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ANALYSIS OF SOLAR RADIATION IN SUDAN AND OPTIMAL LOCATION OF PHOTOVOLTAIC PANELS

Mohammed GMAL OSMAN[1], Dana CIUPAGEANU[2], Adrian STAN[2]

Sudan is in North-Eastern Africa within the sub-Saharan region and has a population of 43 million people and area of 1,886,068 km^2, making it the third-largest country in Africa. The percentage of population's electricity access reaches only 56%, which is lower than the global average (i.e. 89%,). The annual electricity consumption per capita is only 300 kWh, which is two times lower than the African average and almost twenty times smaller than the European one.

Sudan is a big RE market and it's perfectly positioned to support transition to sustainable development. The yearly average solar radiation exceeds 2000 kWh/m^2, making it one of the highest in the world. According to studies, the average wind speed across the country is between 5.1 and 7.1 m/s. Biomass is another renewable energy source with substantial potential for power generation, process heat, and clean cooking applications as major sources including bagasse, bioethanol, agricultural residue, and animal waste Given its considerable technical potential for RE, they can be used to enhance the electricity sector and improve the electricity access.

In this paper HOMER is used to find the best PV solution to supply a specific load in Sudan, and to determine the best location. According to the results, Studer VarioTrack VT-65 with Generic PV is the best form for Sudan. Dongola, Khartoum has the lowest COE (0.08254USD$/KWh), (0.08298 USD$/KWh respectively high intensity of solar radiation, and clearness.

Keywords: Hybrid Optimization Model for Electric Renewables, Renewable Energy, photovoltaic

1. Introduction

The sun has a diameter around 1.4 million kilometers, and it is located approximately 150 million kilometers from the Earth. It has surface temperature close to 5500°C, and it emits radiation at a rate of 3.8×10^{23} kW. This energy is provided by nuclear fusion events at its core, which are expected to last billions of years. The earth captures a tiny percentage of this energy, but it is several thousand times more than our rate of using fossil fuel, and it powers of the all-planet's natural ecosystem functions [1].

[1] PhD stud., Faculty of Power Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: gheorghe.lazaroiu@upb.ro

[2] PhD eng., Dept. of Energy Production and Use, University POLITEHNICA of Bucharest, Romania

On a bright sunny day around midday, the intensity of solar radiation reaching the earth's surface is normally between 900 and 1000 W/m^2. Solar radiation arriving on Earth is the source of most basic renewable energy source (RES). It led the bio-system in the ocean, and the air current system, as well as influencing global temperature. A good database is necessary in any work of energy planners, engineers, and agricultural scientists [3].

In term of solar energy Sudan is regarded as one of the best countries for exploiting it. As indicated in Table *1* and Fig. 1, the daily sunshine duration ranges from 8.5 to 11 hours, with a high level of solar radiation regime averaging 20 to 24 MJ/m^2/day over the horizontal surface. The yearly daily mean global radiation varies between 3.05 and 7.62 kWh/m^2/day. In terms of yearly values, Sudan has an average of 7-9 GJ/m^2/year, which is comparable to 436-639 W/m^2/year [4].

Sudan's Global Horizontal Irradiation is depicted in the Fig. 1.Which shows the geographical location of Sudan and the average temperature. The potential for solar PV electricity generation in Sudan, as calculated by the World Bank's Solar Atlas. Sudan's high radiation intensity values are undoubtedly an asset that might significantly improve the effectiveness of any solar system that is built. The technical potential for renewable energy in Sudan, at both a centralized and a distributed level, is very high, the annual average solar radiation exceeds 2000 kWh/m^2, which is among the highest globally [6].

Due to their modular design and economic competitiveness as compared to grid infrastructure extension, distributed generating systems (including off-grid systems) present a significant opportunity for scaling access to clean and modern energy services in Sudan (and Sub-Saharan Africa). Leading energy organizations such as the International Renewable Energy Agency (IRENA)[7], the International Energy Agency (IEA)[8], and Bloomberg New Energy Finance (BNEF)[9] have all underlined this fact in recent studies. Furthermore, due to economies of scale and manufacturing developments, the cost of renewable energy equipment (such as solar cells and batteries) is decreasing, indicating that its economic feasibility is improving. Sudan's current electricity situation is unstable, accessibility is extremely limited, electricity grid quality is poor, power outages are frequent, the national grid only covers a small percentage of the country, and the country's energy mix is not diversified. The following data shed light on Sudan's electrical situation.[10]

The percentage of people that have access to electricity in Sudan is only 56%, which is lower than the global average of 89%. The low rate of access to power, combined with frequent outages, resulted in inefficient use of electricity for productive purposes. The annual electricity use per capita is only 300 kWh/capita/year, which is two times lower than the African average. There is no diversification in electricity generation with only two sources being used: large-scale hydropower and oil in thermal generation [6].

This work aims to use available techniques for predicting solar radiation data and forward finding optimal location with the fewest measurements feasible and HOMER software.

