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ABSTRACT

Renewable energy (RE) penetration assessment and the development typical meteorological year (TMY) for five cities are considered together in this study. Thus, an integrated method is utilised encompassing RE status assessment and the Sandia method to generate the typical meteorological months of TMY. TMY and long-term data (LT) are then compared as well as a PV system of 3kWc output using TMY and LT under statistical errors. Until 2020 only 11.27% out of 360.02 MW capacity in power demand was RE (hydro and solar). LT and TMY are close for all the towns with a better closeness for Sokode. The latter predicts PV system performance within 2% of the LT in all the sites. More investment has to be put in RE sector because of its potential: 5.27 kWh/m2/day of mean solar radiation, 1238.21 mm of average annual precipitation and 7 m/s of mean wind speed at 50 m above the ground.

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KEYWORDS
Typical meteorological year (TMY); renewable energy; Sandia method; socio-economic impacts; RE deployment; Togo

Introduction

Renewable energy (RE) programmes have been introduced by most countries worldwide into their energy policies as an alternative solution for protecting the environment, a way to increase access to electricity, and a mechanism for poverty reduction through economic development. Over the course of the years, most countries have increased their respective RE portfolios. Accordingly, Togo introduced RE into its energy generation in 2015 because the country has potential resources such as solar, micro-hydro, and wind (MME, 2015). Since 2017, an increasing solar energy system has been integrated into the energy mix through the installation of various mini-solar plants. The purpose was to increase electricity access within the country (AT2ER, 2018). Though RE quota augments, finding quality and accurate hourly/daily meteorological parameters is an issue. This is mostly due to the lack of meteorological stations and/or appropriate equipment for such measurements. However, the selection of good sites necessitates accurate meteorological data assessment to implement any renewable energy-related projects (Oyedepo et al., 2021). How to solve the frequent problem of weather data in the context of Togo?

Typical meteorological year (TMY) data are utilised to well simulate the climate of a particular location and facilitate the performance of energy systems dependent on weather conditions. The

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accuracy of RE studies is increased by that technique (Fan et al., 2020; Givoni, 1998; Herrera et al., 2017). Therefore, the meteorological variables, such as solar radiation, air temperature, relative humidity, and wind speed, are vital for both the study of RE systems and the simulation of buildings' heating and cooling. This knowledge is equally important for the assessment of the performance of solar thermal and photovoltaic systems (Bilbao et al., 2004; Yang & Lam, 2007). Since variation of weather conditions is real with time due to atmospheric conditions and changing climate (Ohunakin et al., 2014), there is a need to perform a generation of location-related weather database that can well portray over a year the long-term average data (Bulut, 2010; Pusat et al., 2015), therein describing the local climate and giving a better overview of renewable energy resources. The TMY data possibly simplifies with meteorological data the work to be done in energy studies such as energy systems comparison and sites selection (Patton, 2013). As such, designers and installers of energy systems will not do without using them as recognised in Sepúlveda et al. (2014).

Several methods have been tested for the TMY's development for various locations across the globe (Georgiou, 2013; Sawaqed et al., 2005). These methods are different from the statistical approach used to generate the typical meteorological months to form the TMY. The procedure varied from one method to another and so were the weather parameters selected and their accuracy (Argiriou et al., 1999; Georgiou, 2013). In 2013, Georgiou et al. reported that the most recent methods were the Gazela-Mathioulakis Crow method, the Miquel-Bilbao method, the Festa-Ratto method, the Danish method and the Sandia method. The performance was found to be similar in the majority of these methods according to a comparative study conducted by (Argiriou et al., 1999; Ebrahimpour & Maerefat, 2010; Janjai & Deeyai, 2009; Skeiker, 2007). Furthermore, out of all the above TMY performing methods, Sandia was found to be the simplest and yet remained the most extensively used method (Janjai & Deeyai, 2009; Sun et al., 2017; Yang et al., 2008). The Sandia method had been developed by Hall et al. (1978) in Sandia Laboratories, U.S., as indicated by (Sawaqed et al., 2005). Regarding the weighting indices related to weather parameters of the Sandia method, Georgieou et al. (2013), said that in recent reviews, the solar radiation-related weighting index was the highest. This fact was also reported by (Ouedraogo, Coulibaly, 2012) and (Ohunakin et al., 2018). These latter studies were conducted in West Africa. For all the above-mentioned reasons, the Sandia empirical method was selected for the present study, with the weighting index of solar radiation being the highest followed by the weighting index of the mean temperature.

Several researchers developed various TMY datasets for both buildings and renewable energy systems studies in many cities or countries, such as Ankara (Turkey), Belgium, Burkina Faso, Canada, China, Damascus (Syria), Greece, Italy, Japan, Nicosia (Cyprus), Nigeria, Madagascar, Saudi Arabia, South Korea, Spain (Jee et al., 2012; Kambezidis et al., 2020). No existing study attempted a TMY data development in Togo to our knowledge. This work was carried out to fill in the gap by utilising 30 years of data, ranging from 1991 to 2020, to approximate a representation of local-related climate patterns. Hence, the current typical meteorological year (TMY) is composed of 12 typical meteorological months (TMMs). The latter TMMs were chosen to form a set of months in the form of a year's weather database. Each month in the TMY was selected using statistical criteria from any specific year, ranging from 1991 to 2020, that best fits the optimal conditions of the location (Lam et al., 1996; Menicucci & Fernandez, 1988; Sawaqed et al., 2005; Wilcox & Marion, 2008). For instance, January 1994 may be taken as the base month, February of 1998 as the second month, and so on.

The main objective of this study is to develop TMY database on hourly/daily scale for renewable energy studies for four regional towns and the capital city of Togo, Lomé, using the second version datasets of Modern-Era Retrospective analysis for Research and Applications (MERRA-2). The study presents a review of renewable energy integration in the socio-economic environment and a way of solving the issues of lack of weather data at hourly/daily scale in Togo.

The remainder of the paper is presented as follows: Section 2 describes the integration of renewable energy systems and their socio-economic impacts in Togo, the methodology of generating the

TMY database along with the steps is described in Section 3; the results are presented and discussed in Section 4, and finally, the conclusions of the overall study are presented in Section 5.

1. Integration of renewable energy systems in Togolese socio-economic environment

1.1 Evaluation of renewable energy technologies

Togo is a coastal country situated in the Sudano-Guinean climatic zone, whereby the weather conditions offer good renewable energy resources for the country. These resources are hydropower, solar energy, wind energy, etc. (Samah, 2016). About 40 hydropower sites were identified across the country. Among these sites, 57.5% have a potential to generate 2–50 MW. The country receives an average annual precipitation between 1047.85 and 1428.57 mm under the new TMY and 1111.56 and 1415.12 mm under the LT conditions. Also, the country has an excellent solar radiation potential throughout the year. The global daily solar radiation varies from 4.97 kWh/m^2/day in the South to 5.56 kWh/m^2/day in the North, with an average of 5.27 kWh/m^2/day under TMY compared to 4.4 kWh/m^2/day found in the existing literature. Hence, Togo has an average insolation exceeding 700 Wc/m^2, especially in the dry season. Concerning wind energy resource, the potential is suitable for energy production, especially near the coastal areas. This study discovered that the Togolese wind energy potential is estimated, on average at 50 m above the ground, to be above 4 m/s. More specifically, this average wind speed is above 7 m/s in the Northern part of the country.

1.2 Access to electricity and rate of electrification

Togo is a developing and low-income country characterised by deprived access to electricity as most Sub-Saharan African and West Africa countries. The existing access is such that it is nonuniform across the country. The rates of electrification per region in 2019 are as follows: 96.70%, 65.52%, 23.84%, 31.61%, 33.91%, and 20.09%, respectively, for Lome, Maritime region, Plateaux region, Central region, Kara region, and Savana Region (ARSE, 2022). The urban areas are more electrified than the rural areas, with the capital city Lome being the most electrified through the years. Even within the towns, the access is not consistent. Up to 2020, the electricity access is still around 50% at the national level, leaving about 4 million inhabitants with no access to electricity. Figure 1 portrays the evolution of the electricity access rate (Presidence togolaise, 2018; SIE, 2019).

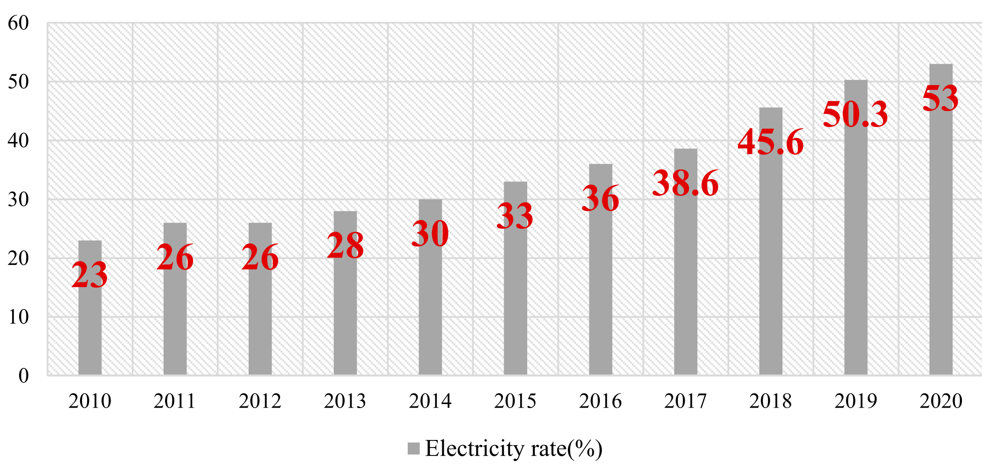

Figure 1. Electricity access rate.

