Techno-economic Modeling of Stand-Alone Solar Photovoltaic Systems: A case Scenario from South Sudan

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***Abstract*—South Sudan is expansive and sparsely populated with over 80% of the population living in rural areas. The country has no national grid connecting its cities and towns, thus making rural areas "good candidates" for stand-alone renewable energy systems. This study was conducted to determine the technical feasibility and economic viability of a stand-alone photovoltaic (PV) system compared to a diesel generator. A techno-economic model was developed to forecast the performance of the PV system. The system was initially designed using the IEEE Recommended Practice for Sizing of Stand-Alone Photovoltaic Systems (IEEE P1562-2021) and the IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic Systems (IEEE 1013-2019). The solar radiation data used for modeling were acquired from the Ineichen clear sky model and then transposed to the plane of array irradiation using pvlib python. The system optimization and sensitivity analysis was performed under various diesel fuel costs using the Hybrid Optimization of Multiple Energy Resources (HOMER) software. Results show that at a fuel price of $ 2 per liter, the levelized cost of electricity (LCOE) of the PV system is 64% lower than that of the diesel generator and that the system can earn 11% return on investment (ROI) and recover the investment in about 5.5 years. With a drop in price of diesel fuel to $1 per liter, the payback period increases to about 7 years. These results show that stand-alone PV systems are technically feasible and economically viable in rural and peri-urban areas of South Sudan.**

***Index Terms*—IEEE Standards, renewable energy, pvlib python, solar photovoltaic, South Sudan, techno-economic modeling**

I. Introduction

"We have entered the decade of renewables!" [1]. In 2019, about 80% of the newly installed global electricity capacity was from renewables, with solar and wind accounting for about 50% of the total capacities [1]. In Africa, the installed renewable electricity capacity has increased in the past decade by around 93.8%, of which about 20% was from solar generation [1]. Despite the deficit in access to electricity in Sub-Saharan Africa, there has been noticeable progress in the past decade. In 2011, countries such as Rwanda, Tanzania, Ethiopia and Kenya had almost null solar electricity capacity in their generation mix and by 2020, they had installed operating solar power plants with total capacities ranging between 20 MW and 105 MW [1].

South Sudan is an oil-rich country with an area of 619,745 square kilometers (sq. km) and a population density of 13.3 people per sq. km [2]. The country has abundant untapped renewable energy resources (solar, hydropower and wind beside others), which can be exploited to generate electricity. However, despite all available resources, South Sudan remains the "least electrified country in the world". The country replaces Yemen and tops the list of the top 20 electricity access-deficit countries in the world [3]. South Sudan has no national grid connecting its cities and towns and the current available distribution network is about 395 km (145 km medium voltage and 250 km low voltage) in the capital city Juba [4], [5].

A study conducted in 2020 showed that many business owners in Juba city meet their electricity needs by deploying stand-alone diesel generators and solar photovoltaic systems (PV) [6]. Diesel generation alone accounted for about 98% of the total stand-alone generation with monthly fuel costs reaching up to 533,204 United States dollars ($) and carbon dioxide emissions (CO2e) amounting to 1553.8 tons (t) in addition to noise pollution [6]. The study also showed that the use of solar energy for electricity generation among the business owners was very limited (2%), mainly due to the inadequate knowledge about their use.

Currently, South Sudan is planning to improve electricity access through developing renewable energy resources besides investing in transmission infrastructure [7], [8]. However, the construction of transmission and distribution lines all over South Sudan may not be feasible in the "near future" as the country is expansive and sparsely populated, with over 80% of the population living in rural areas [9], [10]. The cost of constructing a transmission network in "rural and peri-rural" areas is usually expensive and exceeds the expected economic and social benefits as some stakeholders may remain unconnected even after several years of constructing the electricity [11], [12]. Therefore, in the absence of "near future" plans to construct a reliable transmission backbone in a country with abundant renewable energy resources, rural and remote

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communities usually become “better candidates” for stand-alone renewable energy systems for electricity generation [13]. Stand-alone, or off-grid, renewable energy systems are electrical systems that ”operate independently” from the main electricity grid. A few studies have recommended using hybrid and stand-alone renewable energy systems to improve access to electricity in South Sudan [8], [14]. In fact, several solar Photovoltaic (PV) projects have been developed in the country. For example, the development of a microgrid pilot project to power a local market in Northern Bahr el Gazal state (developed by SunGate Solar, a national company) and the installation of a 350 kW solar PV system in the Equatorial Tower in Juba [15].

To correctly forecast the performance of a stand-alone PV system, it is fundamental to first develop an accurate and reliable techno-economic model of the system through simulation and modeling [16]. Several studies have been conducted on the assessment, design and techno-economic modeling of stand-alone solar PV systems using different methodologies [17]–[19]. However, there is very limited literature on the technical and economic analysis of stand-alone solar PV systems in South Sudan. Therefore, it is necessary to assess the technical and economic performance of stand-alone PV systems in South Sudan through modeling and simulation before scaling up their development. The results obtained will enable informed decisions to be made about country-wide deployment of commercial and non-commercial stand-alone PV systems.

This paper is reporting on studies made for developing a techno-economic model for stand-alone PV systems for commercial and community use in populated rural and peri-urban areas of South Sudan. The specific objective was to assess the technical feasibility and economic viability of the PV system compared to diesel fuel-based generation of electricity, to inform decision making in the development of stand-alone solar PV systems in the country.

Stand-alone PV systems mainly consist of solar PV arrays, solar charge controller, solar battery and a DC-AC solar inverter. In the current work, the solar PV array was designed using the methods in the IEEE Recommended Practice for Sizing of Stand-Alone Photovoltaic (PV) Systems (IEEE P1562-2021) [20]. Also, the battery storage system was designed using the IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems (IEEE 1013-2019) [21]. The PV array was also sized using mathematical modeling with Matlab/Simulink and then the results were compared to check the consistency between the two methods. Subsequently, a financial model was developed using the Hybrid Optimization of Multiple Energy Resources (HOMER) software.

The remainder of this paper is organized as follows:

- Section II elaborates more on the methodology used in this paper to develop the techno-economic model.
- Section III presents and analyzes the results.
- Section IV provides the conclusion to this work and proposes recommendations for future work

II. Methodology

To assess the technical performance of the stand-alone PV system, the size of the system’s components had to be determined. Sizing stand-alone PV systems differs from grid-connected systems [22]. Stand-alone PV systems are designed to meet the daily load demand rather than the annual demand [22]. As a result, each component of the PV system must be carefully sized to satisfy that requirement [22], [23]. The PV array must be sized to fully charge the battery bank [22]. Consequently, the capacity of the PV array (number and wattage of PV modules) that can generate the required power to fully charge the battery bank must be determined [23]. The capacity of the PV array is usually influenced by the solar radiation at the study location, the array-to-load ratio (A:L), the daily load, and the system losses [20]. Therefore, site selection, the solar resource at the site, and the estimate of the average daily load must be carefully considered in the design to avoid over-sizing or under-sizing the stand-alone system. Similarly, the battery bank size that can continuously supply electrical power to the load, at night or during periods of low solar radiation, must be precisely calculated [22]. So, the battery bank size is determined by the average daily load besides the battery type and parameters [24].

