

IN THE FIELD

Analysis of solar photo-voltaic for grid integration viability in Uganda

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Abstract

This study aimed at analyzing grid-connected solar PV in Uganda for viability by evaluating the performance ratio of the already-installed solar systems, and how flexible is the grid to accommodate more power from solar. The data collected from the solar plants included array size, type and rating of each module, array output, cell efficiency, DC to AC ratio, systems capital cost per watt, annual maintenance cost, inverter size and efficiency, array tilt, records of monthly solar irradiation, monthly energy produced, capital costs, operational costs and cost of a unit supplied to the grid. The System Advisor Model was used to analyze the technical and economic performances of solar plants in Uganda. The projected solar penetration by the year 2021 was 6.1%. The total annual energy was estimated at 69.52 GWh. The capacity factor ranges from 13.1% to 17.5% and a performance ratio of 0.76, and are within the recommended values. The grid was flexible up to 25.8% to accommodate more solar energy without destabilizing the network. It is viable to invest in solar energy since all four plants showed a positive net present value.

KEYWORDS

grid integration, performance ratio, capacity factor, solar PV, system advisory model

1 | INTRODUCTION

Global electricity demand is growing and over-reliance on fossil fuel is no longer sustainable. Many countries in the world are increasing their share of renewable energy in total electricity generation.¹ The transformation to renewable energy is increasing since related costs are declining continuously and this makes them cost-competitive compared to conventional energy in many parts of the world.² Therefore, the constant increase of renewable energy sources shares in the world energy mix calls for the transformation of the energy structure and operation.³ Globally, solar PV electricity generating technology has

sustained an impressive annual growth rate compared with other renewable energy generating technologies.⁴ However, connecting renewable energy on the grid is challenging because of its intermittent nature.⁵ As the demand for electric power increases, existing electrical grids should have the capacity to accommodate power from renewable energy generators.

In Uganda, the electricity grid capacity was 1182.2 MW in 2019, of which 7.5 MW is off-grid.⁶ Renewable energy excluding large hydro power plants contributes 22% of the installed capacity to the national grid. Large hydro and thermal power contribute 69% and 9%, respectively. The most renewable energy source supplied to the grid

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is mainly from mini hydro power plants (10%), followed by co-generation/bagasse (8%) and the least is solar contributing 4%.⁶ Among the renewable energy sources, solar photovoltaic is the viable option due to its potential and availability in most parts of the country.⁷ It is because of this abundance that government of Uganda expanded rapidly the application scale and scope of the PV power generation system.

Grid-connected solar PV generation is the trend when large-scale PV power is being developed, which is conducive to the promotion of PV power. Solar energy is currently used to supplement the grid electricity supply since it may not be suitable and reliable as a stand-alone energy system due to its intermittent nature.⁸ Most parts of Eastern and Northern Uganda are not connected to the grid and yet they have the highest potential of solar energy. According to Rafique,⁹ the distributive nature is useful in supplementing the widening gap between energy supply and demand. The characteristics of variable solar PV generation create unique challenges in planning and operating the power system. With the substantial increase in variable generation in recent years, resources in the system will have to be more flexible in order to adjust output. This will result into power output ranges, power ramp rates and energy duration sustainability, which are sufficient to meet the needs of balancing supply with demand at various operational time-scales and to allow for maximum utilization of variable generation.¹⁰ The main hindrances of solar energy to grid stability include; Solar power cannot easily be forecasted for more than a day ahead as other resources. There is need to have a good amount of primary reserve hydro power to cover the intermittent of solar. Due to the high penetration of solar energy on the grid nowadays, power reliability is lower than the traditional power system. Electricity generation from solar energy is heavily reliant on weather conditions, which change constantly and as a result power shortages may happen more often on the grid. This uncertainty calls for observing the spinning reserve for optimum grid operation.¹¹

This study, therefore, focuses on the viability of solar PV supply option for a grid connection. The technical performance and economic evaluation over time through estimation of annual energy yield, array yield, reference yield and system losses of the already-installed solar PV helped in viability study. The study on viability of grid-connected solar plays a vital role in organizing relevant information and have the decision for further improvements in the performance. The correct prediction of energy produced by solar PV modules in any required location is essential for the expansion of solar generation in the country. Depending on the size of grid and its topology, a low power grid-connected solar energy source may not degrade the power quality and system reliability. However,

increasing the injected solar energy onto the existing grid results in compromising the overall system reliability.¹²

Related studies on grid-connected solar PV viability were explored; Chong¹³ studied the evaluation of viability potential for the four grid-connected solar PV power stations in Jiangsu province using RETScreen solar. He focused mainly on techno-economic and environmental feasibility where the net present worth of the system decreased with increasing initial costs at the same electricity export rate. However, the research did not address the influence mechanism of different climatic regions on the technical economy of grid-connected solar PV systems. Michael¹⁴ studied the technical and economic feasibility of a 50 MW grid-connected solar PV UENR Nsoatre campus using RETScreen and PV Syst softwares. The research concluded that the thin-film technology system was the best PV with 77.5% performance ratio. Investment in energy technologies is critical to be evaluated with techno-economic feasibility analysis for resource efficiency optimization.¹⁵ Khaled¹⁶ carried out research on performance evaluation of on-grid PV system in Egypt. He modified a MATLAB Simulink program to incorporate more accurate information on system configuration by calculating the PV module generated power at different solar radiation and temperature values. Comparison between actual power generated by the system and those obtained from mathematical models showed a deviation during all months in the year.