1.3 Evolution of electricity demand

The national electricity demand is met through various sources, such as thermal, hydropower, solar, and importation from neighbouring countries, as presented in Figure 2 (ARSE, 2021). The demand varied from 930.6, 1272.952, 1358.50, 1403.17, 1451.78, 1557.3 and 1638.41 GWh, respectively, in 2010 and 2015–2020 as it can be seen from Figure 2. For many years, the country has been heavily dependent on importation. In 2020, the total power produced was 360.02 MW, and it could cover half of the national needs with the corresponding electrification rate of 53%. A close analysis of the national demand allows us to admit that the share of RE is meagre. According to the utility companies (CEB and CEET), the demand would evolve from 1638.41, 1706.40, 2089.43, 2182.68, 2200.08, and 2353.82 GWh, in 2020, 2021, 2022, 2023, 2024 and 2025 in that order.

1.4 Renewable energy quotas

From the 1557.30 GWh generated in 2019, only 39.56 MW (viz., 11.65%) was renewable, whereas 5.46 MW (1.61%) accounted for solar energy. The quota of renewable energy was 37.59 MW (11.83%) in 2018. In this latter year, 3.49 MW (1.1%) was met through solar energy. Regarding the contribution of RE to the national energy mix, the shares of hydro and solar were 6.63% and 0.64%, respectively, in 2019, as indicated in Table 1 (ARSE, 2019). Thus, taking the year 2019 as a reference, the country would have to install at least an additional capacity of 339.56 MW before achieving 100% access to electricity under a business as usual scenario. However, the reality is different. The country would have to invest more in electricity production in order to meet the growing energy demand caused by the growing economic development and improved human well-being.

1.5 Current and future renewable energy integration onto the Togolese grid.

The adoption of solar energy as a daily energy source is growing in the country and contributes to the electricity access rate. It can be noticed that individuals use solar panels to charge their mobile phones, light, and pump water. The Togolese government has created an agency in charge of rural electrification and renewable energy (AT2ER) in 2016 to foster the promotion and widespread use

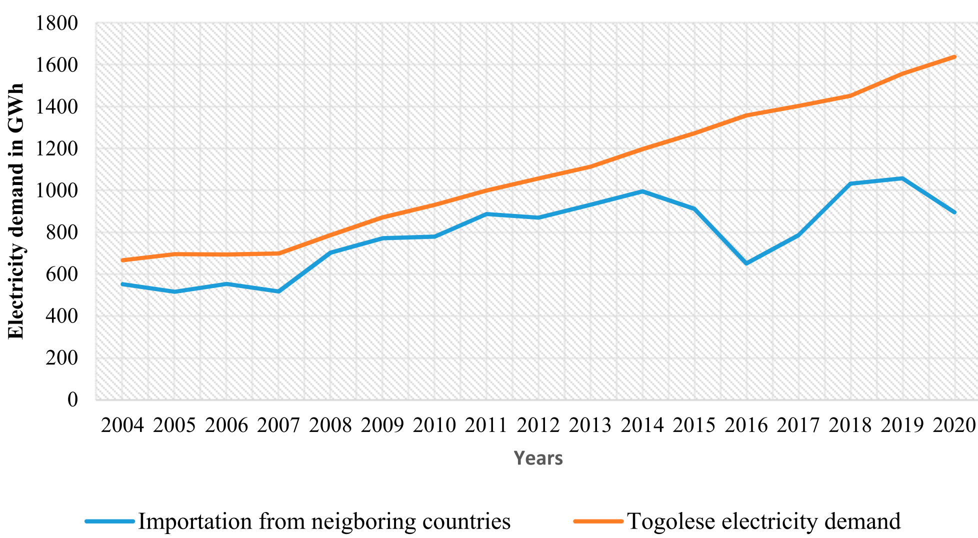

Figure 2. Electricity impartation share in the national electricity balance.

Table 1. Balance of supply sources in the national need for.

	Capacity balance in power demand				Energy mix balance			
	2019		2020		2019		2020	
Sources	Capacity (MW)	%	Capacity (MW)	%	Demand (GWh)	%	Demand (GWh)	%
Thermal	160	47.12	160	44.44	456.83	24.25	523.58	35.16
Hydro	**34.1**	**10.04**	**34.1**	**9.47**	**124.84**	**6.63**	**75.13**	**5.04**
Solar	*5.46*	*1.61*	*6.48*	*1.80*	*12.11*	*0.64*	*14.81*	*1*
Importation	140	41.23	159.46	44.29	862.01	59.21	875.82	58.81
Balance	339.56	100	360.02	100	1455.79	100	1489.34	100

of solar energy, and the following falls in that line. A rural electrification programme, CIZO, was launched in the following year. In 2018, the renewable energy law was voted to promote electricity production based on renewable energy (RT, 2018). Under the CIZO programme, two companies (BBOXX and SOLEVA) were granted licenses to install and sell solar homes systems (SHS) (RT, 2018; World Bank, 2018). In the latter year, the government set up an electrification strategy, where three technologies were chosen to boost the access to electricity. The aim was to achieve a 100% electricity coverage by 2030 through grid-connected systems, mini-grids and SHS (Presidence togolaise, 2018). The mini-grid can be described as a decentralised energy system (DES). The DES could be connected to the national grid in the future if need be. The SHSs are technologies suitable to power an entire household or a small business that are far from the national grid. In addition, the SHSs can be easily deployed and/or scaled up according to the needs of individual households. As a result, three kinds of SHSs were sold; they were (1) Basic system (solar panel, battery, and 3 bulbs), (2) Plus system (solar panel, battery, 4 bulbs, 1 chargeable torch, and 1 radio), and (3) Premium system (solar panel, battery, 4 bulbs, 1 chargeable torch, 1 radio, and 1 TV 24″). The third company, SOLEGIE, was granted also license in 2020. At the end of the latter year, 42924 SHSs were distributed and installed by BBOXX and 2387 by SOLEVA and 4130 by SOLERGIE (ARSE, 2022). Table 2 presents the capacity installed according to the type of system.

RE sub-sector promotion is being ameliorated. The RE law encourages clean electricity production and extends it to consumers in the private sector, but it remains the decree of its application. In addition, mechanisms to regulate the RE sector have been developed. It is possible for power plant and production infrastructure projects to benefit from a tax reduction. In addition, the Togolese off-grid solar market has been assessed; opportunities and barriers have been identified.

Moreover, the electrification strategy indicates:

1. The vision of the Government for universal electricity access,
2. The state of the art in the electricity sector,
3. A new approach to achieve universal electrification, and
4. The national electrification roadmap is developed.

Under that strategy in 2018, projections have been elaborated based on the grid extension, minigrids, and solar homes systems technologies with corresponding investments to attain sustainable

Table 2. Capacity installed according to technology (2020).

Companies	Type of technology	Sites	Installed capacity
CEET	Mini-grids based on solar PV	4 different sites	0.61 MW
	street light	Across the country	3.38 MW
BBOXX – EDF	Solar homes systems	Across the country	2.15 MW
SOLEVA	Solar homes systems	Across the country	0.12 MW
SOLERGIE	Solar homes systems	Across the country	0.21 MW

energy for all goals. Afterward, many power plants are planned, such as AMEA solar power of 50 MW, scaling solar power plant in Sokode of 30–40 MW, scaling solar plant in Kara of 30–40 MW, Tetetou hydropower of 50 MW, and Sarakawa hydropower of 24 MW. AMEA has been constructed and was fully commissioned in 2021, but the data on power produced and transmitted are now yet available to the public.

The country needs to increase its generation capacity to achieve short- and long-term economic development. This fact will, in turn, increase its electricity access rate. Solar PV is one of the most promising alternatives for these economic goals. Therefore, this study focused on assessing solar irradiance and the subsequent PV power yields in Togo. In line with this, developing TMY data is worthwhile for an accurate and appropriate meteorological dataset (Skeiker, 2004). The TMY is a required computer-based building simulation tool to predict the PV performance and, therefore, ensuring efficient policies development (Ohunakin et al., 2018). For instance, a better sizing of photovoltaic (PV) power plants is strictly dependent on the quality of the data.

2. Development of typical meteorological years

All the processes involved in the study are presented in Figure 3. They start from the study area selection to the review of the renewable energy penetration in the Togolese socio-economic context. As it can be seen, the methodology adopted is an integrated approach shown step by step.

2.1 Area of study and data

Five different geographical areas/towns were considered in this study. The five selected towns, located in the five administrative regions of Togo, were: (1) Atakpame, (2) Dapaong, (3) Kara, (4) Lome, and (5) Sokode. Lomé is the capital city of the country and the four other towns are regional capitals. Table 3 presents the selected towns with their respective geographic coordinates.

