Techno-Economic Feasibility Assessment for the promotion of Grid-Connected Rooftop PV Systems in Botswana: A Case Study

Youssef Kassem
Department of Mechanical Engineering, Engineering Faculty, Near East University, Cyprus | Energy, Environment, and Water Research Center, Near East University, Cyprus
yousseuf.kassem@neu.edu.tr
(corresponding author)

Huseyin Gokcekus
Department of Civil Engineering, Civil and Environmental Engineering Faculty, Near East University, Cyprus | Energy, Environment, and Water Research Center, Near East University, Cyprus
huseyin.gokcekus@neu.edu.tr

Fadel Ali Ramadan Agila
Department of Environmental Education and Management, Ataturk Faculty of Education, Near East University, Cyprus
20215633@std.neu.edu.tr

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ABSTRACT

The main aim of the present study is to investigate the solar energy potential and evaluate the economic viability of a 5kW grid-connected rooftop photovoltaic (PV) system as an electricity generation source in three selected regions (Gaborone, Maun, and Tshabong) in Botswana for the first time. In this study, NASA POWER data were used for evaluating the solar potential in the selected regions. The results showed that the selected locations are suitable for the installation of various scales of PV systems due to the high global horizontal solar radiation. RETScreen Expert software was used to assess the techno-economic feasibility of the proposed systems. The performance of the proposed systems with various PV technologies (mono-crystalline silicon and poly-crystalline silicon) is analyzed. Furthermore, economic and financial indicators such as net present value, annual life cycle savings, payback, benefit-cost ratio, and cost of energy production were calculated. The results indicate that the proposed system is very promising for all the selected locations. Additionally, it was found that the PV projects with poly-Si technology produced a large amount of energy and have a low electricity cost compared to mono-Si technology. The results suggest that grid-connected rooftop PV systems have a significant role in covering the electricity demand and in reducing carbon dioxide emissions, especially in high population density and rural regions. This study provides some useful recommendations for decision-makers regarding the development and deployment of PV energy technology in Botswana.

Keywords-Botswana; solar energy potential; grid-connected; rooftop PV system; PV technology; RETScreen software

I. INTRODUCTION

Population growth and the rising living standards led to growing demand of energy, primarily electricity, in a global scale. It is known that environmental pollution impacts human health through emissions of harmful gases caused by conventional energy generation from fossil fuels. Thus, finding alternative energy sources to reduce fossil fuel consumption and environmental pollution is essential. Renewable energies such as solar energy have grown due to the growing demand [1] and solar energy has been widely utilized globally to generate electricity and reduce emissions. It is an inexhaustible and environmentally friendly energy source. Authors in [2] report that solar power will reduce the emission of about 69-100 million tons of CO_2, 68-99 thousand tons of NO_X, and 126-184 thousand tons of SO_2 by 2030. Authors in [3] concluded that solar energy has significant potential to meet the world's electricity requirements in the future. Authors in [4] mention that solar energy technologies have a huge potential to mitigate climate change by reducing energy-related emissions.

Generally, solar PV produces electrical power directly from sunlight [5-8]. Authors in [5] evaluated the performance of a 6.4kW grid-connected PV system and wind system at three locations in Northern Cyprus. The results showed that the most economical option for electricity production in the selected locations is the PV system due to the low electricity prices and the recovery of the initial investment. Authors in [7] investigated the economic and environmental feasibility of a 2-10kW grid-connected rooftop PV system in Greece. The results showed that the successful development of small-scale residential solar energy systems in the country depends on increasing energy selling prices and/or reducing costs in the production of PV systems. Authors in [8] evaluated the feasibility of a 5kW grid-connected rooftop PV system in Lebanon. The results showed that the amount of output from the solar system can help reduce the shortage of energy in the region.

A. Energy Situation in Botswana

Botswana is located between 22.3285° S and 24.6849° E. The country is landlocked in Southern Africa bordering Zimbabwe and South Africa. Presently, fossil fuels and coal are the main sources of electrical energy in the country [9]. Access to electricity in Botswana has reached 77% of the population in urban areas, while in rural areas it is still limited to 37% according to the World Bank. The overall electrification rate at the national level is 60%. Botswana relies mainly on electricity, coal, fuel wood, and oil for its energy requirements. With these sources, CO_2 emissions have increased over the years according to the World Bank database. Furthermore, more than 50% of Botswana's energy requirements are imported from South Africa and Zambia according to United Nations Environment Program. Besides, electricity consumption has been rising over time. For example, the electricity consumption was 586.84kWh/capita in 1981 and 1815.55kWh/capita in 2014 according to the World Bank database. This has exacerbated the electricity deficit over the years. According to electricity information released by the International Energy Agency, population and economic growth have led to an increase in electricity consumption in the country. Therefore, utilizing renewable energy would reduce the consumption of conventional fuels and be a clean source of electricity generation in the country. According to the Wind Power Density (WPD) classification [10], Botswana is placed in class 1 (poor) based on the obtained values of WPD at 10m and 50m. Moreover, the specific PV power output is within the range of 4.74-5.47kWh/kWp according to the World Bank Group (global solar atlas). Moreover, Botswana receives approximately 3200h of sunshine annually and has high insulation on a horizontal surface of 21MJ/m^2. The average daylight hours in Botswana range from 9.9h in summer to 8.2h in winter. Consequently, Botswana has an abundant solar energy potential compared to wind energy. The country is a suitable region for installing PV systems due to the high value of global solar radiation and has a great chance of utilizing solar power in order to reduce the amount of imported energy from the neighboring countries [11]. Additionally, installing a solar system in the country is technically reliable due to the high value of average daily radiation on the horizontal surface [12].

Several studies have investigated the potential of solar energy in the country [13-19]. For instance, authors in [13] estimated the potential of concentrating solar power in Botswana using the Geographical Information System (GIS). The results indicated that the country has a huge concentrating solar power that will be able to meet the maximum energy demand. Authors in [14] examined the status of solar pilot projects at different locations in Botswana. They concluded that solar home systems in rural areas will significantly enhance socio-economic benefits and assist the sustainability of solar power generation in the country. Authors in [15] evaluated the technical performance of solar water heaters in Gaborone, Botswana. Authors in [16] analyzed the energy requirements of a non-electricity off-grid village in Botswana. Authors in [17] designed a hybrid solar-wind system for rural electrification in Botswana using the HOMER software. The results showed that the optimal model (solar-wind-battery system) employed 100% renewable energy, resulting in zero carbon emissions. The results indicated that the minimum and maximum output power of the PV system occurred during June/July and December/January, respectively. Authors in [18] utilized Simulink's single diode model design to present the PV module voltage output and the annual maximum power output profile of the PV module for variable temperature and irradiance. The results demonstrated that the voltage output is generally constant throughout the year while the maximum power from the solar module closely follows the solar radiation profile. Authors in [19] calculated the size of PV panels, batteries, and integrated collector-storage solar water heaters based on the demands for electricity and hot water.

