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Research Article

Electrical power output potential of different solar photovoltaic systems in Tanzania

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Abstract. This study examines the photovoltaic (PV) energy output and levelized cost of energy (LCOE) in seven regions of Tanzania across five different tilt adjustments of 1 MW PV systems. The one-diode model equations and the PVsyst 7.2 software were used in the simulation. The results reveal variations in energy output and LCOE among the regions and tilt adjustments indicating a strong correlation between PV energy output and solar irradiance incident on the PV panel. For horizontal mounting, the annual energy output ranges from 1229 MWh/year in Kilimanjaro to 1977 MWh/year in Iringa. Among the three optimal tilt adjustments, annually, monthly and seasonal, the last two are predicted to yield larger energy outputs, whereas the two axis tracking configuration consistently provides the maximal energy output in all regions, ranging from 1533 MWh/year in Kilimanjaro to 2762 MWh/year in Iringa. The LCOE analysis demonstrates the cost-effectiveness of solar PV systems compared to grid-connected and isolated mini-grid tariffs. The LCOE values across the regions and tilt adjustments range from $0.07/kWh to $0.16/kWh. In comparison, the tariff for grid-connected solar PV is $0.165/kWh, while for isolated mini-grids; it is $0.181/kWh. The monthly optimal tilt configuration proves to be the most cost-effective option for energy generation in multiple regions, as it consistently exhibits the lowest energy cost compared to the other four configurations. The results provide valuable insights into the performance and economic feasibility of various system setups. Through meticulous simulation and data analysis, we have gained a comprehensive understanding of the factors influencing energy generation and costs in the context of solar photovoltaic systems.

Keywords: Solar PV, system configuration, energy output, energy cost, Tanzania

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1. Introduction

Simulating solar photovoltaic (PV) power output for a specific location is of utmost importance in understanding the potential energy production and performance of a system. With the increasing adoption of solar energy worldwide, accurate simulation models are essential for system design, performance assessment, and energy yield predictions. This detailed introduction highlights the importance of simulating solar PV power output and its significance in various applications. Accurate simulation models enable optimal system design and sizing, performance assessment, energy yield estimation, grid integration analysis, and risk analysis for solar PV projects. By considering site-specific solar resource data and system characteristics, these simulations provide valuable insights into the energy output and performance of a PV system (Gurupira and Rix, 2017).

For system design and sizing, simulation models that take into account location-specific solar irradiance, temperature, and weather patterns assist in selecting the appropriate PV module types, configurations, and capacity to meet the energy demands of the intended application. Moreover, these models enable the assessment and optimization of a solar PV system's performance by simulating power output under different operating conditions, allowing for the identification of potential issues and inefficiencies (Iheanetu, 2022).

Accurate estimation of energy yield is crucial for project feasibility studies, financial analysis, and energy planning. Models that incorporate site-specific solar resource data and system characteristics enable the estimation of annual and monthly energy yield, aiding in financial projections and decision-making (Mesquita *et al.,* 2019). Additionally, these models facilitate risk analysis by providing probabilistic assessments of energy production over the project's lifetime, helping stakeholders evaluate project feasibility and assess risks (Zazoum, 2022). Simulating PV output is also vital for grid integration analysis, as it allows the assessment of the impact of solar PV power on the grid. By simulating power output, voltage profiles, and grid interactions, these models aid in evaluating the compatibility of PV systems with the existing grid infrastructure and optimizing energy management strategies (Chouder *et al.,* 2012).

When it comes to solar PV power output and land area requirements, there are several information gaps that can impact accurate assessment and planning for solar energy projects in the developing countries, Tanzania included. Some of the key information gaps include: (i) System Performance

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Data; access to performance data from existing solar PV installations, particularly in the local context, is valuable for benchmarking and understanding the actual power output and performance of PV systems. However, there is limited data sharing or monitoring practices, making it challenging to obtain comprehensive performance data for analysis and comparison (ii) Technology-Specific Data; information gaps exist regarding the performance characteristics, efficiency, and degradation rates of PV modules, inverters, and other system components under local operating conditions. This can impact the accuracy of power output estimates and the selection of suitable equipment for solar projects.

Addressing these information gaps requires collaboration among various stakeholders, including government agencies, research institutions, industry experts, and local communities. Investments in data collection, research studies, and comprehensive impact assessment can help bridge these gaps, providing the necessary information for effective solar PV power output estimation and land area requirements, while ensuring sustainable and responsible project development.

The objective of this work therefore is to address the above information gaps and provide insight into the performance of solar PV power output as well as to estimate the energy cost for different climates in Tanzania. Specifically, this work model solar PV power output and assesses its economic potential in different climatological regions and system configurations in Tanzania.

2. Methodology

2.1. Study sites

Tanzania is divided into nine climatic zones. The division is based on the natural climatology of Tanzania, general vegetation and relief. The division is such that areas with the same natural climatic condition are grouped together. In the present work, seven climatological zones were selected as study sites due to data availability in those zones. The climatological zones selected as study sites in Tanzania are shown in Table 1 and Figure 1.