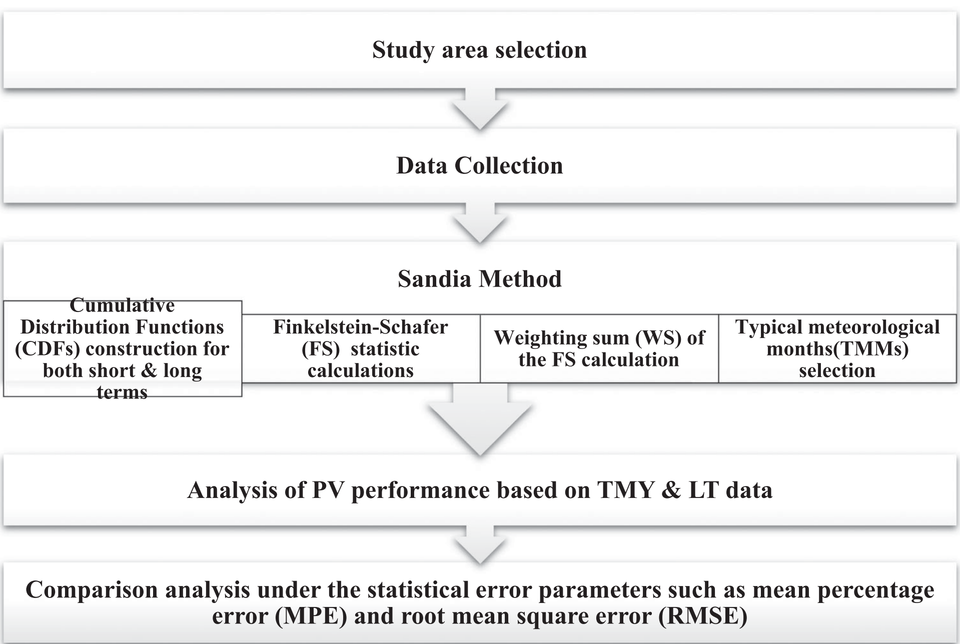

Figure 3. Methodology flowchart.

Table 3. Selected locations.

Towns	Regions	Latitude(deg)	Longitude(deg)	Data range
Atakpame	Plateaux	7.540	1.107	1991–2020
Dapaong	Savanes	10.901	0.206	1991–2020
Lome (capital city)	Maritime	6.133	1.228	1991–2020
Kara	Kara	9.484	1.206	1991–2020
Sokode	Centrale	8.986	1.162	1991–2020

2.2 Data collection

For each town, a set of 30 years of daily weather data from 1991 to 2020 were considered in the study. These data have been derived from MERRA 2 datasets (NASA, 2020). MERRA-2 is produced based on the version 5.12.4 of the Goddard Earth Observing System (GEOS). This system has an approximate resolution of $0.5° \times 0.5°$ (Gelaro et al., 2017). The related missing data had been filled based on linear interpolation using Python. The weather parameters, considered for each location in the present study, consisted of the global solar radiation, mean temperature, maximum temperature, minimum temperature, precipitation, relative humidity, and maximum wind speed. Under the Togolese climate, two weather parameters appeared to be paramount when studying solar energy systems – solar radiation and mean temperature. They were given more importance because of their weighting factors. Thereafter, the global solar radiation was given the highest weighting factor as in Sun et al., (2017). The weighting factors considered in this study are presented in Table 4.

2.3 Sandia's method

The Sandia's approach consists of the selection of individual months from different years in accordance with the period related to the study and the selected sites through a number of steps. In other terms, all the Januarys of the 30 selected years were analyzed and the most typical was selected as the TMY's January. This process was repeated for all the remaining 11 months of the period. The concatenation of these typical 12 months formed the complete TMY. In case the months selected belonged to different years, the discontinuities at the interfaces of those months were smoothened out on each side by 6 h. The steps involved in the process of selecting typical months are summarised as follows:

Step 1: Cumulative Distribution Functions (CDFs) construction

The CDF is constructed for the long-term and the short-term daily mean values for each weather parameter chosen for the study utilising Equation (1) (Sawaqed et al., 2005). The short-term daily mean values represent the daily mean values of a given month in a given year, while the long-term daily mean values stand for the average over the years for each daily mean value in a given month. In a given month of k days, the number of a given weather parameter's values is k. This parameter may assume any given daily values if the probability is h/k. The letter h represents the ranking index.

$$CDFh = \frac{1}{k}h, h = 1, \ 2, \ \ldots, \ k \qquad (1)$$

Step 2: Fintnkelstein-Schafer (FS) statistic calculation

Table 4. Weighting factors.

Parameters	Weighting factor (WF)
1. Global solar radiation	5/12
2. Mean Temperature	2/12
3. Max Temperature	1/12
4. Min Temperature	1/12
5. Precipitation	1/12
6. Relative humidity	1/12
7. Maximum wind speed	1/12

FS statistics are calculated in step 2 through Equation (2). It is consisted of comparing the short-term and the long-term CDFs for each weather parameter. More details regarding the FS statistic calculations can be seen in Fintnkelstein (1971).

$$FS_x = \frac{1}{n}\sum_{i=1}^{n} |CDFm(xi) - CDFy,\, m(xi)| \tag{2}$$

where FS_x (y, m) is the *FS* (y, m) statistics for each weather parameter *x*; *y* represents the year; and *m* is the month. $CDF_{y,m}$ and CDF_m are the short-term and the long-term cumulative distribution functions, in that order, of the weather parameter *x* for the month *m*; and *n* stands for the number of the daily value (i.e. for January $n = 31$).

Step 3: Weighting sum (WS) of the FS calculation.

The weather parameters considered in the study are not equally important, as it can be seen in Table 4. At this step, the weighting sum (WS) of the FS statistics was then determined for each month of the 30 years period by utilising Equation (3). Thus, WS is an aggregation of FS statistics of the seven weather parameters multiplied by their corresponding weighting factor.

$$WS(y, m) = \frac{1}{M}\sum_{x=1}^{M} WFx \cdot FSx(y, m) \tag{3}$$

where *WS (y, m)* is the weighted sum of the FS for the month *m* in the year *y*. *WFx* represents the weighting factor of the *x*th weather parameter; and *M* is the number of these weather parameters.

Step 4: Typical meteorological months (TMMs) selection

Finally, 12 typical months from January to December were selected on the basis of their closeness to the long-term's months. The condition of closeness is obtained with the smallest WS. Therefore, the WSs were ranked and the months with the smallest WS were selected as TMMs to form the TMY database.

2.4 Analysis of PV performance based on TMY and LT data

It is a well-known fact that solar energy is highly intermittent, both in time and space (Renné, 2016). Consequently, this variability needs, not only, to be accurately estimated, but also, to be mitigated with an effective energy storage for a massive grid penetration to be seen. Towards this end, the above-generated TMY was subjected to a validation process. Hence, the performance of a grid-connected photovoltaic (PV) system was simulated using the TMY and the long-term daily mean data (LT). The two most important weather parameters considered for the simulation were the global solar radiation and mean ambient temperature. A 3 kW PV system was chosen for the simulation along with a 3.2 kW string inverter. The latter was 95% efficient as reported in (Ohunakin et al., 2018). The solar PV module characteristics are presented in Table 5. The monthly energy output ($E_{ac,\ m}$) was calculated through Equation (4).

$$Eac,\, m = N \cdot \frac{HT}{1\frac{KW}{m^2}} \cdot f_d \cdot P_{rated} \tag{4}$$

where *N* represents the number of days in a month, *HT* is the daily average global solar radiation in kWh/m^2, P_{rated} is the rated capacity of the PV array in kW, and f_d is the PV derating factor in %; and F_d is hosts two factors – temperature related and non-temperature related.

Additionally, the derating factor ($f_{nontemp}$) encompasses the combination of the module's nameplate DC rating, PV system's age, the inverter's efficiency mismatch, the soiling, and the shading. Moreover, an assumption of 77% was made for the non-temperature derating factor. The former

Table 5. Technical specification of MaxPower CS6X-320P.

Parameter	
Cell Type	Poly-Crystalline, 6 inch
Nominal Maximum Power	320 Wp
Optimum Operating Voltage	36.8 V
Optimum Operating Current	8.69 A
Open Circuit Voltage	45.3 V
Short Circuit Current	9.26 A
Module Efficiency	16.68%
Operating Temperature	−40 +85°C
Temperature Coefficient (Pmax)	−0.41%/°C
Temperature Coefficient (Voc)	−0.31%/°C
Temperature Coefficient (Isc)	0.053%/°C
Nominal Operating Cell Temperature	45 ± 2°C
Dimension	1954 × 982 × 40 mm

derating factor (f_{Temp}) results from the difference between the STC reference temperature (25^0C) and cells' temperature, STC being the Standard Test Conditions. Consequently, the f_{Temp} is computed by means of Equation (5).

$$ftemp = 1 + \left[\left(\frac{\varepsilon}{100}\right) \cdot (Tc - Tc,\, STC)\right] \tag{5}$$

where Tc is the PV cell's temperature [^{0}C] and ε module power coefficient [%/^{0}C]; and $T_{c,STC}$ is the PV cell's temperature under 25^0C.