2. Study area description

Despite all the efforts to support the installation of renewable energy projects around the world, particularly solar PV-based projects, to ensure a sustainable energy transition, there has been very little research focused on the practicality of these technologies in Sudan. Furthermore, this research was limited to only a few areas across the country and did not investigate the entire country.
This research looks on the feasibility of capturing solar energy resources found in Sudan. Simulations for a grid connected solar photovoltaic power plant were run using input data from selected areas in Sudan, including hourly meteorological data, economic considerations, and technology type.

The first goal of this study was to use HOMER software to explore the best solar photovoltaic technology available. The second goal was to find the optimum location in Sudan for photovoltaic solar energy generating.

The solar PV systems under consideration were simulated in 11 Sudanese locales using HOMER software: Port-Sud Algadaref, Al Ubaid, Alfashir, Dongola, Alroseires, Adamar, Nyalaa, Khartoum, Kadogli, Rabak. The goal was to find areas that could deliver the most solar energy with ease and efficiency while keeping in mind the cost of energy (COE). the monthly average of solar radiation and clearness index in kWh/m^2/day for the 11 locations in Sudan in Table 4 and Table 5 and their geographical locations on the map of Sudan are illustrated in Fig. 1.

3. Photovoltaics and total RES evolution in Sudan.

Sudan is a developing country with an urgent need to meet its rising energy demand with long-term energy supply routes based on renewable energy, which is abundant in the country. Based on the statistics of the International Renewable Energy Agency (IRENA) for the period from 2011 to 2020, and compared with Africa and world, we find that Sudan’s exploitation of solar cells is very weak, despite the distinguished geographical position and the enormous potential. The increase is very small, almost negligible Table *1* shows the participation of PV and Renewable Energies in the national grid.

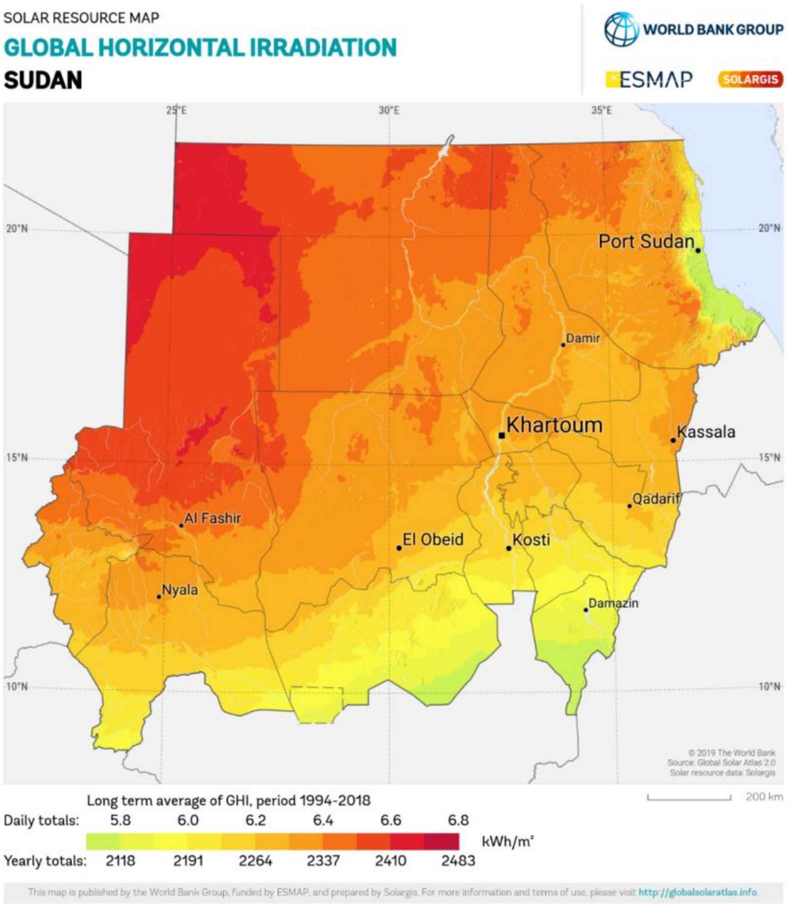

Fig. 1. Sudan solar Irradiation [11]

Table 1

Statistics of total RES and PV on grid [add source]

Total RES [MW] on grid				Photovoltaic [MW] on grid		
Years	Sudan	Africa	world	Sudan	Africa	world
2011	1692	27738	1331177	4	266	72200
2012	1800	28723	1443762	8	346	101654
2013	1800	30920	1566889	8	660	137178
2014	1800	32930	1699085	8	1565	175594
2015	1803	35249	1852768	11	1931	222937
2016	1805	37902	2014645	12	2978	294800
2017	1965	43485	2186145	13	4692	389579
2018	2119	48816	2359753	13	7157	482912
2019	2124	51278	2542035	18	8330	583872
2020	2124	53824	2802004	18	9551	709674

From Table 1, it is noticeable that the total value of RES in Sudan, Africa and the world is relatively high compared to photovoltaic. This is because of the most exploitation of RES consists of hydropower, as well as in Sudan where we find that the total value of Renewable energies is bigger than the other RES, as there are five dams in the river Nile and its tributaries to generate electric power [12][13].