In off-grid systems, inverters are needed to convert the battery DC voltage into AC and it is necessary that the voltage input into the selected inverter matches the system voltage [23]. Inverters may vary in size according to their capacity, power quality, and output voltage [25]. Charge controllers are also important components of the stand-alone system that protect the storage battery from over-charging or over-discharging. Also the charge controller can be integrated with a maximum power point tracker (MPPT), a “DC-to-DC converter”, to increase the energy generated by the PV modules [25].

Once the size of the stand-alone PV system components are determined, its technical performance, in terms of output power and energy yield, can be calculated. The financial performance can then be evaluated by using different economic metrics.

The following sections describe the steps and techniques which were used to evaluate the technical and financial performance of the stand-alone PV system.

A. *Study location*

The preliminary step in the design of the PV system was to identify a suitable location with adequate solar resource. Long-term daily average global horizontal irradiation (GHI) data of South Sudan were downloaded from the Global Solar Atlas to search and locate areas of high solar resource potential in the country. Gok-Machar town market (latitude 9.21850, longitude 26.86787), in the north western part of South Sudan, was selected for the case scenario based on the high solar resource in that location (Fig.1) besides the potential for agribusiness activities and other related businesses.

Gok-Machar is a town in Aweil North county of Northern Bahr el Ghazal state. About 80% of households in Aweil North county depend on farming and agricultural activities

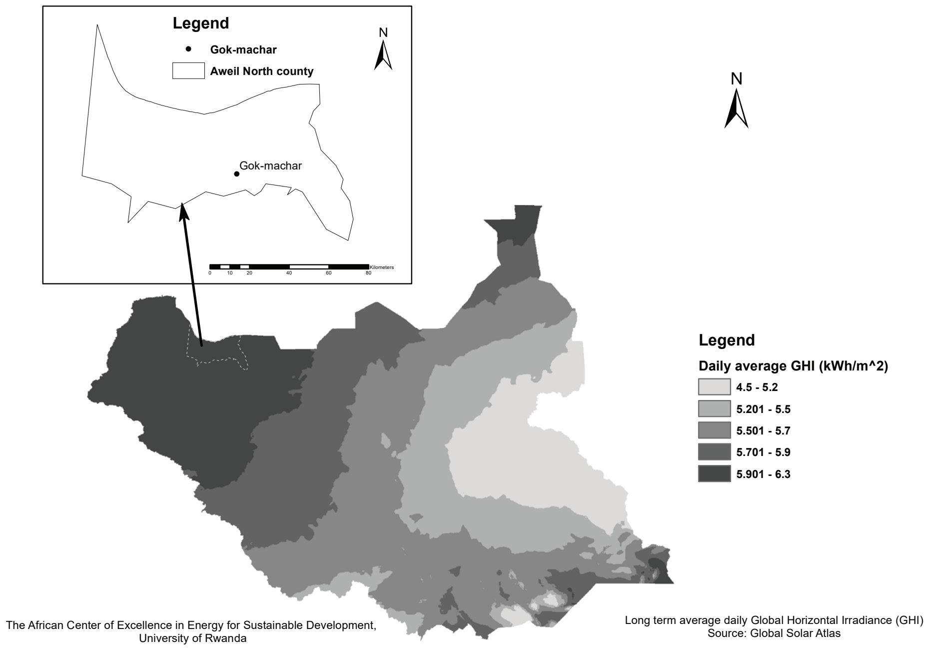

Fig. 1. Long term daily average Global Horizontal Irradiation

for their livelihoods besides undertaking other small-scale business activities [26]. Gok-Machar is located in an area with a daily average GHI on a horizontal plane ranging between 5.9 and 6.3 kWh/m^2 (based on the data from the Global Solar Atlas). Similar to many other towns in South Sudan, Gok-Machar has no access to grid electricity, so businesses there depend on diesel generators and small-scale solar PV systems for their electricity needs.

As of December 2022, one liter of diesel fuel in the parallel market in Gok-Machar was 1400 South Sudanese pounds, which was equivalent to $ 2 [27]. In November 2022, diesel fuel price in the capital city Juba was equivalent to $ 1.32 per liter and the cost of 1 kWh of utility electricity was equivalent to $ 0.334 (calculated from actual monthly residential electricity consumption).

B. Load profile

The main purpose of installing the PV system in the current scenario was to provide electricity to commercial customers in Gok-Machar market. The system was also expected to provide electricity to a few nearby domestic customers. Therefore, 300 commercial and domestic customers were expected to benefit from the solar PV system. The customers were divided into four categories:

- Category one consisted of 82 households (5% high-income, 45% middle-income and 50% low-income).
- Category two consisted of 200 businesses (retail and wholesale shops, motels, groceries, internet cafes, butcheries, restaurants, hair salons, farms and other small businesses).
- Category three consisted of eight public facilities (two schools, three offices, one guest house, one hospital and one community center).
- Category four consisted of 10 private facilities (four offices, two schools, two churches, one mosque and one medical complex).

TABLE I
LOAD DATA

No	Appliance	Average rated power (W)	Running current (A)
1	Refrigerator	150	1.56
2	Deep freezer	500	5.21
3	Cold storage	2400	25
4	Ceiling fan	70	0.73
5	Table/pedestal fan	50	1.0
6	Light bulb (fluorescent)	12	0.3
7	Light bulb (LED)	9	0.2
8	Radio	10	0.2
9	Laptop	75	1.6
10	Computer	150	3.1
11	Phone charger	5	01
12	Television + decoder	140	2.9
13	Water pump (domestic)	250	5.2
14	Water pump (community)	500	10.4
15	Irrigation pump	5500	114.6
16	Air cooler	200	4.2
17	Hair dryer	1800	37.5
18	Iron (clothes)	1000	20.8
19	Grinding mill	1200	25.0

Table I. shows the list of the appliances powered by the solar PV system. The power rating of each appliance is commonly found on the appliance (nameplate or stamp). The total daily load consumption (all appliances) was calculated, using Excel, as shown in the following steps:

- The total daily energy consumption of each individual load (in Wh) was calculated by multiplying the power rating of the appliance (in W) by its daily operational duration (in hrs) and by the total available quantity.

- The daily energy consumed by all loads were then added up to obtain the total daily load consumption (in Wh).

The daily load profile, showing the distribution of the load over the 24 hrs, was developed, as shown in Fig. 2.

