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Analysis and feasibility of 50 kWp self-consumption solar photovoltaic system for four Senegalese typical climatic zones using PVsyst software

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This study investigates analysis and feasibility of 50 kWp self-consumption photovoltaic system used for supplying the electrical load of military bases in Senegal. It refers to a simulation of performance photovoltaic system in four Senegalese typical climatic zones. In constructing the 50 kWp self-consumption photovoltaic simulation, the number of modules is 144, the power of each module is 280 Wp, 18 modules are in series and 8 in strings. Also, two solar SMA technology of 20 kWp with a voltage range of 230 to 800 V are used, and the simulation is done by means of Pvsyst software 6.81. Solar and ambient temperature data sets from Helioclim-3 database corrected by observations are used for this performance study. The variability of performance system in the four climate typical zones are analyzed from the simulations results. This work includes evaluation of the effective energy produced by the photovoltaic system, consumption and other components related to PV production for each climatic region. The 50 kWp PV array of electricity produced at Dakar (69.8 MWh/year), St Louis (64.9 MWh/year), Tambacounda (62.7 MWh/year) and Ziguinchor (59.3 MWh/year) is entirely self-consumed. The annual performance ratio are 0.796 at Dakar, 0.795 at St Louis, 0.775 at Tambacounda and 0.792 at Ziguinchor. The results obtained follow the variability of the solar resource. This variability is often impacted by the effect of temperature and other local climatic conditions such as the number of aerosols and the diversity of seasons. The solar radiation is more important at St Louis than at Dakar but the Dakar region is less impacted by these factors, making the results more important at Dakar. As for the Tambacounda and Ziguinchor regions, the solar resource is less important, likely due to effect of elevated PV panel temperatures and a longer rainy season in these two zones. To know the magnitude of a solar photovoltaic installation, it is good to size for each locality to be able to deduce a larger production.

Key words: Self-consumption, Pvsyst software, climatic zones, Helioclim-3, performance ratio.

INTRODUCTION

Senegal is highly committed to renewable energies, and solar energy is now gaining more attention since it is easy to install and is the most disseminate renewable source in the country. The Government of Senegal

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undertakes to implement an approach with energy objectives and sets the goal of having energy based on sustainable and inexhaustible energy resources from here in 2025, with at least a 15% rate (http://www.ecreee.org). Baseer et al. (2020) conducted a detailed technical study of a PV plant in Abu Dhabi, United Arab Emirates. To meet the energy needs of a University in India, Srivastava and Giri (2017) have been interested in a grid-connected system with Pvsyst software as a tool. Studies based on modeling and on the different aspects of PVsyst software for simulation of grid-connected photovoltaic system are noted in the literature Prasad et al., 2020; Soualmia and Chenni, 2016. In order to meet the needs of electricity generation, Yadav and Bajpai (2018) found it necessary to evaluate renewable energy. Some authors have targeted universities to promote clean and sustainable energy (Satish et al., 2020; Barua and Prasath, 2017). Karki and Kusang (2012) conducted a study to compare the performance of photovoltaic systems of Kathmandu and Berlin. In same context, (Kandasamy, 2013) chose four sites in Tamilnadu and compared their production and annual income with Pvsyst tool. At Khatkar-Kalan in India, Sharma and Chandel (2013) simulated a photovoltaic system in which he compared the simulated results with those obtained by experimentation. For King Faisal University, Bouzguenda et al. (2014) designed, simulated and analyzed a single stand of 2 kWp. A comparison of the performance of a fixed panel and a mobile panel could be interesting. The mobile panel can be adjusted at least once a season (Tallab and Malek, 2015). To install a grid-connected photovoltaic system at Dhalipur located in India, (Matiyali and Ashok, 2016) simulated 400 kWp using the PVsyst simulation tool and focused on the system performance. Other authors (Ayompe et al, 2020; Barua and Prasath, 2017; Bouacha et al, 2015; Kumar et al, 2017; Kumar and Sudhakar, 2015; Kyprianou et al., 2010; Tendra and Raturi, 2013; Chaudhari et al., 2019; Bharathkumar and Byregowda, 2014; Pavlović et al, 2013; HemanthBabu et al., 2019; Erdinc and Uzunoglu, 2012; Turcotte et al., 2001) were interested in the strengthening of photovoltaic production systems to satisfy a quality and quantity distribution of electric energy. In same context, some authors (Erdinc and Uzunoglu, 2012; Turcotte et al., 2001) also used this methodology of sizing a hybrid system. In India, (Goura, 2015) discussed one megawatt photovoltaic system in which he evaluated its performance. The output power of the modules can be evaluated by varying the solar radiation (Irwanto et al., 2014). After estimating the solar potential at different sites in Iran, (Besarati et al, 2013) moved on to simulate a photovoltaic system to determine the performance of its sites with RETScreen tool. Studies with a storage system are also carried out to strengthen the production of photovoltaic power plants (Bolduc et al, 1993; Weniger et al., 2014). Cheikh et al. (2015) examined a photovoltaic module made of monocrystalline silicon to determine its efficiency depending on the location. In a similar context, Ahmed et al. (2018) measured both a clear day and a cloudy day at the Assane Seck University in Ziguinchor, Senegal and then evaluated the performance of the photovoltaic modules. In Ambala location, Saraswat and Sathans (Saraswat and Sathans, 2016) used different PV module materials in the same conditions in which they compared their performance coefficients. In Hamirpur, Himachal Pradesh, Yadav et al. (2015) used measurement data and estimated performance ratio equal to 0.724 for effective energy production with Pvsyst simulation tool. Solar electric vehicles are also direct applications of this renewable resource and provide a solution to the difficulties associated with travel between different areas (Ríos et al., 2017). Other authors have been interested in the technico-economic analysis of solar power plants or mini-grids, but also taking into account environmental protection (Mansur et al., 2017, 2018). In Saudi Arabia and according to Ramli et al. (2015), an optimum production of solar resource depends fully on commissioning of its operating system.

PVsyst is a commercial software platform developed and owned by PVSYST SA, and has been designed for photovoltaic systems (https://www.pvsyst.com and Photovoltaic). It has four main sections, viz; preliminary design, project design, databases and tools.

