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Determination of the optimal solar photovoltaic (PV) system for Sudan

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ABSTRACT

Electricity access in Africa is a major challenge in rural areas. Despite considerable potential for the use of solar energy, investments in renewable energy projects are minimal due to poor promotion of solar energy. As a result, many people still rely on private diesel generators, which release significant levels of pollutants, and have negative effects on both humans and the environment. Situated in the sunbelt, Sudan is one of the largest countries in Africa endowed with an extremely high solar irradiation potential. However, no work has been done in the literature with a strategic context to study specifically the feasibility of renewable energy systems in Sudan despite the abundance of solar resource. The aim of this study was to utilize Hybrid Optimization Model for Electric Renewables (HOMER) to identify the optimal solar photovoltaic (PV) system for Sudan's conditions, identify the best locations, and analyze the costs and the pollution that might be avoided by employing a PV system in place of a diesel system. HOMER simulation results demonstrated that the optimal type of PV for Sudan is the Studer VarioTrack VT-65 with Generic PV. The utilization of a solar PV system will avoid the production of approximately 27 million kg/year of pollutants and will reduce the cost of energy to USD$ 0.08746/kWh. The optimal locations found in Sudan for utilizing solar energy were Wawa, followed by Kutum, Wadi Halfa, Dongola and Al-Goled due to their low costs of electricity, high clearness index and high levels of solar radiation. Given the recent rapid decrease in PV pricing and predictions for continued reductions, the costs of PV were varied to deliver an understanding on the impact of PV costs on the project economics. Reducing the PV costs by 25% has a significant impact; the cost of energy produced reduces in the range of USD$ 0.06697/kWh and USD$ 0.06808/kWh, while a reduction in PV costs of 50% further reduces the cost of energy, ranging between USD$ 0.05273/kWh and USD$ 0.05361/kWh in the top five locations in Sudan. The output of this study is projected to raising the potentiality awareness of renewable energy in Sudan and delivering a valuable reference regarding the optimal utilization of solar PV system in energy sector.

1. Introduction

The depletion of conventional energy resources, the increasing evidence of global warming and the rapid growth of the world's population have led to a noticeable increase in focus on the implementation of renewable energy technologies during the last decade (Yahiaoui et al., 2016). Due to the failure to reach an agreement on the zero CO_2 emissions target set by several countries for 2050 at the 25th session of the Conference of the Parties (COP25) organized in Madrid, Spain in December 2019 (Jäger-Waldau, 2020), drastic measures and credible solutions are needed prior to the upcoming COP26 to pave the way for renewable energy technologies. Among all renewable energy resources, solar energy is by far the most abundant source of energy (Lewis and Nocera, 2006; Timilsina et al., 2011; Kabir et al., 2018). The earth receives solar power at a rate of 120 petawatts, meaning that the energy obtained from the sun in a single day could satisfy the world's energy needs for almost twenty years (Rashad et al., 2015). This untapped solar energy potential, in addition to the aforementioned global challenges, significantly encouraged solar power generation technologies to flourish faster than any other renewable technology. Amongst the existing solar harvesting technologies, solar photovoltaic (PV) stands out distinctively as one of the most rapid growing renewable energy technologies and the most viable solution to mitigate the previously mentioned global challenges (Al Garni and Awasthi, 2017). The World Energy Outlook 2019 stated that the only way to meet the previous zero CO_2 emissions target is to decarbonize the energy supply by increasing the PV installed capacity up to 7208 TWh by 2040 (Fatih, 2019). Knowing that the current estimated installed solar PV capacity is 635 GW, which is attributed mainly to the recorded fall in PV system cost over the past years, further reductions in PV system cost is predicted to result in increased adoption

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of the technology in the next decades (Jäger-Waldau, 2020).