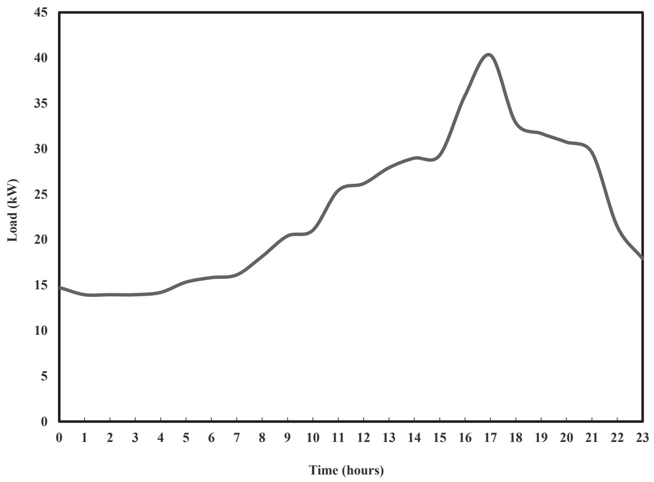

Fig. 2. Daily load profile at Gok-Machar market.

C. System voltage

The total daily load and energy consumption were estimated as 100 kW and 560 kWh respectively. The system voltage was selected based on the daily load consumption. It is recommended to use 12 V for systems with loads less than 1 kWh, 24 V for loads between 1 kWh and 4 kWh and 48 V for loads above 4 kWh a day [13]. Therefore, the nominal voltage of the system in the current study was chosen as 48 V.

D. Sizing of the battery storage system

The solar storage battery is one the most expensive parts in an off-grid PV system [28], [29]. When selecting battery types, some important factors to take into consideration include the effect of overcharging and high temperatures on the characteristics of the battery, maintenance and performance at deep cycle [23]. Two commonly used batteries for energy storage in off-grid PV systems are lead acid and lithium ion (Li-ion) batteries [30]. Lead acid batteries are "the oldest and most widely" used worldwide, commonly and widely available in various sizes, low cost, 100% recyclable, durable, reliable and easy to manufacture [31]–[33]. The main drawbacks of lead acid batteries are short cycle life, low energy density, less efficiency in cold temperatures and fast discharging at high temperatures that affects their lifetime [29], [30]. On the other hand, Li-ion batteries are "relatively new" compared to lead acid batteries. They mainly have long cycle life, high energy density, high charging and discharging capability; and are maintenance free [31]. However, Li-ion batteries have safety concerns due to thermal runaway and overcharging, besides the decrease in performance due to "high temperature and high voltage" [30], [31]. Li-ion batteries are also difficult to dispose of and recycle compared to lead-acid batteries [34]. More information about the advantages, disadvantages, and hazards of deep cycle batteries used in off-grid systems can be found in references [23] and [31].

Lead-acid batteries were used in the current study because they are commonly used in off-grid systems especially in rural areas. Therefore, the solar battery was designed according to the IEEE 1013-2019 recommended practice for sizing lead-acid batteries [21]. The IEEE 1013-2019 is used for sizing flooded and valve-regulated (VRLA) lead-acid batteries for residential and commercial and industrial stand-alone PV systems [21]. The information required to appropriately size the solar battery included the following:

- Total daily load in Ah
- Required days of autonomy
- Depth of discharge (DOD)
- Maximum current withdrawn by the load
- Maximum and minimum battery voltage

At this stage, the selection of a "trial battery type" was necessary to determine the design DOD and maximum and minimum battery voltage. The 2 V OPzS type battery was initially selected as a "trial battery". The OPzS (Ortsfest Panzerplatte Flüssig in German) is a robust, low-maintenance flooded lead-acid battery that is commonly used in stationary off-grid applications. The lifetime of the OPzS battery can exceed 15 years if operated between 20°C to 25°C and 50% depth of discharge (DOD). The sizing method is summarized by the steps presented in Fig. 3.

E. The solar resource at the study location

The PV modules were sized using the IEEE P1562-2021. The IEEE P1562-2021 uses the "Peak Sun-Hour" method to size the solar PV modules [20]. The peak sun-hours (Sh) is defined as the time, in hours, needed to produce average daily solar irradiation in kWh/m^2 when the solar irradiance is 1 kW/m^2 [13], [20]. In this method, the PV system sizing is based on the "worst-case" monthly solar irradiation, energy consumed and system losses [20]. Solar PV modules are usually rated at standard test conditions (STC) that are equivalent to an irradiance of 1 kW/m^2, cell temperature of 25 °C and Air Mass of 1.5 [13]. However, the actual power produced by a PV module can vary depending on the irradiation and the ambient operating temperature [20]. Therefore, to estimate the actual power output from a PV module, it is necessary to calculate the sun-hours from the solar radiation incident on the modules at the optimum tilt and azimuth.

In this study, the solar radiation incident on the tilted PV module, also known as the plane of array (POA) radiation, was calculated from the radiation in the horizontal plane using pvlib python. Pvlib python is an open source software used for modeling and simulating solar energy systems [35], [36]. Solar PV modules are usually inclined at an angle equal to the latitude and directed north if in the southern hemisphere or south if in the northern hemisphere. However, this can be different at locations between latitudes 0° to 15° from the equator [20]. Therefore, the PV modules were modeled at

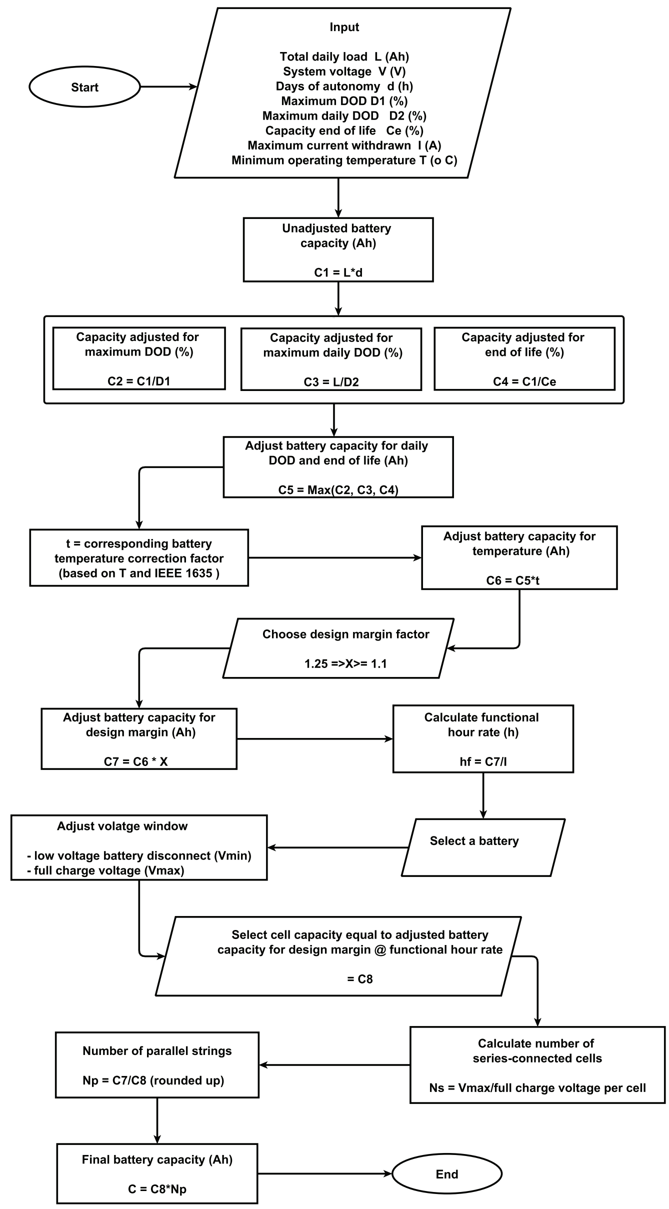

Fig. 3. Methodology used for sizing the battery (created by yEd Graph Editor)

various tilt angles and orientations to get the optimal solar irradiation at each location.