This paper describes the variability of solar resource in four climatic zones for the purpose of a self-consumed 50 kWp photovoltaic solar installation for military bases. The PVsyst software made it possible to properly design and simulate the system to provide renewable electric energy to military bases.

Solar potential in the four sites

Senegal, which is located in West Africa has an important solar potential with an average annual sunshine duration of about 3,000 h and an average irradiation of 5.7 kWh/m^2/day. This irradiation varies between the sunnier northern part (5.8 KWh/m^2/day in Dakar) and the southern part, which is richer in rainfall (4.3 kWh m^{-2} day^{-1} in Ziguinchor).

Meteorological station of the four Senegalese climate zones

These sites are distributed according to their geographical position and have different climatic conditions (Table 1). 50 kW will be developed for each of these sites for electricity needs of military bases.

Solar ressources in the four Senegalese climate zones

Climate zone of Dakar

This zone which is located in the Cape Verde Peninsula

Table 1. Geographical coordinates of study sites.

Location	Latitude (°)	Longitude (°)	Altitude (m)
Dakar	14.733	-17.467	20
Saint Louis	16.140	-16.358	4
Tambacounda	13.767	-13.683	49
Ziguinchor	12.550	-16.267	23

projected into the Atlantic Ocean has the mildest climate in Senegal (Faye, 2019). Its climate is BSh (B : Arid, S : Steppe and h : hot) according to the Köppen-Geiger classification (Kottek et al., 2006). Rains are low in Dakar, and rainy season begins in July and ends in September (data.org/afrique/senegal/). The lowest temperatures are recorded during the winters with a minimum (17°C) in February whereas the highest temperatures are noticed in autumn and attained a peak (31.6°C) in September.

Climate zone of Saint Louis

This is located in the Senegal River Delta (Silver et al., 2013) and its climate is classified as a BWh climate (W : desert) by Köppen and Geiger. The average temperature ranges from 21.6 to 28°C (data.org/afrique/senegal/) with the minimum temperature (15.2°C) in February and the maximum temperature (31.9°C) in October. Rainfall ranges from July to early October with low rainfall.

Climate zone of Tambacounda

Located in-land in the south-eastern Senegal (Budde et al. 2001), the climate of Tambacounda is classified BSh according to Köppen and Geiger. Over the year, the average temperature varies from 25.5 to 32.9°C (data.org/afrique/senegal/) with the minimum temperature (16.7°C) recorded in December and the maximum temperature (40.1°C) recorded in May. The rainy season starts in June and runs until October with low rainfall in October, and August as the rainiest month.

Climate zone of Ziguinchor

Located in the southwestern part of Senegal, its climate is classified Aw (w: winter dry, A: equatorial) according to Köppen and Geiger. The average temperature is between 24.1 and 28.3°C (data.org/afrique/senegal/). The minimum temperature is 15.1°C in January and the maximum temperature is 36.7°C in April. The rainy season runs from June to October with frequent and abundant rainfall in the summer, reaching their peak in August (429 mm).

Load profile used

The monthly average values of the global horizontal, diffuse irradiation and temperature of the Helioclim-3 database are shown respectively in Figures 1 to 3. Please note that as there is no measured data from the solar radiation over a long period, this study is relying on the satellite data (2007-2018) corrected to establish solar resource for the feasibility studies. The monthly variation of solar radiation over a whole year is shown in Figure 1.

The global horizontal solar radiation varies throughout the year from 139.529 to 188.498 kWh/m^2 at Dakar, 136.060 to 197.573 kWh/m^2 at St Louis, 129.336 to 194.339 kWh/m^2 at Tambacounda and 131.122 to 189.177 kWh/m^2 at Ziguinchor. The diffuse radiation parameter considered is shown in Figure 2. From one site to another, the amount of diffuse radiation varies from 48 to 78.5 kWh/m^2 and the monthly average ambient temperature is from 22.6 to 30.7°C (Figure 3).

MATERIALS AND METHODS

HelioClim-3 data correction

This study aims to evaluate the solar resource for electricity production needs in four typical climatic zones of Senegal. In Pvsyst, we can also directly implement data if they are not available in the software and will also determine the ideal direction and inclination of the solar panels for the best generation of electricity. A twelve-year period which extends from 2007 to 2018 Helioclim-3 database is available for each zone. The GHI data used are part of the Meteosat Second Generation (Schmetz et al., 2002; Schumann et al., 2004; Aminou, 2003) hourly HelioClim-3 data product and were acquired from the SoDa website. Described by the Heliosat-2 method (Budde et al, 2004; Schmetz et al., 2002; Schumann et al., 2004; Aminou, 2003), it determines the cloud index by a powerful analysis of satellite images. Its particularity of analysis is based on its visible band (Cano et al., 1986; Rigollier et al., 2009). In this study, version 5 of HelioClim-3 is used. It has a wide coverage and the data exists over a long period from 2004 up to yesterday. It has a temporal resolution of 15 min and a spatial resolution of 3 km (Espinar, 2012; Qu et al., 2014; Wald 2011). The service provides global, direct, and diffuse solar radiation at horizontal, tilted and normal planes. The web service is for fee from Dec. 2006. In addition to these twelve years of HelioClim-3 data, there is one year of observation data for each zone. This year of ground truth for each climatic zone served as a reference to correct and validate the Helioclim data. The following methodological approach is used to correct and validate the Helioclim data.