Table 6. Weighting sums of FS statistics calculated for Atakpame with the lowest values in bold.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.40	0.41	0.31	0.48	0.25	0.16	0.13	0.13	0.19	0.09	0.32	0.37
1992	0.15	0.26	0.18	0.28	0.12	0.15	0.11	0.17	0.15	0.15	0.26	0.25
1993	0.67	0.23	0.22	0.38	0.13	0.18	0.09	0.11	0.08	0.11	0.44	0.35
1994	0.17	0.29	0.22	0.41	0.15	0.10	0.17	0.17	0.16	0.10	0.22	**0.14**
1995	0.63	0.27	0.12	0.25	0.13	0.17	0.10	0.21	0.14	**0.07**	0.33	0.22
1996	0.22	**0.17**	0.18	0.33	0.18	0.12	0.14	0.19	0.14	0.11	0.45	0.16
1997	0.20	0.48	0.25	0.45	0.15	0.31	0.23	0.17	0.10	0.11	0.15	0.27
1998	0.36	0.59	0.24	0.48	0.17	0.16	0.15	0.17	0.18	0.12	0.22	0.39
1999	0.31	0.34	0.12	0.33	0.21	0.24	0.10	0.25	0.09	0.17	0.22	0.24
2000	0.29	0.37	0.25	0.48	0.27	0.18	0.10	0.15	0.16	0.13	**0.09**	0.38
2001	0.46	0.41	0.13	0.30	**0.09**	0.15	**0.08**	0.14	0.14	0.16	0.20	0.21
2002	0.56	0.33	0.18	0.38	0.15	0.19	0.12	0.12	0.14	0.12	0.29	0.39
2003	0.34	0.33	0.23	0.44	0.29	**0.08**	0.16	0.12	0.14	0.10	0.18	0.25
2004	0.32	0.36	0.19	0.39	0.17	0.13	0.10	0.16	0.08	0.12	0.18	0.34
2005	0.37	0.39	0.20	0.38	0.13	0.21	0.12	0.11	0.17	0.16	0.19	0.28
2006	**0.14**	0.34	0.14	0.26	0.24	0.16	0.13	0.27	**0.07**	0.12	0.30	0.43
2007	0.51	0.66	0.22	0.46	0.26	0.14	0.29	0.13	0.18	0.20	0.18	0.38
2008	0.46	0.22	0.24	0.39	0.16	0.12	0.09	0.10	0.14	0.12	0.14	0.36
2009	0.47	0.40	0.25	0.48	0.32	0.14	0.11	0.13	0.14	0.27	0.21	0.25
2010	0.15	0.37	0.21	0.30	0.14	0.17	0.21	0.13	0.13	0.15	0.10	0.26
2011	0.40	0.34	0.17	0.37	0.15	0.08	0.20	0.16	0.15	0.14	0.13	0.16
2012	0.26	0.19	0.34	0.45	0.14	0.16	0.15	0.12	0.14	0.22	0.15	0.20
2013	0.33	0.36	0.13	0.24	0.10	0.18	0.15	0.20	0.09	0.09	0.33	0.27
2014	0.24	0.39	0.18	0.39	0.13	0.22	0.13	0.15	0.09	0.08	0.24	0.33
2015	0.43	0.35	0.31	0.31	0.17	0.20	0.18	0.12	0.15	0.16	0.22	0.43
2016	0.28	0.48	0.23	0.41	0.19	0.17	0.14	0.11	0.09	0.21	0.25	0.26
2017	0.27	0.63	0.11	0.31	0.10	0.12	0.17	**0.07**	0.12	0.17	0.35	0.24
2018	0.41	0.36	**0.10**	**0.24**	0.19	0.21	0.18	0.21	0.16	0.10	0.20	0.35
2019	0.29	0.40	0.17	0.41	0.16	0.23	0.14	0.12	0.12	0.11	0.16	0.23
2020	0.38	0.30	0.15	0.36	0.15	0.17	0.18	0.25	0.15	0.16	0.33	0.18

Table 7. Weighting sums of FS statistics calculated for Dapaong with the lowest values in bold.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.09	0.45	0.17	0.27	0.23	0.14	0.11	**0.09**	0.13	0.16	0.33	0.69
1992	0.20	0.17	0.64	0.31	0.22	0.15	**0.07**	0.21	0.12	0.14	0.35	0.08
1993	0.16	0.35	0.47	0.26	0.14	0.20	0.10	0.21	**0.08**	0.14	0.44	0.76
1994	0.27	0.56	0.12	0.16	0.16	0.20	0.17	0.12	0.18	0.20	0.39	0.10
1995	0.13	0.45	0.24	0.18	0.15	0.10	0.16	0.19	0.16	**0.08**	0.24	0.34
1996	0.22	0.26	0.46	0.13	0.16	0.13	0.12	0.22	0.09	0.15	0.12	0.48
1997	0.41	0.49	0.47	0.12	0.21	0.21	0.16	0.15	0.13	0.13	0.22	0.68
1998	0.58	0.98	0.36	0.26	0.11	0.12	0.12	0.14	0.18	0.12	0.44	0.52
1999	0.30	0.44	0.38	0.16	0.11	0.11	0.14	0.22	0.12	0.18	0.31	0.11
2000	0.44	0.11	0.35	0.12	0.18	0.14	0.08	0.26	0.16	0.15	0.20	0.18
2001	0.10	0.16	0.34	0.18	0.16	0.13	0.23	0.11	0.08	0.31	0.43	0.15
2002	0.51	0.23	0.22	0.40	0.12	0.18	0.15	0.12	0.13	0.26	0.34	0.14
2003	0.36	0.50	0.35	0.19	0.35	0.13	0.15	0.12	0.11	0.09	0.30	0.10
2004	0.28	0.34	**0.12**	0.17	0.15	0.15	0.12	0.15	0.18	0.20	0.24	0.33
2005	0.48	0.41	0.32	0.11	0.15	0.10	0.15	0.12	0.19	0.23	0.34	0.58
2006	0.44	0.58	0.21	0.24	0.19	0.15	0.17	0.13	0.20	0.09	0.38	0.13
2007	0.15	0.86	0.50	**0.11**	0.21	0.23	0.20	0.11	0.21	0.51	0.17	0.77
2008	0.50	0.30	0.21	0.26	0.24	0.38	0.19	0.11	0.11	0.15	0.45	0.68
2009	0.36	0.49	0.16	0.16	0.24	0.22	0.09	0.12	0.15	0.33	0.23	0.44
2010	0.31	0.52	0.35	0.18	0.09	0.18	0.11	0.12	0.13	0.13	0.20	0.08
2011	0.49	0.49	0.26	0.17	**0.09**	0.12	0.16	0.13	0.14	0.15	0.21	0.08
2012	0.24	0.28	0.29	0.25	0.19	0.13	0.12	0.18	0.11	0.21	0.20	0.48
2013	0.33	0.41	0.17	0.16	0.10	0.13	0.14	0.12	0.15	0.14	0.54	0.59
2014	0.21	0.38	0.41	0.21	0.26	0.22	0.09	0.26	0.12	0.15	**0.10**	0.07
2015	0.27	0.47	0.36	0.37	0.13	**0.10**	0.15	0.09	0.16	0.11	0.32	**0.06**
2016	0.11	0.41	0.29	0.32	0.20	0.21	0.13	0.10	0.09	0.15	0.25	0.43
2017	**0.06**	0.97	0.26	0.25	0.11	0.19	0.12	0.12	0.12	0.28	0.49	0.08
2018	0.07	0.48	0.24	0.16	0.16	0.18	0.15	0.11	0.30	0.11	0.20	0.08
2019	0.25	0.96	0.33	0.20	0.11	0.20	0.21	0.19	0.12	0.12	0.19	0.08
2020	0.12	**0.10**	0.23	0.19	0.20	0.16	0.15	0.17	0.21	0.21	0.73	0.57

It is worth pointing out that the aforementioned Tc was estimated by Duffie and Beckman (1982). As a result, Tc can be estimated through Equation (6).

$$Tc = Ta + \left[\left(\frac{9.5}{5.7 + 3.8 \cdot V}\right) \cdot \left(\frac{TcNOCT - Ta,\, NOCT}{GT,\, NOCT}\right) \cdot GT\right] \tag{6}$$

where Ta is the ambient temperature [K]; V is wind speed of the location in m/s; $T_{c,NOCT}$ is the nominal operating cell's temperature [K]; $T_{a,NOCT}$ represents the ambient temperature at which the $NOCT$ is defined (20^{0}C); $G_{T,NOCT}$ equals 0.8 KW/m^2 (solar radiation at which the $NOCT$ is defined); and G_T is the solar irradiation in kW/m^2.

Finally, the overall derating factor is calculated with the help of Equation (7).

$$f_d = f_{nontemp} \cdot f_{temp} \tag{7}$$

2.5 Comparison analysis under the statistical error parameters such as mean percentage error (MPE) and root mean square error (RMSE)

A long-term (LT) evaluation and comparison of the PV system's output were conducted utilising the generated TMY. The methodology was based on the statistical error parameters, such as mean percentage error (MPE), mean bias error (MBE), and root mean square error (RMSE) (Ohunakin et al., 2018). The MPE measured the average percentage bias between predicted values (TMY) and observed values (LT) by providing more insight about any over-estimation and under-estimation of the TMY. The RMSE is mainly concerned about the standard deviation of the differences between the TMY and LT values. It clearly measures with accuracy the predictions. Additionally, the RMSE informs on the correlations of the short-term performance that result into comparisons of the term-

Table 8. Weighting sums of FS statistics calculated for Kara with the lowest values in bold.

