9	18.57	[5]
Malawi	830	a-Si and c-Si; HIT	1551.25	79.5	17.10	[6]
Algeria	2.5	Mono-Si	1737.28	73.82	7.91	[7]
Casablanca, Morocco	2.04	Mono-Si	1653.45	76.7	18.86	[8]
Casablanca, Morocco	2.04	Pc-Si	1631.55	75.6	18.64	[8]
Casablanca, Morocco	1.86	a-Si	1580.45	73.1	18.05	[8]
Port Elizabeth, South Africa	3.2	Multi-Si	1788.50	84.0	15.26	[9]
Kumasi, Ghana		a-Si	1121.0	75.8	12.8	[10]
		CIS	774.0	52.3	8.8	
		HIT mc-Si	1106.0	74.8	12.6	
		pc-Si	1004.0	67.9	11.47	
			1129.0	76.3	12.9	
Nouakchott, Mauritania	954 809	μc-Si thin film	1554.9	60.0–90.0	17.74	[11]
Rest of the world						
Kuwait	5600	pc-Si	1795.3	80.2	20.58	[12]
	5500	Thin film	1794.5	80.0	20.58	[12]
India	10 000	pc-Si	1560.6	85.1	17.68	[13]
India	10 000	pc-Si	1514.8	78.0	17.29	[14]
India	5000		1664.5	67.36	19.00	[15]
India	3000	Mono-Si	1372.0	70.0	15.66	[16]
India	1000	Mono-Si	1693.6	74.73	19.33	[17]
India	11.2	Pc-Si	1368.75	81	15.63	[18]
India	1000	Pc-Si	1325.42	88	15	[19]
Brazil	2.2		1685.5	82.9	19.20	[20]
Tamilnadu, India	5000	Thin film a-Si	1755.7	89.15	20	[21]
Eastern India, India	11.2	Pc-Si	1339.6	78	15.27	[22]
Shah Alam, Malaysia	0.9	a-Si	1262.9	85	14.4	[23]
Dublin, Ireland	1.72	Mono-Si	879.65	81.5	10.1	[24]
Northern Ireland	13	Single c-Si	616.85	61	7.0	[25]
Patagonia, Chile	8.2	Pc-Si	1314	89	15.1	[26]
Nis, Serbia	2	Mono-Si	1161.70	93.6	12.88	[27]
As, Norway	2.07		931.26	83.04	10.60	[28, 29],
Irbid, Jordan	5000	Pc-Si	1617.2	80	18	[30]
Crete, Greece	171.36	Pc-Si	1336.4	67.36	15.26	[31]

Table 2
Grid-connected Solar power plant in operation in Uganda.

Name	Owner/Operator	Template installed Capacity (MW)	Investment cost (US$ million)
Soroti Solar Power Plant (2016)	Access solar Uganda	10	19.0
Tororo Solar Power Plant (2017)	Tororo Solar North Ltd	10	19.6
Kabulasoke Pilot Solar Park (2019)	MSS Xsabo Power Ltd	20	25.0
Bufulubi Solar Power Plant (2019)	Emerging Power U Ltd	10	11.0
Tororo PV Power Project (2020)	Tororo PV Power Co. Ltd	10	Not available

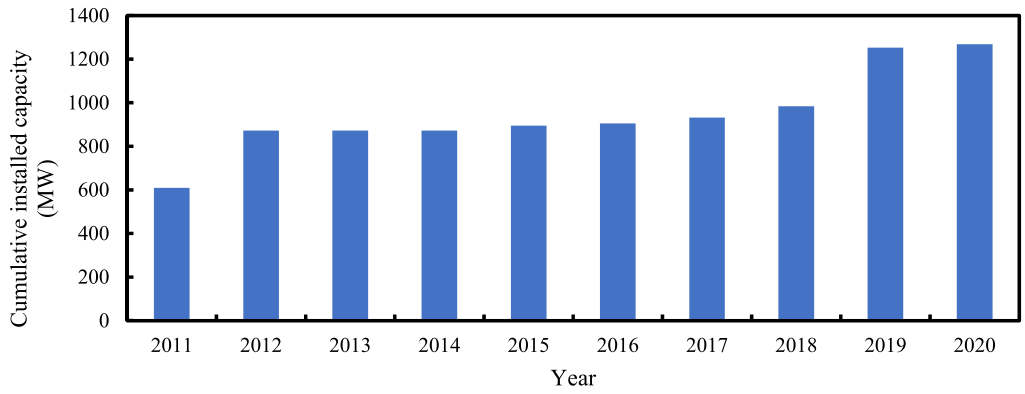

Fig. 1. Historical electricity installed capacity in Uganda from 2011 to 2020 (Data from Ref. [35]).