Insolation data were obtained from the Tanzanian meteorological agency (TMA) for the three climatological zones as shown in Table 1. Since only sunshine duration data were available for the remaining four climatological zones in Tanzania, satellite insolation data from The National Aeronautics and Space Administration (NASA) and measured data from METEONORM were used. Solar insolation data covering a period of 18 years (2000-2018) were obtained from TMA, NASA or METEONORM respectively depending on data availability.

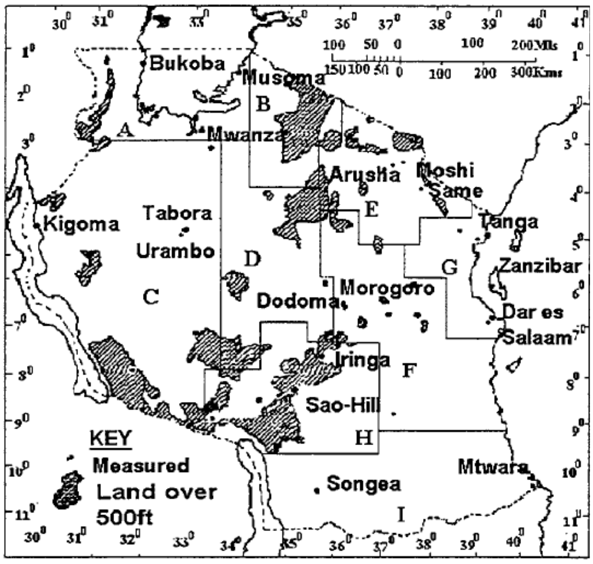

Fig 1. Climatological zone division in Tanzania (Alfayo and Uisvo, 2002)

2.2. Simulation of PV energy output

To characterize the operation of a PV module, the commonly employed Shockley's simplified 'one diode' model, as explained, for instance, in Duffie and Beckman (1991), is utilized. The primary equations that define the general 'one-diode' model under specific reference conditions (typically STC: 1000 W/m2, 25°C, AM=1.5) are presented as Eq 1.

$$I = I_L - I_{PH} - I_D - I_{Rs} - I_{Rsh} \quad (1)$$

where: I represent the output current of the PV module, IL is the light-generated current, Iph is the photocurrent, which is proportional to the incident light intensity, I_D is the diode current, accounting for the behavior of the bypass diode, I_{Rs} is the series resistance current, considering the resistance in the series connection of the solar cells, I_{Rsh} is the shunt resistance current, accounting for the resistance in parallel with the solar cells.

The PV power output is then calculated using the equation 2:

$$P = V_{mpp} * I \quad (2)$$

By adjusting power for temperature, then Eq 3 is obtained.

Table 1
Study sites and data sources

Zone	Region	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Data Source
Central	Dodoma	6.16 S	35.75 E	1120	TMA
Northern Coast	Dar es Salaam	6.82 S	39.27 E	24	TMA
North Eastern Highland	Kilimanjaro	3.07 S	37.36 E	1800	TMA
Western Zone	Kigoma	4.53 S	29.48 E	885	NASA
Southern Coast	Mtwara	10.31 S	40.18 E	113	NASA
Southern Western Highland	Iringa	7.77 S	35.69 E	1640	METEONORM
Lake Victoria Basin	Mwanza	2.52 S	32.92 E	1140	METEONORM

Table 2
System configurations

PV configuration	Description
EO:AO	This is the baseline configuration, it is horizontal and an azimuth of 180 degrees
EA:AO	Annual optimal tilt angles
ES:AO	Seasonal optimal tilt angles
EM:AO	Monthly optimal tilt angles
ET:AO	Two axis tracking

$$P_{adjusted} = P * \left(1 + alpha * \left(T - T_{ref}\right)\right) \quad (3)$$

Where: P is the power output of the PV module calculated without temperature adjustments; alpha is the temperature coefficient of power (per degree Celsius).

The PV power output simulation was conducted using Pvsyst 7.2 software, before the simulation work was conducted; the solar PV tilt angles were first optimized on annual, seasonal and monthly basis. The tilt angle optimization was done using MATLAB for the different PV system configurations given in Table 2. The inputs in the Pvsyst software were meteo data and optimized tilt angles. The outputs were PV array energy production, performance ratios, normalized power production and PV energy losses. The software has been extensively used and validated by different researchers for PV power output simulation studies (Westbrook and Collins, 2013; Gurupira and Rix, 2017; Sadeq and Abdellatif, 2021; Jagadale *et al.,* 2022; Milosavljević *et al.,* 2022; Yakubu *et al.,* 2022; PVsyst, 2023).

In the present work, CS3K-300PB-AG 1500V HE PV modules were used; this module was chosen because its efficiency is above average for the polycrystalline modules. The manufacturer physical and electrical specification and other measurements for the module are given in Table 3.