Uganda has four solar plants connected to the grid contributing 50 MW. However, their operational performance and monitoring under research and development platforms have not been framed. The International Energy Agency (IEA), under photovoltaic power systems program framed a series of 13 tasks¹⁷ for the outreach of operation, performance and monitoring of solar PV plants under the platform of research and development. Since Uganda is not a member of the IEA, the study is a contribution to the much needed research in the renewable energy sector in Uganda, which will facilitate the development and deployment of solar energy in the country. To successfully implement solar PV systems, knowledge of their operational performance under varying climatic conditions is necessary.¹⁸ Variable clean energy sources will become a bigger part of the electricity mix, thus operational flexibility will become more important in the electricity markets by meeting uncontrollable electricity demand.¹⁹

2 | LITERATURE REVIEW

The feasibility study of the grid-connected 10 MW installed capacity PV power plants in Saudi Arabia done by Rehman²⁰ suits very well the situation in Uganda since

most of the installed solar plants are 10 MW. He focused on the technical, environmental and economic aspects for the selection of viable sites for constructing 10 MW capacity grid-connected PV power plants using RETScreen software. Ramli²¹ studied the energy production potential and economic viability of grid-connected PV systems. Comprehensive system evaluation was emphasized as it is necessary to accurately assess the energy resources in terms of potential, technical requirements and economic viability before systems are implemented. The aim was to replace the fossil fuels used to produce electricity while emitting carbon dioxide with clean solar PV. Homer software was used to find the Net present cost (NPC), total emission cost, Levelized Cost of Energy (LCOE) and Renewable Energy Penetration (REP) for different system configurations. NPC increased with improved reliability and power quality since the capacity shortage reduced to zero.²¹ Conventional thermal power plants have low variable costs and default rates, however, solar PV depend on the weather hence large fluctuations in feed into the grid.²² Binash²³ carried out the techno-economic analysis of 67 MW and 144 MW photovoltaic power plants using RETScreen software since it accounts for module efficiency decline due to high temperatures. It assumes an average decrease in the efficiency of 0.4% for each degree of temperature increase above 45°C. Aliyu²⁴ reviewed a technological assessment of grid-connected solar photovoltaic systems to consolidate relevant performance information related to grid-tied PV of different capacities in varied meteorological conditions. However, the study did not consider the viability part of grid-connected solar. Sandhya²⁵ investigated the operational performance of megawatt-scale grid integrated rooftop solar PV systems in tropical wet and dry climates. Energy output, yield factor, capacity factor, performance ratio and error matrices were estimated using PVGIS, PVWatts, and PVsyst simulation tools. Mekonnen et al.²⁶ included the HOMER pro tool on top of PVGIS, PV Watts to model and optimize grid integrated solar PV systems for Ethiopia. The technical performance of the system realized through PV GIS and PV Watts was almost comparable to the Homer pro outputs. The investigation offered clear direction to the concerned target groups and policy developers in the evolution of PV power supply options throughout the technically viable locations in the country. However, different softwares were used because PVGIS and PV Watts were limited to only the technical viability of grid-connected PV systems and lacked a function for economic analysis.²⁶ Regarding the use of PV energy simulation tools, the techno-economic performance was evaluated using the PVsyst software simulation tool.²⁷ PVsyst is generally used for predicting energy output of evaluating real-time operating data.²⁷ Rehman et al.,²⁸ conducted a feasibility

study of grid-tied photovoltaic system for households in Pakistan. The study aimed to suggest a system that can provide uninterrupted energy supply to the consumers connected to the unreliable electric grid with a scheduled outage of 6 h/day beside un-foreseen power failures. The study proposed and developed an optimized grid-connected PV/battery power system for reliable electricity supply considering an unreliable grid for a residential house. The study also considered the effect of PV panel temperature, and tilt angle on the cost of energy and this helped communities in decision making of utilizing the solar-tied PV system. The grid-connected PV was modelled using Homer Pro and found out that the cost of energy of stand-alone unreliable grid power system with battery storage was 48% more costly compared to unreliable grid PV system.²⁸ Habis²⁹ carried out a feasibility study of utilizing an on-grid photovoltaic system for electrification of Cedars hotel in Jordan. The PV system was designed by considering the required electrical load and energy available from the sun. The simulation was done using a photovoltaic geographical information system and PVsyst. This study concluded that the on-grid PV was technically and economically viable for electrification of residential hotel.

Solar power connected to the grid causes instability due to its intermittent, which reverses power flow during minimum load conditions hence resulting into power quality challenges. Therefore, standard parameters such as frequency, voltage and power inverters used in converting renewable solar-generated DC voltage into AC pose harmonic challenges,³⁰ which should be taken care of before power is connected to the grid. The decline of power quality can be quantified for voltage rise, voltage flicker and voltage harmonics.³¹

Photovoltaic performance models are used to estimate the power output of a photovoltaic system, which typically includes PV panels, inverters, charge controllers and other balance of system components. These models create a generation profile based on a specific geographic location, which helps to determine how much solar irradiance is available for harvesting. Models can also be used to evaluate system performance over time by providing a baseline to compare with if performance suddenly decreases and troubleshooting is necessary.³² A study on techno-economic feasibility assessment of grid-connected PV systems for residential buildings by Imam et al.³³ analyzed key performance indicators using system advisor model software. The study realized that residential PV installations were an effective option for energy management. However, the author did not consider the impact of dynamic variations on solar electric power generation technology costs, which helps in predicting production trends toward green and sustainable

energy. The Solar Advisor Model (SAM) is used to conduct parametric analysis of system designs and to calculate performance and LCOE.