Table 3
Present and future cumulative power generation in Uganda.

Source of energy	Current installed capacity (MW), Jan 2021[a]	Proposed installed capacity (MW), 2040[b]
Hydropower	1010.7	4500
Geothermal energy	0	1500
Solar energy	60.8	5000
Cogeneration	96.2	1700
Peat energy	0	800
Nuclear	0	24 000
Thermal (HFO)+diesel	101.1	4300
Total	1268.8	41 800

[a] Ref. [35].
[b] Ref. [34].

solar PV installation is oriented towards south and inclined at fixed tilt angle of 10°.

2.3. Design, arrangement, and connections

The installation consists of 32680 modules, which are assembled into forty-three (43) arrays. Each array consists of 10 units with each unit connected to a separate inverter and comprises of 19 modules/strings x 4 strings (or 76 modules, which is equivalent to 23.56 kW). The total open-circuit voltage per string is 853.1 V and optimum operating voltage is 691.6 V, which are respectively, less than inverter maximum input voltage (1000 V) and within inverter maximum power point (MPP) tracking voltage range of 320 V–800 V. The total short-circuit current and optimum operating current for each unit are 36.32 A and 34.08 A, respectively. The AC output from the 10 inverters is then connected to an AC combiner box. The output power from the combiners is fed to a 10 MVA STEP-UP power transformer, where the installation output voltage is stepped up to 33 kV and linked to the utility grid through a 2.5 km overhead transmission line to Opuyo substation. Fig. 3 shows the selected photos of the solar power plant installation.

2.4. Analysis techniques

The overall performance and economic viability of a solar power plant can be assessed by examining using different technical and economic performance indicators. The technical indicators indicate overall ‘efficiency’ of the system subjected to its site

Fig. 2. Administrative map of Uganda showing Soroti city (Source: Ref. [37]).

Table 4
Selected technical specifications for CS6X–310P module [38].

Parameter	Value
Rated nominal power, P_{mpp} (W)	310
Current at P_{mpp}, I_{mpp} (A)	8.52
Voltage at P_{mpp}, V_{mpp} (V)	36.4
Short circuit current, I_{sc} (A)	9.08
Open circuit voltage, V_{oc} (V)	44.9
Nominal operating cell temperature, NOCT (°C)	45 ± 2
Module efficiency (%)	16.16
Weight (kg)	22
Dimension (mm)	1954 × 982 x 40
Maximum system voltage (V)	IEC (1000) or UL (1000)
Temperature coefficients P_{max} (%/°C)	−0.41
V_{oc} (%/°C)	−0.31
I_{sc} (%/°C)	0.053

Table 5
Selected technical specifications for Sunny Tripower STP 20000TL-30 [39].

Parameter	Value
Maximum input voltage (Vdc)	1000
Maximum input current (Idc)	33A
MPPT voltage range (V)	320–800
Nominal output power (kW)	20
Maximum output power (kVA)	20
Nominal operating voltage (V)	415
Nominal frequency range (Hz)	50/60
AC voltage range (V)	180–280
European efficiency (%)	98

Fig. 3. Selected photos of Soroti solar power plant (Pictures: Ivan T Oloya).

environmental conditions and technical properties of the installation's components. On the order hand, economic indicators show how economically viable the installation is, when considering the system's investment cost and other relevant economic parameters as well as cost of the alternative energy resources in the installation area or country. The following sub-sections present the selected technical and economic indicators used in this study.

2.4.1. Estimating solar PV energy output

The energy output from a solar PV is a function of the location peak sun hour, installed capacity of the installation, and combination of efficiencies of the system's components and environmental conditions of the location, termed 'derate factor'. Mathematically, daily energy output (kWh) from a solar PV system can be estimated from:

$$E_d = f_d * S_h * P_{IC} \tag{1}$$

where S_h is the peak sun hour (h/day), P_{IC} is the solar PV installed capacity (kW) and $f_d$is the average daily derate factor or performance ratio. The peak sun hour is then determined from

$$S_h = \frac{H_c(kWh/m^2/day)}{1kW/m^2} \tag{2}$$

where $H_c$is the solar radiation on the plane of the solar PV array.