A time series of 16 years (2005 to 2020) of hourly global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) for the study location was acquired from the Ineichen clear sky model through pvlib python. The Ineichen model is one of the "most accurate" clear sky models for global horizontal irradiance (GHI), which is simple to use as it does not require site specific data apart from the geographic location (latitude and longitude) [37]. The irradiance data were then transposed to POA using the Hay/Davies transposition model. Transposition models calculate the POA irradiance by estimating the direct irradiance, ground diffuse and sky diffuse components [19].

To get the maximum monthly ambient temperature at the study location, daily maximum temperatures (from January 2005 to December 2020) were downloaded from NASA's Prediction of Worldwide Energy Resource (POWER) [38]. The long-term monthly average temperatures were calculated and the value for the month with the maximum temperature was selected.

F. Sizing of the PV module using IEEE P1562-2021

The IEEE P1562-2021 calculated the voltage of the PV module at a temperature different from the standard temperature (i.e. 25 °C) using the following equation:

$$V_{m\_new} = V_m(k_v \times (T_n - 25°C) \qquad (1)$$

where, V_{m_new} is the maximum power point voltage at the operating temperature, V_m is the maximum power point voltage at STC, T_n is the module maximum operating temperature at standard operating conditions (SOC) in °C, and k_v is the open circuit voltage temperature coefficient in V/°C. If k_v is given in %/°C then it must be converted to V/°C first before substituting in (1).

Similarly, the maximum power point current (I_{m_new}) and power (P_{m_new}) at the operating temperature were calculated by replacing V_m in (1) with the maximum power point current (I_m) or power (P_m) at STC using similar equations when the short circuit current (k_i) and maximum output power temperature coefficients (k_p) are given. The temperature, T_n, at SOC was estimated using by the following expression [13]:

$$T_n = T_a + (NOCT - 20°C) \qquad (2)$$

where T_a is the ambient operating temperature. The nominal operating cell temperature (*NOCT*) is usually given in the PV module manufacturer's data sheet.

For a system with an MPPT, the minimum number of series connected PV modules are estimated using the following expression [20]:

$$N_{series} = \frac{V_{max}}{V_{m\_new} - V_{losses}} \qquad (3)$$

where N_{series} is the minimum number of series connected PV modules, V_{max} is the absorption battery voltage, and V_{losses} are voltage losses (assumed 0 because voltage losses are included in system losses).

The number of parallel connected PV modules, $N_{parallel}$, of the PV modules were calculated using the following expression [20]:

$$N_{parallel} = \frac{L_{DW} A : L}{(1 - \sigma_L) P_{m\_new} Sh \eta} \qquad (4)$$

where L_{DW} is the average daily load in watt hours (Wh), *A:L* is the array to load ratio, σ_L is the system losses, *Sh* is the sun hours, and η is the MPPT charge controller efficiency. Results from (3) and (4) were rounded up to the nearest whole number.

The technical specifications of the selected PV module for this case scenario are presented in Table II, where I_{sc} and V_{oc} are the PV cell short-circuit current and open-circuit voltage respectively.

TABLE II
SELECTED PV MODULE TECHNICAL INFORMATION

Parameter	Value/description
Model	Trina Solar 360TSM
P_m	360 W
V_m	39 V
I_m	9.24 A
V_{oc}	47.7 V
I_{sc}	9.7 A
N_S	72 cells
k_v	-0.29%/ °C
k_i	0.05%/°C
k_p	-0.39%°C

The following assumptions were considered for the PV system design:

- The daily load was constant throughout the month for all months.
- No shading of the PV array throughout the day.
- System losses are 30% (typical system losses are 10% to 35%) [20].

G. Sizing of the PV module using MATLAB/Simulink

One of the most widely used methods for the design of solar PV systems is mathematical modeling using Matlab/Simulink [39]–[41]. To validate the results obtained using the IEEE P1562-2021, the PV modules were also designed using the equations of the single diode circuit of a solar PV cell using Matlab/Simulink. The hourly current from a solar PV module can be expressed by the following equation [42]:

$$I = I_{ph} - I_0 \left[exp\left(\frac{q(V + IR_s)}{nN_sKT} \right) - 1 \right] - \left(\frac{V + IR_s}{R_{sh}} \right) \quad (5)$$

where, I is the hourly output current of the PV module in ampere, N_s the number of PV cells connected in series, I_{ph} the hourly generated current of solar modules in ampere (photo-current), I_0 the hourly saturation current in ampere, q the charge of the electron in Coulombs, 1.6 × 10–19 C, V the hourly output voltage in volts, R_s the series resistance in ohm, n the ideality factor for the p–n junction, K the Boltzmann's constant in Joules per Kelvin, 1.38 × 10–23 J/k, T the operating cell temperature in Kelvin, I_{sh} the current through the shunt resistor in ampere, and R_{sh} the shunt resistance in ohm.

The series and shunt resistors (R_s and R_{sh}) and the ideality factor (n) were estimated using iterations starting with an initial value of R_s equals 0 [43]. Also the ideality factor (n) was chosen arbitrarily depending on the parameters of the model [43].

The detailed equations of the photo current (I_{ph}) and saturation current (I_0) can be found in references [25], [29] and [43]. The output from the Simulink model were then compared with the output from the IEEE P1562-2021 method.

H. Sizing of the charge controller

In this study, the MPPT charge controller was used to regulate the "charging and discharging" of the PV system storage battery. One of the merits of the MPPT charge controller is that it can handle PV modules at a higher voltage and then match the output voltage with the voltage of the battery. The MPPT charge controller was sized, based on the PV module open circuit voltage,V_{oc}, using the following equations [44]:

$$N_{strings} = \frac{0.95 \times V_{mppt}}{V_{oc}} \quad (6)$$

where $N_{strings}$ is the maximum number of PV modules that can be connected (in series) to the charge controller, 0.95 a safety factor, and V_{mppt} the charge controller maximum input voltage.

I. Sizing of the inverter

In South Sudan, the standard voltage required by electrical appliances and equipment is 230 V for single-phase connection and 400 V for three-phase at a frequency of 50 Hz. Therefore, an inverter was necessary to convert the battery DC voltage into AC. Inverters are normally listed by their "capacity in watts or kilowatts and output voltage" [25]. When sizing the solar inverter, it was necessary to ensure that the input power into the inverter exceeded the total power needed by the AC load [23]. The minimum inverter input power, P_{i_min}, was calculated using the following expression [23]:

$$P_{i\_min} = \text{Wattage of simultaneous running appliances} \times 1.25 \quad (7)$$

where 1.25 is a safety factor. Current for momentary (surge) loads were estimated as seven times the running current.