First is an application of a filter for each zone and for each year to remove the aberrant data. Secondly, is to apply a correlation

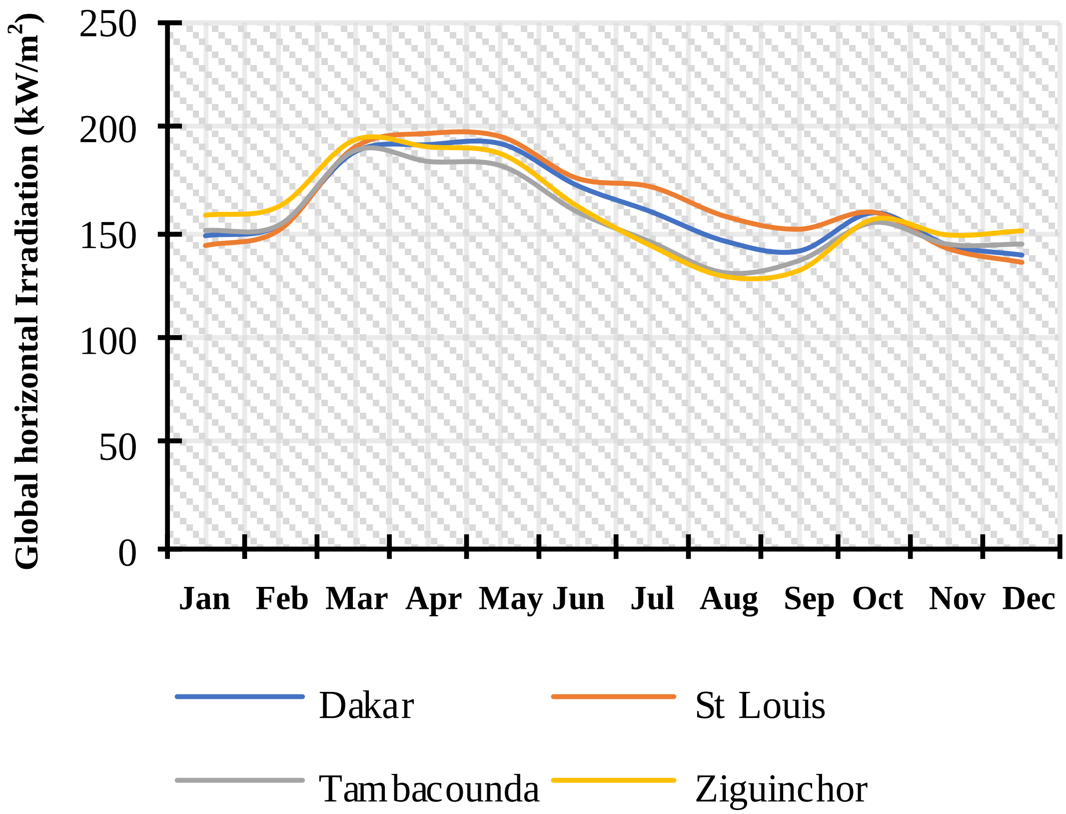

Figure 1. Global horizontal irradiation.

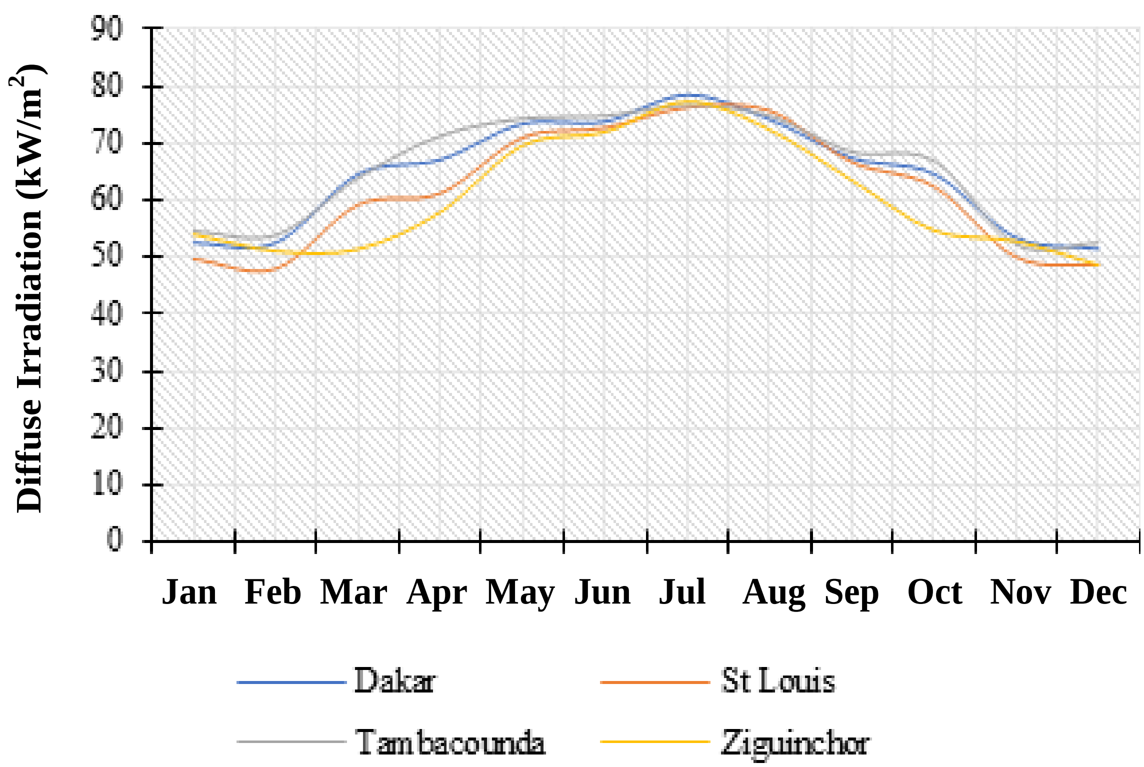

Figure 2. Diffuse irradiation.