Shiva and Sudhakar³⁴ evaluated the performance of a 10 MW grid-connected solar PV power plant using PV SYST software and solar GIS to compare the performance. The study provided an insight to identify the location and suitable PV technology for large scale deployment of the solar photovoltaic system. PV SYST software is capable of evaluating the performance of grid-connected and stand-alone systems based on the specified module selection. The program predicts system yields computed using detailed hourly simulation data. Solar GIS combines solar resource and meteorological data with a web-based application system to support the planning, development and operation of solar energy systems. The evaluation is based on the energy output.³⁴ HOMER can be used to analyze solar energy production and storage while PV Design Pro is a commercial model commonly used for the analysis of solar system designs.³⁵ Other PV models and their characteristics are summarized in Table 1. In this study, SAM was preferred in the analysis of solar PV performance because it analyzes the entire PV system, evaluates the economics of installed system including energy cost, financing options, depreciation, tax credits, LCOE and provides access to many different array performance models. SAM can also perform sensitivity analysis and gives the user the ability to run many simulations.

3 | METHODS AND TOOLS

3.1 | Technical analysis

The energy performance of the grid-connected PV systems was analyzed using data collected during its operation. The data collected from the solar plants included array size, type and rating of each module, array output, cell efficiency, DC to AC ratio, systems capital cost per watt, annual maintenance cost, inverter size and efficiency, array tilt, records of monthly solar irradiation and energy produced by solar plants. The parameters that were determined included total energy generated by the PV system, yield factor, capacity factor and performance ratio. These performance indicators act as a base under which the PV system was compared under various operating conditions. The grid-connected solar PV performance was assessed with the technical operation indicators. These indicators are used to compare the system's performance with that of any other system with similar installations, regardless of their location and installed capacity.

The solar modules installed and their capacities for the different solar plants were assessed for their performance using SAM. SAM analyses the technical as well as economic performances of various solar plants. SAM's performance models make time-step by time-step calculations of a power system's electric output, generating a set of time series data that represent the system's electricity production over a single year. The monthly energy produced by each plant and number of modules used to produce the power capacity of the plant were also used as inputs into SAM software. The solar irradiation data are very important in the design of the solar PV system; therefore, the weather data were downloaded from the National Solar Radiation Database (NSRDB). The solar resource library in SAM provides the weather data information of a particular location where one can download the latest weather file of the desired location.

The performance ratio (PR) quantifies the overall effect of losses on the rated output due to inverter inefficiency, wiring, mismatch and other losses associated with conversion from DC to AC power. The performance ratio shows the proportion of the energy that is available for export to the grid after the deduction of energy losses. It also indicates the overall effect of losses on a PV array's normal power output depending on array temperature, and incomplete utilization of incident solar radiation and system component inefficiencies or failures. PR shows how close it approaches ideal performance during real operation and allows comparison of PV system independent of the location, tilt angle, orientation and their nominal rated power capacity.⁴ PR is computed using Equation 1.

$$PR = \frac{\text{Final PV system yield } (Y_f)}{\text{Reference yield } (Y_r)} \quad (1)$$

where;

Final PV system yield (Y_f); this represents the number of hours that the PV array would need to be operated at its rated power to provide the same energy (see Equation 2).

$$\text{Final PV system yield } Y_f \text{ (hours)} = \frac{\text{Net energy output } (E)}{\text{DC power } (P_o)} \quad (2)$$

where DC power is determined by summing the module rated power in the array. The final system yield value can also be read at the end of the year from the grid export meter.

Reference yield (Y_r); this represents an equivalent number of hours at the reference irradiance. Reference yield defines the solar radiation resource for the PV system. It is a function of the location, orientation of the PV array, and

TABLE 1 Solar PV system models

Software name	Array performance	Model PV technology	Economics	Model status
PV Design Pro	Sandia PV array Performance model	cSi, CPV, mj-CPV TF (CdTe, CIS, aSi)	Financial analysis including lifecycle and energy costs	Developed in the late 1990s. Maintained by the developer with v6.0 released in 2004
PVSYST	One-diode equivalent circuit. Modified one-diode for stabilized aSi, CIS and CdTe thin-film modules, incident angle modifier, and air mass correction	cSi, μ c-Si, HIT, TF (CdTe, CIS, aSi)	System financing, feed-in tariffs, annual and used energy costs	Developed in the mid 1990s. Currently updated in 2009 with version 5.05
System Advisor Model	Sandia PV Array, Performance Model 5-Parameter Array Performance simple-efficiency model, Model, PVWatts	cSi, CPV, HIT, TF (CdTe, CIS, aSi)	Energy cost, financing options, depreciation, tax credits/incentives, cash flow, LCOE. Residential, commercial and utility financing	Developed around 2006. Maintained by NREL. Last update in 2009 with version 2009.10.2
PVSol	Based on irradiance and module voltage at STC and efficiency characteristic curve. Linear or dynamic temperature model. Incident angle modifier	cSi, μ c-Si, Ribbon, HIT, TF (CdTe, CIS, aSi)	Economic efficiency for cash value factor, capital value, amortization period and electricity production costs	Developed in 1998. Last update of Expert was in 2009 with version 4.0
SolarPro	One-diode equivalent circuit. Simple temperature model	cSi, HIT, TF (CdTe, aSi)	System O& M costs	Developed in 1997. Current version at time of this report is 3.0
PV Watts	Uses PVForm Equation	cSi	Calculates electricity cost and energy value	Maintained by NREL. Last update in 2008. Used in SAM
PVForm	Modified power temperature coefficient model (efficiency, temperature and POA). Different equation used for two low and high irradiance levels. Fuentes thermal model	cSi	Basic input and fuentes thermal model	Developed in 1985 with the last update made in 1988. No longer maintained. PVForm can still be licensed from SNL
SOLCEL	One-diode equivalent circuit, simple temperature model, passive or active cooling	cSi, CPV	Basic cost and LCOE	Developed and used from the mid-1970s to the mid-1980s. No longer used or maintained

month to month or year to year weather variability (see Equation 3).

$$Y_r \text{ (hours)} = \frac{\text{Total plane irradiance (H)}}{\text{PV reference irradiance (G)}} \quad (3)$$

The average solar irradiation intensity was obtained from NSRDB. The system Advisor model allows the user to download data files for Irradiation levels, temperature and hours of sunlight, from the NSRDB database. Generator area of the PV plant, efficiency factor of the PV modules and electrical energy actually exported by the plant to grid were obtained from Uganda Electricity Regulatory authority (ERA). The annual energy records were obtained from ERA and Uganda Electricity Generation Company Limited (UEGCL).