Table III presents technical data and information on the selected MPPT charge controller and inverter.

TABLE III
DATA OF SELECTED MPPT CHARGE CONTROLLER AND INVERTER

Parameter	Value/description
Model	Trina Solar 360TSM
Charge controller	
Model	MPPT 100 600
Max array V_{oc}	600 V
Max output power	6000 W
Max array I_{Sc}	35A
Max input operating current	29 A
Max output charge current	100 A
Inverter	
Model	XW+ 8548
Ac output (continuous)	6800 W
Overload 30mins/60sec	8500/12000 W
Output voltage	230 VAC
Max input current	180 A

J. Building a financial model using HOMER

The Hybrid Optimization of Multiple Energy Resources software (HOMER Pro) was used for the optimum design and economic modeling of the PV system. HOMER Pro is a powerful software used in the techno-economic design of stand-alone off-grid and grid-connected renewable energy systems [45]–[49]. The input and output data to HOMER are shown in Fig 4.

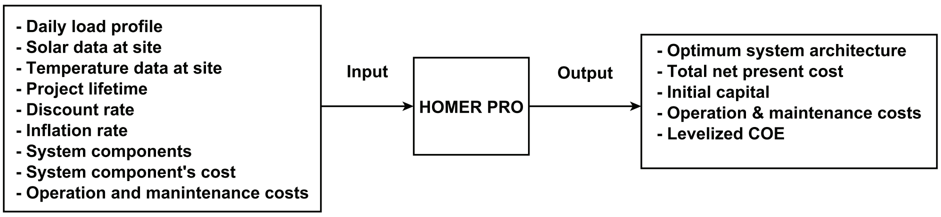

Fig. 4. HOMER input and output data

HOMER selects the best system by optimizing the model and through sensitivity analysis and then estimates the system's total net present value of costs (NPC), initial capital, operation and maintenance costs (O&M), levelized cost of electricity (LCOE) and other economic metrics. HOMER ranks system configuration based on the NPC. The NPC involves the conversion of all costs occurring in the future to their present equivalent and combining them with the initial investment cost to get the total value of the costs of the project [50]. Therefore, the project with the lowest NPC is the most preferred [50]. The NPC can be expressed by the following [50]:

$$NPC = \sum_{t=1}^{N} \frac{C_t}{(1+i)^t} + I_o \tag{8}$$

where, N is Project lifetime in years, C_t is the costs in year t (\$), i is the discount rate (%), and I_o is the initial investment (\$).

Although HOMER does not rank systems based on the LCOE, the LCOE can be useful when comparing two or more systems. The LCOE is the break-even price needed to recover the initial investment and it is defined as the NPC divided by the present value of costs of energy produced by the system [51], [52]. LCOE can be expressed mathematically by the following expression [51], [52]:

$$LCOE = \frac{\sum_{t=1}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+i)^t}} \tag{9}$$

where, E_t is the energy production in year t (kWh).

Other important economic metrics calculated by HOMER included Return on Investment (ROI) and Discounted Payback Period (DPP). ROI is defined as "the net profit per year as a ratio of initial investment" [50]. ROI is expressed as a percentage and is an indicator of the profitability of a project. The DPP is the time required to recover an investment after which the project starts generating profits [53]. The DPP is a convenient way to assess investments especially in risky environments as the shorter the DPP, the better the investment as profits can be recovered faster.

Cost information input into HOMER are shown in Table IV. Initial capital included purchasing, transport and installation costs. HOMER modeled the MPPT charge controller together with the PV module. Sensitivity variables were diesel fuel price and battery lifetime.

TABLE IV
INFORMATION USED IN HOMER SIMULATION

Item	Diesel generator	battery storage	PV module	Inverter
Capital	\$ 700/kW	\$ 1600/pc	\$ 1200	\$ 600
Replacement	\$ 600/kW	\$ 1500/piece	\$ 1200/kW	\$ 600/kW
O&M	\$ 0.799 \$/hr	\$10/pc	\$10/kW	\$10/kW
Lifetime	60,000 hrs	10 yrs	25 yrs	10 yrs
Derating	-	-	70%	-
Conv. ratio	-	-	1.3	-
Efficiency	-	-	18.5%	-
DOD	-	50%	-	-

III. RESULTS AND DISCUSSION

A. Battery bank size

The results obtained from sizing the solar battery system using IEEE 1013-2019 are shown in Table V.

TABLE V
PV SYSTEM BATTERY SIZING DATA

Parameter	Value
Total daily load	1170 Ah
Days of autonomy	5 days (120 hrs)
Maximum running current	750 A
Maximum momentary current	3303.125 A
Surge power	36700 W
Selected trial battery	Sunlight 2 V OPzS 3780
Full-charge voltage (V_{max})	54.48 VDC
End of discharge voltage (V_{min})	43.2 VDC
Number of series cells (N_s)	24
Cell capacity @ functional hour rate	2810 Ah @ C10 x 3 strings
Number of parallel strings (N_p)	46
Final capacity (C) @ functional hour rate	129260 Ah
Capacity for each day of autonomy	25852 Ah

Based on the obtained results, the solar system battery bank consisted of 46 parallel strings. However, the practical cell capacity available of the selected type at the functional-hour rate was 8430 Ah (that is 2810 Ah x 3 strings in parallel), which meant that the parallel strings must be a number divisible by 3 (45 or 48 parallel strings instead of 46). For cost effectiveness, the battery size was selected as 45 parallel strings of 24 batteries each. Therefore, the final battery capacity became 126450 Ah, rated at the 172 h functional-hour rate (15 banks, each with 3 strings of 24 batteries) and the battery's capacity for each day of autonomy will be 25290 Ah (3 banks, each with 3 strings of 24 batteries).

B. The POA irradiation

The solar resource in Gok-Machar was modeled at tilt angles ranging between 8° and 25° with south, southeast, southwest, north, east and west orientations using pvlib python. To identify the optimum tilt and orientation, long term monthly and annual averages and sums of POA irradiation values with percentage transposition gain, were compared at each tilt and orientation, as shown in Fig. 5 and Fig. 6.