Known to be a continent with high economic growth potential (Adenle, 2020), Africa faces a continuous increase in energy demand leading to the impossibility of achieving the sustainable development goals. Electricity access in Africa is considered as the major challenge facing the population living in rural areas. Almost 700 million people still depend on traditional biomass to meet their daily energy needs (Adenle, 2020). In addition to that, diesel generator systems and transmission line extensions dominate electricity access in African rural areas (Core International Inc., 2003). While most African countries show a great renewable energy potential, investments in such projects remain little due to the slow implementation of government road map towards the promotion of renewable energy utilization (Adenle, 2020). Several studies have been performed to assess the techno-economic feasibility of renewable energy technologies to mitigate the low electricity access in the continent. Szabo et al. (2011) designed a cost model to investigate and determine the least cost resource of electricity to be implemented in remote areas in Africa. The study compared diesel generators, extension of the grid and photovoltaic systems. The results of the study revealed that solar energy constitute an alternative to diesel and transmission line extension in several locations like Sudan, Niger, Chad, Mali, Mauritania and Western Sahara. Furthermore, the analysis demonstrated that for decentralised electricity production, PV systems are about to become competitive with diesel and transmission line extension. Following the recommendation proposed by Szabo et al. (2011) to compare PV and diesel to another renewable energy resource, Gabra et al. (2019) performed a techno-economic analysis of a stand-alone wind micro-grids system and compared it with the previously mentioned technologies. The analysis results showed that wind energy can be competitive only in regions with an average wind velocity of at least 6 m/s (that is, Somalia, Western Sahara, Chad and South Africa). Moreover, in other countries PV and diesel showed a superior economic performance due to the abundance of solar energy resources and fuel subsidy schemes. However, due to the expected reforms targeting the removal of fuels subsidy, it is anticipated that diesel generators will become less attractive compared to PV and wind systems (Whitley and van der Burg, 2015; Gabra et al., 2019).

With the geographical position lying between latitudes 3° N and 23° N, and longitudes 21° 45′ E and 39° E, Sudan is one of the largest countries in Africa. Ranked 166 out of 187 countries in the human development index, Sudan's current energy situation is extremely alarming. Biomass resources constitute 62%, electricity 4% and conventional fuels 34% of the total energy supply in Sudan (Saeed et al. 2019). About 70% of Sudan's population estimated not to have access to electricity. Among all energy resources mentioned before, diesel generators are one of the most used means of energy conversion. In fact, only 30% of the population living in the city have access to national grid, while 70% of the population living in rural areas rely on diesel generators (Alhaj and Sopian, 2018; Saeed et al., 2019). This domination of diesel-based electricity systems is due to the low investment cost of these systems, permanent electricity shortages caused by low energy generation and the low coverage of national transmission lines. However, these systems have high maintenance costs, are noisy, and cause air pollution (Elkadeem et al., 2019a,b). This has led the government to initiate a promising renewable energy program which is supposed to increase electricity production from renewable resources to 20% from 0.38% by 2030 and 100% by 2050 (Murdock et al. 2019). Given that Sudan is endowed with an extremely high solar irradiation potential, the government has set a target of achieving a 667 MW of PV installed capacity by the end of 2031 (Murdock et al. 2019). This clearly reflects that the latter technology will play a key role in adjusting the electricity crisis of Sudan in the near future. With the lifting in 2017 of the economic sanctions imposed by the United States in 1997, a whole new chapter for Sudan's economy has opened up. Sudan currently is eligible for debt relief under the International Monetary Fund (IMF) and World Bank's heavily indebted poor countries' initiative (Leading Edge, 2019).

Table 1
Geographical details of the 21 locations under study.

No.	Location	Latitude (°N)	Longitude (°E)
1	Port Sudan	19.590	37.190
2	Omdurman	15.647	32.481
3	Al-Qadarif	14.024	35.368
4	Kassala	15.458	36.404
5	Kosti	13.123	32.650
6	Al-Obeid	13.178	30.216
7	Dongola	19.146	30.470
8	Al-Junaynah	13.448	22.465
9	Al-Fashir	13.620	25.355
10	Nyala	12.052	24.880
11	Wadi Halfa	21.799	31.371
12	Al-Damazin	11.785	34.342
13	Haiya	18.333	36.385
14	Ad-Damar	17.580	33.969
15	Abu Hamed	19.535	33.321
16	Merowe	18.469	31.816
17	Kutum	14.203	24.664
18	Salala	21.321	36.216
19	Wawa	20.444	30.351
20	Karima	18.532	31.827
21	Al-Goled	18.471	30.644

Moreover, the removal of sanctions will encourage international banks to re-establish banking relationships with Sudanese banks and encourage international companies to invest in the promising and productive sectors in Sudan. This debt relief, along with the economic reforms, will enable the unleashing of Sudan's solar energy potential.