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.41	0.42	0.28	0.25	0.27	0.17	0.10	0.10	0.22	**0.08**	0.21	0.40
1992	0.19	0.66	0.21	0.21	0.12	0.16	0.19	0.16	0.14	0.12	0.32	0.39
1993	0.15	0.29	0.31	0.21	0.14	0.18	**0.10**	0.13	0.11	0.13	0.46	0.52
1994	0.26	0.30	0.15	0.17	0.20	0.14	0.13	0.13	0.17	0.17	0.32	0.10
1995	0.67	0.49	0.23	0.16	0.14	0.18	0.13	0.14	0.15	0.13	0.27	0.22
1996	0.27	**0.24**	0.29	0.14	0.21	0.16	0.12	0.24	0.12	0.15	0.53	0.29
1997	0.36	0.49	0.29	0.17	0.16	0.10	0.18	0.24	0.17	0.13	0.17	0.31
1998	0.52	0.75	0.33	0.29	0.11	0.17	0.17	0.15	0.21	0.16	0.26	0.40
1999	0.27	0.41	0.17	0.22	0.13	0.14	0.12	0.16	0.15	0.11	0.16	0.54
2000	0.54	0.31	0.37	**0.09**	0.28	0.16	0.10	0.29	0.17	0.11	0.16	0.42
2001	0.50	0.35	0.21	0.20	0.12	0.13	0.18	0.12	0.16	0.18	0.23	0.09
2002	0.54	0.37	0.18	0.25	0.13	0.16	0.16	0.10	0.11	0.22	0.26	0.44
2003	0.39	0.45	0.29	0.19	0.32	0.10	0.13	0.14	0.16	0.12	0.30	0.19
2004	0.31	0.38	0.29	0.12	0.15	0.17	0.12	0.12	0.15	0.10	0.17	0.42
2005	0.41	0.37	0.30	0.16	0.18	0.12	0.22	0.12	0.20	0.27	0.22	0.30
2006	0.23	0.38	0.11	0.24	0.25	0.18	0.17	0.16	0.14	0.14	0.35	0.53
2007	0.52	0.81	0.44	0.20	0.29	0.17	0.18	0.14	0.15	0.25	0.18	0.47
2008	0.45	0.26	0.20	0.25	0.13	0.15	0.12	0.12	0.16	0.12	0.24	0.40
2009	0.45	0.41	0.33	0.18	0.33	0.11	0.13	0.18	0.12	0.33	0.22	0.32
2010	0.21	0.39	0.26	0.17	0.28	0.13	0.16	0.12	0.16	0.15	0.20	0.39
2011	0.50	0.36	0.18	0.13	0.11	**0.09**	0.15	**0.10**	0.15	0.14	0.20	0.12
2012	0.34	0.24	0.47	0.24	0.19	0.15	0.16	0.14	0.18	0.28	**0.13**	0.37
2013	0.34	0.40	0.12	0.13	**0.10**	0.13	0.23	0.19	0.13	0.13	0.47	0.28
2014	0.46	0.43	0.26	0.22	0.16	0.19	0.14	0.21	0.13	0.12	0.15	0.38
2015	0.47	0.47	0.43	0.29	0.17	0.18	0.16	0.20	**0.11**	0.13	0.33	0.07
2016	0.15	0.44	0.22	0.27	0.24	0.29	0.14	0.10	0.14	0.13	0.20	0.34
2017	0.27	0.87	0.24	0.18	0.16	0.23	0.14	0.13	0.15	0.28	0.46	0.21
2018	**0.05**	0.50	0.15	0.19	0.15	0.19	0.20	0.19	0.23	0.15	0.20	**0.07**
2019	0.37	0.39	0.18	0.18	0.13	0.28	0.19	0.14	0.19	0.16	0.25	0.35
2020	0.43	0.32	0.16	0.14	0.17	0.16	0.15	0.32	0.13	0.21	0.73	0.27

by-term differences between the predicted and observed values. The predictions were good for smaller errors. Hence, the MPE and RMSE are expressed as in Equation (8) and Equation (9), in that order.

$$MPE = \frac{100\%}{\mathrm{n}} \sum_{i=1}^{n} \frac{LTi - TMYi}{LTi} \tag{8}$$

$$RMSE = \sqrt{\sum_{I=1}^{n} \frac{(TMYi - LTi)^2}{n}} \tag{9}$$

where LTi and $TMYi$ are, respectively, the long-term and developed TMY variables.

3. Results and discussions

3.1 Typical meteorological year (TMY)

Weather parameters were used in the study to construct the TMY for five selected Towns in Togo. In selecting the typical meteorological months, the indices with the highest weighting factor, such as global solar radiation and mean temperature, were utilised. The values of WS of the FS statistics of the five (5) selected locations over a span of 30 years were calculated and presented in Tables 6–10. The months with the lowest WS were selected for each month in the various years as the typical meteorological months (TMMs) over the study period. Furthermore, these selected months were written in bold as can be seen from the aforementioned tables. The bold months then automatically formed the Togolese TMY. It is worthy of note to point out that, due to similar weather patterns, the

Table 9. Weighting sums of FS statistics calculated for Lomé with the lowest values in bold.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.46	0.33	0.28	0.19	0.22	0.16	0.17	0.19	0.15	0.11	0.28	0.41
1992	**0.09**	0.26	0.25	0.16	0.15	0.17	0.12	0.25	0.15	0.15	0.23	0.19
1993	0.46	0.27	0.18	0.16	0.12	0.14	0.18	0.17	**0.08**	0.12	0.35	0.36
1994	0.28	0.30	0.23	0.22	0.21	0.20	0.16	0.29	0.14	0.13	0.24	**0.12**
1995	0.50	0.39	0.11	0.20	0.21	0.20	0.16	0.24	0.12	0.13	0.45	0.17
1996	0.18	**0.12**	0.10	0.19	0.15	0.15	0.23	0.17	0.15	0.16	0.53	0.12
1997	0.32	0.45	0.18	0.15	0.15	0.16	0.28	0.20	0.21	0.10	0.28	0.21
1998	0.46	0.53	0.19	0.20	0.17	0.13	0.17	0.28	0.19	0.16	0.20	0.21
1999	0.28	0.37	0.08	0.15	0.28	0.31	0.13	0.32	0.09	0.17	0.22	0.24
2000	0.21	0.31	0.22	**0.11**	0.12	0.25	0.16	0.24	0.19	0.15	0.11	0.29
2001	0.28	0.48	0.18	0.12	**0.09**	0.18	0.20	0.20	0.13	0.16	0.20	0.13
2002	0.46	0.32	0.15	0.19	0.14	0.23	0.18	0.18	0.16	0.09	0.21	0.32
2003	0.22	0.32	0.18	0.19	0.17	0.16	0.23	0.14	0.16	0.12	**0.10**	0.20
2004	0.29	0.23	0.19	0.12	0.22	0.32	0.13	0.16	0.14	0.15	0.26	0.29
2005	0.55	0.30	**0.06**	0.18	0.17	0.18	0.19	0.32	0.21	0.10	0.21	0.26
2006	0.18	0.29	0.11	0.20	0.22	0.13	0.17	0.32	0.16	0.16	0.32	0.37
2007	0.51	0.57	0.24	0.29	0.16	0.15	0.28	0.17	0.26	0.10	0.18	0.29
2008	0.42	0.23	0.33	0.25	0.22	0.12	0.30	0.19	0.11	0.16	0.17	0.35
2009	0.34	0.37	0.22	0.14	0.33	0.28	**0.11**	0.16	0.15	0.25	0.25	0.22
2010	0.14	0.39	0.15	0.12	0.18	0.18	0.27	0.15	0.13	0.10	0.12	0.20
2011	0.22	0.34	0.13	0.13	0.12	0.18	0.20	0.19	0.20	0.17	0.15	0.28
2012	0.41	0.17	0.24	0.12	0.19	0.27	0.18	0.16	0.25	0.19	0.21	0.16
2013	0.41	0.31	0.14	0.13	0.10	0.22	0.17	0.22	0.12	**0.07**	0.21	0.28
2014	0.14	0.24	0.18	0.13	0.14	0.24	0.19	0.17	0.10	0.10	0.31	0.32
2015	0.41	0.43	0.29	0.27	0.20	0.19	0.31	0.16	0.25	0.14	0.27	0.41
2016	0.25	0.39	0.15	0.14	0.17	0.25	0.18	0.16	0.16	0.18	0.18	0.21
2017	0.31	0.33	0.15	0.17	0.15	0.19	0.15	**0.08**	0.13	0.08	0.26	0.23
2018	0.34	0.44	0.08	0.32	0.19	**0.12**	0.16	0.22	0.16	0.11	0.11	0.15
2019	0.41	0.30	0.17	0.13	0.18	0.13	0.20	0.19	0.15	0.17	0.17	0.20
2020	0.34	0.37	0.16	0.15	0.16	0.27	0.23	0.23	0.15	0.09	0.17	0.15

researchers, investors, and lawmakers of the neighbouring countries — Benin, Ghana, and Burkina Faso – may greatly benefit from this TMY.