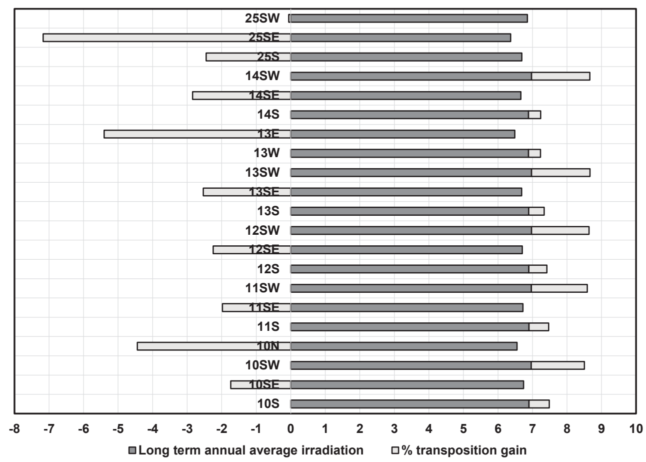

Fig. 5. Annual average irradiation and transposition gain

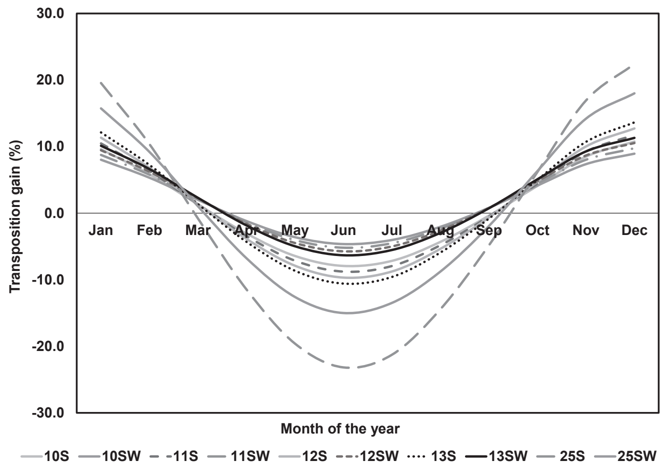

Fig. 6. Monthly average transposition gain

Results show that the highest monthly transposition gain obtained was 22.4% with a tilt angle of 25° south. However, the highest drop in POA irradiation (up to 23.2%) was also found at the same tilt and orientation. The southwest facing PV modules produced the best results in terms of monthly, annual and percentage gain in POA irradiation, followed by the south and west facing modules, respectively. Results also show that the best monthly average POA irradiation was produced with tilt angles between 10° and 13° southwest and that the optimum tilt and orientation was 13° southwest. It was also observed that as the tilt angle increased beyond 13°, the drop in irradiation increased with all orientations.

The month with the lowest POA irradiation at the optimum tilt and orientation was June and it had a GHI of 6.54 kWh/m^2. That value was converted to 6.54 sun hours for PV design calculations using the IEEE P1562-2021 method. Also, the maximum ambient average temperature at the study location was observed in March and it reached 40.72 °C.

C. The calculated size of the PV array

The P-V and I-V curves of the PV module, produced using Simulink at different operating temperatures, are shown in Fig. 7. Using iterations, the values of R_s, R_{sh} and n were estimated as 0.237, 460.28 and 1.086 respectively.

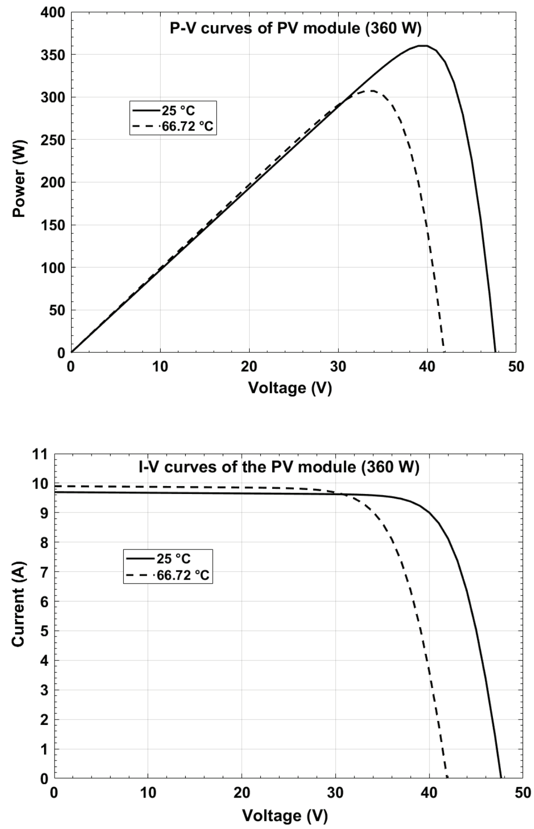

Fig. 7. P-V and I-V curves plots using using Simulink

The calculated PV array size, using IEEE P1562-2021 and Simulink are shown in Table VI. Examining the results obtained, it is observed that the PV array sizing using the IEEE P1562-202 method yielded the same results as the sizing using Simulink. This showed that the IEEE P1562-202 recommended method is a reliable method for sizing PV arrays in a PV system. The "IEEE PES 1013 and 1562 standalone solar system battery and array sizing Calculator" presents a simple and efficient way to implement both the IEEE P1562-202 and IEEE 1013-2019 methods [54].

D. Calculated size of the MPPT charge controller

- $N_{strings}$ = 10
- Selected number of series connected modules = 9
- Number of parallel connected PV strings/ MPPT = 2

TABLE VI
PV ARRAY SIZING USING IEEE P1562-202 AND SIMULINK

Parameter	IEEE P1562-202	Simulink
A:L	1.3	1.3
Peak sun hours	6.54 h/day	6.54 h/day
Charge controller model	Schneider MPPT 100 600	Schneider MPPT 100 600
Charge controller efficiency	95%	95%
Maximum operating ambient temperature	40.72 °C	40.72 °C
Nominal operating cell temperature (NOCT)	46 °C	46 °C
Maximum operating cell temperature	66.72 °C	66.72 °C
P_{m_new} at maximum module operating temperature	301.43 W	307.09 W
V_{m_new} at maximum module operating temperature	33.2 VDC	34 VDC
I_{m_new} at maximum module operating temperature	9.44 A	9.03 A
Minimum number of PV modules in series	2	2
Individual module daily yield	1,315 Wh	1,340 Wh
Number of parallel strings	278	273
Total number of PV modules (N_t)	556	546
PV System output power	167.59 kW	167.67 kW

- Total number of MPPT charge controllers = 31
- Final number of PV modules = 558
- Final PV system output power = 168.20 kW

E. Calculated size of the inverter

- Inverter output power = 50.4 kW
- Number of inverters = 8

F. HOMER simulation results

The best possible size of the PV system components were determined using the HOMER optimizer. The battery storage was sized using search space values of 0, 3, 6, 9, 12, 36, 39, 42, 45, and 48 strings (values divisible by 3). The selected sensitivity variables were diesel fuel prices of $ 1.0, and $ 2.0 per liter, and battery lifetime of 6 and 10 years.

Table VII shows the results of the simulation and optimization performed by HOMER. HOMER ranked PV system no.1 as the best (winning system) because it had the lowest NPC compared to the other simulated systems. System no. 1 earned 78.5% ROI and recovered the investment in about 15 months, when diesel fuel prices were at their lowest (i.e. $ 1/liter). Also, the ROI and DPP of system no. 1 were not affected by the decrease in battery lifetime. However, system no. 1 had 26.2 hrs of autonomy (about 1 day and 2 hours) due to its designed storage capacity. In stand-alone off-grid PV systems, the battery storage is designed to assist the electrical load during periods of low solar irradiation. Hence, the battery is a critical part of the stand-alone system and any trade-off between reliability and cost may compromise the reliability of the entire system. That's why the IEEE P1562-202 recommends a minimum of five days of autonomy (120 hrs) for stand-alone PV systems in areas of high solar potential to ensure system reliability and availability. Therefore, system no. 2, which was ranked by HOMER as the best system with 122 hrs of autonomy, was selected as the winning system in this study.