Prior to installation of any type of renewable energy facilities, a detailed techno-economic feasibility study is normally required to be performed and the decision to establish such systems must be taken after considering the results of the feasibility assessment (Tamir, 2011). In most situations due to absence of optimum designing or proper sizing, a renewable energy system is over-sized or not properly designed or planned, which makes the cost of installation high. The techno-economic analysis of a renewable energy system is vital for the efficient utilization of renewable energy resources. Feasibility analysis necessitates software tools and models which can be utilized for the design, analysis, optimization and economic planning (Sinha and Chandel, 2014). Given the recent worldwide interest in the transition from conventional to renewable energy systems, different tools have been established to predict the performance of renewable energy systems prior to their implementation. Sinha and Chandel (2014) reviewed various software tools (19 in total) that have been used for optimal planning and design of renewable energy systems including HOMER, iHOGA, HYBRIDS, RETScreen, TRNSYS, Hybrid2, iGRHYSO, INSEL, SOMES, IPSYS, HySim, Hybrid Design, SOLSTOR, Dymola/Mode-lica, ARES, APSIM, HySys, SOLSIM and HybSim. Among these tools, HOMER (Hybrid Optimization of Multiple Electric Renewables) is founded as the most integrated and powerful tool that is widely recommended as the global standard for optimal planning and design of renewable energy systems in all energy sectors. Developed by the National Renewable Energy Laboratory (NREL), HOMER allows the user to design and investigate financial and technical options for on-grid and off-grid energy systems. The software permits project investigation by exploring different aspects of energy projects (including location, system sizing, weather data, and economic parameters). This allows the investigation of the feasibility of projects, especially during the design stage. The software's optimization and sensitivity analysis algorithms also allow designers to evaluate the technical and economic feasibility of a large number of technology options and to account for variations in energy resource availability and technology costs. The flexibility that HOMER provides has attracted many researchers worldwide in recent years (Abdul-Wahab et al., 2019 (Oman); Hossain and Rahman, 2020 (Bengladesh); Khormali and Niknam, 2019 (Iran); Oulis Rousis et al., 2018 (Greece); Huang et al., 2011 (USA)).

Fig. 1. The geographical locations in Sudan under investigation for production of solar energy (Google Earth).

Table 2
The capital, replacement, and operation and maintenance costs for solar PV in countries near Sudan.

Reference	Country	Costs		
		Capital (USD$/kW)	Replacement (USD$/kW)	Operational and maintenance (USD$/kW)
Olatomiwa et al. (2015)	Nigeria	2500	2000	–
Diab et al. (2016)	Egypt	3000	2250	10
Ramli et al. (2016)	Saudi Arabia	2000	1200	30
Maatallah et al. (2016)	Tunisia	1382.58	0	88.48
Issak (2018)	Chad	3000	2000	1
Gebrehiwot et al. (2019)	Ethiopia	1500	1000	50
Abdul-Wahab et al. (2019)	Oman	1504	1316	19

As mentioned earlier, Africa faces enormous challenges in the energy sector. This has motivated researchers to utilize HOMER to investigate the feasibility of renewable energy systems' implementation to mitigate issues related to electricity affordability, reliability and accessibility. For instance, Maammeur et al. (2017) investigated a PV on-grid system for a reference farm in the North-Western part of Algeria. Energy consumption was assessed with the help of data from the national electricity and gas company Sonelgaz. The study found that the designed system was able to cover almost 50% of the total energy needs. An economic study of the system showed that the net present cost (NPC) of the project was very high compared to the lifetime of the project (25 years). Consequently, the study suggested that policies to encourage PV promotion need to be implemented to reduce the cost of such investments. Finally, environmental analysis of the carbon dioxide emission reductions showed that the PV system contributed to a remarkable reduction in emission of pollutants. Kebede (2015) carried out a study to investigate the feasibility of a grid-connected 5 MW solar PV power plant, in which 35 different locations across Ethiopia were considered. HOMER was utilized to analyse the technical and economic performance of the PV system. The analysis results demonstrated that the mean energy output that could be generated from the different locations was up to 8674 MWh/yr. The simulation results showed that such a project was economically feasible, though not highly attractive to private investors. The study advised that more support from the government is needed to support such investments, as relying only on hydropower may be risky in the near future. With the cost development and international financing programmes in Africa having changed significantly since 2015, REN21′s latest 2019 global status report indicated that Ethiopia still lags behind many African counties regarding regulatory policies and fiscal incentives to support the introduction of PV into the national share of energy production (Murdock et al. 2019). Akinyele (2017) conducted a techno-economic study of photovoltaic mini-grid systems in three locations in Nigeria, using a worst-case scenario for household energy demand. The study included system losses, the state of battery charge

Table 3
Solar global horizontal irradiance (GHI) data for every month of the year in Sudan.