B. Research Gap and Objectives

To the best of our knowledge, there is not any study that investigates the economic feasibility of a grid-connected rooftop PV system in Botswana. The findings of the literature review reveal a clear lack of proposed solar PV systems as a power source for households in Botswana. Thereby, there is no doubt that a comprehensive economic and environmental study must be conducted to obtain results that could be a roadmap for solar energy investments in the country. Consequently, it can be concluded that the small-scale solar systems in the country can not only bridge the energy gap but would also reduce the environmental impact. Therefore, the present paper aims to evaluate the techno-economic and environmental feasibility of small-scale rooftop grid-connected solar systems at different locations and climate conditions in Botswana. To achieve this, the solar radiation data are analyzed to classify the solar resource in the selected locations. Moreover, the techno-economic feasibilities for the rooftop solar systems at three comparative locations were developed for various policy scenarios, based on variations in financial parameters using RETScreen Experts.

II. MATERIALS AND METHODS

A. Study Area

Figure 1 shows the locations of the three regions considered in this study. The solar radiation data were taken from the NASA POWER data over 16 years (2005-2020).

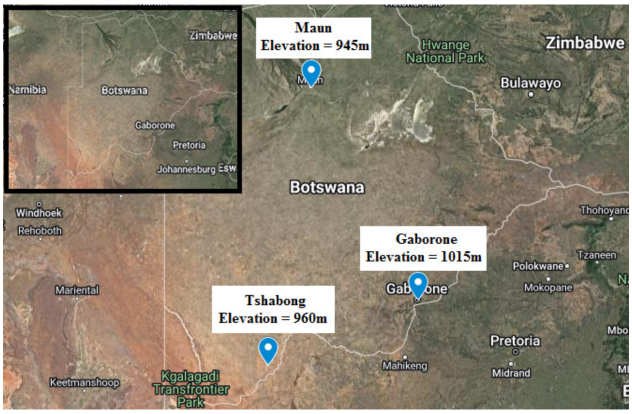

Fig. 1. Location of the selected regions used in this work. Screenshot from Google Earth. © TerraMetrice, Map data © AfriGIS (Pty) Ltd.

1) Gaborone

Gaborone (24.6282°S, 25.9231°E) is the capital and largest city of Botswana with a population of over 200,000. It is located in the southern part of the country. The monthly variation of Global Horizontal Irradiation (GHI) and Average Temperature (AT) are illustrated in Figure 2. The minimum and maximum values of GHI are recorded in June and October with values of 121.43kW/m^2 and 217.30kW/m^2, respectively. The annual value of GHI is estimated to be 2094.52kW/m^2. The solar resource at this location is categorized as outstanding (2035.9-2221.8kW/m^2) [19]. Additionally, it is found that the monthly value of AT is within the range of 13.24-25.20°C with an average value of 20.69°C.

2) Maun

Maun (19.9953°S, 23.4181°E) is located in Northwest Province. It is the capital of the Northwest Province with a population of 55,784. As can be seen in Figure 2, the monthly value of GHI varies from 138.56kW/m^2 to 227.41kW/m^2 with an average value of 182.35kW/m^2. The solar resource at this location is also classified as outstanding (annual GHI = 22188.16kW/m^2) [19]. The maximum mean AT is recorded in October with a value of 28.03°C, while the minimum value of 16.72°C is recorded in July.

3) Tshabong

Tshabong (26.0208°S, 22.4113°E) is located in the Kalahari Desert with a population of 8,939 according to the 2011 census. The monthly value of GHI is within the range of 117.99-250.38kW/m^2 with an average of 188.52kW/m^2 as shown in Figure 2. The annual value of GHI at the selected location is 2262.25kW/m^2. The solar resource at this location is categorized as superb (>2221.8kW/m^2). Additionally, it is found that the monthly value of AT is within the range of 12.93-27.89°C with an average value of 21.58°C.

B. On-grid Photovoltaic System

Grid-connected PV systems have PV panels that supply the required power during the day and are connected to the local electrical grid to be supplied with power at night. Moreover, the excess power from the PV system is fed back to the grid when the power generated is more than the load required [20]. In general, the grid-connected PV system consists of solar panels, inverters, a power-conditioning unit, and grid-connection equipment. To get more power from the PV arrays, the PV panels should have high cell efficiency and a high operating temperature. The inverter is one of the most crucial components of a grid-connected system because it converts Direct Current (DC) to Alternating Current (AC). In addition, electricity meters are utilized to read the flow of electricity to and from the grid. Recently, on-grid PV systems have attracted substantial attention due to the advantages of their compatibility with the electricity grid. In this system, the output power of the PV system is connected directly to the grid and the household. The electric energy produced by the PV system can cover the energy demand of the household. When the produced energy by the PV system is high, the remaining produced energy can be fed into the grid through an electric meter. This system comprises PV panels, which absorb sunlight and produce direct current, an inverter that is used to convert the direct current to alternating current, a distribution controller, and load as shown in Figure 3. Generally, it is necessary to estimate the optimal sizing of grid-connected PV systems as the first step to meet the energy demands of the household. According to [21], the amount of output energy by the PV system (E_{PV}) should be greater than the amount of electricity taken from the grid (E_{grid}) as shown in (1). In this case, the energy demand of the household can be shared between the PV system and the electric grid.

$$E_{PV} > E_{grid} \tag{1}$$

The generated energy from the PV system is utilized to cover the household/building instantaneous electricity load and the surplus energy is injected into the grid (i.e. if the load of the building at time *t* is greater than the generated PV electricity, the required energy is absorbed from the grid. In general, the effect of the ambient temperature is one of the most important factors that affect the output power of the PV system (P_{PV}), which can be expressed as [22]:

$$P_{PV} = \eta_{PV}\eta_{in}A_{PV}\gamma\frac{G}{G_{STC}}[1+\gamma_T(T-T_{STC})] \tag{2}$$

where η_{PV} is the PV module efficiency, η_{in} is the inverter efficiency, G_{STC} is the Standard Test Conditions (STC) irradiance (1kW/m^2), T and T_{STC} are the PV cell operating temperature in °C and the PV cell STC temperature (25°C), respectively, γ_T is the module's maximum power temperature coefficient (%/°C), and γ is the derate factor to account for the losses in system performance given by [23]:

$$\gamma = \gamma_{DC}\gamma_{AC}\gamma_{AGE}\gamma_{ext} \tag{3}$$

where γ_{DC} is the DC power derate factor to account for factors like module mismatch, diodes and connection losses, and DC wiring losses, γ_{AC} is the AC interconnection derate factor with a value of 0.99, γ_{AGE} is the derate factor to account for the loss in system performance with age, and γ_{ext} represents the losses due to external factors like dust, shading, snow cover, or anything else that would vary the power output of the PV module to deviate from that expected under ideal conditions.