In summary, the bold months were all compiled in Table 11, which presents the TMY generated for each of the selected towns. As it can be noticed from Table 11, the TMMs are evenly spread within the study's period across the locations.

The divergence of the TMY and LT was then analyzed based on the performance indicators (MPE and RMSE) considering the global solar radiation parameter. Table 12 presents the results of the analysis for the two main parameters. In that table, one can see the extent of the difference between the two values. The values of TMY are slightly higher than the values of LT for Dapaong, Kara, Lome and Sokode (MPE < 0); slightly lower than the values of LT for Atakpame (MPE > 0).

In the case of Sokode, the MPE varies between −8.12% and 13.34% throughout the typical meteorological months. TMY overestimated the LT in January, March, April, May, September, October, and December. This same TMY underestimated their counterpart's LT in the rest of the months, thus resulting in a negative mean bias error of −0.03% inferior to 1%. With that percentage of error, it could be assumed that there is good agreement between predictions from the TMY and the corresponding long-term means. As such, the developed TMY could be considered as appropriated weather database for the study and sizing of renewable energy, especially solar energy system and therefore, be useful for designers of solar energy systems and researchers.

In general, the TMY fits the LT for the global solar irradiation in the selected towns as it can be seen in Table 10 with the best fit in Lomé (MPE = −0.26%, RMSE = 0.24), Sokodé (MPE = −0.03%, RMSE = 0.30) and Dapaong (MPE = −1.09%, RMSE = −0.32). It is followed by the mean temperature and in case of Sokodé (MPE = 0.77%, RMSE = 0.55). The MPE and RMSE for the rest of parameters in the latter location were relative humidity (MPE = −4.8%. RMSE = 6.73), precipitation (MPE = −4.96%. RMSE = 29.37) and maximum wind speed (MPE = 1.32%. RMSE = 0.47). The

Table 10. Weighting sums of FS statistics calculated for Sokode with the lowest values in bold.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	0.40	0.45	0.28	0.17	0.22	0.17	0.10	0.13	0.23	0.10	0.23	0.35
1992	0.17	0.58	0.17	0.22	0.12	0.15	0.15	0.17	0.15	0.13	0.30	0.36
1993	0.16	0.27	0.28	0.20	0.16	0.15	0.12	0.11	0.10	0.12	0.46	0.46
1994	0.23	0.28	0.18	0.18	0.17	0.12	0.15	0.11	0.15	0.13	0.28	0.13
1995	0.68	0.48	0.18	0.18	0.16	0.17	0.16	0.13	0.13	0.11	0.26	0.22
1996	0.26	**0.21**	0.28	0.15	0.21	0.11	0.13	0.22	0.14	0.13	0.36	0.27
1997	0.24	0.50	0.31	0.15	0.15	0.12	0.20	0.20	0.15	0.14	0.15	0.31
1998	0.48	0.69	0.34	0.27	0.13	0.17	0.15	0.13	0.19	0.16	0.25	0.44
1999	0.25	0.39	0.15	0.16	0.16	0.13	0.11	0.16	0.12	0.11	0.20	0.54
2000	0.53	0.32	0.32	**0.08**	0.34	0.14	0.08	0.22	0.15	**0.08**	0.14	0.40
2001	0.50	0.34	0.18	0.17	0.11	0.12	0.13	0.12	0.15	0.21	0.22	0.09
2002	0.60	0.38	0.18	0.20	0.17	0.15	0.16	0.13	**0.10**	0.20	0.27	0.43
2003	0.38	0.42	0.26	0.16	0.28	0.09	0.13	0.14	0.15	0.13	0.29	0.22
2004	0.30	0.40	0.25	0.11	0.18	0.12	0.09	0.18	0.11	0.10	0.23	0.35
2005	0.36	0.38	0.27	0.21	0.20	0.16	0.21	0.12	0.21	0.22	0.18	0.26
2006	0.19	0.36	0.12	0.28	0.26	0.16	0.19	0.19	0.11	0.12	0.32	0.51
2007	0.53	0.75	0.39	0.21	0.30	0.16	0.22	0.18	0.19	0.23	0.19	0.44
2008	0.44	0.23	0.20	0.24	0.14	0.16	0.11	0.12	0.17	0.12	0.23	0.37
2009	0.46	0.41	0.30	0.19	0.35	0.15	**0.15**	0.14	0.14	0.28	0.21	0.31
2010	0.22	0.39	0.23	0.17	0.25	0.15	0.18	0.12	0.15	0.16	0.21	0.46
2011	0.48	0.42	0.20	0.12	0.12	**0.09**	0.18	0.11	0.12	0.16	0.19	0.14
2012	0.31	0.24	0.47	0.20	0.18	0.16	0.16	0.13	0.14	0.29	**0.10**	0.31
2013	0.32	0.39	**0.09**	0.17	0.12	0.17	0.21	0.15	0.13	0.11	0.45	0.27
2014	0.39	0.45	0.21	0.19	0.18	0.18	0.12	0.24	0.16	0.11	0.17	0.35
2015	0.44	0.44	0.35	0.29	0.15	0.17	0.20	0.16	0.14	0.11	0.33	0.46
2016	0.47	0.50	0.20	0.29	0.23	0.24	0.12	**0.10**	0.12	0.14	0.22	0.32
2017	0.25	0.83	0.19	0.10	0.17	0.19	0.14	0.11	0.21	0.26	0.43	0.23
2018	**0.06**	0.43	0.12	0.20	0.11	0.19	0.16	0.20	0.22	0.13	0.24	**0.05**
2019	0.30	0.47	0.20	0.21	**0.11**	0.31	0.20	0.12	0.16	0.18	0.24	0.29
2020	0.41	0.31	0.15	0.14	0.21	0.20	0.16	0.29	0.15	0.20	0.62	0.24

Table 11. Generated typical meteorological years for selected Towns.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ATAKPAME											
2006	1996	2018	2018	2001	2003	2001	2017	2006	1995	2000	1994
DAPAONG											
2017	2020	2004	2007	2011	2015	1992	1991	1993	1995	2014	2015
KARA											
2018	1996	2006	2000	2013	2011	1993	2011	2015	1991	2012	2018
LOME											
1992	1996	2005	2000	2001	2018	2009	2017	1993	2013	2003	1994
SOKODE											
2018	1996	2013	2000	2019	2011	2000	2016	2002	2000	2012	2018

Table 12. Performance indicators of the TMY and LT average of the main weather parameters.

	Indicators	Atakpame	Dapaong	Kara	Lome	Sokode
Global solar irradiation	MPE (%)	1.55	−1.09	−1.89	−0.26	−0.03
	RMSE	0.21	0.32	0.27	0.24	0.3
Mean temperature	MPE (%)	0.75	−0.91	0.76	0.67	0.77
	RMSE	0.88	1.01	0.49	0.47	0.55
Mean wind speed	MPE (%)	−5.12	−7.3	1.31	−0.95	0.54
	RMSE	0.37	0.77	0.51	0.23	0.38
PV energy system output	MPE (%)	1.55	−1.09	−1.89	0.2	−0.03
	RMSE	14.68	22.94	19.14	15.93	21.37

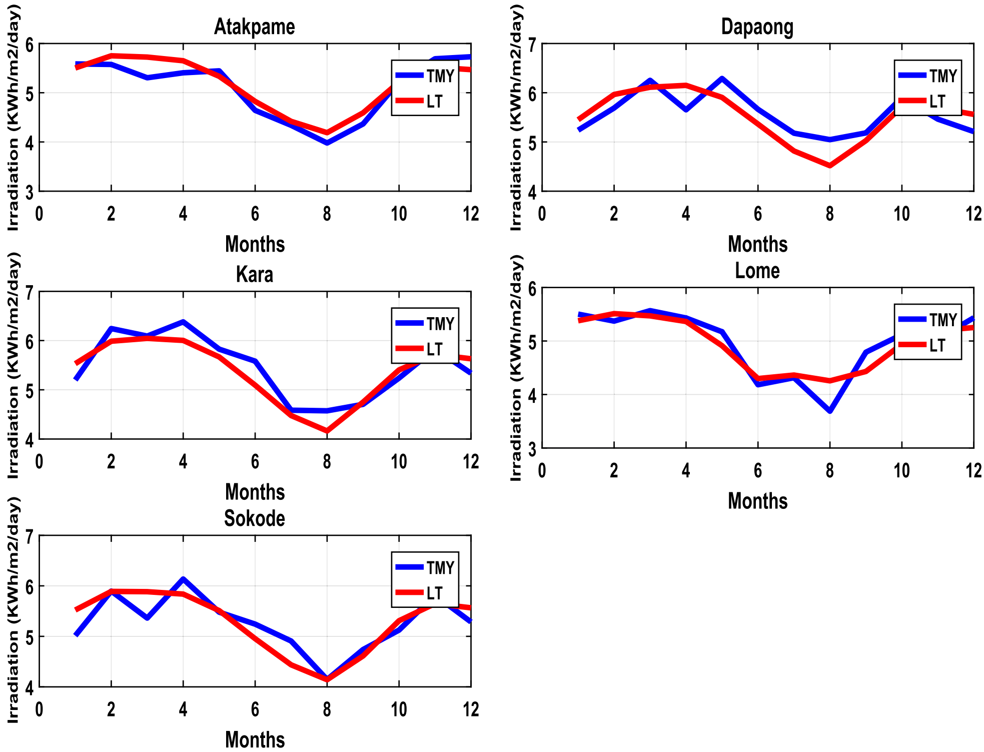

Figure 4. Global solar irradiation for the five locations.

difference in the results related to the two weather parameters might be attributed to the importance of the global solar irradiation being assigned with a major weighting factor of 5/12 in comparison with the second with a factor of 2/12. It is important to point out that the rest of the parameters were ascribed with a weighting factor of only 1/12. Derived from the TMYs, the daily mean global solar irradiation (kWh/m2/day) in Atakpame, Dapaong, Kara, Lome and Sokode is 5.11, 5.56, 5.46, 4.97, 5.26, respectively. With the close variation observed between the two kinds of data for each location, the TMYs could well represent their climate and be used as input for the performance's study of renewable energy systems in the aforementioned towns and the surroundings.