Month	Radiation (kWh/m^2/day)	Clearness index
January	5.59	0.657
February	6.17	0.664
March	6.64	0.657
April	6.88	0.652
May	6.38	0.603
June	6.08	0.579
July	5.57	0.53
August	5.52	0.526
September	5.75	0.565
October	5.79	0.613
November	5.63	0.652
December	5.35	0.65

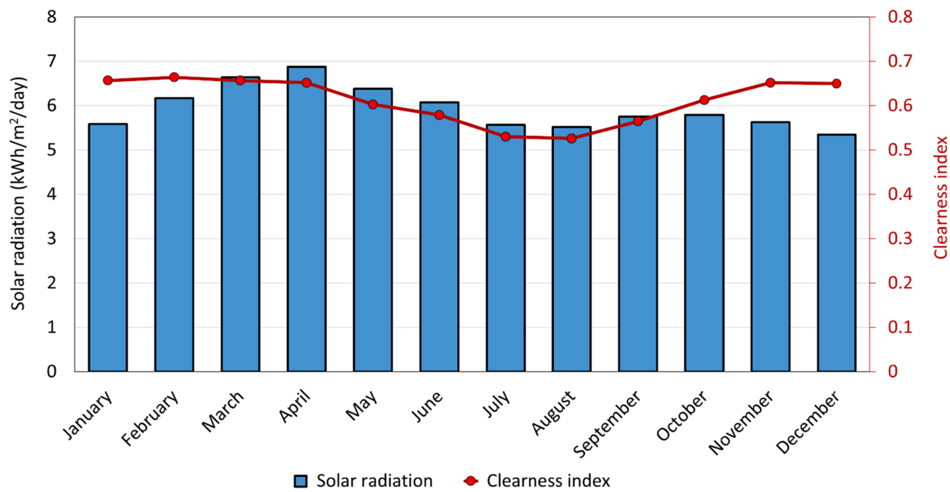

Fig. 2. The average monthly solar radiation data and clearness index values.

Table 4
HOMER project configuration input parameters.

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

and the possibilities of increased load. The results indicated that systems of 61, 76, and 68 kW_p could cover the needs of users with a yearly load of 63,500 kW/h. A diesel generator was included in the system and comparisons showed that there was a higher initial cost compared to PV mini-grid systems. However, electricity availability throughout the year was 100%, thus diesel generation provided a more reliable system. In Egypt, Nassar and Saleh (2015) carried out an investigation on the feasibility of a grid-connected PV power plant located in Qena Al-Gadida city. An analysis of the power plant was performed by comparing two economic assumptions. First, the cost of electricity purchased from the grid was considered to be equal to the cost of electricity sold to the grid. In contrast, the second assumption set the price of selling back to the grid higher than the cost of purchase from the grid. The results indicated that the first case scenario was not economically feasible because of the high investment cost and the low electricity sell-back price. However, in the case where the sell back price was higher, the project became more feasible. The latter economic model was also adopted by the Egyptian government in one of the largest solar PV installations in the world (Benban Solar Park). By using loans from international finance corps, the government offered a competitive price for produced electricity for the coming 25 years (Nordrum, 2019).

Focusing on Sudan, Salehin et al. (2011) conducted a study on the conceptualization of an emergency energy system to deliver electricity to a refugee camp situated on the Sudan-Chad border. HOMER software was used to model and optimize the system. The camp's electricity load was determined and compared with the different configurations of the designed energy systems. The assessment results showed that solar PV panels, a biogas polyethylene digester and a micro wind turbine system could provide enough electricity to the camp. As for Omar et al. (2019), their HOMER-based study focused on modelling and optimizing a hybrid micro-grid system that consists of PV, wind turbine and battery bank system, integrated with diesel generator to provide electricity for