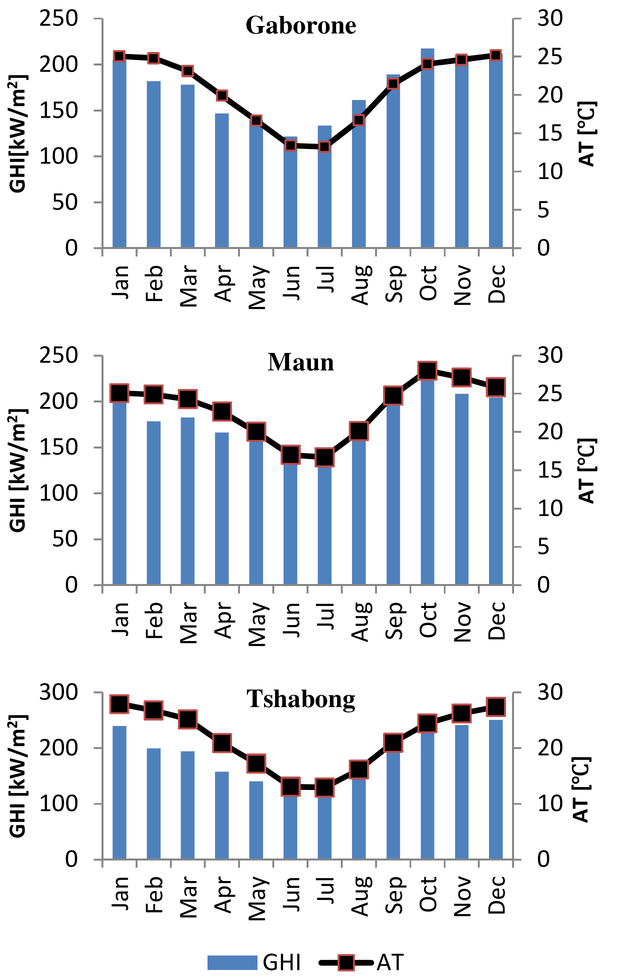

Fig. 2. Monthly mean variation of GHI and AT for all selected locations during the 2005-2020 period.

Moreover, (4) is used to estimate the PV cell operating temperature (T) [24]. Furthermore, the solar radiation incident (G) on the tilted angle (ϕ) can be determined by (5) [25]:

$$T = T_a + \frac{G}{0.8}(T_{NOCT} - 20) \tag{4}$$

$$G = G_d \left[cos(\theta) + C \cdot cos^2\left(\frac{\phi}{2}\right) + \rho \cdot \left(cos(\chi) + C \cdot sin^2\left(\frac{\phi}{2}\right)\right)\right] \tag{5}$$

where T_a is the ambient temperature, T_{NOCT} is the nominal operating cell temperature, G_d is the direct normal irradiance, θ is the angle between the tilted surface and the solar rays, C is the diffuse portion constant, ρ is the reflection index, and χ is the zenith angle. θ, χ, and the sun azimuth angle ξ can be obtained from:

$$cos(\theta) = [cos(\phi) \cdot cos(\chi) + sin(\phi) \cdot sin(\chi) \cdot cos(\xi - \zeta)] \tag{6}$$

$$cos(\chi) = sin(\delta) \cdot sin(\lambda) + cos(\delta) \cdot cos(\lambda) \cdot cos(\alpha) \tag{7}$$

$$tan(\xi) = \frac{sin(\alpha)}{sin(\lambda) \cdot cos(\alpha) - cos(\lambda) \cdot tan(\delta)} \tag{8}$$

where ζ is the plat azimuth angle, δ is the solar declination angle, λ is the latitude, and α is the solar angle, defined by:

$$\alpha = \frac{360}{24}[(LST + EOT - 4L + 60t_z) - 2] \tag{9}$$

where t_s is the solar time depending on Local Standard Time (LST), longitude L, time zone t_z, and EOT is the Equation Of Time that accounts for the irregularity of the earth's speed around the sun.

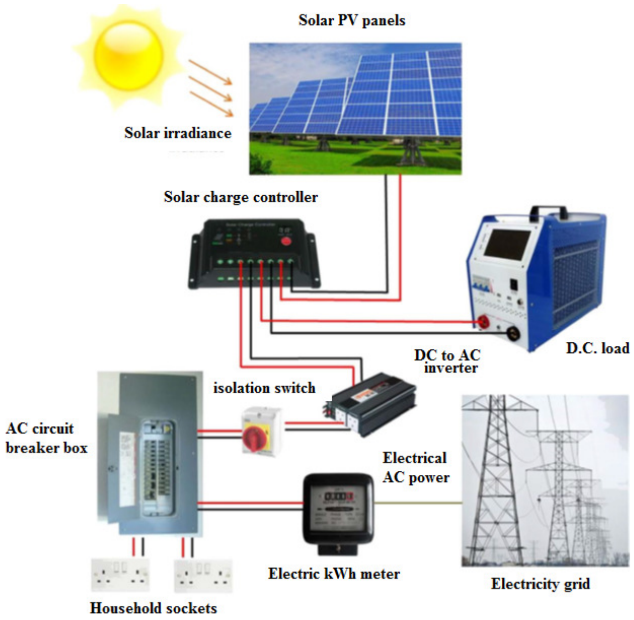

Fig. 3. Components of an on-grid PV system.

Moreover, the maximum power (P_{max}) of the developed on-grid solar PV system can be estimated as a function of global solar radiation G_{sr} (kWh/m^2/d), solar radiation at standard test conditions P_i (kW/m^2), PV derating factor f_{PV}, household daily power consumption E_{AC} (kWh/d), and inverter yield η_{inv}. This relationship can be expressed as [22]:

$$P_{max} = \frac{E_{AC} P_i}{G_{sr} f_{PV} \eta_{inv}} \tag{10}$$

The average daily output of the PV system coincides with the utility's peak demand period, therefore decreasing the capacity losses in the utility distribution network and improving the delay issues of the Transmission and Distribution (T&D) network [26-28]. Moreover, this system does not require batteries hence it has lower cost than an off-grid PV system [28].

C. RETScreen Expert Software

RETScreen Expert is a renewable energy management tool developed by the Canadian government. It is a decision support tool that is utilized to determine the potential of energy, costs, savings, greenhouse gas (GHG) emission reduction, and economic viability [29, 30]. RETScreen uses global meteorological data collected from the National Aeronautics and Space Administration (NASA) database. RETScreen is commonly employed to explore the feasibility of grid-connected wind and PV power systems. For instance, authors in [30] used RETScreen to evaluate the techno-economic feasibility of a grid-connected PV system in Nigeria. Authors in [31] utilized RETscreen to investigate the potential of PV systems for electricity generation in various locations in Libya. Authors in [32] evaluated the cost-benefit of 100MW Solar PV in Pakistan using RETScreen. In the current study, the initial and operations and maintenance costs were assumed based on the previous studies related to techno-economic feasibility in African countries. Capacity Factor (CF), GHG reduction (A-GHG), and economic assessment parameters: Net Present Value (NPV), Levelized Cost of Energy (LCOE), Simple Payback (SP), Equity Payback (EP), Annual Lice Cycle Saving (ALCS), and Benefit-Cost Ratio (B-C) are determined using the equations below.