Capacity factor (CF) is the ratio of actual annual yield of a PV array to the energy it would produce when operating at full capacity over one year. The Capacity factor estimates the percentage of PV array that is usable and it was estimated using the Equation 4.

$$\text{Capacity factor} = \frac{\text{net annual energy (kWhAC/yr)}}{\text{system capacity (kWDC)}} \text{ (h/yr)} \quad (4)$$

where net annual energy is the total annual electric generation in the first year of operation and system capacity is the system's nameplate capacity. For PV systems, the capacity is in DC (kW). The DC system capacity is the DC power rating of the PV array in kW at Standard Test Conditions (STC). The type of module nominal efficiency, module cover, temperature coefficient of power and fill factor were obtained from the existing solar plants and data fed into SAM software.

Grid flexibility quantitatively determines the scope of intermittent renewable energy that the grid can contain taking into account its required costs of operation and this was estimated using Equation 5.

$$\text{Grid flexibility} = \frac{\text{Peak demand} - \text{minimum demand}}{\text{Peak demand}} \times 100 \quad (5)$$

Power demand data were obtained from Uganda electricity regulatory authority.

3.2 | Economic analysis

The solar plants available were evaluated based on the economic analysis. The economic feasibility of the grid-connected solar PV relied on the project's capital cost, analysis period, discount rate, inflation, power purchase price for utility financial model, operation and maintenance cost. PV systems have no tangible operational

costs though minimum maintenance costs are required for sweeping the dust accumulated on the PV modules' surface. In the economic analysis, the financial model of SAM software considered cash inflow and outflow of the solar plants during their operational lifetime. SAM's financial models calculate financial metrics for various kinds of power projects based on a project's cash flow over an analysis period. The financial models uses the system's electric output calculated by the performance model to calculate the series of annual cash flows. Levelized Cost of energy (see Equation 6), net present worth (NPW) and internal rate of return (IRR) were estimated and these addressed the time frame required for the total after-tax cash flow to cover the initial capital cost of the project. The financial parameters such as the interest and inflation rates in Uganda were acquired from the bank of Uganda website.³⁶

$$\text{LCOE} = \frac{\text{Life cycle cost (LCC)}}{\text{System energy yield}} \quad (6)$$

LCOE estimates the price of per unit energy over the project's lifetime. It was used to compare the kWh cost of the different power system technologies. This cost enables one to compare the electricity cost across a wide range of technologies. However, LCOE is not adequate for measuring financial profitability, therefore Net present worth was estimated to cater for that gap using (equation 7).

$$\text{NPW} = \sum_{t=0}^N \frac{\text{Revenue} - \text{Cost}}{(1+d)^t} \quad (7)$$

where N is projects life, t is the year variable in each summation, and d is discount rate.

4 | CASE STUDY DESCRIPTION

Four solar plants were considered in the study. These included; Access solar located in Soroti district, Tororo solar, Kabulasoke solar (Xsabo solar) and Mayuge solar (Emmeging power limited). Their locations are shown on the Map of Uganda as indicated in Figure 1.

5 | RESULTS AND DISCUSSION

All the four solar plants currently connected to the Uganda's grid, contribute 50 MW with their annual energy contribution to the grid amounts to 21.277 GWh as shown in Table 2. Access Solar found in Soroti district has been supplying more energy to the grid from 2016 to 2019, thereafter Xsabo solar became the leading energy

producer simply because it has more generating capacity as compared to the rest. From 2016 when solar PV was accommodated onto the Uganda grid, the total energy from solar has been increasing from 3716 MWh to 36086 MWh in 2019. The energy for 2020 was low because the information gathered was for only one quarter of the year. However, Xsabo solar was producing more than any other solar PV plant in 2020. All the four solar plants in Uganda were made of polycrystalline cells type with an

average nominal efficiency of 16.67%, and the number of modules per plant range from 30,500 to 68,00 depending on the power capacity. The tilt angle for Soroti and Tororo solar plants was 10°, 15° for the 20 MW Kabulasoke solar plant and single-axis tracker for Mayuge solar as shown in Table 3. Array specifications are summarized in Table 4.

The planned solar generating capacity by the year 2022 is 102 MW and 114 MW by the year 2024 (see Table 5). This gives a projected solar penetration as of the year (2021) of about

$$\text{Projected solar penetration} = \frac{102}{1676} \times 100\% = 6.1\% \quad (8)$$

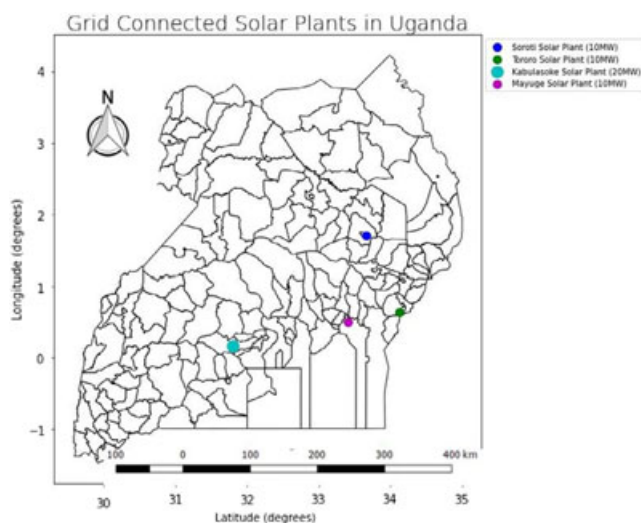


FIGURE 1 Location of grid connected solar plants in Uganda

TABLE 2 Energy generated (MWh) from solar plants

Year	Access solar	Tororo solar	Xsabo solar	Emerging solar
2020	3995	4242	8969	4071
2019	17,341	16,076	280	2389
2018	16,325	15,863		
2017	16,441	6598		