The simulated system size was 1 megawatt; the choice of simulation scale of solar PV system is often arbitrary and can vary depending on the specific context and objectives of the simulation study. However, there are a few reasons why 1 MW capacity is commonly used. 1 MW capacity represents a moderate-scale solar PV system that is large enough to be representative of real-world installations involving several thousand solar panels, while still being within a manageable range for analysis and simulation purposes. 1 MW systems are frequently employed in commercial and utility-scale applications, making them relevant for assessing performance, energy production, and financial viability. Furthermore, simulating a 1 MW system allows for the evaluation of grid integration considerations and enables researchers to explore technical challenges and optimization opportunities associated with larger-scale solar PV installations (Stapleton and Neill, 2012).

Table 3
Manufacturer specifications for the PV modules

Reference conditions (GRef)	1000 W/m^2
Reference temperature (TRef)	25 ^{0}C
Short-circuit current (ISC)	9.650 A
Max power point (Impp)	9.180 A
Open circuit Voc	39.30 V
Vmpp	32.70
Temperature coefficient muIsc	4.8 mA/^{0}C

2.3. Normalized production and performance ratio

Several normalized performance indices were calculated to facilitate energy output performance comparisons in different locations. These performance parameters include: normalized system yield (Y_f), normalized array production (Y_a) performance ratio (PR), collection loss (L_c), and system loss (L_s). System yield (Y_f) is the system's daily useful energy (energy to the grid), referred to the nominal power.

$$Y_f = \frac{E_{Grid}}{P_{NomArray}} \quad (4)$$

Where: E_{Grid} = energy injected into the grid, $P_{NomArray}$ = Nominal Installed Power (= Nb. PV modules * nameplate PNom). Array yield (Y_a) is the array daily normalized output energy, referred to the nominal power (kWh / kWp / day) (Sagonda and Folly, 2019).

$$Y_a = \frac{E_{array}}{P_{NomArray}} \quad (5)$$

Where: EArray = Effective energy at the array output, Y_r is Normalized reference nominal energy at STC;

$$Y_r = E_{ArrRef} / P_{NomArray} \ [kWh/kWp] \quad (6)$$

Where: E_{ArrRef} = Array reference energy for PR calculation (as defined in the IEC EN 61724 norm) = GlobInc * PNomArray, GlobInc= Global incident irradiation. Array losses (Lc) are the difference between the ideal array yield at STC, and the effective yield as measured at the output of the array.

$$L_c = Y_r - Y_a \quad (7)$$

System losses (L_s) are losses due to the difference between the system yield (Y_f) and array yield. These include inverter losses, AC ohmic losses, etc.

$$L_s = Y_f - Y_a \quad (8)$$

The performance ratio (PR) represents the ratio of energy fed to the grid (final yield) to the energy that the system could have produced had it operated at its rated conditions (STC) of 1 kW/m^2/(reference yield). It represents the fraction of energy actually available after deducting energy losses (IEC, 1998). Performance ratio is expressed as:

$$PR = \frac{Y_f}{Y_r} \quad (9)$$

To assess the solar energy received by each location; clearness index ratio (Kt) was used. Mathematically, the clearness index Kt is defined as Global Horizontal Irradiance / Extraterrestrial Radiation, where global horizontal Irradiance is the actual solar radiation received at the Earth's surface in watts per square meter (W/m²), extraterrestrial radiation is the solar radiation that would be received on a surface perpendicular to the sun's rays outside Earth's atmosphere, also in watts per square meter (W/m²) (Tanu *et al.*, 2021).

Table 5
Economic modeling inputs and assumptions

Category	Modeled value	Description	Sources
Different tilt adjustments	1 MW	Commercial scale system capacity, Commercial range is 100 kW- 5 MW	Model assumption; (Barbose *et al.,* 2021)
Module efficiency (%)	20.36 %	Efficiency per cell area	Manufacturer's specification
Module price	$ 0.38/WDC	Ex-factory gate (first buyer) average selling price, Tier 1 monocrystalline modules	(Wiser *et al.,* 2020)
Inverter price	Three-phase string inverter: $0.08/WDC	Ex-factory gate prices (first buyer) average selling price, Tier 1 inverter	Wood and SEIA (2021)
Inverter efficiency (%)	96	The efficiency of the three-phase string inverter	Wood and SEIA (2021) Manufacturer specification
Structural components (racking)	$0.11–$0.18/WDC	Ex-factory gate prices; flat-roof ballasted racking system or fixed-tilt ground-mounted racking system	(Fu *et al.,* 2018) Model assumption
Two axis trackers	$1-$ 2	Ex-factory gate price for two axis solar tracking trackers	Lane (2020)
Electrical components	$0.13–$ 0.45/WDC	Conductors, conduit and fittings, transition boxes, switch gear, panel boards, and other parts	Model assumptions; (Ramasamy *et al.,* 2021)
Permits and other administration fees	$ 0.03- 0.05	Building and construction permits, etc.	Model assumption; https://www.wikiprocedure.com/index.php/ Tanzania_Obtain_a_Construction_Permit
Project lifetime	20 years	The lifetime of the project, simulated over a twenty-year period	(Wiser *et al.,* 2020); Model assumption
Income tax	18 %	National averages	TRA
Cooperate tax	30 %		
Discount rate	10%	All values discounted over a twenty-year period	Model assumption; Central Bank of Tanzania (BOT)
Annual degradation (%)	0.70	Annual degradation percentage over the lifetime of the project	(Ramasamy *et al.,* 2021); (Wiser *et al.,* 2020)
Levelized O&M expenses over life of asset ($/W-yr.)	0.06	Levelized operations and maintenance cost for the solar plants	(Ramasamy ***et al.,*** 2021); Model assumptions