Figure 4 represents the climatological variation of global solar irradiation for the five locations using the TMY vs LT, whereas Figures 5 and 6 illustrate the mean temperature and wind speed variations of TMY vs LT for the selected towns. A close variation is observed between the monthly average values of TMY versus LT for all the locations as presented in Figures 4–6 based on most important weather parameters (global solar irradiation, the mean temperature and mean wind speed). This could be explained by the small values of the FS statistics as well as the close fit of TMY and LT CDFs.

The variation of TMY vs LT of other weather variables considered for Sokode is presented in Figure 7. It can also be observed that, precipitation, relative humidity at 2 m, minimum and maximum temperature at 2 m, maximum, minimum and mean wind speed at 50 m present almost a same pattern in their trend under TMY vs LT. It is, therefore, resulted in a close variation between TMY and LT.

3.2 Performance of the PV system

The PV system's performance had been analyzed under typical weather conditions of Sokode, the city chosen, as case study. Monthly PV system's output of 3 KW was simulated using the generated TMY and LT data. The results are presented in Figure 8. The curves related to the two data were

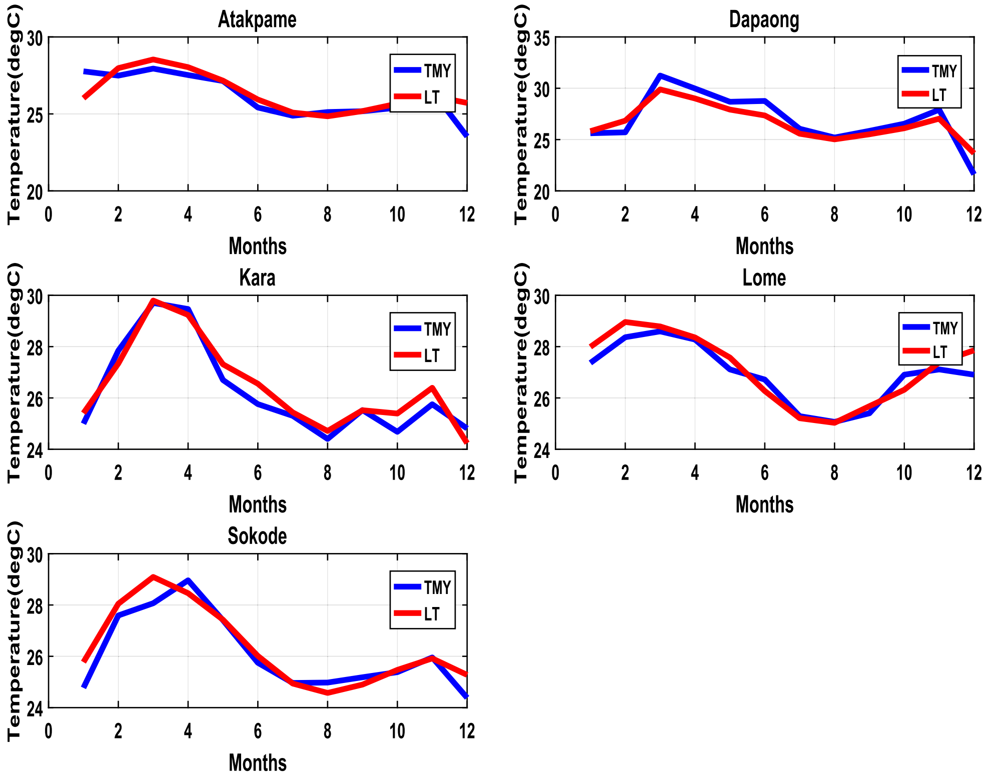

Figure 5. Mean temperature for the five locations.

found to closely follow the same trend. Nevertheless, it can be observed that the PV system generated less energy when using the TMY values than the LT data for the same year. The exceptions to the rule can be remarked for the months of February, April, June, July, August, September and November. The MPE varied between −10.62% in July and 9.11% in January. A value of −0.011% was obtained in February and August of the same year. The overall MPE of Sokode was −0.03%. On an annual basis, the energy generated by the LT and TMY data were 1.486 and 1.481 MWh/kWc, respectively. A surplus of 4.61 kWh in favour of the LT was achievable. Accordingly, it could be realised that the PV system underperformed when the TMY data were fed in the annual energy simulator compared to the energy production based on LT mean values in Sokode. The overall RMSE values calculated for Sokode was 21.37 kWh, which represented 0.31%. The TMY database also underestimated the PV's output in Atakpame and Lome with an MPE of 1.55% and 0.2%, respectively. In general, the RMSE calculated for the five aforementioned sites were 14.68 kWh (0.34%), 22.94 kWh (0.49%), 19.14 kWh (0.41%), 15.93 kWh (0.38%), 21.37 kWh (0.48%) in that order. Also, the PV system's performance, when TMY is fed in, was compared with existing experimental results.

An experiment had been conducted in 2019 under Lome real conditions with two solar modules from different technologies: (1) polycrystalline silicon (pc-Si) and (2) amorphous silicon (a-Si) by (TCHAKPEDEOU, 2022) while the technology under consideration in the study is polycrystalline (MaxPower CS6X-320P). The results show that the energy produced monthly by the pc-Si technology varies between 117.55 kWh/kWp in June and 153.71 kWh/kWp in March while the a-Si technology production varies between 112.55 kWh/kWp in June and 146.45 kWh/kWp in March. The two technologies generated annually 1.67 and 1.59 MWh/kWp in that order. Considering the PV system output simulation based on TMY data, the system's monthly energy generation varies

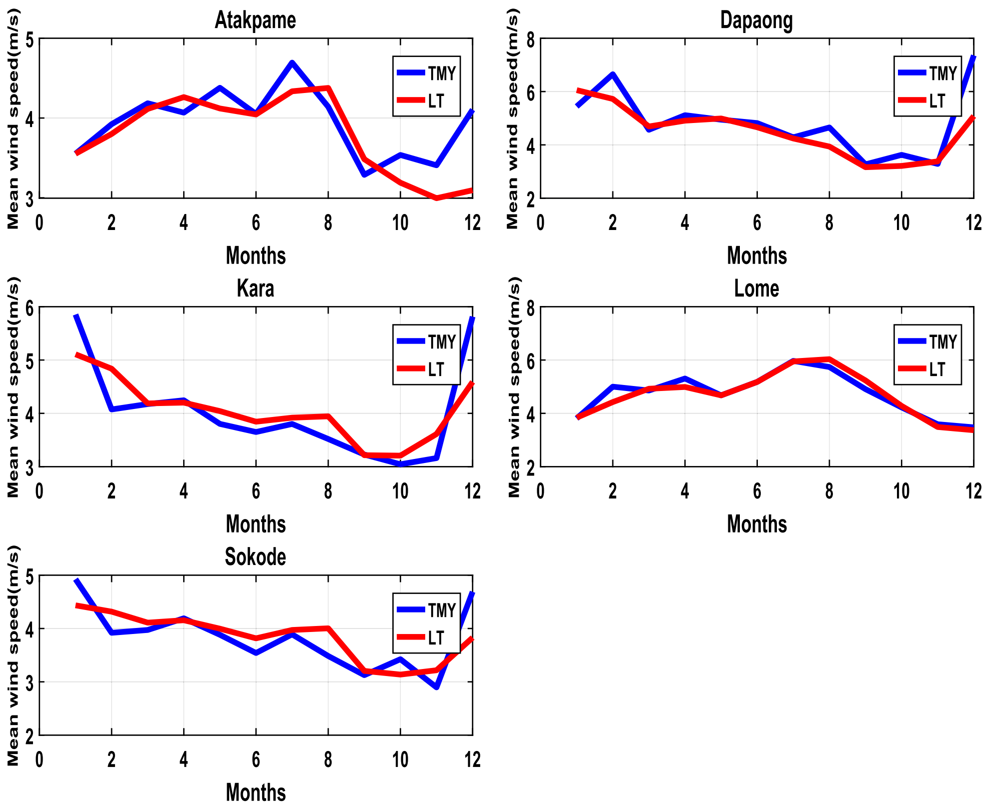

Figure 6. Mean wind speed for the five locations.

between 88.03 kWh/kWp in June and 132.887 kWh/kWp in March with an annual production of 1.393 MWh/kWp. On an annual basis, the difference between the performance of the PV system output based on the TMY data and the two technologies under actual meteorological conditions in Lome in 2019 is 0.187 and 0.007 MWh/kWp, respectively. Accordingly, the TMY data could allow simulating of the pc-Si and a-Si PV systems output at 87.53% and 95%, respectively.