2.4.2. Technical indices

In this study, the technical performance of the study is evaluated by determining the final energy output, final energy yield, performance ratio and capacity factor performance parameters. These parameters provide information about the overall performance of the installation with respect to available solar resource and other environmental variables. It should be noted that depending on the resolution of available information and purposes of the analysis, these performance indexes can be evaluated on hourly, daily, weekly, monthly, and annual basis. For a grid-tied solar PV system, which has mainly solar PV array and inverter as main equipment, the final energy output is defined as the amount of alternating current (AC) power produced by the system over a given period. Mathematically, the final energy output of such system is given (see for examples [2,12,14,31,40]):

$$E_{AC} = \sum_{t=1}^{N} E_{AC(t)} \tag{3}$$

where E_{AC} (kWh) EAC, tis final energy output at time t and NN is the number of data set. The final energy yield is then determined as (see for examples [2,12,14,18,19,31,40,41]):

$$Y_f = \frac{E_{AC}(kWh)}{P_{IC}(kW)} \cdot (\mathrm{kWh/kW}) \tag{4}$$

The performance ratio (PR) measures the overall effect of losses on the rated output of the system due to the site's environmental conditions, installation components efficiencies and system's installation angles (such as tilt angle and orientation angle). The PR indicates how close a solar PV performance approaches ideal situation during real life operation. Mathematically, it is expressed as (see for examples [2,12,14,18,31,40]):

$$PR = \frac{E_{AC}}{P_{IC}} * \frac{G_{STC}}{H_C} = \frac{Y_f}{Y_r} \cdot (-) \tag{5}$$

where H_C (kWh/m^2/day) is the in-plane array radiation, G_{STC} (kW/m^2) is the reference irradiance and Y_r is the reference yield.

The capacity factor of a solar PV installation is defined as the ratio of the final energy produced by the installation over a given period to the energy output that would have been generated if the system was operated at full capacity for the entire period. It is given as (see for examples [18,41,42]):

$$C_f = \frac{E_{AC(t)}}{P_{IC} * T_h} \tag{6}$$

where T_h is the total expected number of hours of operation in a given period, commonly taken as a year (for a regular year, which consists of 365 days, $T_h = 8760$ h) and $E_{AC(t)}$ (kWh) is the actual total final energy generated within this given period.

2.4.3. Financial and economic indicators

As indicated in Table 2, the total investment costs, which consist of various pre-operation costs (such as equipment cost, pre-installation cost, actual installation cost and licence application cost) of the facility is US$19 million. The facility was granted Feed-in tariff (FiT) of US$0.1637/kWh for 20 years.

In order to examine the economic viability of the installation, the following financial indicators are used in this analysis: discounted payback and simple payback periods; internal rate of return (IRR); net present value (NPV); profitability index or benefit-cost ratio (BCR) and levelized cost of energy (LCOE) of the generated electricity. The NPV is expressed as:

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+i)^t} = -C_o + \sum_{t=1}^{n} \frac{NCF_t}{(1+i)^t} \tag{7}$$

where $C_o$is the investment cost (US$19 million), n is the project economic life and $NCF_t$is the annual net cash flow (which is annual revenue minus annual expenses (such as operation cost, maintenance and replacement) for year t. From monetary benefit viewpoint, NPV of a project needs to have a positive value ($NPV > 0$). The internal rate of return is the value of the discount rate (i) that would result at NPV of zero, and it can be determined from Equation (8):

$$-C_o + \sum_{t=1}^{n} \frac{NCF_t}{(1+IRR)^t} = 0 \tag{8}$$

To determine IRR, Equation (8) must be solved by iteration or trial-and-error approach. In this study, this equation is solved using inbuilt IRR function in Microsoft excel.

The levelised cost of energy (LCOE) is an economic assessment of the total cost to building and operating a solar PV installation over its lifetime divided by the total energy output of the asset over that lifetime. It can also be regarded as the minimum cost at which electricity must be sold in order to achieve break-even over the lifetime of the project. The LCOE is simply expressed as, (see for examples [41,44,45]):

$$LCOE = \frac{Life\ cycle\ cost(LCC)}{Lifetime\ energy\ production\ (kWh)} \tag{9}$$

Alternatively,

$$LCOE = \frac{C_0 + \sum_1^n \frac{C_{i,t} + C_{O\&M,t}}{(1+i)^t}}{\sum_1^n \frac{E_t}{(1+i)^t}} \tag{10}$$

where $C_{i,t}$, $C_{O\&M,t}$ and E_t are the investment cost (such as replacement cost), operation and maintenance cost and electricity generated at year t respectively.