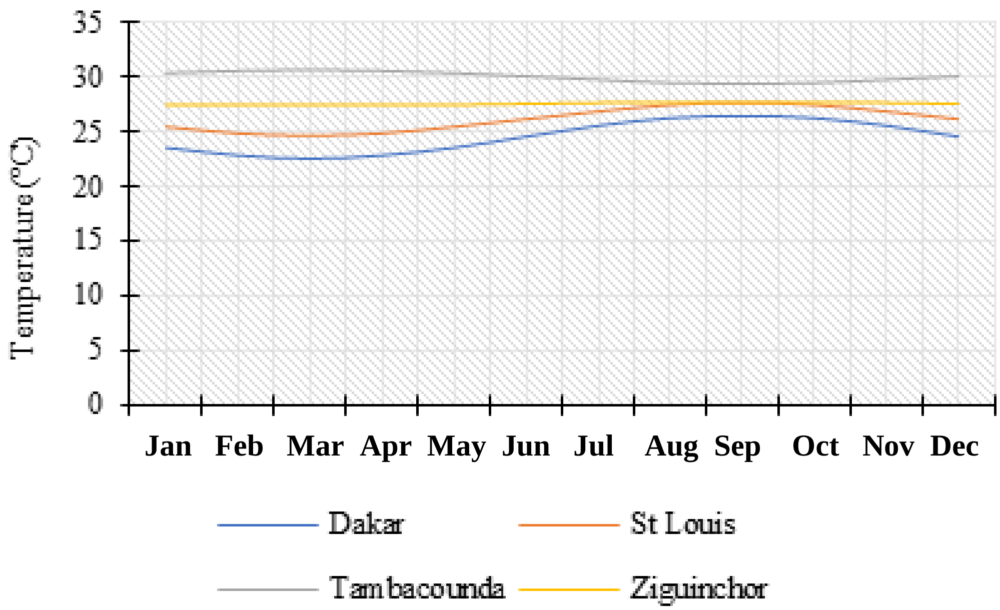

Figure 3. Temperature of sites.

Table 2a. Global system summary.

Modules number	144
Module area	280 m^2
Inverters number	2
Nominal PV power	40.3 kWp
Maximum PV power	38.2 kWdc
Nominal AC power	40 kWac

Table 2b. PV module specifications.

Module type	Si-poly
Rated power	280 Wp, 30V
Efficient	16.07%
Impp	7.88 A
Vmpp	35.63 V
Temperature coefficient	-0.44 %/°C

coefficient of the reference year (ground measurement year) to validate the Helioclim data. After this correction, the twelve years of Helioclim-3 data are calibrated with the reference year and the results given in terms of correlation coefficient shows an R^2 greater than 0.70 for Dakar (0.93) and St Louis (0.74), and it is 0.50 for Tambacounda and 0.68 for Ziguinchor.

Lastly, a summary of the major results of the performance variability was proposed. This database was used to simulate a 50-kW mini power station for military bases in Senegal.

Description of self-consumption solar PV system

Self-consumption can be defined as the proportion of solar energy that is used directly in the building where the PV system is installed. The energy needed for internal use should neither be fed into nor drawn from the grid. The E back-up or EFrGrid (Energy From Grid) is the energy drawn from the grid for the internal consumption (when PV is not sufficient), and during night. Three main parts are noted in this block diagram (Figure 4), viz; a part consisting of photovoltaic modules, a part reserved for inverters and a part intended for loads. The panels produce direct current energy from the sun's rays, which will then be transformed into alternating current by the inverters. At the load control level, the control of the site is carried out by a combined distributed-centralised planner, with its consumption the average consumption of a domestic user.

Simulation with PVsyst software in four climatic zones

The direction of a solar panel is determined by two dimensions, the azimuth that defines the direction of the sun and the tilt (inclination) of the panel. Those sites are in the northern region, whereas the best orientation is to the south (Figure 5). The optimum tilt angle is set equal to the latitude to gain maximum solar irradiation.

Table 2a and b represents the global system summary and the PV module. All modules represent the photovoltaic field. The modules are connected in series to maximize voltage.

Calculation of performance analysis parameters for each climatic zone

This part of the work describes the photovoltaic system parameters for performance analysis of a self-consumption system. Evaluation of a solar system is based on certain parameters that are often defined by a solar vocabulary based on international standards. It should be noted that the International Electrotechnical Commission IEC 1724:1998 and the International Energy Agency (IEA) (Sharma and Chandel, 2013), (Marion et al., 2005; Milosavljević et al., 2015; Attari et al., 2016; Bashir et al., 2014) defines the energy efficiency, efficiency factor, performance ratio and capacity factor detailed in Table 3. The parameters and their meanings are as follows : Array yield expresses the time which the photovoltaic system has to

Table 3. Method of calculation of the performance parameters performance analysis

Array yield (kWh d^{-1} kWp^{-1})	Array energy (kWh)	Reference yield (Hour or day)	Final yield (kWh d^{-1} kWp^{-1})	Performance ratio	Inverter efficiency	System efficiency	System losses
$Y_A = \frac{E_A}{P_O}$ (1)	$E_A = Idc * Vdc * t$ (2)	$Y_R = \frac{H_t}{G_O}$ (3)	$Y_F = \frac{E_{PV\ AC}}{P_{maxG\ STC}}$ (4)	$P_R = \frac{Y_F}{Y_R}$ (5)	$Y_R = \frac{P_{AC}}{P_{DC}}$ (6)	$\eta_{syt.T} = \eta_{PV.T} * \eta_{inv.T}$ (7)	$L_S = Y_A - Y_F$ (8)

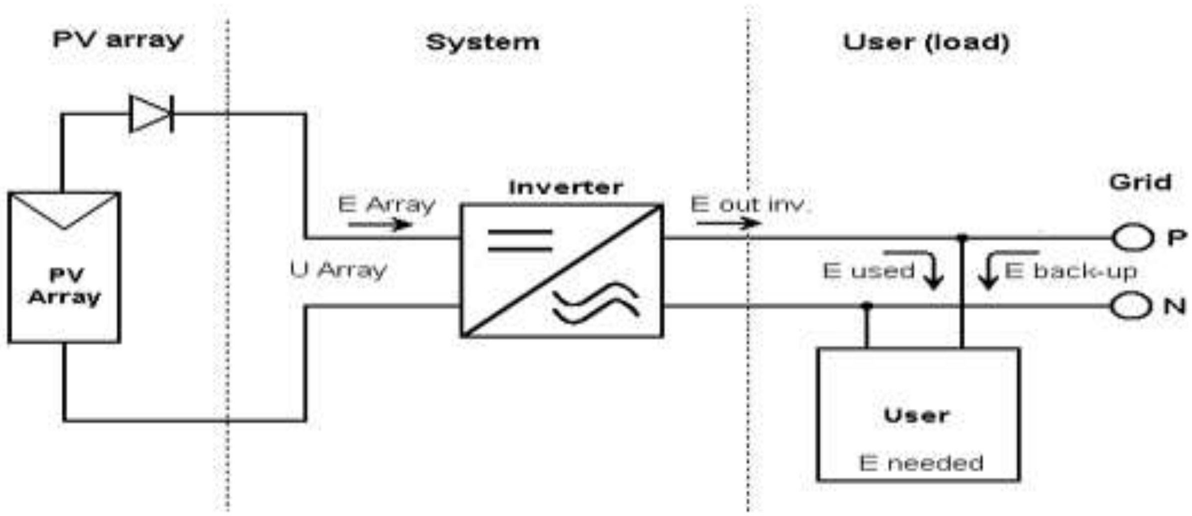

Figure 4. Block diagram of self-consumption PV system.