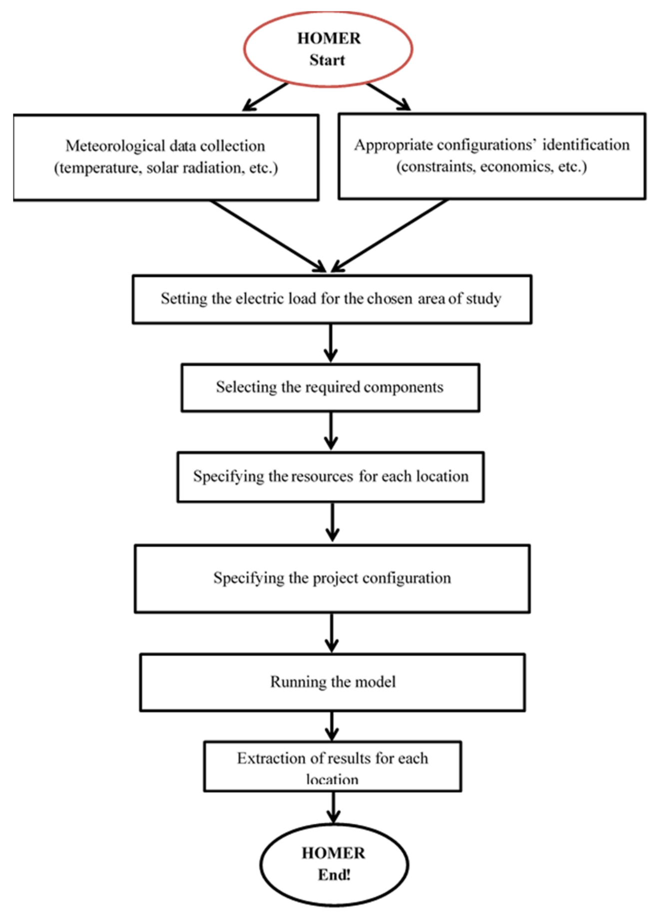

Fig. 3. HOMER operation flow diagram.

Table 5
The capital, replacement, and operation and maintenance costs for diesel generator (Elkadeem et al., 2019).

Type	Diesel generator
Capital cost (USD$/kW)	1000
Replacement cost (USD$/kW)	900
Operation and maintenance cost (USD$/op. hr)	0.39
Fuel price (USD$/L) (GlobalPetrolPrices.com, 2020)	0.159

Table 6
Monthly average solar radiation in kWh/m^2/day for the 21 locations in Sudan.

Location	January	February	March	April	May	June	July	August	September	October	November	December
Port Sudan	4.17	5.10	6.25	7.04	7.10	7.15	6.78	6.56	6.40	5.59	4.17	3.66
Omdurman	5.35	6.09	6.84	7.29	6.94	6.98	6.62	6.43	6.38	6.09	5.60	5.10
Al-Qadarif	5.61	6.21	6.61	6.85	6.47	6.51	5.95	5.84	6.16	5.91	5.70	5.50
Kassala	5.40	6.01	6.36	6.92	6.74	6.74	6.46	6.25	6.32	5.90	5.49	5.21
Kosti	5.43	6.07	6.61	6.99	6.56	6.42	5.84	5.74	5.98	5.85	5.50	5.22
Al-Obeid	5.67	6.26	6.84	7.27	6.94	6.72	6.08	5.98	6.22	6.11	5.73	5.35
Dongola	4.82	5.74	6.62	7.23	7.33	7.56	7.17	6.92	6.43	5.91	5.14	4.45
Al-Junaynah	5.55	6.33	6.94	7.14	6.88	6.66	6.09	5.89	6.04	5.92	5.70	5.33
Al-Fashir	5.56	6.22	6.86	7.21	7.03	6.63	5.99	6.00	6.14	5.99	5.69	5.27
Nyala	5.55	6.19	6.72	6.99	6.56	6.16	5.52	5.45	5.66	5.70	5.71	5.44
Wadi Halfa	4.46	5.57	6.48	7.21	7.43	7.78	7.49	7.13	6.48	5.61	4.85	4.21
Al-Damazin	5.96	6.38	6.61	6.65	5.94	5.27	4.82	4.89	5.33	5.44	5.97	5.84
Haiya	4.99	5.70	6.36	6.97	6.91	6.99	6.79	6.62	6.27	5.62	4.91	4.63
Ad-Damar	4.84	5.75	6.62	7.17	6.87	6.93	6.63	6.42	6.20	5.63	5.08	4.59
Abu Hamed	4.62	5.67	6.65	7.42	7.32	7.38	7.09	6.88	6.45	5.74	5.02	4.42
Merowe	4.95	5.89	6.64	7.28	7.20	7.24	6.94	6.65	6.28	5.80	5.08	4.59
Kutum	5.60	6.26	7.00	7.33	7.23	6.91	6.37	6.26	6.30	6.09	5.75	5.27
Salala	4.73	5.63	6.44	6.89	7.04	7.14	6.85	6.4	6.15	5.42	4.55	4.25
Wawa	4.71	5.64	6.60	7.27	7.43	7.79	7.40	7.15	6.60	5.92	5.15	4.38
Karima	4.95	5.89	6.64	7.28	7.20	7.24	6.94	6.65	6.28	5.80	5.08	4.59
Al-Goled	4.98	5.89	6.66	7.34	7.27	7.34	6.99	6.73	6.34	5.94	5.29	4.59

Table 7
Monthly average clearness index for the 21 locations in Sudan.