2.4. PV modules energy cost

After simulating PV modules energy output, economic modeling of the systems was performed on the basis of the defined parameters and the simulation results; it allows the definition of the initial installation costs and the yearly operating costs in order to calculate Levelized Cost of Energy (LCOE). The formula used for LCOE calculation is:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (10)$$

Where: It is investment and expenditures for the year (t), Mt is operational and maintenance expenditures for the year (t), Et is electricity production for the year (t), r is discount rate that could be earned in alternative investments and n is lifetime of the system. Detailed breakdown of cost and assumptions used in the economic analysis is given in Table 4.

3. Results and discussions

This section presents PV power output and energy cost results and provides a comprehensive analysis of the actual power output generated by the photovoltaic (PV) systems under consideration. The section provides insights into the variation of power output with changing environmental conditions, including solar irradiance levels and ambient temperatures. It also includes a comparison between the simulated or predicted power output and the actual measured values to assess the accuracy of the models and simulation methodologies used

Table 4
Global system summary

Number of modules	3335
Module area	5611 m^2
Number of inverters	1
Nominal PV power	1001 kWp
Maximum PV power	1016 kWDC
Nominal AC power	875 kWAC
Pnom ratio	1.143

Table 5 presents the global system summary. The results indicate that for a 1 MW capacity solar PV system, a total of 145 strings of 23 modules in series will be required. This configuration leads to a total of 3,335 PV modules. The number of strings and modules in the series is determined based on the electrical characteristics of the modules and the desired system voltage.

In terms of land area requirements, the analysis shows that the system will occupy an area of 5,611 square meters (m^2). This area is slightly larger than one acre of land, which typically measures around 4,900 square meters (m^2). It is important to note that the specific land area required for a solar PV system may vary depending on factors such as module efficiency, tilt angle, and shading considerations. The given information

Table 7
Solar PV system production (MWh/year) for different system configurations

Configuration	Dar es Salaam	Dodoma	Kilimanjaro	Kigoma	Mtwara	Iringa	Mwanza
EO:AO	1507	1811	1229	1563	1755	1977	1827
EA:AO	1517	829	1229	568	1809	2019	1836
ES:AO	1580	1929	1282	1650	1902	2134	1941
EM:AO	1593	1930	1278	1661	1910	2150	1959
ET:AT	1953	2467	1533	2024	2414	2762	2475

provides an estimation of the amount of modules and land area required for a 1 MW solar PV system in Tanzania and other countries in sub Saharan Africa with similar climatic conditions.

3.1. PV arrays energy production for different system configuration

This section discusses the energy injected into the grid (E_{Grid}) after taking into consideration all the energy losses from the system. To calculate the PV system's energy output, the Pvsyst 7.2 software utilizes the standard one diode model as described in equations (1)-(3) in section 2.2. Different figures and tables are automatically generated by the software after completing the simulation process.

Table 6 presents PV system's energy production from different climatological regions in Tanzania. Regarding the seven regions, it is evidently that Iringa is predicted to produce the most while Kilimanjaro the least PV energy; and that is for each tilting configuration. The amount of solar energy output considered good for a 1 MW scale can vary depending on various factors such as location, weather conditions, system efficiency, and specific project goals (Hernandez *et al.*, 2014). However, as a general guideline, a 1 MW solar PV system can be expected to generate an average annual energy output of approximately 1,000 to 2,000 megawatt-hours (MWh) per year (Duffie et al., 2020). In a similar work done by Kumi and Brew-Hammond (2013) in Ghana, it was observed that 1 MW PV plant produces 1,159 MWh. It is also worth noting that advancements in solar PV technology and improvements in system design and efficiency continue to enhance the energy output of solar PV systems (Tyagi *et al.*, 2013). Therefore, what may be considered a good energy output for a 1 MW system today might be surpassed in the future as technology and practices evolve. As such, the present work can be a benchmark for future solar energy output studies. It appears that the Kilimanjaro region receives less solar insolation compared to other regions under considerations. Fig 4 presents daily averaged clearness indexes for the seven regions under considerations;