spend with nominal solar generator power (Po) to produce DC energy from EA grid Reference yield is defined as the total Irradiation in module plane (kWh/m^2) divided by the reference irradiance (1 kW/m^2) of the PV system.. Final PV system yield is defined as the net AC energy output divided by the DC power peak of the PV system installed. PR is defined as the ratio of final PV system yield to that of the reference yield. Inverter efficiency is the ratio of output power generated by the inverter to input power generated by the photovoltaic system. System efficiency is the instantaneous daily system efficiency given as PV module efficiency multiplied by inverter efficiency. System losses represent the difference of array yield to the final system yield.

RESULTS AND DISCUSSION

Balances and main results

The PV energy internally consumed called E_Solar is 69797 kWh/year for Dakar, 64948 kWh/year for St Louis, 62681 kWh/year for Tambacounda and 59299 kWh/year for Ziguinchor (Figure 6). The energy really used by the system called EArray is 71213 kWh/year for Dakar, 66257 kWh/year for St Louis, 63980 kWh/year for Tambacounda and 60505 kWh/year for Ziguinchor (Figure 7).

Figures 8, 9 and 10 represent the normalized productions. The power of the plant for the normalized productions is 50 kWp. It includes collection losses, system losses and useful energy produced per kWp/day and are defined by International Electrotechnical Commission (IEC, 1998) The collection losses value is 1.12 kWh/kWp/day at Dakar, 1.05 kWh/kWp/day at St Louis, 1.15 kWh/kWp/day at Tambacounda and 0.98 kWh/kWp/day at Ziguinchor. The system losses is respectively 0.1, 0.09, 0.09 and 0.08 kWh/kWp/day. A major part of the losses in production is the loss of energy at solar panels (Figure 8). The produced useful energy is 4.74 kWh/kWp/day at Dakar, 4.41 kWh/kWp/day at St Louis, 4.26 kWh/kWp/day at Tambacounda and 4.03 kWh/kWp/day at Ziguinchor. In addition to that, the Figure 10 shows that the daily amount of produced useful energy is higher in Dakar than in other alternatives zones. From site to site, the collection losses varied between 0.98 and 1.15 kWh/kWp. Losses are highest during the quarter March-April-May, when irradiations also reach their maximum values. There are losses which are often due to temperature, cell mismatch and wiring. Other observed factors include the PV module and inverter technology, workmanship of installation and scheduled maintenance and cleaning.

Performance ratio

The performance ratio designated by PR is one of the

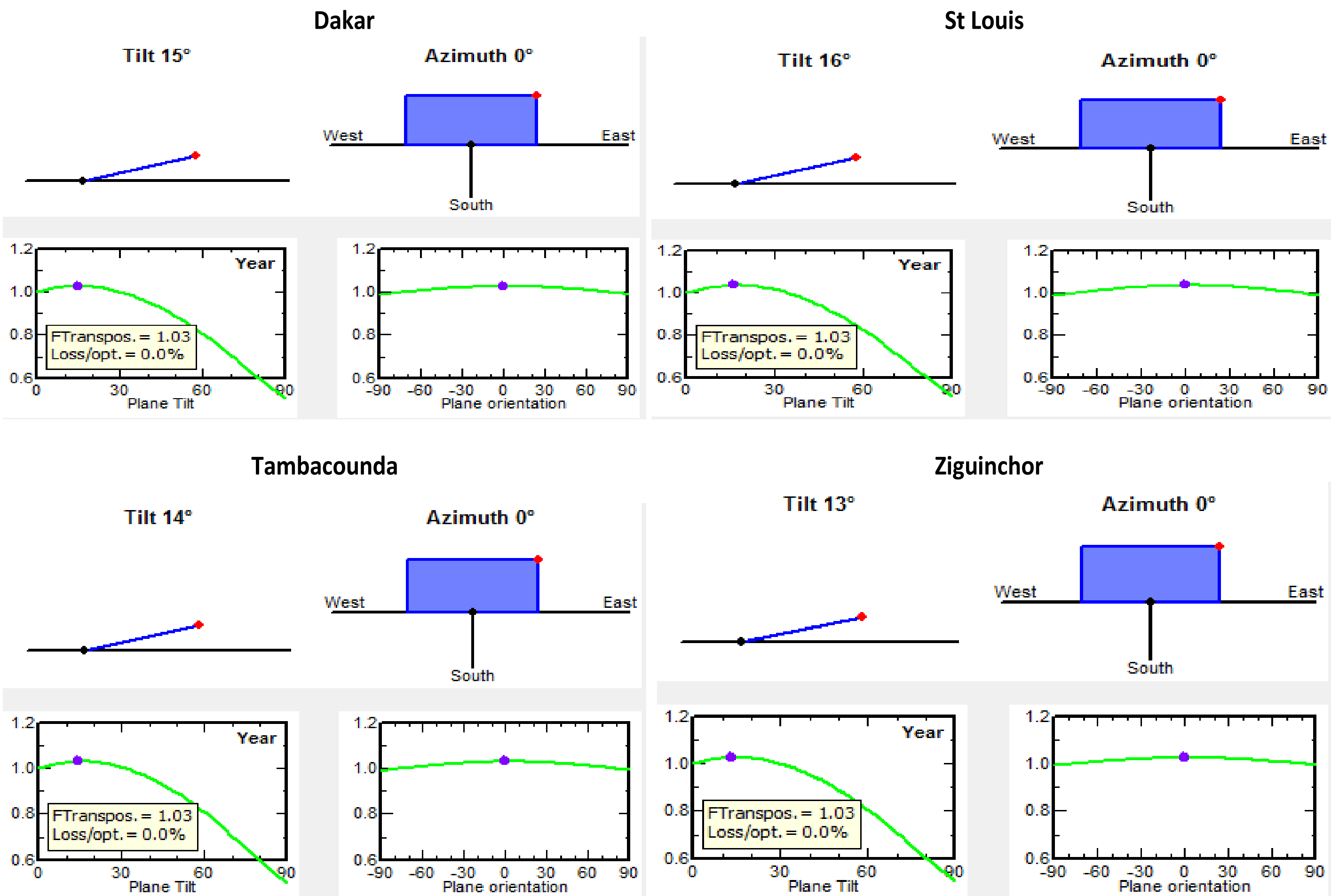

Figure 5. Orientation.