$$CF = \frac{P_{out}}{P \times 8760} \quad (11)$$

$$A - GHG = [(\text{Base case GHG emission factor}) - (\text{Proposed case GHG emission factor})] \times \text{End use energy delivered} \quad (12)$$

$$\text{GHG} - \text{E} - \text{RC} = \frac{ALCS}{\Delta_{GHG}} \quad (13)$$

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (14)$$

$$LCOE = \frac{\text{sum of cost over lifetime}}{\text{sum of electricity generated over the lifetime}} \quad (15)$$

$$SP = \frac{C - IG}{(C_{ener} + C_{capa} + C_{RE} + C_{GHG}) - (C_{o\&M} + C_{fuel})} \quad (16)$$

$$EP = \sum_{n=0}^{N} C_n \quad (17)$$

$$ALCS = \frac{NPV}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)} \quad (18)$$

$$B - C = \frac{NPV + (1 - f_d)C}{(1 - f_d)C} \quad (19)$$

where P_{out} is the energy generated per year, P is the installed capacity, N is the project life in years, C_n is the after-tax cash flow in year n, r is the discount rate, C is the total initial cost of the project, f_d is the debt ratio, B is the total benefit of the project, IG represents the incentives and grants, C_{ener} is the annual energy savings or income, C_{capa} is the annual capacity savings or income, C_{RE} is the annual Renewable Energy (RE) production credit income, C_{GHG} is the GHG reduction income, $C_{o\&M}$ is the yearly operation and maintenance costs incurred by the clean energy project, C_{fuel} is the annual cost of fuel, which is zero for renewable projects, and Δ_{GHG} is the annual GHG emission reduction.

III. RESULTS AND DISCUSSION

RETScreen Expert software was utilized to evaluate the viability of small-scale rooftop PV systems in three selected locations in Botswana.

A. Technical Viability

In this study, 5kW grid-connected fixed solar tracking mode is considered for all the selected locations with the solar PV modules tilted to an angle of 25° and azimuth angle of 180°. These angles were chosen based on the highest value of solar irradiance and electricity exported to the grid for each location. In this study, the solar module CS6X-340M-FG, manufactured by Canadian Solar, was used (Table I). The output AC power, the DC-AC conversion efficiency, and the capital cost of the inverter are the main factors when selecting a suitable inverter. GROWATT 5500MTL-S DUAL MPPT 6KW SOLAR INVERTER was selected (Table II). In general, the solar resource assessment is the first step of the PV system design. Figure 4 depicts the monthly average daily global irradiation on a horizontal surface and the global radiation on a horizontal surface and a 25° inclined plane for all chosen sites. It is observed that June is the period with the lowest solar irradiation in Botswana. The minimum tilted solar radiation was found to be 5.52kW/m^2/d for Gaborone, 5.57kW/m^2/d for Maun, and 5.40kW/m^2/d for Tsabong. The maximum value of tilted solar radiation was recorded in September (i.e. 6.69kW/m^2/d) for Gaborone, August (i.e. 6.91kW/m^2/d) for Maun, and December (i.e. 6.96kW/m^2/d) for Tsabong.

TABLE I. SPECIFICATIONS OF THE SELECTED PV MODULE

PV module technology	Mono-Si	Poly-Si
Manufacturer	Canadian Solar	Canadian Solar
Model	mono-Si - CS6X-300M	poly-Si - CS6X-310P
Nominal power [W]	300	310
Open-circuit voltage [V]	45	44.9
Short-circuit current [A]	8.74	9.08
Voltage at point of maximum power [V]	36.5	36.4
Current at point of maximum power [A]	8.22	8.52
Module area [m^2]	1.919	1.918
Efficiency [%]	15.63	16.16

TABLE II. SPECIFICATIONS OF THE SELECTED INVERTER

PV module Technology	Value
Rated Power [W]	6000
Min PPT Voltage [V]	100
Max PPT Voltage [V]	550
DC Startup Voltage [V]	100
DC Shutdown Voltage [V]	80
Max Input Voltage [V]	550
Max DC Power [W]	6500
Max AC Power [W]	5000
Max DC Current [A]	30
Warranty [year]	10
Efficiency [%]	97.9
Cost [USD]	550

The performance of the PV systems in terms of PV output and CF is dependent on the orientation angles [33]. Thus, the Electricity Exported to the Grid (EEG) and the CF were estimated at a tilted angle of 25° and an azimuth angle of 180° for all selected locations. It should be noted that fixed-tilt mounting systems are simpler, cheaper, and require less maintenance compared to tracking systems. The mean monthly value of EEG for all the selected locations is shown in Figure 5. The following are observed:

- In Gaborone, the EEG is within the range of 664.01-793.74kWh for mono-Si and 686.14-820.20kWh for poly-Si.
- In Maun, the EEG varied from 604.69 to 834.89 kWh for mono-Si and from 624.84 to 862.72kWh for poly-Si.
- In Tsabong, the EEG ranged between 665.26 and 828.70kWh for mono-Si and from 677.11 and 856.33kWh for poly-Si.

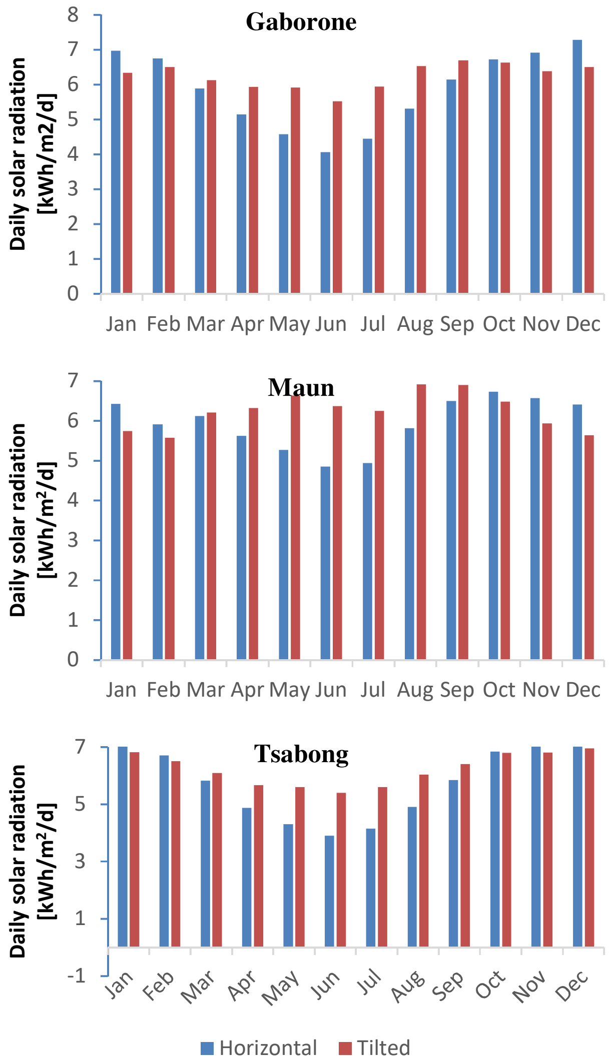

Fig. 4. Monthly average daily global radiation on a horizontal surface and a 25° tilted plane.