Fig. 2 and Fig. 3 illustrate the growth in the total value of the Renewable energies in Sudan and the photovoltaic in the national grid from 2011 to 2020 based on the statistics of the International Renewable Energy Agency IRENA.

The total RES in Sudan in 2011 is 1692 MW and in 2020 is 2124 MW the increase is only 432 MW compared to the Africa in 2011 is 27738 MW, and the world 1331177 MW and in 2020 Africa is 53824 MW and the world is 2802004 MW we notice that the growth of renewable energies at the world level is at a significant increase compared to Africa.

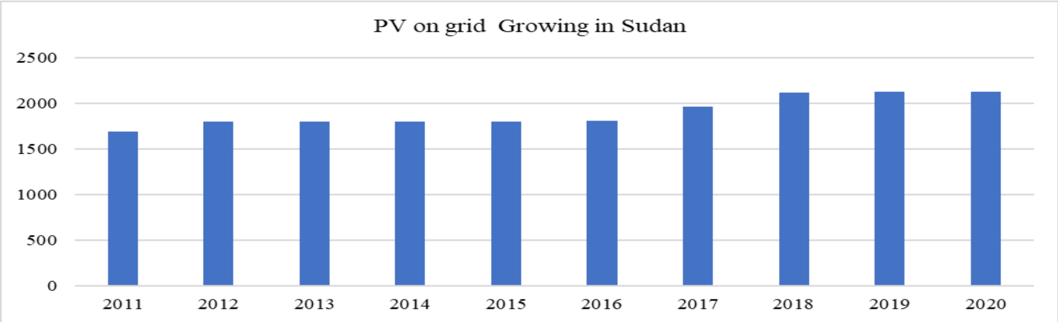

Fig. 2. PV growing on grid in Sudan

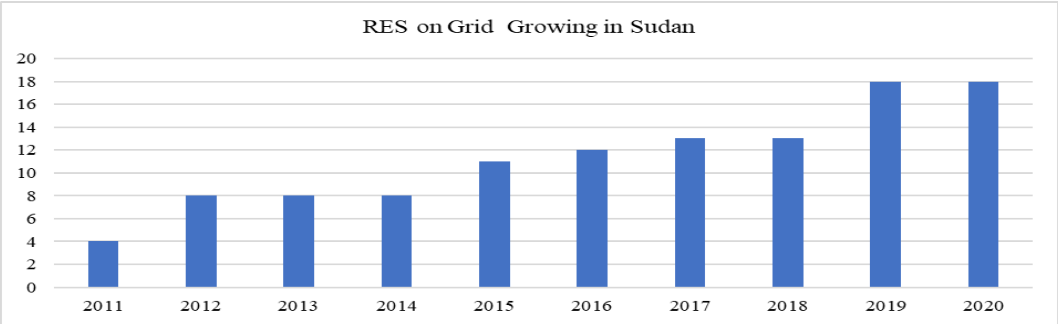

Fig. 3 RES growing on grid in Sudan

4. HOMER model

Hybrid Optimization Model for Electric Renewable (HOMER) software was created by the National Renewable Energy Laboratory (NREL) in the United States. It's most utilized in the design and analysis of hybrid power systems.

Input data and HOMER Operation

The first stage of HOMER's operation was to select relevant input data for the study domain (including load profile, capital, replacement, operational and maintenance costs, and meteorological data). For the purposes of this study, the load profile was assumed to be 40 MW throughout the year. Various types of solar PV systems were selected from HOMER's accessible library, with a minimum capacity of 2.48 kW and a maximum capacity of 1164 kW it 19 PV. Each of the 19 different solar PV systems was studied separately.