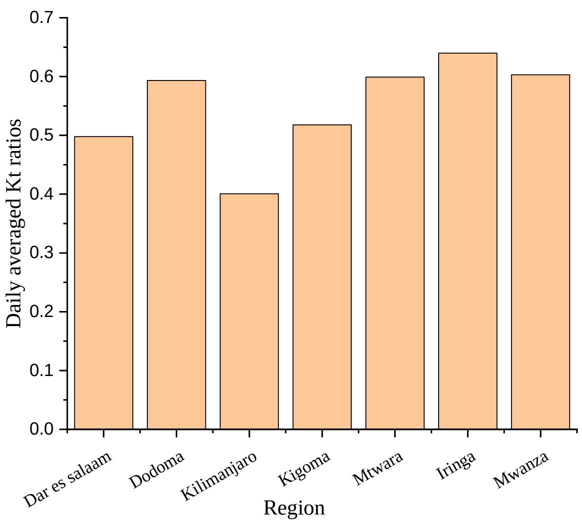

Fig. 4 Daily averaged clearness indexes

Table 6
Percentage energy gains compared to horizontal configuration

Regions	EA:AA	ES:AS	EM:AM	ET:AT
Dar es salaam	0.7	4.8	5.7	29.6
Dodoma	1	6.6	6.6	36.3
Kilimanjaro	0	4.3	4	24.7
Kigoma	0.3	5.6	6.3	29.5
Mtwara	3.1	8.4	8.8	37.6
Iringa	2.1	7.9	8.8	39.7
Mwanza	0.5	6.2	7.2	35.5

The clearness index (Kt) is a dimensionless value that ranges from 0 to 1. The higher the clearness index, the higher the radiation received (Perez *et al.*, 1990). Figure 4 shows that Kilimanjaro has more cloudy days on average compared to other regions hence lower PV power outputs relative to the other regions.

Table 7 presents the percentage gain in energy output in each region for all orientations against horizontal configuration (EO:AO). All two-axis tracking configurations have the highest energy percentage gains. This is due to the fact that in this configuration, the arrays are tracking both the tilt and azimuth angles with respect to the sun. The highest gain was in Iringa region with 39.7%, while the lowest was in Kilimanjaro with 25.7%. The general trend in all regions except Kilimanjaro is that the annual optimal orientations have the lowest gains, followed by seasonal optimal orientations, monthly optimal orientations and two axes tracking in an increasing order.

This comparative analysis provides valuable insights into the potential for PV energy generation variability among different regions in Tanzania and other sub Saharan countries based on various tilt angle configurations. It aids in understanding the influence of tilt angles on energy output and can guide decision-making processes in optimizing PV system design and deployment for specific locations.

3.2. Performance ratios

The solar PV performance ratio (PR) is a metric used to evaluate the efficiency and performance of a solar photovoltaic system. It provides an indication of how effectively the system converts sunlight into usable electrical energy. The

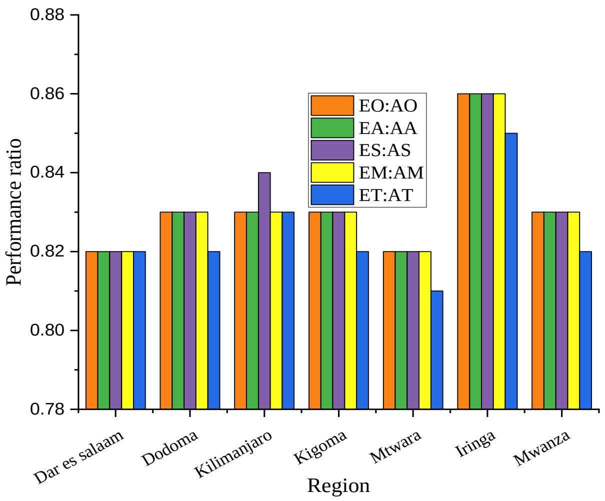

Fig. 5 Performance ratios for different tilt configurations

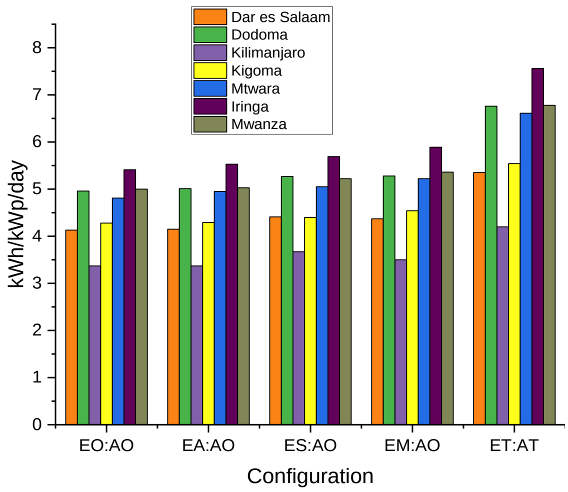

Fig. 6 Normalized energy productions

performance ratio is expressed as a percentage and represents the ratio of the actual energy output of the system to its expected or theoretical energy output under standard conditions. A higher PR indicates a more efficient and productive PV system, while a lower PR suggests that the system is experiencing higher losses or not performing optimally (Khalid *et al.*, 2016).