- The maximum amount of EEG is recorded in August while the minimum value is recorded in June for Gaborone.
- The lowest and highest values of EEG are recorded in February and August, respectively for Maun.
- For Tsabong, the highest and lowest values of EEG occurred during June and December, respectively.
- The poly-Si technology delivered higher energy to the grid than the mono-Si technology.

The annual value of EEG and CF for each location is shown in Table IV. It was found that the maximum annual EEG value of 9159.63kWh for poly-Si and 8864.16kWh for mono-Si occurred at Tsabong. The CF values were within the range of 19.84-19.78% with an average value of 19.81%. It was noticed that the CF of poly-Si technology is a slightly higher than mono-Si technology. These results can be supported by [34, 35]. The authors in [34] found a CF of 15.37% for mono-Si technology and 15.41% for poly-Si technology, while the authors in [35] estimated that the CF value for mono-Si and poly-Si technology is 11.47% and 12.9%, respectively.

TABLE III. THE ANNUAL VALUE OF EEG AND CF OF EACH LOCATION

Location	PV technology	EEG [kWh]	CF [%]
Gaborone	Mono-Si	8854.36	19.80
	Poly-Si	9149.50	19.82
Maun	Mono-Si	8836.07	19.78
	Poly-Si	9130.61	19.80
Tsabong	Mono-Si	8864.16	19.82
	Poly-Si	9159.63	19.84

B. Economic Sustainability

The techno-economic feasibility for rooftop PV systems at the three selected locations was evaluated for different values of electricity export rate (0.03-0.21 USD/kWh with a step of 0.03 USD/kWh). The assumed input financial parameters included 7.2% inflation rate, 3.75% discount rate, 9% reinvestment rate, 25 years of project life time, 70% debt ratio, 0% debt interest rate, and 20 years of debt payments, based on previous studies. Based on these input parameters, NPV, ALCS, SP, EP, LCOE, and the Internal Rate of Return (IRR) were estimated BY RETScreen. The NPV was determined for each location and the calculated values of Electricity Export Rate (EER) are listed in Table V. It was found that the NPV for each value of EER is positive, which indicated that the project is potentially feasible [36, 37]. There is a strong correlation between NPV and EER. IRR was estimated to evaluate the economic viability of the project [30, 36], as it provides the true return of interest generated by equity over the life of the project [29]. The results showed that increasing the rate of exporting electricity led to an increase in IRR. In addition, it was observed that the IRR of the three locations is higher than the required rate of return of the project. Furthermore, ALCS was calculated by using NPV, discount rate, and project lifetime. It was found that ALCS is within the range of 70.35-3099.09 USD/year. Additionally, the results of economic viability using poly-Si technology are higher than those for mono-Si technology (Table V).

TABLE IV. ANNUAL VALUE OF EEG AND CF FOR EACH LOCATION

Location	**Parameter**	**PV technology**	**Electricity export rate [USD/kWh]**						
			0.03	0.06	0.09	0.12	0.15	0.18	0.21
Gaborone	Pre-tax IRR-equity	Mono-Si	5.96	17.78	28.38	39.00	49.74	60.58	71.49
	Pre-tax IRR-assets		-0.64	5.98	10.65	14.62	18.27	21.75	25.14
	Net Present Value (NPV) [USD]		1171.19	8959.66	16748.13	24536.60	32325.08	40113.55	47902.02
	Annual life cycle savings [USD/year]		73.00	558.47	1043.94	1529.41	2014.88	2500.35	2985.81
	Simple payback [Year]		31.68	15.84	10.56	7.92	6.34	5.28	4.53
	Equity payback [Year]		17.94	7.09	4.13	2.88	2.20	1.78	1.49
	Benefit-Cost (B-C) ratio		1.46	4.55	7.63	10.72	13.80	16.89	19.97
	Energy production cost [USD/kWh]		0.0466	0.0466	0.0466	0.0466	0.0466	0.0466	0.0466
	Pre-tax IRR-equity	Poly-Si	6.42	18.49	29.44	40.42	51.54	62.76	74.04
	Pre-tax IRR-assets		-0.35	6.33	11.07	15.13	18.86	22.44	25.92
	Net Present Value (NPV) [USD]		1430.81	9478.89	17526.98	25575.07	33623.15	41671.24	49719.33
	Annual life cycle savings [USD/year]		89.18	590.84	1092.49	1594.14	2095.79	2597.44	3099.09
	Simple payback [Year]		30.66	15.33	10.22	7.66	6.13	5.11	4.38
	Equity payback [Year]		17.23	6.78	3.97	2.77	2.12	1.72	1.44
	Benefit- Cost (B-C) ratio		1.57	4.75	7.94	11.13	14.32	17.51	20.69
	Energy production cost [USD/kWh]		0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451
Maun	Pre-tax IRR-equity	Mono-Si	5.93	17.73	28.32	38.91	49.63	60.45	71.33
	Pre-tax IRR-assets		-0.66	5.96	10.62	14.59	18.24	21.71	25.09
	Net Present Value (NPV) [USD]		1122.57	8844.16	16565.75	24287.34	32008.92	39730.51	47452.10
	Annual life cycle savings [USD/year]		70.35	554.23	1038.11	1521.99	2005.87	2489.75	2973.63
	Simple payback [Year]		1.87	7.36	9.75	11.31	12.47	13.41	14.19
	Equity payback [Year]		31.74	15.87	10.58	7.94	6.35	5.29	4.54
	Benefit- Cost (B-C) ratio		1.44	4.50	7.56	10.62	13.68	16.74	19.80
	Energy production cost [USD/kWh]		0.0468	0.0468	0.0468	0.0468	0.0468	0.0468	0.0468
	Pre-tax IRR-equity	Poly-Si	6.39	18.45	29.37	40.33	51.43	62.62	73.87
	Pre-tax IRR-assets		-0.37	6.30	11.04	15.09	18.82	22.39	25.87
	Net Present Value (NPV) [USD]		1379.95	9358.93	17337.90	25316.88	33295.86	41274.83	49253.81
	Annual life cycle savings [USD/year]		86.48	586.49	1086.50	1586.51	2086.52	2586.53	3086.54
	Simple payback [Year]		30.72	15.36	10.24	7.68	6.14	5.12	4.39
	Equity payback [Year]		17.27	6.80	3.98	2.78	2.13	1.72	1.44
	Benefit- Cost (B-C) ratio		1.55	4.71	7.87	11.03	14.19	17.35	20.51
	Energy production cost [USD/kWh]		0.0453	0.0453	0.0453	0.0453	0.0453	0.0453	0.0453
Tsabong	Pre-tax IRR-equity	Mono-Si	5.97	17.80	28.42	39.04	49.80	60.66	71.57
	Pre-tax IRR-assets		-0.63	5.99	10.66	14.64	18.29	21.78	25.17
	Net Present Value (NPV) [USD]		1147.11	8893.24	16639.37	24385.50	32131.63	39877.76	47623.89
	Annual life cycle savings [USD/year]		71.88	557.30	1042.72	1528.14	2013.56	2498.98	2984.40
	Simple payback [Year]		31.64	15.82	10.55	7.91	6.33	5.27	4.52
	Equity payback [Year]		17.92	7.08	4.13	2.88	2.20	1.78	1.49
	Benefit- Cost (B-C) ratio		1.45	4.52	7.59	10.66	13.73	16.80	19.86
	Energy production cost [USD/kWh]		0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467
	Pre-tax IRR-equity	Poly-Si	6.43	18.52	29.47	40.47	51.61	62.84	74.12
	Pre-tax IRR-assets		-0.34	6.34	11.08	15.14	18.88	22.46	25.95
	Net Present Value (NPV) [USD]		1405.31	9409.65	17413.98	25418.32	33422.65	41426.99	49431.33
	Annual life cycle savings [USD/year]		88.07	589.66	1091.26	1592.86	2094.46	2596.06	3097.66
	Simple payback [Year]		30.62	15.31	10.21	7.66	6.12	5.10	4.37
	Equity payback [Year]		17.21	6.77	3.96	2.76	2.12	1.71	1.44
	Benefit- Cost (B-C) ratio		1.56	4.73	7.90	11.07	14.24	17.41	20.58
	Energy production cost [USD/kWh]		0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451