Flowchart of software

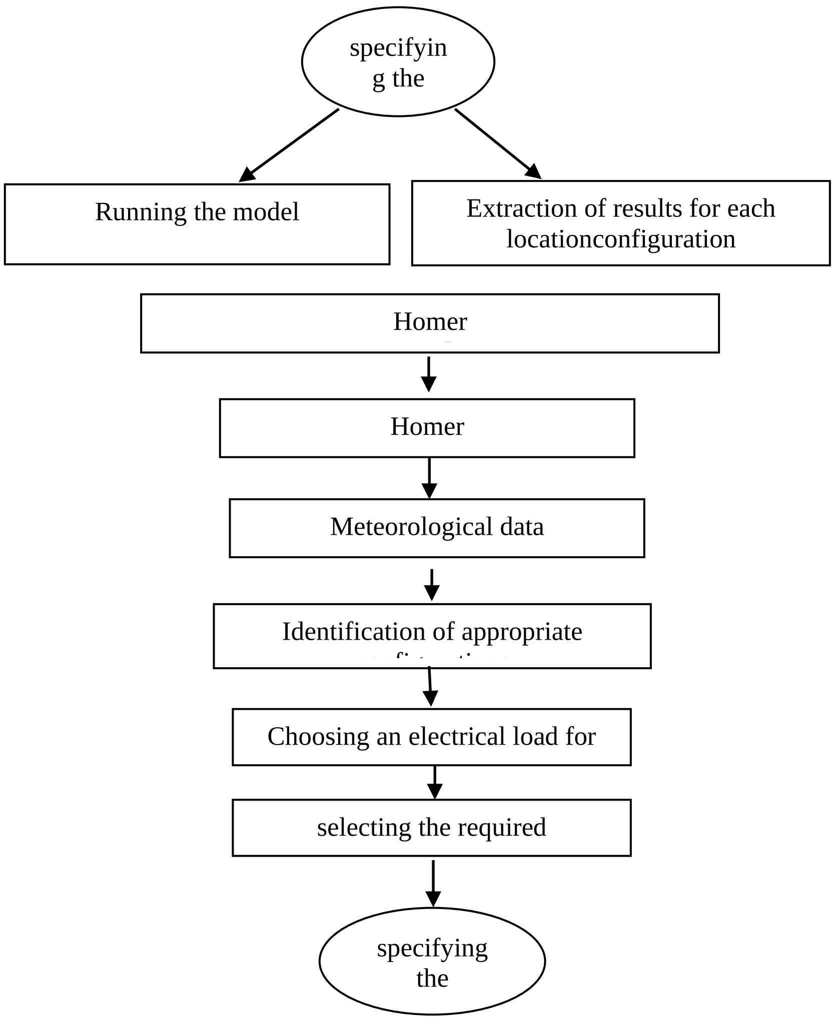

Fig. 4. HOMER operation flow diagram.

The final step was to plan out the project's layout (i.e., constraints, economics, optimization, and emissions). To begin with the limitations, the solar power output was set to 100% to increase the yield from solar energy, which is the only source of energy studied in this study. The greatest yearly capacity deficiency was calculated to be 100% because the solar system is not supported by any other energy source. In the project economics section, a 25-year project lifetime, the nominal discount rate of is 6% (a measure of the country's weighted average cost of capital for electrical energy distribution)[15].

Table 2

Parameter Value

Capital cost (USD$/kW)	1500
Replacement cost (USD$/kW)	1000
Operational and maintenance cost (USD$/kW)	50
Project lifetime (Year)	25
Solar power output (%)	100
Maximum annual capacity shortage (%)	100
Nominal discount rate (%)	6%
Time step (Minute)	60
Emission penalty (USD$/ton)	0

Different situations were studied with various economic scenarios using HOMER. The study indicated that the use of renewable energy systems presents a significant opportunity for the Sudanese telecommunications industry [18]. The utilization of solar energy necessitates the identification of acceptable resources (such as solar radiation, temperature, etc.) for the renewable energy component of choice. To do so, data on monthly average global horizontal irradiation (GHI), solar radiation, and clearness index for every month in Sudan over a one-year period were obtained from the National Aeronautics and Space Administration (NASA) database. Temperatures were obtained from the NASA database as well.

Table 3

HOMER simulation results for various types of solar PV systems

No.	Type	(Kw)	COE (USD $/Kwh)	NPC (USD$)	Unmet electric load (%)	No. of PV units
1	Fronius Galvo 3.1-1 with Generic PV	2.48	0.09023	42.8 M	78.8	16130
2	Fronius Symo 4.5-3-S with Generic PV	4.4	0.08867	42.8 M	78.5	9091
3	Fronius Symo 8.2-3-M with Generic PV	8.2	0.08883	42.8 M	78.5	4879
4	Fronius Primo 8.2-1 with Generic PV	8.25	0.08955	42.8 M	78.7	4849
5	Schneider Conext CL20000 E with generic PV	20	0.09871	42.8 M	80.6	2000
6	Fronius Symo 20.0-3-M with Generic PV	20	0.08879	42.8 M	78.5	2000
7	Fronius Symo 24.0-3-M with Generic PV	24	0.0887	42.8 M	78.5	1667
8	Schneider Conext CL25000 E with generic PV	25	0.09871	42.8 M	80.6	1600
9	Huawei SUN 2000 25kW with Generic PV	25	0.08903	42.8 M	78.5	1600
10	Huawei SUN2000 30kW with Generic PV	30	0.08789	42.8 M	78.3	1334
11	SMA Sunny Tripower 60-US with Generic PV	60	0.08838	42.8 M	78.4	667
12	SolarMax 500RX A with Generic PV	500	0.08828	42.8 M	78.4	80
13	Schneider ConextCoreXC 540kW with Generic PV	540	0.08803	42.8 M	78.3	75

14	Schneider ConextCoreXC 630kW with Generic PV	630	0.08771	42.8 M	78.2	64
15	Studer VarioTrack VT-65 with Generic PV	680	0.08746	42.8 M	78.2	59
16	Studer VarioString VS-120 with Generic PV	680	0.08828	42.8 M	78.4	59
17	Schneider ConextCoreXC 680kW with Generic PV	680	0.08787	42.8 M	78.3	59
18	Studer VarioTrack VT-80 with Generic PV	680	0.08746	42.8 M	78.2	59
19	Ingeteam (1164kVA) with Generic PV	1160	0.08792	42.8 M	78.3	35

NPC = net present cost; COE = cost of energy.