At the current diesel fuel price of $ 2/liter in Gok-Machar and with battery lifetime of 10 years, the PV system no. 2 can sell a kWh of electricity for $ 1.08 (nearly 62% lower than the price of electricity generated by the diesel generator), earn 11% ROI and recover the investment in 5.5 years. With a drop in price of diesel fuel to $1 per liter, the PV system can still recover the investment in about 7 years and earn a reasonable 6.6% ROI.

The battery bank is one of the most expensive components of the PV system. If battery lifetime is reduced to 6 years with diesel fuel price of $ 2/liter, the PV system can recover the investment in about 10 years. However, if fuel prices drop to the current price in Juba or less, then the PV system will not be able to payback the invested capital until the end of its lifetime. Hence, the system will not be economically viable compared to a diesel generator. This shows that the decrease in the lifetime of the storage system has a great impact on the the economic viability of a standalone PV system as replacement costs increase. To increase the lifetime of a lead-acid battery in environments with elevated temperatures, it is recommended to install and operate the batteries in ambient temperatures ranging between 20°C and 25°C [55]. This can be achieved by using ”well-designed” ventilation and air conditioning systems [55]. However, ventilation fans and air-conditioning systems will need extra energy from the PV system. This makes economically viable systems with excess energy (about 4.78% excess energy), such as PV system no. 3, preferable. The LCOE of system no. 3 is the same as system No. 2 but the NPC of system no. 3 is higher by 0.003% compared to the NPC of system no. 2, making the difference between the two negligible.

Although the LCOE of system no. 2 was lower than the LCOE of the diesel generator, it was still high compared to system no. 1 and to the utility electricity price in Juba. The LCOE can be lowered by reducing the maintenance and operation expense of the system (cleaning and maintaining the PV arrays, battery storage and inverter) and the replacement cost of the storage batteries. Cleaning of the PV arrays and the surface of the storage battery bank can be performed by trained community volunteers. The replacement expense of the battery can be reduced by extending the battery life. Lead acid batteries are about 99% recyclable and part of their cost can be recovered through recycling.

These results show that stand-alone PV systems are technically feasible and economically viable for commercial and

TABLE VII
THE TECHNO-ECONOMIC MODEL OF THE SOLAR PV SYSTEM

Item/parameter	**Base system**	**PV system no. 1**	**PV system no. 2**	**PV system no. 3**
System autonomy	26.2 hrs	26.2 hrs	122 hr	122 hrs
System Architecture	Diesel Genset 45 kW Battery - 9 strings of 24 batteries Inverter 27.2 kW	PV array 208 kW Battery - 9 strings of 24 batteries Inverter 47.6 kW	PV array 162 kW Battery - 42 strings of 24 batteries Inverter 47.6 kW	PV array 168 kW Battery - 42 strings of 24 batteries Inverter 47.6 kW
Renewable fraction	0%	100%	100%	100%
Excess energy (kWh/yr)	0	70,623 (23.4%)	3,551 (1.51%)	11,610 (4.78%)
AC primary load (kWh/yr)	202,780	202,684	202,809	202,809
Production (kWh/yr)	221,431	301,599	234,577	242,955
Unmet electric load (kWh/yr)	29 (0.01%)	125 (0.06%)	0	0
Capacity shortage (kWh/yr)	79.6 (0.04%)	195 (0.1%)	0	0
CAPEX ($)	$ 393,420	$ 678,891	$ 1,878,372.8	$ 1,886,837.6
OPEX ($/yr)	$ 179,762	$ 6,325	$ 13,425	$ 13,528
Diesel fuel price ($/L) = $ 1.32 - battery lifetime = 10 yrs				
NPC ($)	$ 5,321,040	$ 1,212,104	$ 3,760,086	$ 3,771,889
Operating cost ($/yr)	$ 287,121.4	$ 31,069.12	$ 109,643.2	$ 109,837.8
LCOE ($/kWh)	$ 1.53	$ 0.349	$ 1.08	
DPP (yrs)	-	1.14 yrs	6.63 yrs	6.67 yrs
Diesel fuel price ($/L) = $ 1.32 - battery lifetime = 6 yrs				
ROI (%)	-	85.7%	8%	7.9%
NPC ($)	$ 5,691,852	$ 1,582,916	$ 5,490,542	$ 5,502,345
Operating cost ($/yr)	$ 308,727.8	$ 52,675.5	$ 210,473	$ 210,667.6
LCOE ($/kWh)	$ 1.64	$ 0.455	$ 1.58	$ 1.58
ROI (%)	-	85.7%	2.7%	2.6 %
DPP (yrs)	-	1.14 yrs	22.52 yrs	22.61 yrs
Diesel fuel price ($/L) = $ 1.0 - battery lifetime = 10 yrs				
NPC ($)	$ 4,965,948	$ 1,212,104	$ 3,760,086	$ 3,771,889
Operating cost ($/yr)	$ 266,431	$ 31,069.12	$ 109,643.2	$ 109,837.8
LCOE ($/kWh)	$ 1.43	$ 0.349	$ 1.08	$ 1.08
ROI (%)	-	78.5%	6.6%	6.6%
DPP (yrs)	-	1.24 yrs	7.29 yrs	7.34 yrs
Diesel fuel price ($/L) = $ 1.0 - battery lifetime = 6 yrs				
NPC	$ 5,336,760	$ 1,582,916	$ 5,490,542	$ 5,502,345
Operating cost ($/yr)	$ 288,037.4	$ 52,675.5	$ 210,473	$ 210,667.6
LCOE ($/kWh)	$ 1.53	$ 0.455	$ 1.58	$ 1.58
ROI (%)	-	78.5%	1.3%	1.2 %
DPP (yrs)	-	1.24 yrs	N/A	N/A
Diesel fuel price ($/L) = $ 2.0 - battery lifetime = 10 yrs				
NPC ($)	$ 6,075,608	$ 1,212,104	$ 3,760,086	$ 3,771,889
Operating cost ($/yr)	$ 331,088.5	$ 31,069.12	$ 109,643.2	$ 109,837.8
LCOE ($/kWh)	$ 1.75	$ 0.349	$ 1.08	$ 1.08
ROI (%)	-	101.1%	11%	10.9%
DPP (yrs)	-	0.97 yrs	5.55 yrs	5.59 yrs
Diesel fuel price ($/L) = $ 2.0 - battery lifetime = 6 yrs				
NPC	$ 6,446,420	$ 1,582,916	$ 5,490,542	$ 5,502,345
Operating cost ($/yr)	$ 352,694.9	$ 52,675.5	$ 210,473	$ 210,667.6
LCOE ($/kWh)	$ 1.85	$ 0.455	$ 1.58	$ 1.58
ROI (%)	-	101.1%	5.6%	5.6 %
DPP (yrs)	-	0.97 yrs	10.03 yrs	10.08 yrs

community use in populated rural and peri-urban areas of South Sudan. Therefore, authorities should encourage investment in such systems by adapting favorable policies and regulations for the installation of sustainable energy systems (long term contracts, capital subsidies beside others). This will attract and encourage local and international investors to develop commercial and community stand-alone PV systems and other renewable energy systems in the country.