Location	January	February	March	April	May	June	July	August	September	October	November	December
Port Sudan	0.552	0.597	0.644	0.667	0.651	0.653	0.623	0.619	0.647	0.636	0.540	0.507
Omdurman	0.659	0.677	0.687	0.690	0.647	0.652	0.620	0.609	0.633	0.662	0.678	0.652
Al-Qadarif	0.672	0.677	0.658	0.648	0.607	0.615	0.562	0.555	0.608	0.632	0.672	0.683
Kassala	0.663	0.666	0.638	0.655	0.628	0.631	0.606	0.592	0.627	0.641	0.662	0.664
Kosti	0.641	0.655	0.654	0.662	0.619	0.610	0.555	0.547	0.588	0.621	0.640	0.638
Al-Obeid	0.670	0.676	0.677	0.688	0.654	0.639	0.578	0.569	0.612	0.648	0.667	0.654
Dongola	0.633	0.668	0.680	0.685	0.673	0.692	0.660	0.653	0.649	0.669	0.661	0.611
Al-Junaynah	0.659	0.685	0.688	0.676	0.648	0.632	0.578	0.560	0.595	0.630	0.666	0.655
Al-Fashir	0.662	0.675	0.681	0.683	0.661	0.628	0.568	0.571	0.605	0.638	0.667	0.649
Nyala	0.644	0.660	0.662	0.663	0.622	0.590	0.528	0.520	0.555	0.599	0.654	0.652
Wadi Halfa	0.618	0.673	0.679	0.686	0.677	0.702	0.682	0.673	0.663	0.656	0.656	0.613
Al-Damazin	0.689	0.678	0.650	0.631	0.564	0.506	0.462	0.467	0.522	0.570	0.681	0.697
Haiya	0.645	0.656	0.650	0.660	0.637	0.642	0.627	0.625	0.630	0.630	0.622	0.625
Ad-Damar	0.617	0.655	0.673	0.679	0.635	0.640	0.615	0.607	0.620	0.625	0.635	0.610
Abu Hamed	0.611	0.663	0.685	0.703	0.672	0.674	0.652	0.649	0.652	0.652	0.650	0.612
Merowe	0.642	0.679	0.679	0.689	0.663	0.665	0.641	0.628	0.631	0.651	0.645	0.621
Kutum	0.673	0.684	0.697	0.694	0.678	0.652	0.601	0.595	0.622	0.653	0.680	0.656
Salala	0.649	0.676	0.672	0.655	0.642	0.646	0.625	0.604	0.628	0.630	0.609	0.612
Wawa	0.635	0.668	0.684	0.690	0.680	0.708	0.678	0.675	0.670	0.680	0.678	0.619
Karima	0.642	0.679	0.679	0.689	0.663	0.665	0.641	0.628	0.631	0.651	0.646	0.622
Al-Goled	0.646	0.679	0.681	0.695	0.670	0.674	0.646	0.636	0.637	0.667	0.672	0.621

Shalateen city, located within a disputed territory between Sudan and Egypt.

Salih et al. (2014) on the other hand investigated the utilization of a hybrid micro system composed of PV panels and a wind turbine to satisfy the energy needs of telecommunication equipment in remote locations in Sudan. The results indicated that the system was able to deliver enough energy to cover the full load. Using HOMER, different cases were examined with various economic scenarios. The study concluded that the application of renewable energy systems constitutes an important opportunity for the telecommunication industry in Sudan.

Elkadeem et al. (2019a,b) carried out a feasibility study of a grid-isolated hybrid renewable energy system to generate electricity for an agriculture and irrigation site in Dongola, situated in the north of Sudan. Of the investigated systems, hybridization of PV showed the best techno-economic performance. Moreover, the inclusion of renewable energy systems helped to support the total energy demand. The study also showed the importance of incorporating renewable energy resources into government plans for meeting the international aims of the United Nations regarding clean and sustainable energy transitions.

Ibrahim et al. (2020) conducted a study to design and optimize a photovoltaic system integrated with an already existing diesel-grid system to deliver electricity to El Daein city (East Darfour), situated in the southwestern of Sudan. Among the various combinations investigated, four in total, HOMER simulation results revealed that the hybridization of 2000 kW PV, 5000 kW diesel generator, 2 batteries (1000 kWh nominal capacity each) and 2000 kW power converter provides the optimal and better techno-economic performance among all investigated four cases.

Despite all the attempts to encourage the worldwide implementation of renewable energy projects, solar PV-based projects in particular, to ensure a sustainable energy transition, there has been a very limited amount of research focused on the feasibility of these technologies in Sudan. Furthermore, these studies were limited to a very few locations in the country and did not cover the whole country in their investigations. This paper deals with the possibility of harvesting the solar energy resources locally available in Sudan. Starting with input data related to the selected locations in Sudan, including hourly weather data, economic factors, and type of technology, simulations were performed for a grid-connected solar photovoltaic power plant. The objectives of this research were firstly to investigate the best solar photovoltaic

Table 8
HOMER simulation results for various types of solar PV systems.