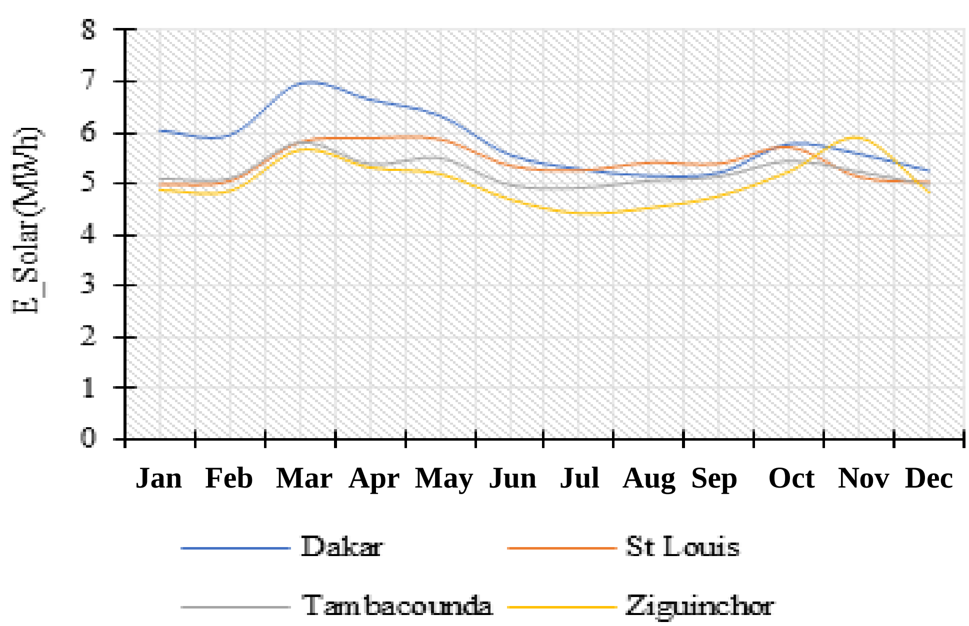

Figure 6. PV energy internally consumed.

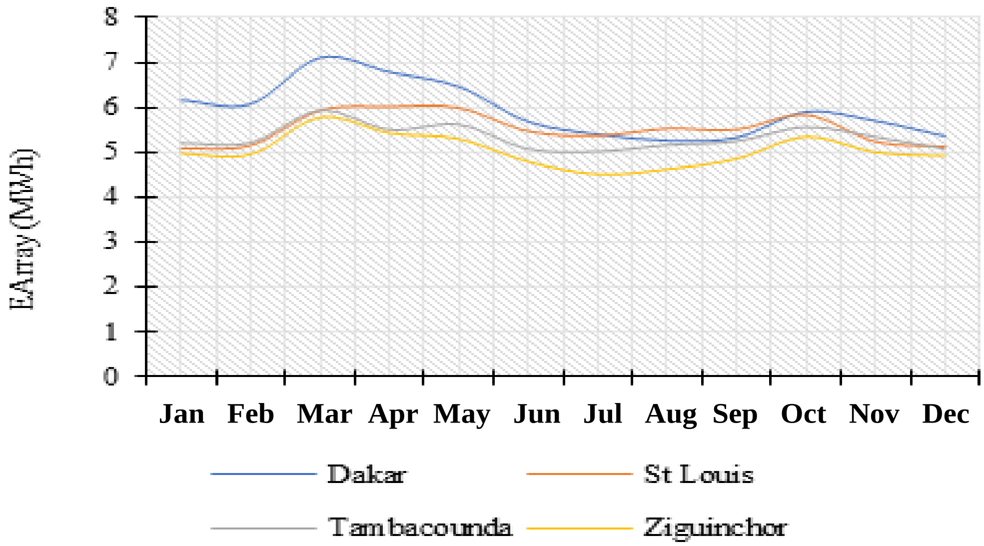

Figure 7. Energy really used by the system.

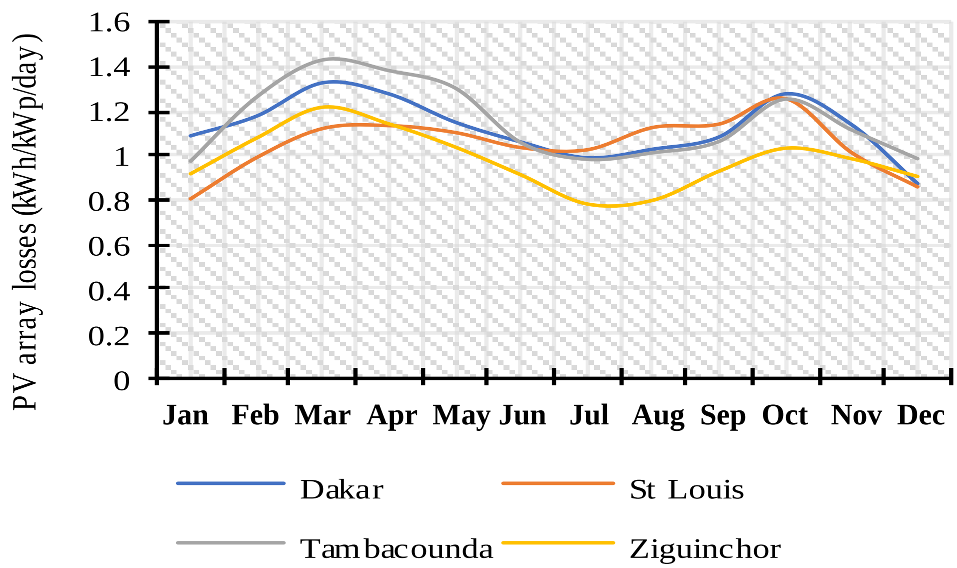

Figure 8. Collection losses.