Fig 5 is a graphical description of the performance ratios; it is observed that the PV systems for all configurations in all regions are more than 80%. Performance ratios of 70% and above are considered to be very good performing systems (Kumi and Brew-Hammond, 2013). As such, all regions under considerations are good candidates for solar PV installation. Regarding the different tilt angle configurations, the PR range from 81% (ET:AT) in Mtwara to 86% (EO:AO, EA:AO, ES:AO and EM:AO) in Iringa region. There are higher PR ratios for Iringa because the region has high Kt ratios which indicates that Iringa's climatic conditions, such as reduced cloud cover, could lead to higher and more consistent solar irradiance throughout the year. Adequate sunlight ensures that PV panels operate closer to their optimal conditions, resulting in higher energy production and better PR ratios.

The angle at which sunlight strikes the PV panels can significantly impact their efficiency. If the panels are not optimally oriented towards the sun (tilt and azimuth), they may receive sunlight at angles that are less than optimal (Jacobson and Jadhav, 2018). This can result in lower energy absorption and conversion, leading to reduced performance ratios. Even if the PV panels are the same, the tilt and azimuth adjustments can impact the overall performance of the system due to variations in incident sunlight angle, shading, temperature effects, and other factors. These differences can lead to varying energy outputs and subsequently different performance ratios for the same PV panels, but with different tilt and azimuth angles as observed in Figure 5. As such, the ET:AT system configuration performance ratios are generally lower compared to other configurations, this may be due to temperature effect since the tracking system tracks the sun throughout a day, the panels may be at a higher average temperature hence lower PR (Dubey *et al.*, 2013).

3.3. Normalized power production

Normalized production in the context of solar energy refers to the daily energy output of a photovoltaic (PV) system, typically measured in kilowatt-hours (kWh), relative to its installed capacity in kilowatts-peak (kWp). It is a metric used to standardize and compare the energy generation performance of different PV systems, regardless of their size or capacity.

Normalization is necessary because solar PV systems can vary in terms of installed capacity, geographic location, tilt angle, orientation, and other factors that can influence energy production. For example, in Dar es Salaam, the "EO:AO" configuration yields an average of approximately 4.13 kWh per kWp of installed capacity per day. Similarly, in Dodoma, the same configuration generates around 4.96 kWh/kWp/day. By normalizing the power or energy output, these variations are accounted for, enabling a standardized comparison and evaluation of system performance. Figure 6 displays the graphical representation of normalized energy production in the seven regions.

As expected, the two axis tracking configurations have the highest normalized energy production in all regions, this is due to the fact that in this configuration the systems are tracking both tilt and azimuth angles of the sun throughout a day. The normalized production ranges from 3.37 kWh/kWp/day (EO:AO) in Kilimanjaro to 7.56 kWh/kWp/day (ET:AT) in Iringa.

3.4. PV losses

Array losses refer to the factors that affect the performance of individual PV modules within a solar array. These losses can be caused by shading, soiling, module Mismatch, aging and degradation and temperature Effects. System losses encompass various factors that affect the performance of the entire solar PV system, including the electrical components, balance of system (BOS) components, and overall system design.

Fig 7 demonstrates different types of PV energy loss/gain, positive numbers presents energy gain and negative numbers are energy losses. Some common system losses include electrical Losses, DC and AC Wiring Losses, inverter efficiency, performance and availability losses as well as system design and sizing, Fig 8 and 9 presents array and system losses respectively. The lowest array losses occur under the "ES:AO" configuration in Dar es Salaam, which is approximately 0.82 kWh/kWp/day. The highest array losses are observed in the "ET: AT" (Two-Axis Tracking) configuration in Mwanza, which is around 1.40 kWh/kWp/day.

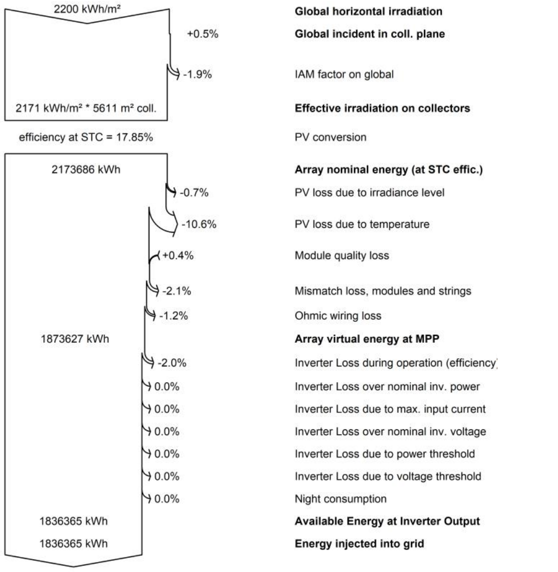

Fig. 7 PV losses for annually optimized system configurations (EA:AO) in Mwanza region