TABLE 3 PV modules and array specification for the solar plants

PV module/array	Access solar	Tororo solar	Xsabo solar	Emerging solar
Capacity	10 MW	10 MW	20 MW	10 MW
Type	Polycrystalline	Polycrystalline	Polycrystalline	Polycrystalline
Nominal efficiency	16.16%	16.7%	17.0%	16.97%
Maximum power (Pmax)	310 W	320 W	330 W	330 W
Open circuit voltage	44.9 V	45.0 V	37.7 V	45.6 V
Short circuit current	9.08 A	9.05 A	9.27 A	9.45 A
Total array area	33 acres	32 ha	130 acres	59 acres
Number of modules	32,680	32,450	68,000	30,500
Tilt angle (degrees)	10	10	15	Single axis tracker
Ground coverage ratio			1.37	

The annual energy for the four solar plants ranged between 11.4 GWh and 30.7 GWh with Kabulasoke contributing the highest and Tororo solar share the least. Capacity factor ranged from 13.1% to 17.5% and an average performance ratio of 0.76, with Tororo solar having the least capacity factor and Kabulasoke & Mayuge solar plants with the highest as indicated in Table 6. Capacity factor values were reasonable compared to similar grid-connected systems.

Capacity factor and performance ratio are the two main parameters to evaluate the PV system performance. Performance ratio is directly related to the system energy loss. The standard value of performance ratio is between 0.6 and 0.8.³⁰ According to IRENA,³⁷ the global weighted average capacity factor for a utility-scale solar PV ranges between 13.8% to 18% and it is more in sunny locations. The capacity factor and performance ratio the solar plants analyzed were still within acceptable range. Performance ratio values are typically reported on a monthly or yearly basis; however, values calculated for smaller intervals, such as weekly or daily may be useful for identifying occurrences of component failures. The module loss due to temperature is higher in the dry season, which decreases the performance

Inverter specification	Access solar	Tororo solar	Xsabo solar	Emerging solar
inverter type	string	string	central	string
Number of inverters	430	4	20	93
Inverter efficiency	98.4%	98.2%	98.6%	99%
Total inverter DC capacity (kW)	10,130	10,120	22,700	10,020
Maximum MPPT Dc voltage	800 V	840 V	825 V	1500 V
Minimum MPPT voltage	320 V	350 V	580 V	650 V
Inverter DC:AC ratio	2.5:1	2.5:1	1.185:1	1.875:1

TABLE 4 Inverter specifications for the solar plants

TABLE 5 Grid power demand-supply balance

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Total demand (MW)	554	595	643	699	756	822	887	956	1035	1121
Generation										
Hydro (MW)	536	540	753	964	1485	1491	1491	1983	2725	2725
Solar (MW)		24	37	37	102	102	102	102	114	114
Co-generation (MW)	36	46	77	83	83	83	83	83	83	83
Total (MW)	572	610	867	1084	1670	1676	1676	2188	2922	2922
Primary spinning reserve (MW)	18	15	224	385	914	854	789	1212	1887	1801
Thermal plants (MW)	50	100	50	100	100	260	240	220	200	180
Total spinning reserve (MW)	68	115	274	485	1014	1114	1029	1432	2087	1981

TABLE 6 Summary of simulated results

Parameters	Tororo solar	Access solar (Soroti)	Kabulasoke solar (XSABO solar)	Mayuge solar (Emerging power Ltd)
Name plate capacity	10 MW	10 MW	20 MW	10 MW
Annual energy	11,436,513 kWh	12,038,429 kWh	30,700,892 kWh	15,345,271 kWh
Capacity factor	13.1%	13.7%	17.5%	17.5%
Energy yield	1144 kWh/kW	1204 kWh/kW	1535 kWh/kW	1535 kWh/kW
Performance ratio	0.76	0.76	0.77	0.77

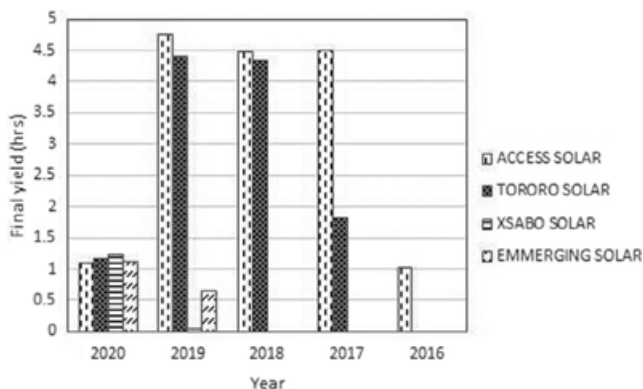


FIGURE 2 Annual PV system final yield

ratio. Performance ratio values were greater in the rainy season because there are no losses due to PV module temperature. PR is also affected by the soiling of modules. The values for capacity factors depend on the solar irradiance, weather data, array tracking system and orientation. The determination of performance ratio at fixed regular intervals does not provide an absolute comparison but instead, it provides the operator with option of checking performance and output. Taking of PR values over time enables the identification of deviations, meaning that appropriate countermeasures can be promptly initiated.³⁸

The annual final yield for the four installed solar plants from 2017 to 2019 has been almost constant with an

average of 4.58 but in 2016 the yield was low because the plants had not reached their production capacities. Access solar has the highest yield factor followed by Tororo solar as illustrated in Figure 2. Xsabo solar and Emerging solar have the lowest final yield because the solar plants have just been connected to the grid and have not yet reached their production capacities.