Investment in renewable energy projects in countries like South Sudan may come with risks due to various factors (economic, environmental, social beside others). Consequently, investors may favor investment in systems similar to system no.1 to secure shorter payback periods and higher ROIs. However, it is important to note that when designing and developing electrical systems, it is crucial to adhere to national and international standards, regulations and recommendations. This will ensure system safety, optimal design and performance, quality and reliability.

G. Comparison of study results with the literature

The results of the current study were compared with results obtained from similar case studies within the region as shown in Table VIII. Considering the viability of off-grid solar PV systems for domestic and commercial use in remote, rural, and peri-urban areas across Africa, the findings of these studies showed agreement with the findings of the current study.

TABLE VIII
MAPPING OF THE CURRENT STUDY WITH SIMILAR STUDIES IN THE REGION

Item	Current study	Study 1 [56]	Study 2 [57]	Study 3 [58]	Study 4 [59]	Study 5 [60]	Study 6 [61]
Scope	Rural and peri-urban areas in South Sudan.	Residential buildings in Jos, Nigeria.	Villages in western Uganda.	Rural communities in Chad.	Supermarkets in Port Harcourt, Nigeria.	Remote pastoral communities in Oromia region, Ethiopia.	Off-grid communities in the Bono region of Ghana.
Operational mode	Off-grid	Off-grid	Off-grid\mini-grid	Off-grid	Off-grid	Off-grid	Off-grid\mini-grid
	Domestic & commercial	Domestic	Domestic & commercial	Domestic	Commercial	Domestic & commercial	Domestic & commercial
Objective	Assess the techno-economic viability of solar PV compared to diesel in a rural area in South Sudan.	Examine the techno-economic viability of solar PV in residential buildings in Jos.	Assess the technical performance of the Kyamugarura and Kanyegaramire villages solar PV mini-grid systems.	Examine the technical and economic feasibility of solar PV mini-grids in five villages in Chad.	Assess the viability of commercial Solar PV System in Port Harcourt, Rivers State, Nigeria.	Examine the feasibility of off-grid solar for electricity supply to the remote pastoral communities of Moyale, Dire, and Yabelo.	Investigate the viability of a solar mini-grid system for the Nkrankrom community in Ghana compared to grid electricity.
System components	Solar PV with battery	Solar PV with battery	Solar PV with battery	Solar PV with battery	Solar PV with battery	Solar PV with battery	Solar PV with battery
Days of autonomy	5 days	0.8 days	3 days	N/A	1 day	N/A	N/A
Methodology	Mathematical modeling using IEEE standards, pvilb python and HOMER. MATLAB & Simulink for validation.	Mathematical modeling using various mathematical equations	Mathematical modeling using various mathematical equations	PVGIS and PVsyst	PVsyst and Mathematical modeling using various mathematical equations	Mathematical modeling using HOMER software	Mathematical modeling using HOMER software
Main findings	• The LCOE for the PV system was 1.08 \$/kWh while for the diesel generator it ranged between 1.53 \$/kWh and 1.75 \$/kWh (with increase in fuel prices). • Stand-alone solar PV systems are technically and economically viable in populated rural and peri-urban areas of South Sudan.	• The LCOE for the off-grid PV system was 0.18 \$/kWh while for the utility company it ranged between 0.207 \$/kWh and 0.337 \$/kWh • Off-grid solar PV system is both technically and economically viable for electricity generation of residential buildings in Northern-Nigeria	• The energy demand exceeds supply, therefore upgrade is needed for economic viability. • The mini-grids provide social and economic benefits to the rural communities. • The Kanyegaramire and Kyamugarura mini-grids are reliable and economically viable and can replace the diesel generators.	• The LCOE for all the villages over project lifetime is estimated between 30 and 0.31 €/kWh while for the National Electricity Company is about 0.45 €/kWh. • Solar energy is viable for electrification of rural communities in Chad.	• LCOE for solar PV was 0.14 \$/kWh, while for the diesel generator was 0.36 \$/kWhh. • Replacing the diesel generator would save 14,543 tonnes of CO_2. • Replacing diesel generators with solar PV is feasible and cost-effective in Supermarkets in Port Harcourt.	• LCOE for subsidized solar PV was 0.40 \$/kWh while for diesel generators it was 0.42 \$/kWh • Subsidized off-grid solar PV systems are economically viable compared to diesel generators. • Solar PV with battery is the best option for the electrification of off-grid pastoral communities in Ethiopia.	• The LCOE for the solar PV was 0.107 \$/kWh compared to 0.124 \$/kWh if the area were to be connected to the national grid. • Unelectrified areas in Nkrankrom are located about 36 km from the grid. The break-even distance was found to be 1.11 km. • Nkrankrom solar mini-grid is more economically viable for unelectrified areas with similar properties.

IV. CONCLUSION

The main purpose of this study was to assess the technical feasibility and economic viability of a stand-alone solar photovoltaic (PV) system and compare it to a diesel generator in densely populated rural and peri-urban areas of South Sudan. Gok-Machar, a town in Aweil North county of Northern Bahr el Ghazal, was selected as the study case scenario. To correctly forecast the performance of the PV system, a techno-economic model was developed through simulation and modeling. The PV arrays were sized using the IEEE Recommended Practice for Sizing of Stand-Alone Photovoltaic Systems (IEEE P1562-2021). The IEEE P1562-2021 was validated using Matlab/Simulink. The battery storage was also sized using the IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic Systems (IEEE 1013-2019). Then, the PV system optimization and financial modeling was performed using the Hybrid Optimization of Multiple Energy Resources (HOMER) software.

Results show that at the current diesel fuel price in Gok-Machar, the PV system can sell 1 kWh of electricity at a price 62% lower than the price of the electricity generated by the diesel generator. The system can then earn 11% return on investment (ROI) and recover the investment in about 5.5 years. Even when one liter of diesel fuel drops to $ 1 in Gok-Machar, the PV system can still earn 6.6% return and recover the funds invested in 7 years, after which it will generate profits until the project ends. The study concluded that, stand-alone PV systems are technically feasible and economically viable in densely populated rural and peri-urban areas of South Sudan. Results from this research were compared with other similar studies from the region and the findings were found in agreement with the current study. This shows that this research has broader implications beyond South Sudan. The outcome of the study is indeed of benefit to the research community specifically, countries in the region and developing countries with similar challenges.

The following are recommendation to consider for further future studies:

- Techno-economic modeling of stand-alone PV systems in rural and peri-urban areas of low solar resources.
- Techno-economic modeling of direct-coupled (DC) stand-alone PV systems.
- The economics of Lithium-ion and salt-water batteries in stand-alone PV systems including recycling and disposal costs.
- Study the cost of recycling and disposal of the PV arrays at the end of the project life.

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