No.	Type	Capacity (kW)	COE (USD $/kWh)	NPC (USD$)	Unmet electric load (%)	No. of PV units required to achieve the desired demand of 20 MW $\left(\text{No. of PV units} = \frac{20\ \text{MW}}{\text{Capacity of the selected PV type}}\right)$
1	Ingeteam (1164kVA) with Generic PV	1164	0.08792	42.8 M	78.3	18
2	Schneider ConextCoreXC 680 kW with Generic PV	680	0.08787	42.8 M	78.3	30
3	Studer VarioString VS-120 with Generic PV	680	0.08828	42.8 M	78.4	30
4	Studer VarioTrack VT-65 with Generic PV	680	0.08746	42.8 M	78.2	30
5	Studer VarioTrack VT-80 with Generic PV	680	0.08746	42.8 M	78.2	30
6	Schneider ConextCoreXC 630 kW with Generic PV	630	0.08771	42.8 M	78.2	32
7	Schneider ConextCoreXC 540 kW with Generic PV	540	0.08803	42.8 M	78.3	38
8	SolarMax 500RX A with Generic PV	500	0.08828	42.8 M	78.4	40
9	SMA Sunny Tripower 60-US with Generic PV	60	0.08838	42.8 M	78.4	334
10	Huawei SUN2000 30 kW with Generic PV	30	0.08789	42.8 M	78.3	667
11	Huawei SUN 2000 25 kW with Generic PV	25	0.08903	42.8 M	78.5	800
12	Schneider Conext CL25000 E with generic PV	25	0.09871	42.8 M	80.6	800
13	Fronius Symo 24.0–3-M with Generic PV	24	0.08870	42.8 M	78.5	834
14	Fronius Symo 20.0–3-M with Generic PV	20	0.08879	42.8 M	78.5	1000
15	Schneider Conext CL20000 E with generic PV	20	0.09871	42.8 M	80.6	1000
16	Fronius Primo 8.2–1 with Generic PV	8.25	0.08955	42.8 M	78.7	2425
17	Fronius Symo 8.2–3-M with Generic PV	8.2	0.08883	42.8 M	78.5	2420
18	Fronius Symo 4.5–3-S with Generic PV	4.4	0.08867	42.8 M	78.5	4546
19	Fronius Galvo 3.1–1 with Generic PV	2.48	0.09023	42.8 M	78.8	8065

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

technology available, using HOMER software. The second objective was to determine the best location for photovoltaic solar energy generation in Sudan. The avoidance of pollutant emissions by implementing a solar photovoltaic project were assessed by comparing the PV plant to a power plant of the same capacity using diesel fuel. Finally, the effect of solar panel price on the total economics of the project was investigated.

2. Materials and methods

2.1. Area of study description

The present study was carried out to identify the optimal type of solar PV to utilize to meet an electric load of 20 megawatts (MW) for a chosen village in Sudan. The solar PV systems under consideration were simulated in HOMER software in 21 locations in Sudan: Port Sudan, Omdurman, Al-Qadarif, Kassala, Kosti, Al-Obeid, Dongola, Al-Junaynah, Al-Fashir, Nyala, Wadi Halfa, Al-Damazin, Haiya, Ad-Damar, Abu Hamed, Merowe, Kutum, Salala, Wawa, Karima, and Al-Goled. The objective was to identify locations that could effortlessly and effectively deliver the most solar energy while taking into account the cost of energy (COE). The geographical details of the 21 locations assessed are listed in Table 1 and their geographical locations on the map of Sudan are illustrated in Fig. 1.

2.2. Input data collection and operation of HOMER

The initial stage in the operation of HOMER was to amass the essential input data for the study domain (including load profile; capital; replacement, operational and maintenance costs; and meteorological data). In this investigation, the load profile was assumed to be 20 MW for all months of the year. Various types of solar PV systems, with a minimum capacity of 2.48 kW and a maximum capacity of 1164 kW, were chosen from the accessible library provided in HOMER. Each type from the 19 diverse solar PV systems was examined individually.

Looking at the capital, replacement, and operational and maintenance costs of solar PV, it must be noted that Sudan lacks such information. Therefore, a comparison was carried out (Table 2) to identify the costs of PV in countries near Sudan. Based on this comparison, the study was based on the recent costs provided by Gebrehiwot et al. (2019) (Capital cost = 1500 USD$/kW, Replacement cost = 1000 USD $/kW, Operation and Maintenance (O&M) cost = 50 USD$/kW). Further analysis will be carried out to identify the impact of PV costs on the project economics.