Payback period compares revenue with investment costs and determines the length of time required to recoup an initial investment. Alternatively, the payback period is the length of time an investment reaches a break-even point. There are two approaches, which are generally used to determine the payback period: simple and discounted methods. The simple payback period (SPP) is given as:

$$SPP = \frac{C_o}{A_r - C_{O\&M}} = \frac{C_o}{A_s} \tag{11}$$

where A_r is the annual revenue and A_s is the annual saving. Although, the method is simple to use and gives a reasonable value payback period for an investment, its inability to account for time value of money (TVM) make it not desirable for business decision. The discounted payback period, which account for TVM, can be determined from (by solving for t):

$$DPP \rightarrow \sum_{t=1}^{n} \frac{NCF_t}{(1+i)^t} = C_o \tag{12}$$

2.5. Technical and economic data

During field visit to the solar power plant, a couple of technical data (such as production data, major equipment names and models, and design arrangement) and economic data (such as investment cost) were collected by the authors. However, for confidentiality, some data that are not provided during the field visit to the power plant site, were sought from other sources, such as Electricity Regulatory Authority of Uganda for detailed electricity delivered to the grid [46]; NASA website for solar radiation and other environmental data (Ref. [47]); and other scientific and relevant publications.

Fig. 4 and Fig. 5 shows the monthly daily solar radiation, ambient temperature and wind speed (at 10 m height) in Soroti, respectively. In these two figures, monthly (or seasonal) variations in solar radiation, ambient temperature and wind speeds can be observed. These variations could lead to monthly and seasonal variations in a solar PV performance. As would be shown in Section 3, ambient temperature, wind speeds, and dust accumulation are some of the sites' variables that influence the performance ratio (PR) of a solar PV installation. As shown in Fig. 4, monthly daily solar radiation on horizontal surface varies between 5.22 kWh/m^2/day in July to 6.28 kWh/m^2/day in March, with annual daily average of 5.85 kWh/m^2/day. Even though, solar radiation on horizontal and inclined surface follows the same trend, overall, the inclined surface, on average, received about 3.1% solar radiation annually, when compared with horizontal surface. In addition to this higher solar radiation, inclined surface can easily be passively cleaned by rain, and accumulate less dust.

Fig. 5 shows that ambient temperature varied between 23.78 °C (in July) and 27.64 °C (in March) with annual average of 25.31 °C, while the wind speeds have daily average minimum and maximum values of 2.02 m/s (in September) and 2.69 m/s (in February), respectively, with annual average of 2.31 m/s. Therefore, the combination of relatively high temperature and low wind speed in this location could lead to high temperature losses in the solar PV power plant performance. Overall, the weather conditions in Soroti can be roughly be classified into two seasons: dry season (monthly from November to March) and wet season (from April to October). According to Köppen-Geiger climate classification, Soroti weather is classified as *Aw*.

3. Results and discussion

3.1. Technical performance

3.1.1. Energy output and final energy yield

Fig. 6 shows the quarterly reported electricity delivered to Uganda Electricity Transmission Company Ltd by the solar power plant from 2017 to 2019. For a given year, quarterly variation in energy production by the plant can be observed, which also varies from year to year. This seasonal variations in the energy output from the installation is due to a combination of changes in various environmental and meteorological variables from January to December (as illustrated in Figs. 4 and 5; and seasonal variation in dust accumulation and rainfall in Soroti). Furthermore, there is variation in total annual energy production. The total annual energy output in 2017, 2018 and 2019 are 16 441 MWh, 16 325 MWh and 17 341 MWh, respectively, with mean average of 16 702 MWh and coefficient of variability of 3.33%. In addition, the average monthly energy production is 1392 MWh over the reported three years. At end of 2019, about 1 457 563 residentials users were supplied with 697 794 750 kWh of electricity [48]. This translated to, on average, 478.74 kWh/year (or 40 kWh/month) per residential (or household) user. Therefore, if each household, on average consumed this amount of electricity per month, the electricity generated by the solar plant can supply electricity to over 34 880 domestics electricity consumption. This is equivalent to about 63.5% of households in Soroti, which was 54 921 based on the 2014 national census ([49], page 20).

Fig. 7 presents the daily quarterly and annual mean final energy yield for the solar power plant. As previously defined, final energy yield is the ratio of the daily energy production to the rated installed capacity of a solar power plant. In this analysis, the quarterly energy output of the installation is divided by total number of days within the specific quarter and thereafter by installed capacity of the plant to give the daily energy yield in this quarter. Quarterly and yearly variations in final yield can be observed from Fig. 7. The minimum and maximum quarterly daily average values are 4.00 h/day and 5.19 h/day respectively. The yearly average final yields are respectively, 4.51 h/day, 4.47 h/day and 4.75 h/day in 2017, 2018 and 2019, with an overall average annual value of 4.58 h/day and interannual coefficient of variability of 0.15 h/day (or 3.35% of the average value).