The economic viability of a project is estimated by determining the payback period [30. 36]. Table IV lists the payback period including EP and SP for all selected locations. It is found that the EP is within the range of 1.44-17.99 years. The developed PV project with mono-Si technology in Maun has the longest EP and SP of 17.99 years and 31.74 years, respectively, followed by one in Gaborone. The proposed project with poly-Si technology at Tsabong has the shortest EP of 1.44 years and SP of 4.37. The results reveal that the increase in EER will lead to a decrease in EP and SP. Besides, the results demonstrate that the SP value exceed the lifetime of the project (25 years) when the EER is equal to 0.03 USD/kWh. This indicates that installing PV projects at the selected locations is not economically viable when the EER is equal to 0.03 USD/kWh. In addition, the value of B-C, which is utilized to determine the cash flow generated viability, is higher than 1 as shown in Table V. These findings indicate the feasibility of the projects [27]. Moreover, the LCOE sets a minimum selling cost of electricity that may result in an NPV of zero. Table V shows the LCOE for each location with various PV technologies. It is observed that the LCOE is within the range of 0.0451-0.0468 USD/kWh. These values are within the range of 0.0199-3.165 USD/kWh [38]. Besides, the LCOE of PV systems is less than the current electricity tariffs in Botswana (0.098 USD/kWh for households and 0.117 USD/kWh for businesses).

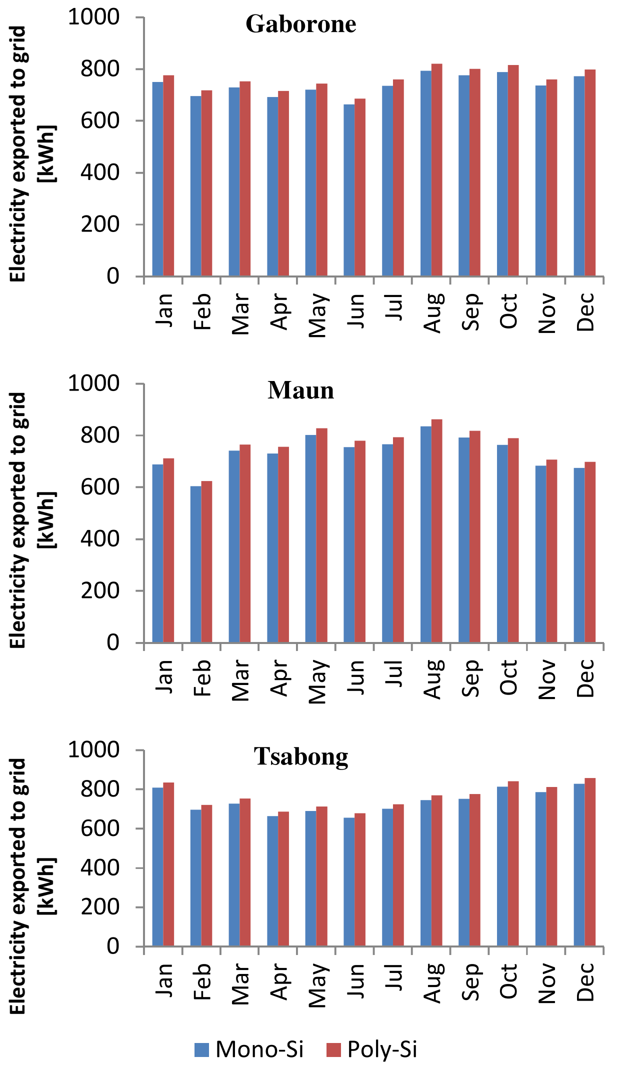

Fig. 5. Monthly average value of EEG on a 25° tilted plane.

C. Climate Co-Benefits Assessment

In addition to economic feasibility, an estimate of the environmental benefits in terms of reduced GHG emissions of the proposed system would be attractive. The climate co-benefits in terms of GHG emission reduction were calculated using RETScreen for each location and are listed in Table VI in multiple equivalent formats. The results indicate that a large amount of CO_2 emissions can be avoided by implementing the developed PV project in each considered location. It is noticed that the PV projects with poly-Si technology have the highest amount of CO_2 emission reductions. It should be noted that the total amount of CO_2 emission reduction for each location is determined based on the electricity generated annually [39]. Tsabong and Maun have the highest and lowest amount of CO_2 emission reduction, respectively.

TABLE V. GHG EMISSION REDUCTION (tCO_2)

Location	Annual GHG emission reduction [tCO_2] equivalent to	PV technology	
		Mono-Si	Poly-Si
Gaborone	Gross annual GHG emission reduction	15.83	16.35
	Care and light trucks not used	2.90	3.00
	Liters of gasoline not consumed	6800.39	7027.07
	Barrels of crude oil not consumed	36.81	38.03
	People reducing energy use by 20%	15.83	16.35
	Acres of forest absorbing carbon	3.60	3.72
	Hectares of forest absorbing carbon	1.46	1.50
	Tons of waste recycled	5.46	5.64
Maun	Gross annual GHG emission reduction	15.79	16.32
	Care and light trucks not used	2.89	2.99
	Liters of gasoline not consumed	6786.35	7012.56
	Barrels of crude oil not consumed	36.73	37.96
	People reducing energy use by 20%	15.79	16.32
	Acres of forest absorbing carbon	3.59	3.71
	Hectares of forest absorbing carbon	1.45	1.50
	Tons of waste recycled	5.45	5.63
Tsabong	Gross annual GHG emission reduction	15.84	16.37
	Care and light trucks not used	2.90	3.00
	Liters of gasoline not consumed	6807.92	7034.85
	Barrels of crude oil not consumed	36.85	38.08
	People reducing energy use by 20%	15.84	16.37
	Acres of forest absorbing carbon	3.60	3.72
	Hectares of forest absorbing carbon	1.46	1.51
	Tons of waste recycled	5.46	5.65

IV. CONCLUSION

The solar energy potential and techno-economic feasibility of grid-connected rooftop PV systems at three selected locations in Botswana were investigated in this study. For this purpose, the annual value of GHI was estimated to categorize the solar resource in the selected locations. Furthermore, the feasibility of a grid-connected PV system was assessed utilizing RETScreen. Based on the value of GHI, the selected regions are suitable for installing large-scale or small-scale PV systems. The results demonstrated that small-scale PV projects are feasible and economical viable. Besides, the price of the electricity generated by PV systems is less than that of the conventional system. It can be concluded that the developed systems provide a very good insight into the economic feasibility of such project for all the considered locations. Consequently, a huge potential of solar energy exists in the country, which if used effectively can play a vital role to overcome the current energy deficit.