Generally, the monthly energy production from solar plants (see Figure 3) is higher from January to May and August to December. This is because, during those months, there is a lot of solar radiation due to sunny weather. Between June and July, the monthly energy production is low. This is attributed to high temperature, which results in heat hence affecting the performance of the solar module. Monthly energy production from simulation over the first year varies between 1.05 GWh in June to 1.47 GWh in January and March for the

20 MW Kabulasoke solar plant. On average the monthly energy for the 10 MW plants ranged from 0.94 GWh to 1.2 GWh. Tororo and Soroti plants had almost the same monthly energy in January. These monthly energy variations according to Dasilva³⁹ were a result of the earth's location and local characteristics implying that there was differences in the amount of electricity generated by the installation each month. Some characteristics that might affect energy output include cloudiness, temperature, dust on top of the panels and humidity which can deteriorate some components of the PV system. However, SAM software takes into account some losses on the system.

The total energy supplied by solar plants annually is estimated to be 69.52 GWh as summarized in Table 6 taking into an assumption of annual reduction in the energy yield due to degradation of 0.5% in the output power of

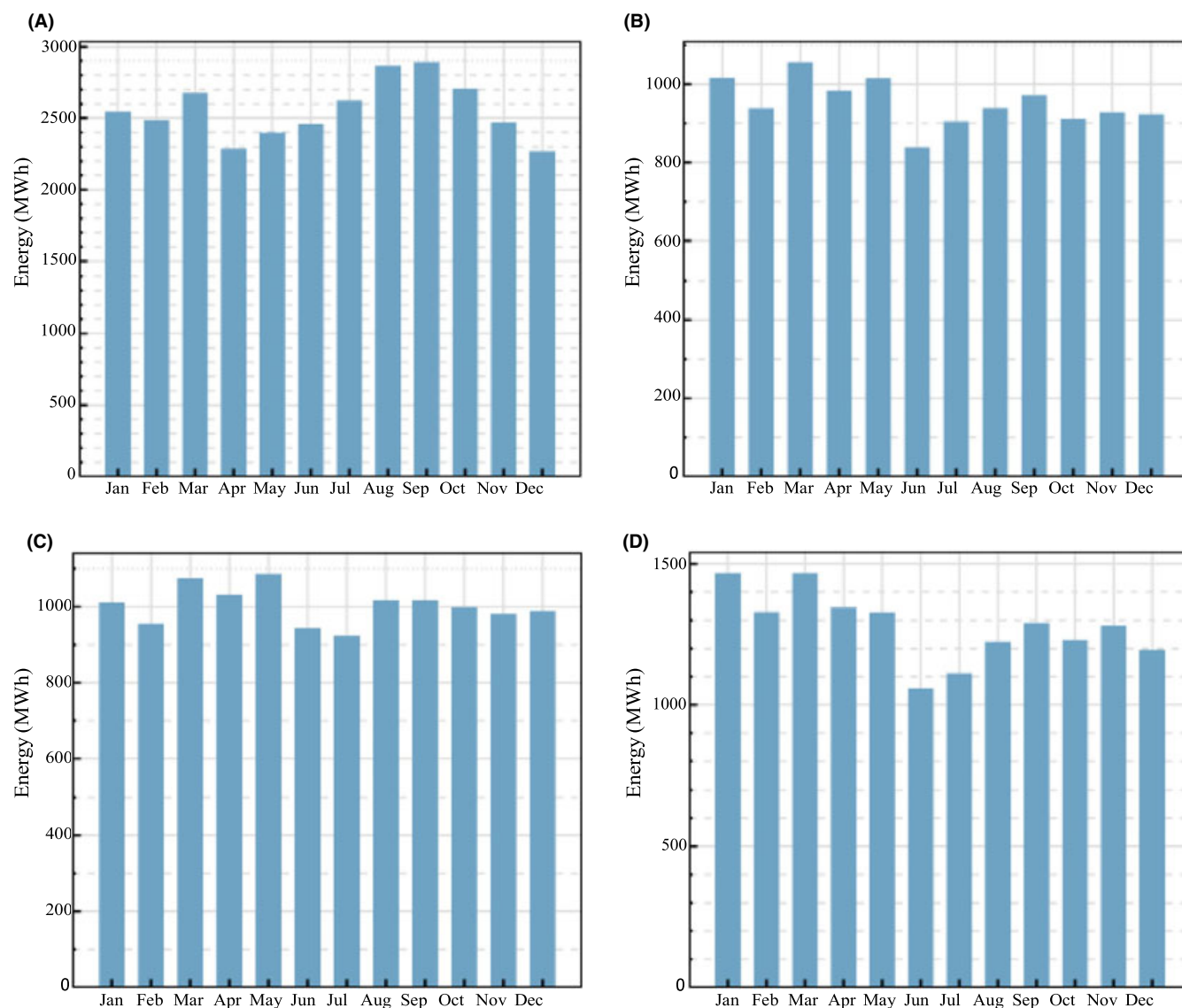


FIGURE 3 Monthly energy production for (A) Kabulasoke, (B) Tororo, (C) Soroti, (D) Mayuge