3.1.2. Performance ratio and capacity factor

The performance ratio, which is equivalent to derate factor or overall system's efficiency relative to available solar radiation arriving on the surface of solar PV array, is an essential parameter in accessing and evaluating solar PV performance. The performance of this installation varies between 73.88% and 78.74% with an average annual value of 75.84%. Using the average quarterly energy output of the installation, the quarterly capacity factor is estimated and shown in Fig. 8. The capacity varied between 17.80% in Q2

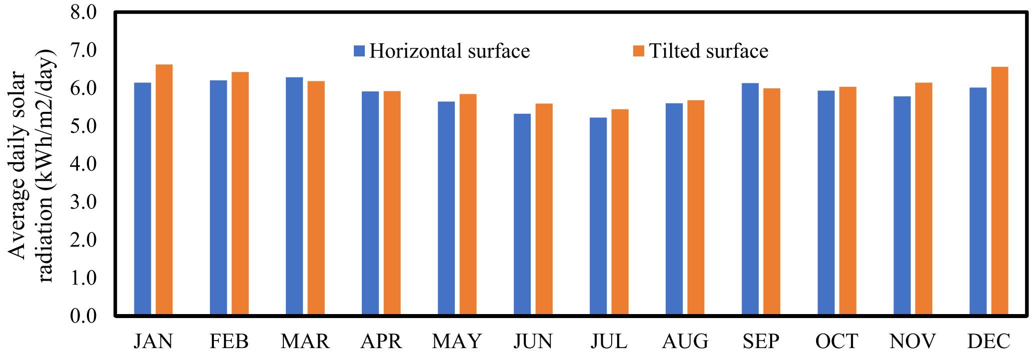

Fig. 4. Monthly average daily solar radiation in Soroti.

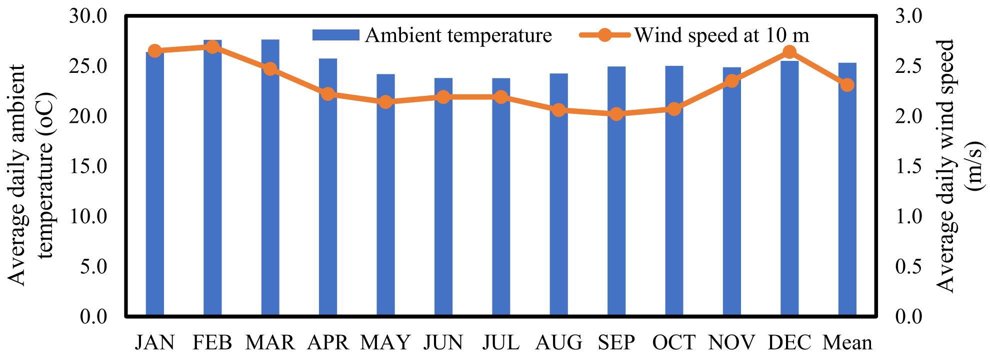

Fig. 5. Monthly average daily ambient temperature and wind speeds in Soroti.

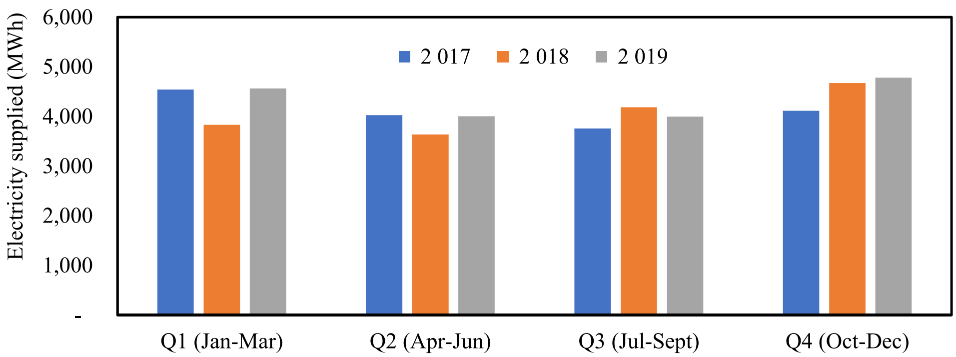

Fig. 6. Quarterly energy production by Access Solar plant.

(April to June) and 20.48% in Q4 (October to December), with an average annual value of 19.07%.