To simulate the solar energy system for each hour of the year, the time step was set to 60 minutes in the optimization setup. Emission fines were also set at zero because there are no penalties for emissions in Sudan. Table 2 summarizes the HOMER project's input parameters. HOMER software simulated the functioning of the system and computed the results based on the provided data after all relevant data was provided and project configurations were defined [19].

The optimal PV determined in the first part of the study was simulated operating in the 11 locations selected in Sudan in the second part of the investigation. The solar radiation (Table 5) and clearness index (Table 4) values were different at each of these locations. The first stage of the analysis employed the identical project parameters and electric load profile.

Table 4

Monthly average clearness index in kWh/m^2/day for the 11 locations in Sudan

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port-Sud	0.709	0.714	0.707	0.692	0.637	0.637	0.608	0.606	0.643	0.69	0.723	0.707
Algadaref	0.633	0.665	0.682	0.691	0.651	0.659	0.626	0.611	0.628	0.65	0.659	0.633
Al Ubaid	0.632	0.659	0.679	0.691	0.654	0.663	0.629	0.612	0.626	0.644	0.65	0.623
Alfashir	0.637	0.662	0.681	0.691	0.653	0.661	0.627	0.611	0.627	0.647	0.655	0.628
Dongola	0.703	0.71	0.705	0.692	0.638	0.639	0.609	0.606	0.642	0.686	0.718	0.700
Alroseires	0.619	0.649	0.674	0.691	0.659	0.67	0.634	0.614	0.624	0.637	0.638	0.609
Adamar	0.682	0.695	0.697	0.691	0.641	0.644	0.614	0.607	0.637	0.674	0.698	0.678
Nyalaa	0.621	0.651	0.675	0.691	0.658	0.669	0.633	0.614	0.624	0.638	0.64	0.611
Khartoum	0.657	0.677	0.688	0.69	0.647	0.653	0.62	0.609	0.631	0.659	0.674	0.650
Kadogli	0.611	0.643	0.672	0.692	0.662	0.674	0.638	0.616	0.623	0.632	0.63	0.600
Rabak	0.632	0.659	0.679	0.691	0.654	0.663	0.629	0.612	0.626	0.644	0.65	0.623

Table 5

Monthly average solar radiation in kWh/m^2/day for the 11 locations in Sudan

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port-Sud	122.2	129.3	181.5	180.6	166.6	134.1	110.0	100.7	127.5	144.6	119.4	100.7
Algadaref	206.1	180.2	191.0	168.8	152.9	122.5	90.6	82.8	122.3	173.6	192.0	202.7
Al Ubaid	205.6	176.7	183.7	168.4	148.6	119.7	101.6	94.1	120.6	155.3	194.5	205.6
Alfashir	217.9	184.6	185.7	169.1	157.4	133.8	104.6	103.3	124	155.2	204.7	221.1
Dongola	197.3	176.2	192.7	177.8	172.0	160.8	147.8	125.0	127.7	152.2	181.7	189.0
Alroseires	196.6	167.4	178.1	156.8	132.7	96.5	76.5	80.4	102.8	147.7	186.5	197.2
Adamar	197.9	179.0	195.0	183.9	163.9	131.6	111.7	96.4	115.7	154.1	178.8	187.3
Nyalaa	218.2	181.7	179.7	161.8	152.1	125.1	106.4	102.1	124.1	156.1	203.4	221.6

Khartoum	192.4	171.5	184.3	170.2	148.7	123.1	106.2	93.6	115.0	153.2	181.1	189.6
Kadogli	210.4	172.3	174.1	153.6	134.8	105.6	92.3	83.8	109.3	144.8	190.9	207.9
Rabak	200.3	175.1	182.4	161.1	143.1	113.5	93.6	84.6	113.6	163.2	190.7	200.0

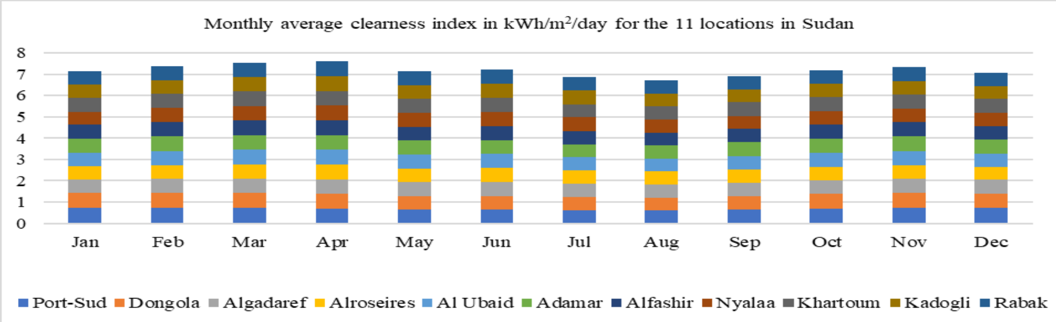

Fig. 5 Monthly average clearness index in kWh/m^2/day for the 11 locations in Sudan