V. LIMITATIONS AND FUTURE WORK

This study has some limitations that may be addressed in the future. The impact of meteorological parameters including air temperature, and relative humidity on the performance of the PV system was neglected. The influence of these parameters can be addressed using HOMER [41]. The financial parameters were assumed based on previous studies. Therefore, the impact of policy changes and critical variables such as the initial costs of the project, inflation rate, and discount rate on the feasibility of grid-connected rooftop PV systems should be investigated in the future. Moreover, the interaction between the distribution network and the PV system must be realized in order to understand the impact of the grid-connected PV systems on the distribution network.

REFERENCES

[1] E. A. Al-Ammar, N. H. Malik, and M. Usman, "Application of using Hybrid Renewable Energy in Saudi Arabia," *Engineering, Technology & Applied Science Research*, vol. 1, no. 4, pp. 84–89, Aug. 2011, https://doi.org/10.48084/etasr.33.

[2] M. Hosenuzzaman, N. A. Rahim, J. Selvaraj, M. Hasanuzzaman, A. B. M. A. Malek, and A. Nahar, "Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 284–297, Jan. 2015, https://doi.org/10.1016/j.rser.2014.08.046.

[3] J. Khan and M. H. Arsalan, "Solar power technologies for sustainable electricity generation – A review," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 414–425, Mar. 2016, https://doi.org/10.1016/j.rser.2015.10.135.

[4] A. Shahsavari and M. Akbari, "Potential of solar energy in developing countries for reducing energy-related emissions," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 275–291, Jul. 2018, https://doi.org/10.1016/j.rser.2018.03.065.

[5] Y. Kassem, R. Al Zoubi, and H. Gokcekus, "The Possibility of Generating Electricity Using Small-Scale Wind Turbines and Solar Photovoltaic Systems for Households in Northern Cyprus: A Comparative Study," *Environments*, vol. 6, no. 4, Apr. 2019, Art. no. 47, https://doi.org/10.3390/environments6040047.

[6] R. Opoku, E. A. Adjei, D. K. Ahadzie, and K. A. Agyarko, "Energy efficiency, solar energy and cost saving opportunities in public tertiary institutions in developing countries: The case of KNUST, Ghana," *Alexandria Engineering Journal*, vol. 59, no. 1, pp. 417–428, Feb. 2020, https://doi.org/10.1016/j.aej.2020.01.011.

[7] A. Sagani, J. Mihelis, and V. Dedoussis, "Techno-economic analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece," *Energy and Buildings*, vol. 139, pp. 277–290, Mar. 2017, https://doi.org/10.1016/j.enbuild.2017.01.022.

[8] H. Camur, Y. Kassem, and E. Alessi, "A Techno-Economic Comparative Study of a Grid-Connected Residential Rooftop PV Panel: The Case Study of Nahr El-Bared, Lebanon," *Engineering, Technology & Applied Science Research*, vol. 11, no. 2, pp. 6956–6964, Apr. 2021, https://doi.org/10.48084/etasr.4078.

[9] M. R. Motsholapheko, J. E. Mbaiwa, D. L. Kgathi, and T. Oladiran, "Access to grid electricity in Botswana: Implications for energy transition in the Okavango Delta," *PULA: Botswana Journal of African Studies*, vol. 32, no. 1, pp. 141–160, 2018.

[10] K. Mohammadi and A. Mostafaeipour, "Using different methods for comprehensive study of wind turbine utilization in Zarrineh, Iran," *Energy Conversion and Management*, vol. 65, pp. 463–470, Jan. 2013, https://doi.org/10.1016/j.enconman.2012.09.004.

[11] W. R. Mutoko and P. Mutoko, "Literature Review on the Solar Energy Potential for Botswana," *European Scientific Journal ESJ*, vol. 15, no. 34, pp. 27–43, Dec. 2019, https://doi.org/10.19044/esj.2019.v15n34p27.

[12] P. G. O. Anderson, "The role, reliability and limitations of solar photovoltaic systems in Botswana," in *Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441)*, Orlando, FL, USA, Oct. 2000, vol. 3, pp. 973–982, https://doi.org/10.1109/ICHQP.2000.896861.

[13] K. Tlhalerwa and M. Mulalu, "Assessment of the concentrated solar power potential in Botswana," *Renewable and Sustainable Energy Reviews*, vol. 109, pp. 294–306, Jul. 2019, https://doi.org/10.1016/j.rser.2019.04.019.

[14] C. Ketlogetswe and T. H. Mothudi, "Solar home systems in Botswana—Opportunities and constraints," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 6, pp. 1675–1678, Aug. 2009, https://doi.org/10.1016/j.rser.2008.08.007.

[15] E. Bakaya-Kyahurwa and M. T. Oladiran, "Performance of solar water heating systems in Botswana," *Journal of Energy in Southern Africa*, vol. 11, pp. 156–160, Feb. 2000.

[16] K. P. Motladiile, T. Bader, A. Pugsley, M. Smyth, and J. Mondol, "Energy requirement analysis for the design of solar photovoltaic micro-grids in Botswana: a study of Jamataka village," in *BIUST Research and Innovation Symposium*, Palapye, Botswana, Jun. 2019.

[17] K. P. Motladiile, T. Bader, A. Pugsley, M. Smyth, and J. Mondol, "Energy requirement analysis for the design of solar photovoltaic micro-grids in Botswana: a study of Jamataka village," in *BIUST Research and Innovation Symposium*, Palapye, Botswana, Jun. 2019, pp. 101–106.

[18] K. Tsamaase, J. Sakala, E. Rakgati, I. Zibani, and K. Motshidisi, "Solar PV Module Voltage Output and Maximum Power Yearly profile using Simulink-based Model," in *10th International Conference on Renewable Energy Research and Application*, Istanbul, Turkey, Sep. 2021, pp. 31–35, https://doi.org/10.1109/ICRERA52334.2021.9598794.

[19] A. Pugsley *et al.*, "Solar electricity & hot water for dispersed off-grid households in Botswana: Demand-based sizing & Prototype testing initial results," in *2nd International Conference on Solar Technologies & Hybrid Mini Grids to improve energy access*, Palma de Mallorca, Spain, Oct. 2018.