The technical performance indicators of the Soroti solar power plant (as found in this study) are compared with performance indicators of selected installations in different locations (as shown in Table 1), especially with installation in African countries. Overall, the performance of the Soroti solar PV plant is comparable with installations within African countries and tropical countries. The annual specific yield of 1670.2 kWh/kW and performance ratio of 75.84%, are respectively within reported ranges of 1419.1 kWh/kW and 1788.5 kWh/kW, and 67.9% and 84.0%.

3.2. Economic performance indicators

In estimating the economic indicators, which are discussed in this section, the following assumptions are made:

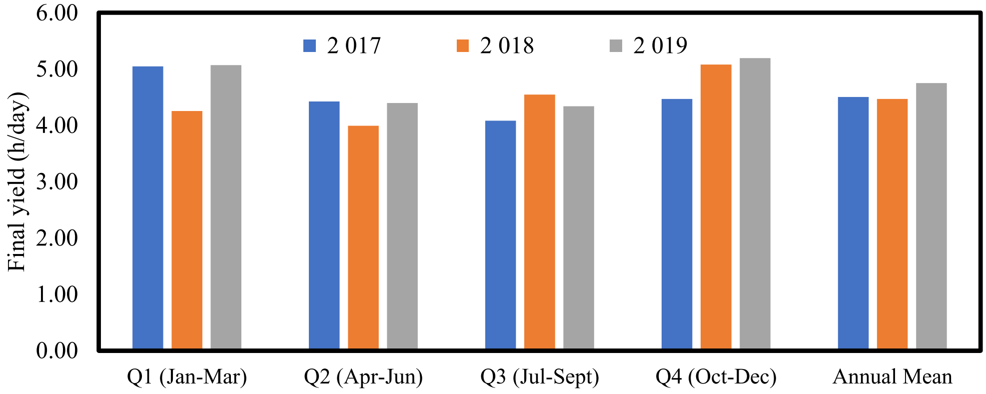

Fig. 7. Quarterly variation in daily average final yield.

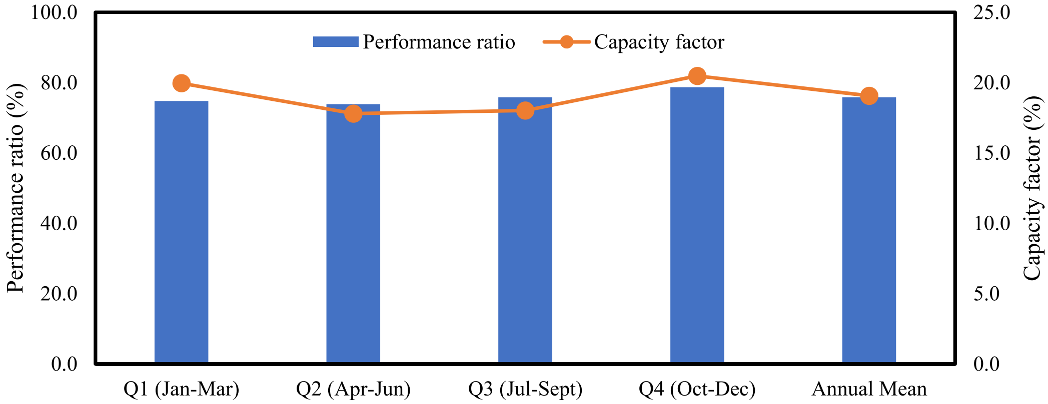

Fig. 8. Three-year average quarterly performance ratio and capacity for the solar PV installation.

i. The economic life of the installation is taken as 20 years, which is the number of years for the approved FiT.
ii. For revenue (or income) estimation, two tariffs are used in this analysis. The first is US$0.1637/kW, which is the actual approved FiT for the project, while second tariff used is the tariff paid by end users in Uganda, which is US$0.1104/kWh.[1] The difference is covered by the GET FiT Solar Facility in form of result-based premium payments per kWh of delivered electricity.
iii. The 3-year average capacity factor (19.07%, see Section 3.1.2) of the installation is assumed to be constant, which indicate that annual energy production from the installation is constant and calculated as 16 702 MWh (see Section 3.1.1).
iv. The annual operation and maintenance cost of the installation is taken as 2.2% on the investment cost [2], which translate to US $418 000 per year.
v. Due to lack of open information about the discount rate used for this project finance, and the fact that the project is financed through funding from KfW Development Bank,[2] which '*mainly deploy grants and very low-interest standard loans in poor and poorly developed countries*[3]', a discount rate of 4% is used in this study. For sensitivity of the analysis, the following discount rates from 2% to 12%, at an interval of 2%, are used.