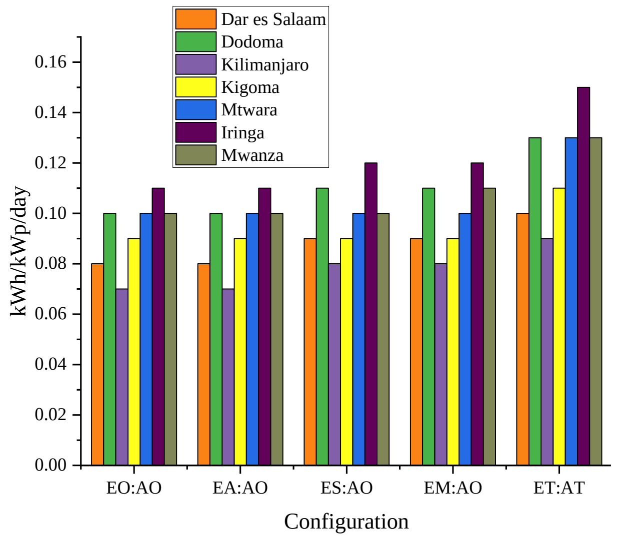

Fig. 9 System losses

It is observed that the array losses are higher compared to the system losses, typically, array losses are higher than system losses in a solar PV system due to the nature of the losses and their specific impact on the performance of the individual PV modules. The losses are lowest in Kilimanjaro, initial analysis of the loss diagrams as presented in the example (Fig 9) suggest that this may be due to lower temperature losses in Kilimanjaro. However a detailed analysis of all loss diagrams across all system configurations is required to confirm.

Overall, the energy losses from the PV system depend on the tilt and azimuth angle configuration since these configurations have a direct impact on the amount of solar irradiance incidence on the PV modules. The losses also depend on the temperature; therefore variations are expected during different times of the day as well as during different months in a year.

3.5. PV energy cost

The levelized cost of energy is a widely used metric for evaluating the economic viability and competitiveness of solar photovoltaic (PV) systems. It represents the average cost of generating each unit of electricity over the system's lifetime. The LCOE takes into account various factors, including the initial capital costs, operational and maintenance expenses, system performance, financing terms, and the expected energy output (Hernández-Moro and Martinez-Duart, 2013). By considering the entire lifecycle costs and energy production, the LCOE enables comparisons between different energy sources and provides insights into the long-term affordability of solar PV systems.

For the horizontal configuration, the LCOE values range from 0.08 $/kWh to 0.13 $/kWh across the regions. The annual optimal tilt configuration shows similar LCOE values, indicating that the performance and economic feasibility of the system are relatively consistent across these tilt angles. The seasonal and monthly optimal tilts exhibit some variations in the LCOE values among the regions, with values ranging from 0.07 $/kWh to 0.13 $/kWh and from 0.08 $/kWh to 0.13 $/kWh, respectively. The two-axis tracking configuration generally have higher LCOE values, ranging from 0.09 $/kWh to 0.16 $/kWh, indicating that the added cost of the tracking system affects the overall economy.

In terms of comparative analysis among all tilt angle configurations, the LCOE values for the different regions remain relatively close, with only slight variations. This suggests that

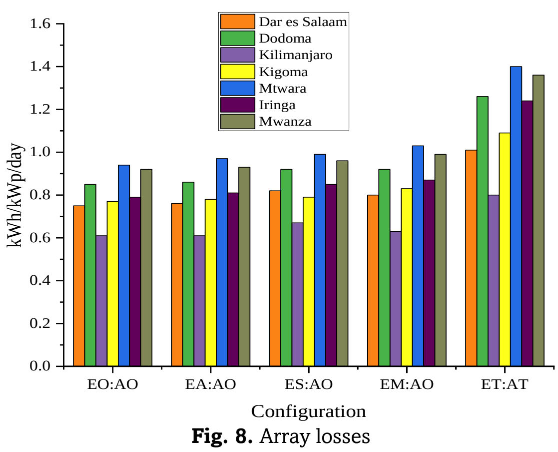

Fig. 8. Array losses

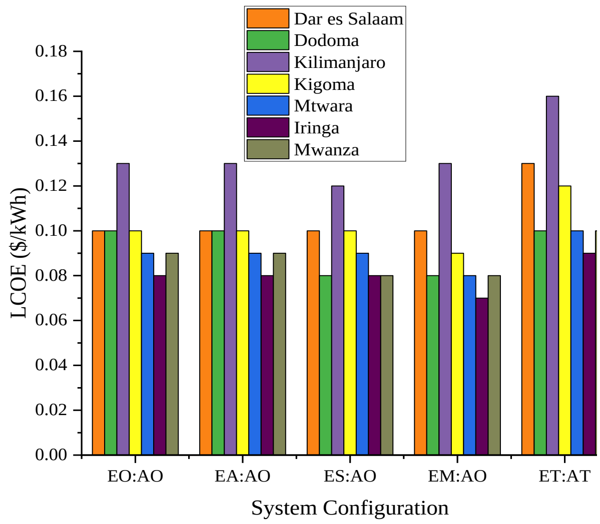

Fig. 10 Levelized cost of energy for different tilt adjustments

Table 8
Main and isolated grid tariffs for solar and wind installations up to 1 MW in Tanzania