key parameters for analyzing or evaluating the efficiency of a photovoltaic solar system installation. The annual average performance ration is 79.6% at Dakar, 79.5% at St Louis, 77.5% at Tambacounda and 79.2% at Ziguinchor. The results show good energy efficiency and reliability PV plant in Dakar and St Louis compared to Tambacounda and Ziguinchor. The modules are manufactured under Standard Test Conditions (STC) and have an efficiency related to these conditions. For applications under outdoor conditions, the efficiency of the modules change. The efficiency ratio between the two conditions gives the performance ratio. Dakar has a monthly PR from 77.1 to 81.5%; for St Louis, the PR is between 77.2 and 81.9%; for Tambacounda, the PR ranges from 75.1 to 79.4%; and the PR in Ziguinchor varies from 77.6 to 80.6% (Figure 11). The PR is a function of both the PV system efficiency and the weather. Weather affects the PR by affecting the module temperature. The temperature is higher in Tambacounda compared to the other three zones (Figure 3). It is noted that an elevated temperature leads to a decreased performance of solar system cells. And since cells are manufactured under specific conditions, their performance will also depend on the characteristics of location where

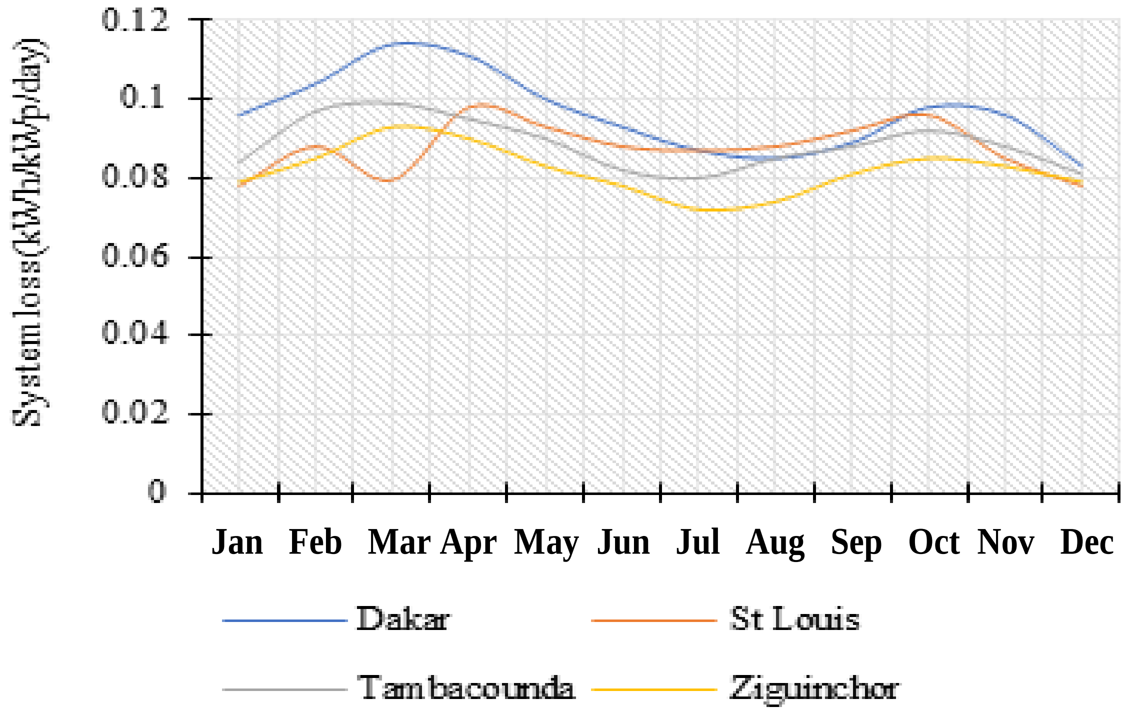

Figure 9. System loss.