Using the above-listed assumptions, the results of the economic indicators for the two categories of feed-in-tariff presented in (ii) above for project economic life of 20 years and discount rate of 4%, are presented in Table 6. As expected, all the indicators except

[1] ERA and GET FiT announce the first 20 MW of Solar Photovoltaic (PV) projects to be developed in Uganda (Source: https://africa-investment-exchange.com/2014/12/15/era-and-get-fit-announce-the-first-20-mw-of-solar-photovoltaic-pv-projects-to-be-developed-in-uganda/).
[2] ERA and GET FiT announce the first 20 MW of Solar Photovoltaic (PV) projects to be developed in Uganda (Source: https://africa-investment-exchange.com/2014/12/15/era-and-get-fit-announce-the-first-20-mw-of-solar-photovoltaic-pv-projects-to-be-developed-in-uganda/).
[3] https://www.kfw-entwicklungsbank.de/International-financing/KfW-Development-Bank/Tasks-and-goals/Unsere-Finanzprodukte/.

levelized cost of energy (LCOE), changes with feed-in tariff. The calculated LCOE for this solar power is US$0.1087/kWh, which is less than the global weighted average of US$0.1200/kWh and within the range of LCOE (US$0.0900/kWh to US$0.3000/kWh [50], for solar PV power plants commissioned in 2016. Furthermore, irrespective of assumed discount rate, the estimated LCOE for this projected is within LCOE ranges for solar PV (utility-scale) reported by Ref. [51]. The IEA [51] reported, for example, that LCOE should range from US$24/MWh to US$126/MWh when a discount rate of 3% is used, and for this Soroti solar plant project, the discount rate yielded LCOE of US$101.47/MWh.

When a tariff of US$0.1637/kWh is used, which is the amount receivable by the project owner, the simple payback period and discounted payback period are estimated as 8.20 years and 9.28 years, respectively. For an economically viable utility-scale grid connected solar PV system, a payback period between 8 and 18 years is recommended by Ref. [52]. Therefore, at this tariff rate, it can be concluded that Soroti solar power plant is economically viable. In addition, other economic indicators, NPV, BCR and IRR, with calculated values of US$12 484 177, 1.51 and 10.55% respectively, also support economic viability of this project. However, the internal rate of return is slightly higher and outside the range recommended values, which are 5%–10% [53], for a project that is supported by a feed-in-tariff mechanism. Hence, it can be implied that, if the assumptions used in this analysis are valid, the approved FiT should have been lower than US$0.1637/kWh.

Furthermore, Table 6 revealed that with FiT of US$0.1104/kWh, the all-economic indicators still indicate the solar plant project is economically viable, but less attractive when compared with the higher FiT. In addition, the internal rate of return (4.23%) at this tariff is less than the lower value of recommended rate (of 5%) for FiT supported project. Using the recommended IRR range, the approved FiT for this project should have been between US$0.1163/kWh and US$0.1586/kWh, for internal rate of return of 5% and 10%, respectively.

Fig. 9 and Fig. 10 show the effect of changes in discount rate on the net present value and levelised cost of energy, and discounted payback period and benefits-costs ratio, respectively. As can be observed from Fig. 9, the project's NPV decreases while LCOE increases as discount rate increases, which indicate that the project becomes less economically viable at higher discount rates. Furthermore, the project becomes unviable (with negative NPV) at discount rate of 10.55% (IRR) or more.

Similarly, both discounted payback period and benefits-costs ratio shows undesirable trends as the discount rate increases from 2% to 12% (Fig. 10). For instance, the discounted payback period increases from 8.47 years (when discounted rate is 2%) to 24.43 years when the discount rate is 12%, which is more than the duration of the approved Fit for this project. Therefore, for this kind of project to be attractive to investors, financial sources that offer relatively low to moderate discount rates (less than 8%) are suggested.

4. Concluding remarks

Using IEC standard 61724–1 and a combination of dynamic and static capital investment methods, the technical performance and economic viability of the first utility-scale grid-connected solar PV power plant in Uganda is examined in this study. Based on the analysis carried out in this paper, the performance of the plant can be summarized as follows:

- Within the reporting period, the plant delivered 50, 107 MWh of electricity to the grid.
- The annual average final yield was found to be 4.58 h/day.
- The annual performance ratio and capacity factor of the installation are respectively, 75.84% and 19.07%.
- With favourable positive economic indicators, it is concluded that this power plant is highly profitable. Furthermore, discounted payback period is found to be 9.28 years, which is less than 10 years (half duration of approved FiT for the project).