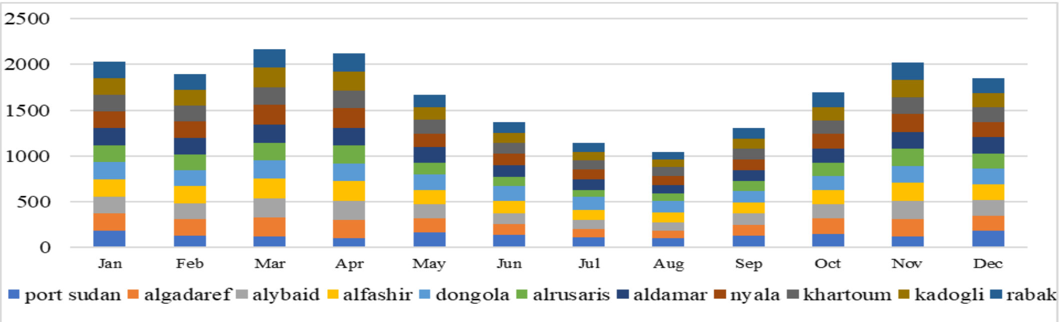

Fig. 6 Monthly average solar radiation in kWh/m^2/day

The results indicate that the maximum amounts of solar electricity generation occur between March and April, with greater levels in March. In comparison to the previous months, this time has the highest levels of solar radiation and clearness indices, which explains the high levels of power generation. Furthermore, electric production begins to diminish in April and continues to decline gradually until July. This is due to the impact of temperature on the PV array's operation [21]. Temperature has been shown to affect the power output of PV systems in an inverse manner, with high temperatures lowering the PV cell's voltage and, as a result, the PV system's power output.

Following the identification of the optimal locations that deliver the most solar energy while accounting for the cost of energy (COE), the costs of PV were modified to provide an understanding of the impact of PV cost on project economics.[23]

5. Determination of the Optimal PV

Table 3 shows the results of HOMER simulations for 19 different types of solar PV systems. All the PVs had a net present cost (NPC) of roughly USD$ 42.8 million. The greatest COE was reported for types (Schneider Conext CL25000 E with generic PV) and (Schneider Conext CL20000 E with generic PV) at USD$ 0.09871/kWh, according to the data. The lowest COE (USD$). Was found in Studer VarioTrack VT-65 with Generic PV, and (Schneider ConextCoreXC 630 kW with Generic PV). Types 15 and 14 has cost 0.08746/kWh, 0.08771/kWh whereas type 13 costs 0.08771/kWh.[24]

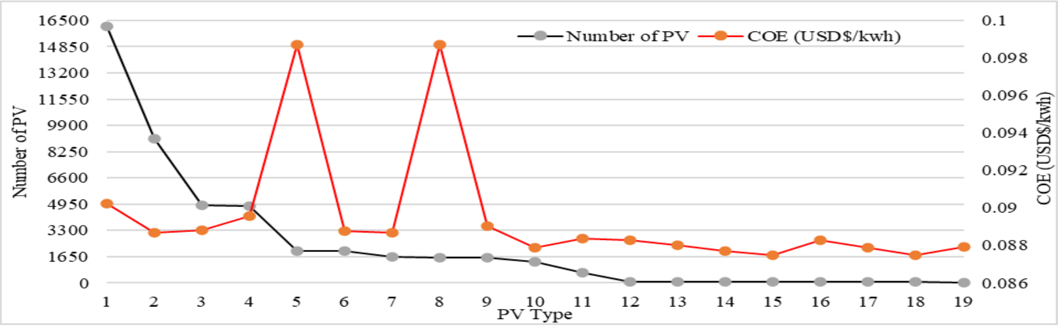

Fig. 7 Cost of Energy (COE) of the examined 19 PVs.

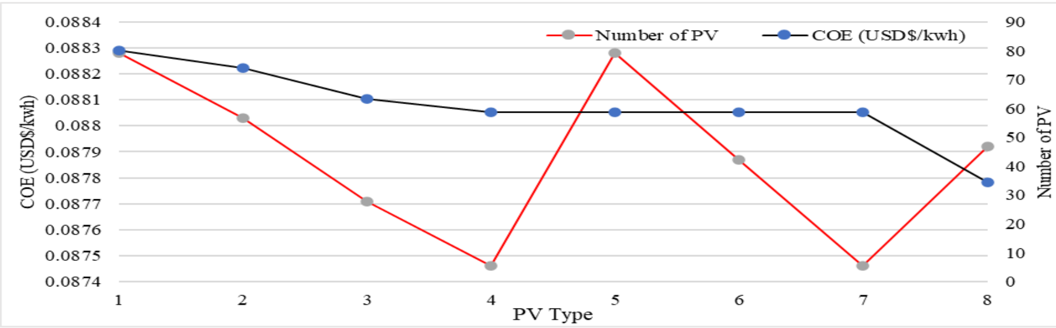

Fig. 8 Cost of Energy (COE) of the examined best 8 PVs.

Fig. 7 and Fig. 9 show the COE and unmet electrical load of the 19 solar PVs under studding. The findings of the unmet electrical load were substantially identical, ranging between 78.2 % and 80.6%. The COE outcomes, on the other hand, are a different story. The number of PV units necessary for electricity generation to meet the targeted demand of 40 MW has a significant impact on operation and maintenance costs. The fewer solar PV panels required, the lower operation and maintenance costs. Type 19 (Ingeteam (1164kVA) with Generic PV) required the fewest PV units, whereas type (Fronius Galvo 3.1-1 with Generic PV) required a lot[13].