Approved Tariff ($/kWh)	Description
0.165	Standardized small power purchase tariff for Solar and Wind projects of up to 1MW connected to the main Grid
0.181	Standardized small power purchase tariff for Solar and Wind projects of up to 1MW connected to the Isolated mini-grid 1

Source: (Mayanjo and Justo, 2023)

the choice of tilt angle has a relatively small impact on the overall LCOE. However, it's important to consider the specific characteristics of each region, such as solar resource availability and local energy prices, when interpreting the results (Komilov, 2021).

Overall, the LCOE results highlight the economic feasibility of solar PV systems across different tilt angles and regions. The relatively low LCOE values indicate that solar PV systems can provide cost-competitive and sustainable electricity generation options. These results can be valuable for decision-makers, investors, and policymakers in assessing the economic viability and potential of solar PV installations in the respective regions. As such, these results were compared with the existing main grid and isolated mini grid connected tariff for solar and wind small power producers (SPPs) in Tanzania as presented in Table 8.

Comparing these LCOE values with the tariffs, we observe that the LCOE values for solar PV systems in all regions and configurations are generally lower than both the grid-connected solar PV tariff and the isolated mini-grid tariff. This suggests that solar PV systems offer a more cost-effective option for electricity generation compared to the given tariff rates. The LCOE values indicate that solar PV systems can provide competitive electricity costs and potentially offer savings to consumers. However, it's important to consider other factors such as local financing terms, subsidies, and additional economic considerations that may impact the overall cost-effectiveness of solar PV systems in specific regions and configurations.

3.6. Validation

Measured solar power output values for a period of twelve months was obtained from the Sustainable Agriculture, Tanzania Farmer Training center located in a village situated 20 km from Morogoro town. The center, through its agrivoltaic project has a 36 kW solar PV power plant. The system dimensions are 34(w) x 13(d) x 3(h) m, and it has a panel density of 50%, which is appropriate for the location due to the high solar radiation and the need to reduce evaporative water loss. The system consists of one hundred and twenty six 280 WP solar panels tilted at a thirty degree angle and a 35 kW inverter with built in data logger. The system power output simulation was done using Pvsyst 7.2 software and the simulation results were compared with the measured results as presented in Figure 11.

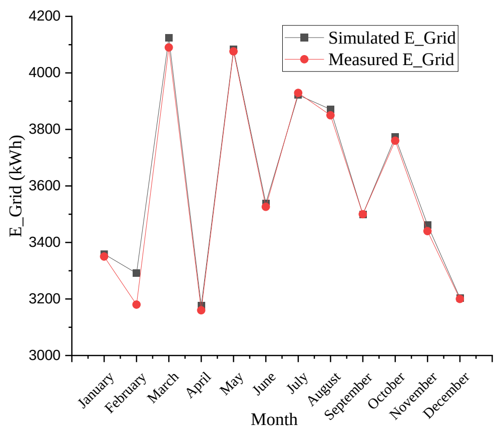

Fig. 11 Measured and simulated PV power output in Morogoro, Tanzania

The results indicate that the model prediction is slightly higher than the measured output, but the distributions are similar. A paired sample t-test was conducted and results showed that the two outputs were not significantly different (p-value 0.8).

4. Conclusion

In this study, we conducted an in-depth analysis of solar PV energy output and associated costs across different panel configurations and regions in Tanzania. The results provide valuable insights into the performance and economic feasibility of various system setups. Through meticulous simulation and data analysis, we have gained a comprehensive understanding of the factors influencing energy generation and costs in the context of solar photovoltaic systems.

Our findings reveal distinct trends across the configurations and regions. We observed that certain configurations, such as the "ET:AT" (Two-Axis Tracking), demonstrated about 30% higher energy output potential, indicating the effectiveness of advanced tracking mechanisms. However, these configurations were associated with higher upfront costs, warranting careful consideration when making investment decisions. Moreover, the impact of geographical location on energy output and costs is evident. Kilimanjaro, for instance, exhibited consistently lower PV power output compared to other regions, attributed to factors such as solar irradiance levels and climate conditions.

From an economic perspective, the levelized cost of energy analysis highlights the significance of minimizing energy costs to ensure the feasibility of solar PV installations. The LCOE results underscore the importance of selecting configurations that balance energy output with costs to achieve cost-effective and sustainable energy solutions. Looking forward, these results provide a foundation for informed decision-making in solar PV system planning and deployment. As technology continues to evolve, incorporating emerging innovations such as more efficient panels, advanced tracking mechanisms, and improved system designs will likely contribute to further optimizing energy production and reducing costs.

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