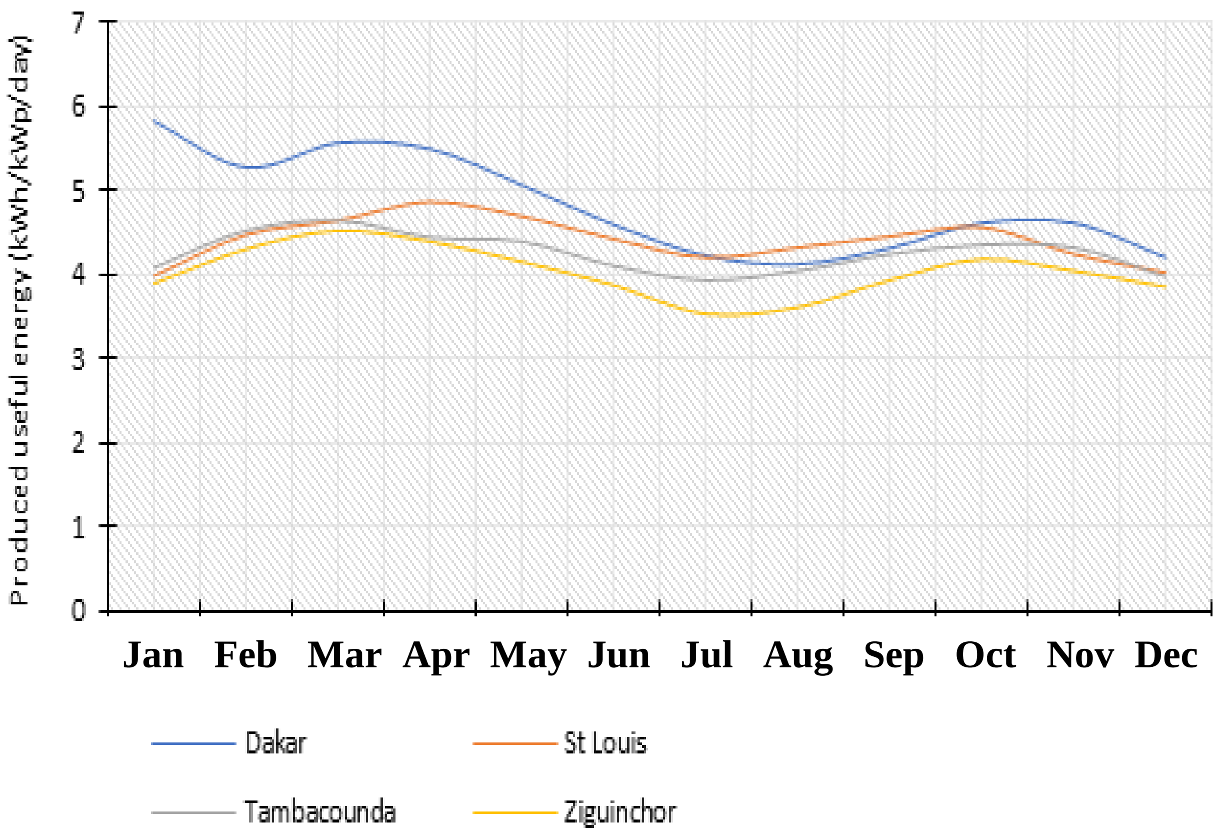

Figure 10. Produced useful energy.

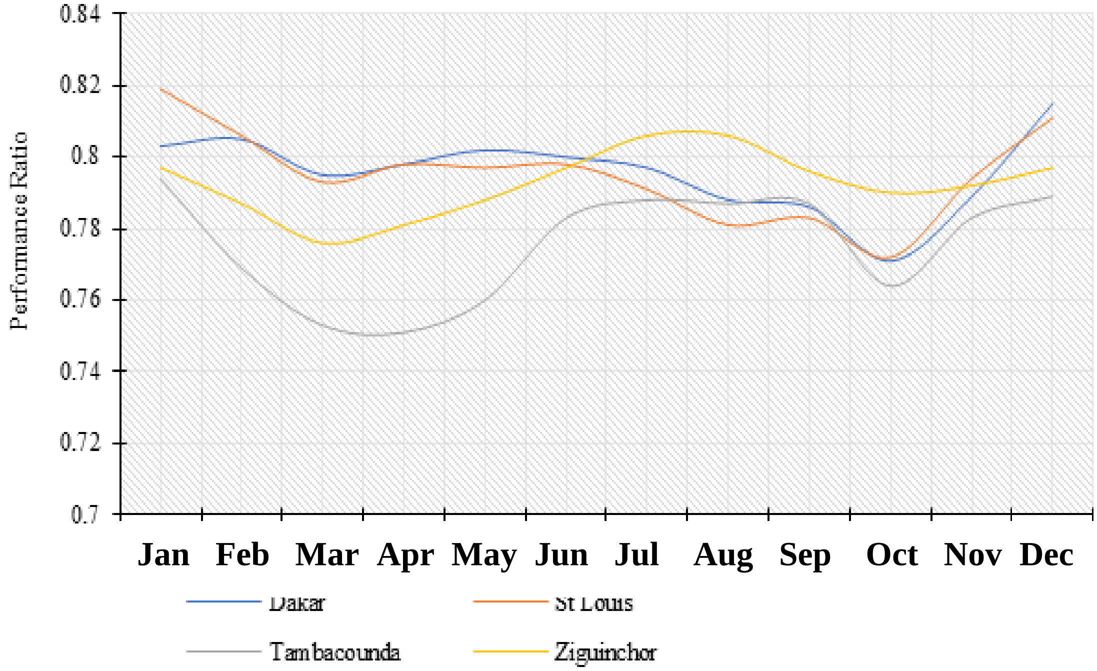

Figure 11. Performance ratio.

Table 4. System performance throughout the year.

Site	Horizontal global irradiation (kWh/m^2)	Effective irradiance on collectors (MWh)	Array nominal energy (MWh)	Array virtual energy (MWh)	Grid consumption (MWh)
Dakar	2107	2111	85.6	71.2	69.8
St Louis	1965	1966	97.7	66.3	64.9
Tambacounda	1952	1946	66.3	64	62.7
Ziguinchor	1819	1966	64.9	60.5	59.3

they will be used.

System energy loss throughout the year

Table 4 shows that on an annual basis, the system produced about 69.8 MWh of electricity, which is entirely self-consumed for Dakar and respectively 64.9, 62.7 and 59.3 MWh for St louis, Tambacounda and Ziguinchor. For all sites, the main losses from converter efficiency is 2%. The nominal PV array energy at STC is 85.6 MWh; however, only 71.2 MWh is available as output from it in Dakar. The losses due to the PV array are 17.3%. The nominal PV array energy at STC in MWh is respectively 79.7, 78.9 and 72.8 for St Louis, Tambacounda and Ziguinchor and the output from it is respectively 66.3, 64.0 and 60.5 MWh. The losses due to the PV array are respectively 17.4% in St Louis and 17.6% for Tambacounda and Ziguinchor. Table 4 summarized the system performance throughout the year.

Conclusion

The performance analysis of 50 kWp self-consumption system is designed and evaluated using Pvsyst in this work. The variability of the different performance parameters is studied in four alternative zones. The production energy is most important in Dakar (69.8 MWh/yr) as compared to other sites such as St Louis (64.9 MWh/yr), Tambacounda (62.7 MWh/yr) and Ziguinchor (59.3 MWh/yr). The energy cost is respectively 0.076 Euro/kWh in Dakar, 0.082 Euro/kWh in St Louis, 0.085 Euro/kWh in Tambacounda and 0.090 Euro/kWh in Ziguinchor. The efficiency module array is over 14%. The total investment is 36,285 Euro. Comparing the four zones, the maximum energy generation of 6963 kWh observed in Dakar is in the month of March and lowest energy generation of 4422 kWh observed in Ziguinchor is in the month of July. Military sites are often located in isolated zones and their power supply through the local network is sometimes difficult. This study, favorable to exploitation of solar energy, is a solution for military bases in these four Senegalese typical climatic zones.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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