The optimal solar PV to meet a 40 MW-demand for a city in Sudan is either type 61 (Studer VarioTrack VT-65 with Generic PV), which was selected for the subsequent analyses, or type 15 (Studer VarioTrack VT-80 with Generic PV), based on the obtained results and the fact that it had the lowest COE and a relatively low number of PV units required. The properties of the chosen optimal PV system are summarized in Table 6. In comparison to the other systems studied previously, this one has the lowest COE (approximately USD$ 0.08746/ kWh), and it only requires 30 PV panels to meet the demand.

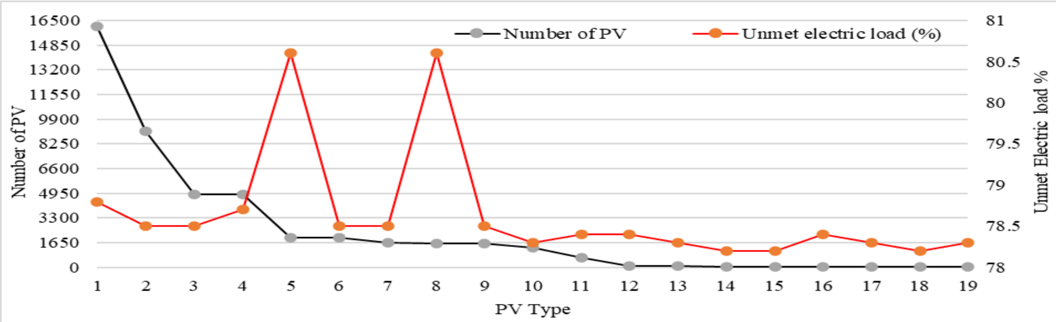

Fig. 9 The unmet electrical load of the examined 19 PVs

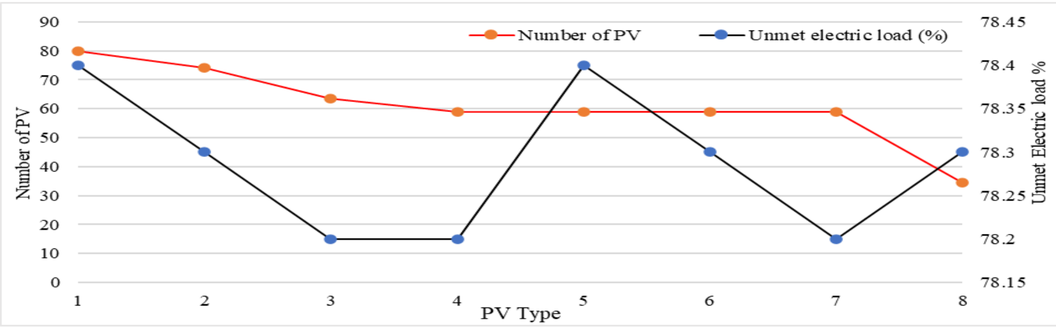

Fig. 10 The Unmet Electrical load of the examined best 8 PVs

Table 6

Properties of the optimal PV system.

Name	Studer VarioTrack VT-65 with Generic PV
Panel type	Flat plate
Dimensions [height/width/ length]	[120 mm/220 mm/310 mm]
Rated capacity	680.08 kW
Derating factor	96%
Operating temperature	45 ◦C
Temperature coefficient	− 0.41
Efficiency	17.3%

The results of the HOMER simulation using the optimal solar PV system (Studer VarioTrack VT-65 with Generic PV) for the 11 locations in Sudan are shown in Table 7

Table 7

HOMER simulation results using the best solar PV (Studer VarioTrack VT-65 with Generic PV) for the 11 locations in Sudan

Location	COE(USD$/KWh)	NPC(USD$)	OC (USD$)	Unmet electric load
Port-Sud	0.08916	42.8 M	1 M	78.6
Algadaref	0.08546	42.8 M	1 M	77.6
Al Ubaid	0.08334	42.8 M	1 M	77.1
Alfashir	0.08347	42.8 M	1 M	77.1
Dongola	0.08254	42.8 M	1 M	76.9
Alroseires	0.0902	42.8 M	1 M	78.8
Adamar	0.08573	42.8 M	1 M	77.7
Nyalaa	0.08712	42.8 M	1 M	78.1
Khartoum	0.08298	42.8 M	1 M	77
Kadogli	0.08721	42.8 M	1 M	77.9
Rabak	0.08734	42.8 M	1 M	78.1

From Table 7, Dongola (USD$ 0.08254/kWh) achieved the lowest COE. Alroseires USD$ 0.09020/kWh had the highest COE, followed by Port-Sudan USD$ 0.08916/kWh, Rabak USD$ 0.08734/kWh, Nyala USD$ 0.08712/kWh, and Ad-Damar USD$ 0.08573/kWh. The COE for the investigated 21 locations in Sudan is illustrated in Fig. 11