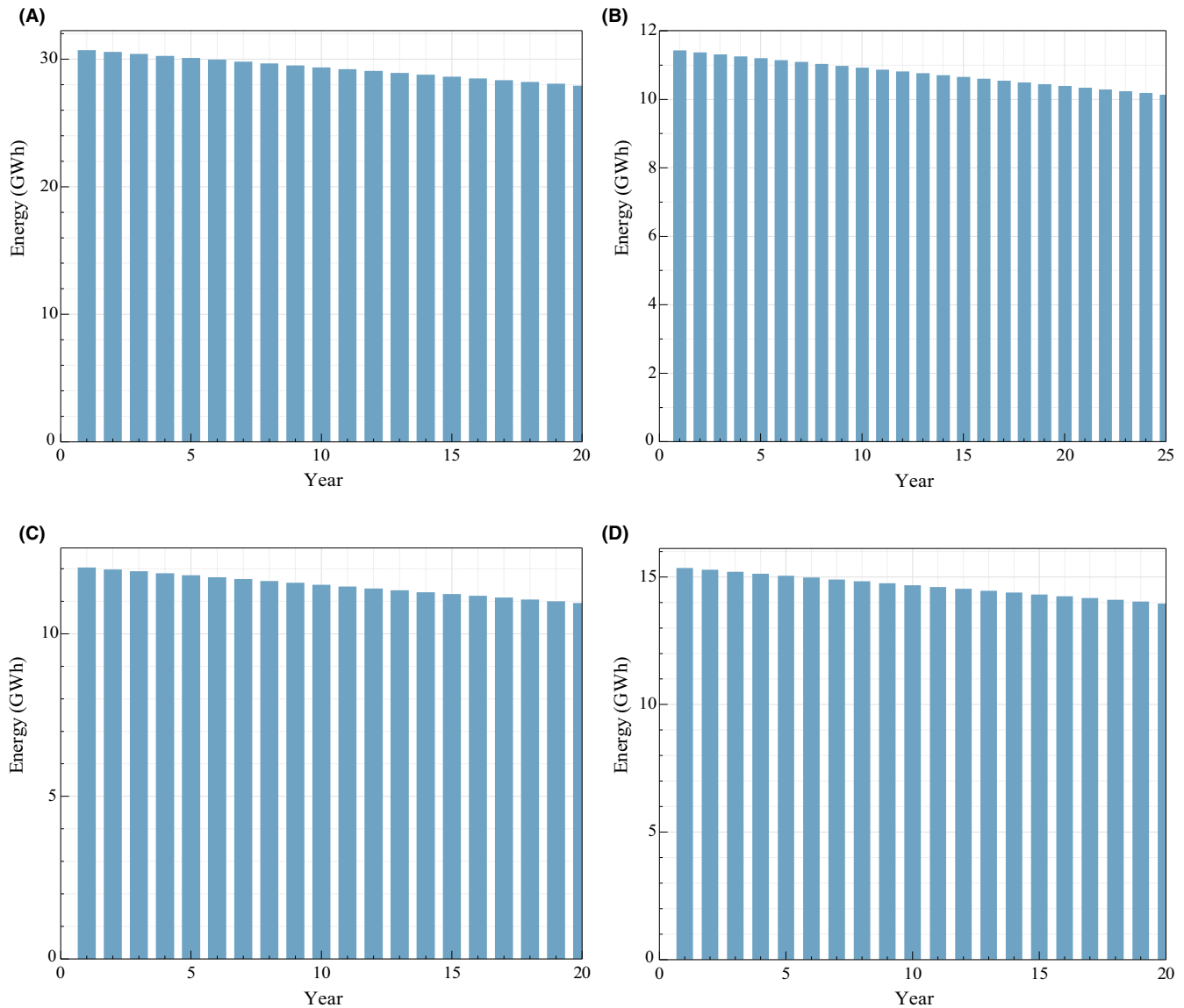


FIGURE 4 Annual energy production for (A) Kabulasoke, (B) Tororo (C) Soroti (D) Mayuge

TABLE 7 Grid flexibility parameters

Flexibility parameters	September (2019)
Peak demand (MW)	596
Minimum demand (MW)	442
Flexibility (MW)	153
Grid flexibility (%)	25.839

the PV modules.³³ Figure 4 shows the annual energy production during the lifetime of 20 years. Since there is an annual degradation in energy yield, the general trend is that energy production kept on reducing from 31 GWh to 28 GWh after 20 years for a 20 MW Kabulasoke plant. The annual energy trend of the three 10MW solar plants (Tororo, Soroti and Mayuge) ranges between 10.2 GWh and 15.2 GWh.

The grid flexibility from Table 7 shows that the grid has room for 153 MW of intermittent solar power. The grid is flexible up to 25.8% of accommodating more solar energy without destabilizing the network. Operational flexibility ensures that grid operators can meet daily, hourly fluctuations in supply and demand. The Flexibility concept has emerged as the major criterion for power system planning, operations and markets due to the growth of variable energy resources. While grid operators have always needed to instantaneously balance supply with demand and respond to loss of a generator or transmission line, more recent changes in power systems including the growth of variable energy resources are increasing the need for flexibility.¹⁹

The Primary reserve by the end of 2017 was about 225 MW, which is about 34% of the demand and this primary spinning reserve is projected to increase up to the year 2024 as indicated in Figure 5. Increasing the