[20] Y. Kassem, H. Camur, and R. A. F. Aateg, "Exploring Solar and Wind Energy as a Power Generation Source for Solving the Electricity Crisis in Libya," *Energies*, vol. 13, no. 14, Jan. 2020, Art. no. 3708, https://doi.org/10.3390/en13143708.

[21] S. Rehman, M. A. Ahmed, M. H. Mohamed, and F. A. Al-Sulaiman, "Feasibility study of the grid connected 10MW installed capacity PV power plants in Saudi Arabia," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 319–329, Dec. 2017, https://doi.org/10.1016/j.rser.2017.05.218.

[22] T. Nacer, A. Hamidat, O. Nadjemi, and M. Bey, "Feasibility study of grid connected photovoltaic system in family farms for electricity generation in rural areas," *Renewable Energy*, vol. 96, pp. 305–318, Oct. 2016, https://doi.org/10.1016/j.renene.2016.04.093.

[23] H. Maammeur, A. Hamidat, L. Loukarfi, M. Missoum, K. Abdeladim, and T. Nacer, "Performance investigation of grid-connected PV systems for family farms: case study of North-West of Algeria," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1208–1220, Oct. 2017, https://doi.org/10.1016/j.rser.2017.05.004.

[24] J. K. Copper, A. B. Sproul, and S. Jarnason, "Photovoltaic (PV) performance modelling in the absence of onsite measured plane of array irradiance (POA) and module temperature," *Renewable Energy*, vol. 86, pp. 760–769, Feb. 2016, https://doi.org/10.1016/j.renene.2015.09.005.

[25] N. D. Nordin and H. Abdul Rahman, "A novel optimization method for designing stand alone photovoltaic system," *Renewable Energy*, vol. 89, pp. 706–715, Apr. 2016, https://doi.org/10.1016/j.renene.2015.12.001.

[26] A. V. da Rosa and J. C. Ordonez, *Fundamentals of Renewable Energy Processes*. Cambridge, MA, United States: Academic Press, 2021.

[27] E. Tarigan, Djuwari, and F. D. Kartikasari, "Techno-economic Simulation of a Grid-connected PV System Design as Specifically Applied to Residential in Surabaya, Indonesia," *Energy Procedia*, vol. 65, pp. 90–99, Jan. 2015, https://doi.org/10.1016/j.egypro.2015.01.038.

[28] Y. Kassem, H. Gokcekus, and A. Guvensoy, "Techno-Economic Feasibility of Grid-Connected Solar PV System at Near East University Hospital, Northern Cyprus," *Energies*, vol. 14, no. 22, Jan. 2021, Art. no. 7627, https://doi.org/10.3390/en14227627.

[29] A. M. Ramli, A. Hiendro, K. Sedraoui, and S. Twaha, "Optimal sizing of grid-connected photovoltaic energy system in Saudi Arabia," *Renewable Energy*, vol. 75, pp. 489–495, Mar. 2015, https://doi.org/10.1016/j.renene.2014.10.028.

[30] R. Rabbani and M. Zeeshan, "Impact of policy changes on financial viability of wind power plants in Pakistan," *Renewable Energy*, vol. 193, pp. 789–806, Jun. 2022, https://doi.org/10.1016/j.renene.2022.05.049.

[31] A. B. Owolabi, B. E. K. Nsafon, J. W. Roh, D. Suh, and J.-S. Huh, "Validating the techno-economic and environmental sustainability of solar PV technology in Nigeria using RETScreen Experts to assess its viability," *Sustainable Energy Technologies and Assessments*, vol. 36, Dec. 2019, Art. no. 100542, https://doi.org/10.1016/j.seta.2019.100542.

[32] Y. Kassem, H. Camur, and O. a. M. Abughinda, "Solar Energy Potential and Feasibility Study of a 10MW Grid-connected Solar Plant in Libya," *Engineering, Technology & Applied Science Research*, vol. 10, no. 4, pp. 5358–5366, Aug. 2020, https://doi.org/10.48084/etasr.3607.

[33] M. Asad, F. I. Mahmood, I. Baffo, A. Mauro, and A. Petrillo, "The Cost Benefit Analysis of Commercial 100 MW Solar PV: The Plant Quaid-e-

Azam Solar Power Pvt Ltd.," *Sustainability*, vol. 14, no. 5, Jan. 2022, Art. no . 2895, https://doi.org/10.3390/su14052895.

[34] J. D. Mondol, Y. G. Yohanis, and B. Norton, "The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system," *Renewable Energy*, vol. 32, no. 1, pp. 118–140, Jan. 2007, https://doi.org/10.1016/j.renene.2006.05.006.

[35] M. Obeng, S. Gyamfi, N. S. Derkyi, A. T. Kabo-bah, and F. Peprah, "Technical and economic feasibility of a 50 MW grid-connected solar PV at UENR Nsoatre Campus," *Journal of Cleaner Production*, vol. 247, Feb. 2020, Art. no. 119159, https://doi.org/10.1016/j.jclepro.2019.119159.

[36] D. A. Quansah, M. S. Adaramola, G. K. Appiah, and I. A. Edwin, "Performance analysis of different grid-connected solar photovoltaic (PV) system technologies with combined capacity of 20 kW located in humid tropical climate," *International Journal of Hydrogen Energy*, vol. 42, no. 7, pp. 4626–4635, Feb. 2017, https://doi.org/10.1016/j.ijhydene.2016.10.119.

[37] S. S. Rashwan, A. M. Shaaban, and F. Al-Suliman, "A comparative study of a small-scale solar PV power plant in Saudi Arabia," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 313–318, Dec. 2017, https://doi.org/10.1016/j.rser.2017.05.233.

[38] A. H. Mirzahosseini and T. Taheri, "Environmental, technical and financial feasibility study of solar power plants by RETScreen, according to the targeting of energy subsidies in Iran," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 2806–2811, Jun. 2012, https://doi.org/10.1016/j.rser.2012.01.066.

[39] Y. Kassem and M. H. A. Abdalla, "Modeling predictive suitability to identify the potential of wind and solar energy as a driver of sustainable development in the Red Sea state, Sudan," *Environmental Science and Pollution Research*, vol. 29, no. 29, pp. 44233–44254, Jun. 2022, https://doi.org/10.1007/s11356-022-19062-9.

[40] K. Mohammadi, M. Naderi, and M. Saghafifar, "Economic feasibility of developing grid-connected photovoltaic plants in the southern coast of Iran," *Energy*, vol. 156, pp. 17–31, Aug. 2018, https://doi.org/10.1016/j.energy.2018.05.065.

[41] A. Alahmer and S. Alsaqoor, "Energy efficient of Using Chilled Water System for Sustainable Health Care Facility Operating by Solar Photovoltaic Technology," *Energy Procedia*, vol. 156, pp. 65–71, Jan. 2019, https://doi.org/10.1016/j.egypro.2018.11.092.