Togo presents acceptable conditions for renewable energy production. The country is characterised by insolation of 5.27 kWh/m^2/day, 1238.21 mm of average annual precipitation, and 7 m/s of mean wind speed at 50 m above the ground. However, clean energy represents a meagre percentage of hydropower and solar energy. A rigorous clean energy production planning strategy and a subsequent investment in the renewable sector under a favourable environment (political, social, …) could accelerate a massive RE deployment across the country by increasing:

a) Decentralised PV mini/micro-grid construction to supply rural areas,
b) PV power plants a part from AMEA plant,
c) Micro hydropower, as the country possesses potential sites, and
d) Wind plant near the sea.

4. Conclusion

RE penetration in the Togolese energy mix is still very low. The hydropower and solar energy are the main RE produced. With a total installed capacity of 360.02 MW in 2020, 40.58 MW (11.27%) was renewable out of which 6.48 MW (1.8%) was solar and 34.1 MW was hydro (9.47%). This study

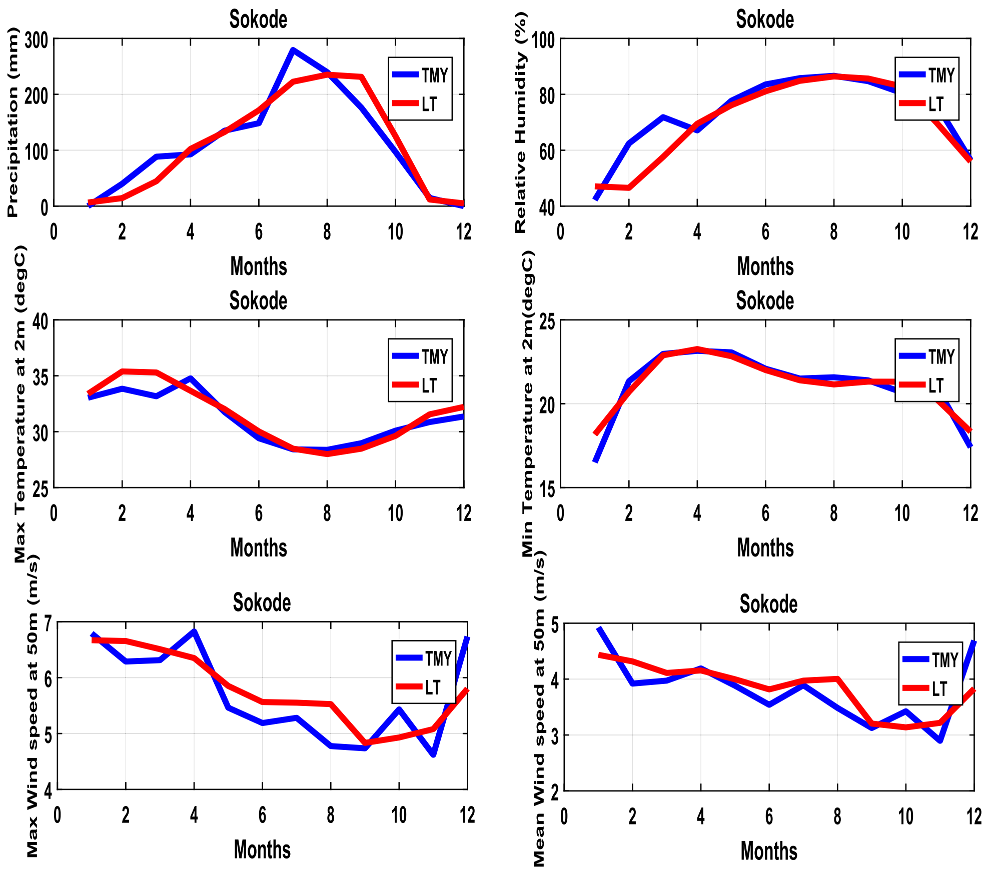

Figure 7. Other considered weather variables for Sokode.

is intended to build up a clear climatic picture of the five principal towns in Togo: Atakpame, Dapaong, Kara, Lome, and Sokode. A typical meteorological year (TMY) data were generated for annual renewable energy output estimation and analysis. This approach serves as an alternative to the missing weather data, which causes potential issues and barriers in the juvenile field of R&D. The TMY is a set of 12 months' data that clearly describe most of the insolation patterns at the selected sites. For this study, the Sandia method was utilised due to its popularity and simplicity based on Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) datasets. The following seven (7) weather variables were considered: (1) global solar radiation, (2) mean temperature, (3) maximum temperature, (4) minimum temperature, (5) precipitation, (6) relative humidity, and (7) maximum wind speed. The global solar irradiation was allocated with the most importance. The methodological process followed consisted of constructing the cumulative distribution function of the short and long terms, the Finkelstein-Schafer statistics calculation, the weighting sums calculation, and the selection of the typical meteorological months to form the TMY. In addition, a PV system performance had been simulated using the generated TMY and the long-term average data (LT). Finally, the constructed TMY, the LT data, and the PV system output were subjected to the mean percentage error and the root mean square error analysis. As a result, the TMY and LT were determined and presented a close variation under the weather conditions of the sites with a particular closeness in Sokode. The analysis of MPE and RMSE allowed to observe that the divergence between TMY and LT is quite better for global solar irradiation and mean temperature compared to other variables. This could be attributed to the importance given to each variable and their respective assigned weighting factors. In general, the PV energy system

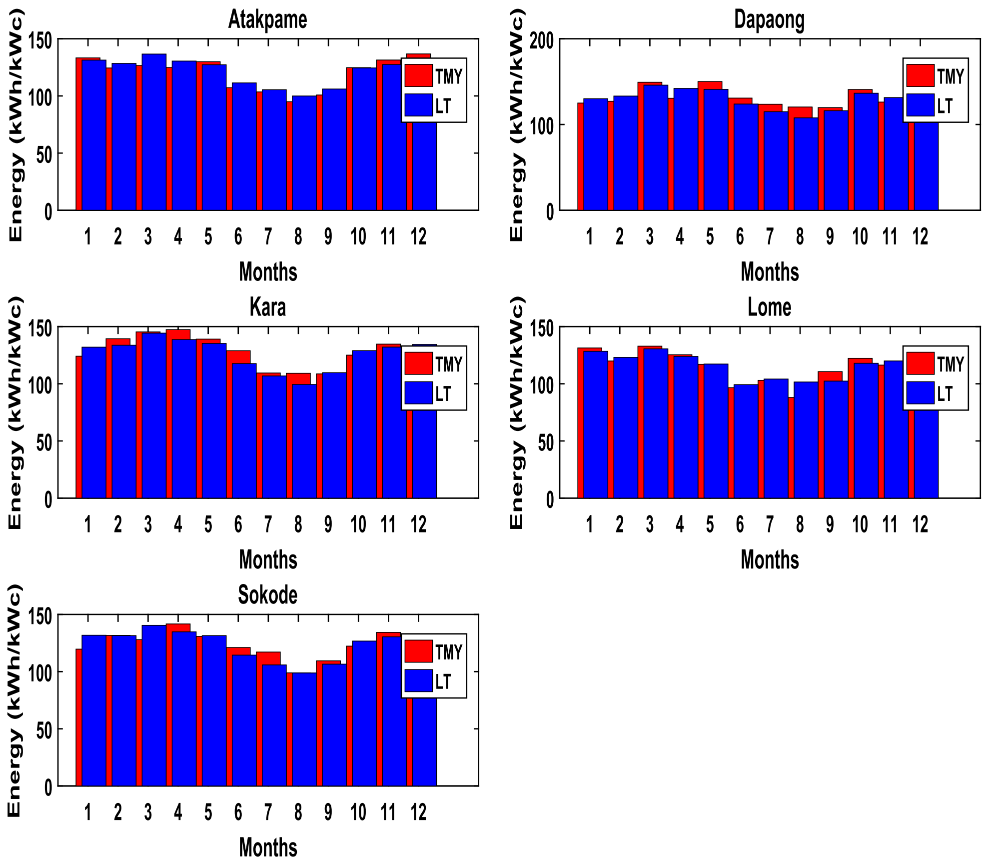

Figure 8. Monthly average energy produced by a grid-connected PV system for the five locations.

output based-TMY and the PV energy system output LT-based presented the same trend with a slight underestimation under the TMY data. The TMY data was able to predict the performance of the PV system to within 2% (<5%) for the long-term data in all the selected towns and to 0.85% in average. With the generated TMY weather variables, any government energy agencies, professionals, utility companies, and researchers in any of the chosen towns, may characterise the performance of their renewable energy systems before deployment. Therefore, the novel TMY permits not only an adjustment at the planning stage to be made, but allows also any future PV systems to be effectively sized in order to gain full benefit.

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