FIGURE 5 Graph of spinning reserve trend

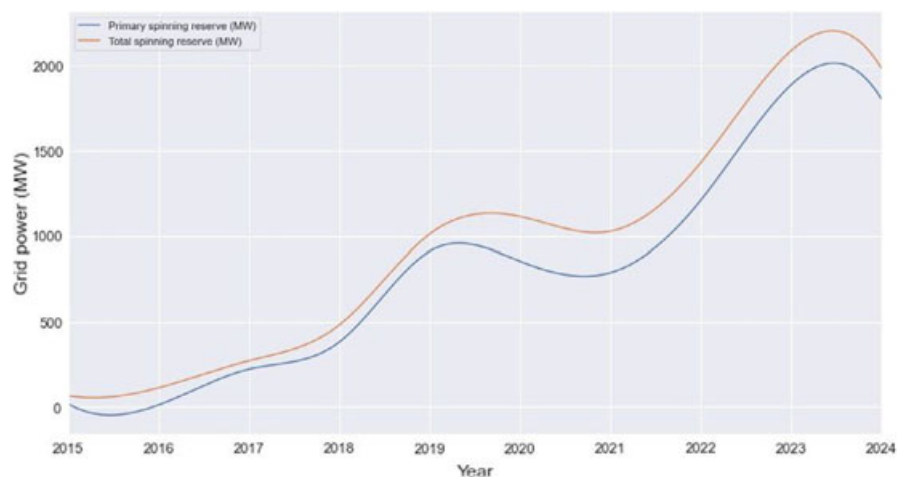


TABLE 8 Economic analysis

Parameters	Tororo solar	Access solar (Soroti)	Kabulasoke solar (XSABO solar)	Mayuge solar (Emerging power Ltd)
Capital cost	\$19 million	\$19.6 million	\$30 million	\$11 million
Operating cost (annual)	\$200,000	\$200,000	\$360,000	\$200,000
Levelized COE	26.33 ¢/kWh	25.44 ¢/kWh	16.33 ¢/kWh	13.48 ¢/kWh
Net present value	\$28,890,770	\$28,890,770	\$87,418,328	\$19,626,874
IRR at end of project	12.86%	12.86%	12.82%	12.90%
Net capital cost	\$21,824,466	\$21,229,994	\$33,258,040	\$12,535,834

spinning reserve available implies that there is room for the integration of solar energy resources into the grid. Spinning reserves are essential in the electricity grid for maintaining stability and reliability.⁴⁰ Operating reserve is the generating capacity available to the system operator within a short time in case of a disruption to the supply/generation and is categorized into the Spinning reserve, which is extra generating capacity that is available by increasing the power output of the generating units already connected to the grid, that is, for the case of hydro power plants and non-spinning/supplementary reserve, which is extra generating capacity that is not currently connected to the system but can be brought on-line for a short delay as in fast-start generators and isolated power systems.⁴¹ Operating reserve can also be power available on short notice by importing power from other systems or retracting power that is being exported to other power systems. Operating reserve is a crucial concept for ensuring that day-ahead planning of generation schedule can withstand the uncertainty due to unforeseen variations in the load profile or even equipment failure and faults.

In conforming validity of the model, annual energy generated during the years 2016–2020 calculated by the model is compared with the inverters reading from solar plants. In comparison with energy generated by the solar plants per year (see Table 2), there was still room to harvest more solar energy that can be accommodated onto the

grid since all four solar plant sites still have the potential to produce more. The total annual energy from SAM software was estimated at 69.52 GWh, which is three times what is being currently harvested from the solar plants. The reasons for those deviations are the conditions affecting operation of the system such as power failure, cleaning of the panel surface, and also the weather parameters variation such as wind, fog and clouds.

Economic analysis; The solar PV system installation costs for the four plants are summarized in Table 8 and this consisted of the PV modules, inverter, electrical accessories, support structure and installation. In the economic evaluation, the Levelized Cost of electricity (LCOE) was used to compare the lifetime costs of generating electricity across various generation PV plants (see Table 8). The LCOE for Tororo, Soroti, Kabulasoke and Mayuge solar PV plants were 0.0126, 0.0122, 0.0078 and 0.0065 \$/kWh, respectively. The research done by Rehman⁴² on a comprehensive global review of building integrated photovoltaic systems showed that the cost of energy varied from 0.013 to 0.824 USD/kWh depending on the plant size and climatic zone. Kabulasoke and Mayuge solar plants have their LCOE values close to the generation tariff of 0.0053 \$/kWh. According to IRENA,³⁷ LCOE values as years pass by are reducing due to reduced costs of solar modules. This is shown in the 2019 IRENA report as LCOE reduced from 0.378 \$/kWh in 2010 to 0.068 \$/

kWh in 2019. Generally, LCOE emphasizes the ability of grid-connected solar PV systems to compete as electricity utilities in terms of the cost of energy.³³ The Net Present Value (NPV) is positive for the four solar power plants analyzed implying that investment is feasible. Kabulasoke has the more positive NPV followed by Tororo solar and Soroti solar. This is because Kabulasoke solar supplies more power to the grid compared to the rest and yet the operation costs differ by a small margin.

6 | CONCLUSION

Uganda has given more consideration to increasing the share of energy supply from solar to the grid. In this research, modeling and analysis of solar photovoltaic for grid integration viability were done using a system advisory model and revealed the following;

- Four grid-connected solar plants currently contribute 50 MW and their annual energy supply amount to 21,277 GWh. The four solar plants are categorized into polycrystalline with an average nominal efficiency of 16.677%.
- The planned solar generating capacity by the year 2022 gave a projected solar penetration of 6.1%.
- The annual energy from the solar advisory model for the four solar plants ranged from 11.4 GWh to 30.7 GWh with Kabulasoke contributing the highest. The total annual energy was estimated at 69.52 GWh, which is three times what is being currently harvested.
- The capacity factor ranges from 13.1% to 17.5% and performance ratio of 0.76. All these values are within the recommended range.
- The grid is flexible up to 25.8% to accommodate more solar energy since the spinning reserve was estimated at 225 MW.
- The Levelized Cost of energy ranged from 0.065 to 0.0126 \$/kWh implying that the grid-connected solar PV can compete with other electric utilities in terms of the cost of energy. The Net Present Value (NPV) is positive for the four solar power plants analyzed implying that investment is feasible. Kabulasoke has the more positive NPV followed by Tororo solar and Soroti solar. This is because Kabulasoke solar supplies more power to the grid compared to the rest and yet the operation costs differ by a small margin.

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