From our analysis, it seems that both the approved FiT and its duration can be considered as on the high side. Therefore, it is recommended that the responsible government agency should consider shorter durations for guaranteed FiT for future solar PV installations, with the possibility of negotiating FiT conditions to reflect dynamic economic conditions in the country.

CRediT authorship contribution statement

Ivan T. Oloya: Conceptualization, Data collection and curation, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Tar JL. Gutu:** Data collection and curation, Data curation, Formal analysis, Writing – review & editing. **Muyiwa S. Adaramola:** Conceptualization, Resources, Supervision, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 6
Summary of the estimated economic indicators for the Soroti solar power plant.

Indicators	Feed-in-Tariff (FiT) (US$0.1637/kWh)	Feed-in-Tariff (FiT) US$0.1104/kWh
Simple payback period (SPP), years	8.20	13.32
Discounted payback period (DPP), years	9.28	19.25
Net present value (NPV), US$	12 484 177	383 438
Benefits-costs ratio (BCR)	1.51	1.01
Internal rate of return (IRR), %	10.55	4.23
Levelised cost of energy (LCOE), US$/kWh	0.1087	0.1087

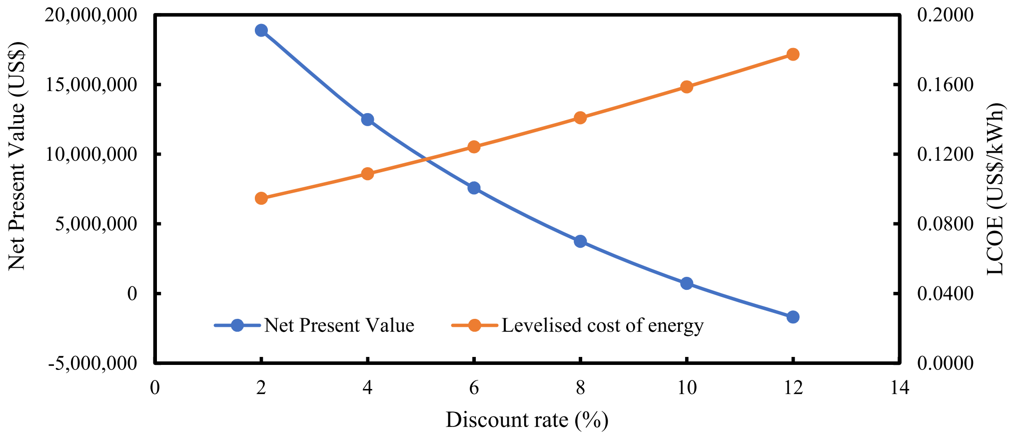

Fig. 9. Effect of discount rate on net present value (NPV) and levelised cost of energy (LCOE) with FiT of US$0.1637/kWh and project economic life of 20 years.

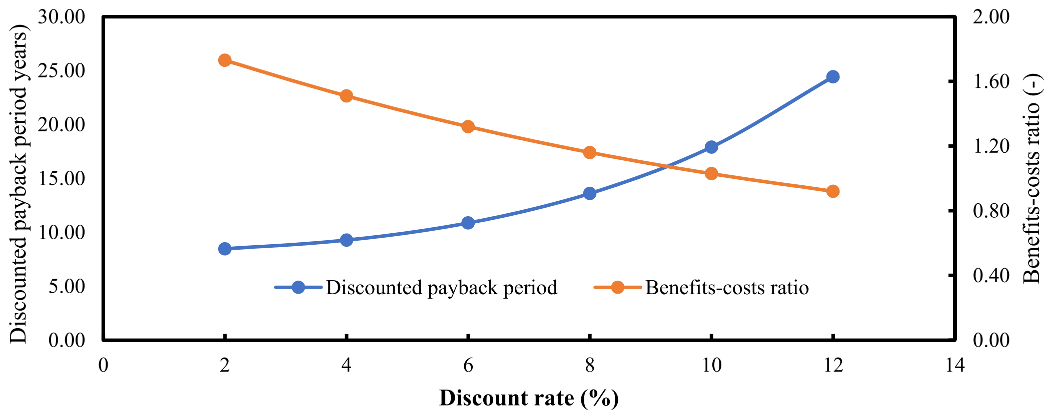

Fig. 10. Effect of discount rate on discounted payback period and benefits-costs ratio (BCR) with FiT of US$0.1637/kWh and project economic life of 20 years.

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