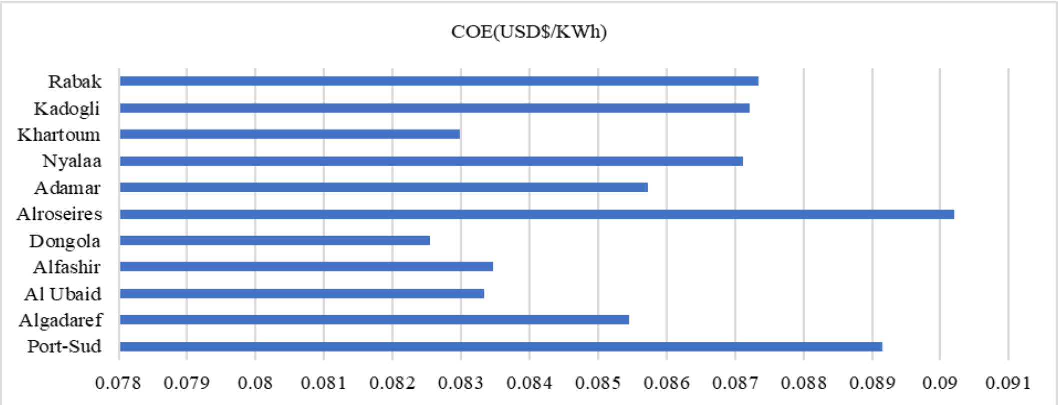

Fig. 11 The Cost of energy (COE) for the 11 cities investigated in Sudan

The percentage of unmet electric load varies between 76.5 and 78.8%, with Alroseires having the highest percentage and Dongola having the lowest. Fig. 12 illustrates the unmet electrical load for the 11 Sudanese cities evaluated.

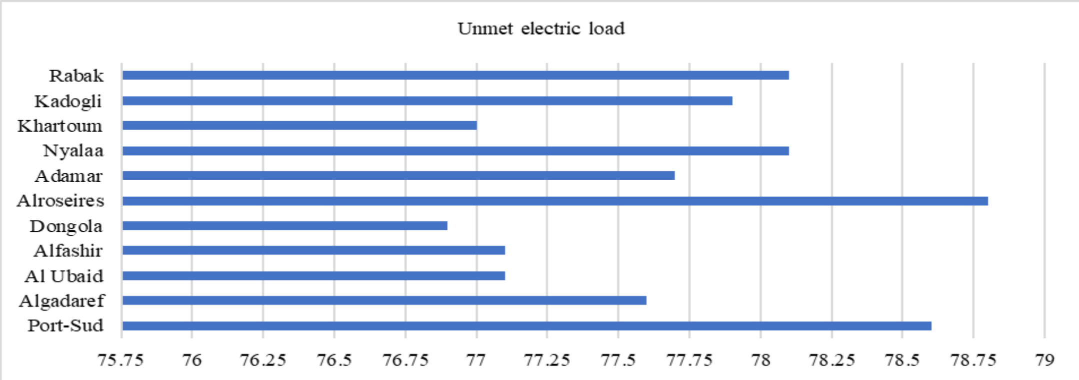

Fig. 12 The unmet electrical load for the 11 cities investigated in Sudan

Solar photovoltaic systems are best adapted to electrical power production in distant desert areas due to the high intensities of solar radiation that define these places. However, dust deposition on PV panels, which is a complicated phenomenon that occurs primarily in dry climates and is regulated by a variety of site-specific environmental and climatic factors, has a detrimental impact on PV panel output [26].

6. Conclusion

With the use of HOMER software, this work was undertaken to determine the best type of solar PV to achieve a 40 megawatt (MW) electric load for a Sudanese city. The Studer VarioTrack VT-65 with Generic PV is the optimal solar PV to satisfy the specified demand, based on the findings obtained and the fact that it has the lowest COE (USD$ 0.08746/ kWh) and a relatively low number of PV units required only (30 PV Panel). The identified optimal solar PV system was then simulated in 11 different locations across Sudan to see which location would produce the most solar energy effectively. The software-based assessments found that Dongola (0.08254 USD$/KWh) and Khartoum (0.08298 USD$/KWh) out as the best sites for solar energy utilization due to the comparatively low COE, high intensity of solar radiation, and clearness indices that characterize these regions.

The clearness index values were quite constant throughout the year (between 0.664 and 0.526). The same cannot be stated of solar radiation data. the average daily radiation value peaked in April (6.880 kWh/m^2/day) and peaked in March (5.350 kWh/m^2/day). The presence of very large areas outside the range of the electric network is a very motivating factor to exploit solar energy as a solution instead of using diesel.

The implementation of such a project will be a watershed moment in Sudan's renewable energy sector, not just raising capacity but also addressing energy security and environmental concerns. The conclusions of this study are extremely important, and they should inspire politicians, investors, and other solar energy actors in Sudan to invest more in solar energy. This, in turn, will create jobs and provide an innovative way to attaining a cleaner, more sustainable energy future not only for Sudanese, but also for others throughout the world, given Sudan's potential to become a major renewable energy exporter.

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