The use of solar energy requires identifying the suitable resources (i. e. solar radiation, temperature, etc.) for the chosen renewable energy component. In order to do so, information on the monthly average global horizontal irradiation (GHI), solar radiation, and clearness index (a measure of the atmosphere's clearness, defined as the fraction of the solar radiation that is transmitted through the atmosphere to strike the earth's surface) for every month over a period of one year in Sudan were

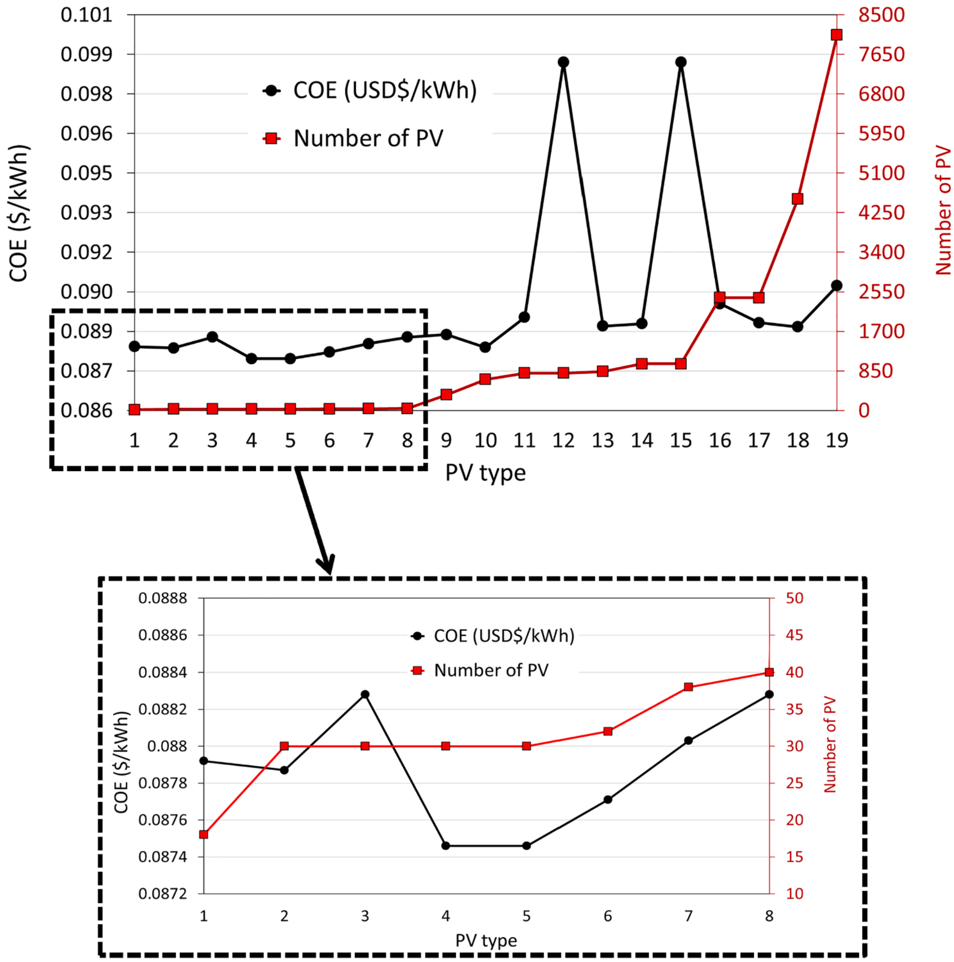

Fig. 4. Cost of energy (COE) of the examined PVs. 1 Ingeteam (1164kVA) with Generic PV. 2 Schneider ConextCoreXC 680 kW with Generic PV. 3 Studer VarioString VS-120 with Generic PV. 4 Studer VarioTrack VT-65 with Generic PV. 5 Studer VarioTrack VT-80 with Generic PV. 6 Schneider ConextCoreXC 630 kW with Generic PV. 7 Schneider ConextCoreXC 540 kW with Generic PV. 8 SolarMax 500RX A with Generic PV. 9 SMA Sunny Tripower 60-US with Generic PV. 10 Huawei SUN2000 30 kW with Generic PV. 11 Huawei SUN 2000 25 kW with Generic PV. 12 Schneider Conext CL25000 E with generic PV. 13 Fronius Symo 24.0–3-M with Generic PV. 14 Fronius Symo 20.0–3-M with Generic PV. 15 Schneider Conext CL20000 E with generic PV. 16 Fronius Primo 8.2–1 with Generic PV. 17 Fronius Symo 8.2–3-M with Generic PV. 18 Fronius Symo 4.5–3-S with Generic PV. 19 Fronius Galvo 3.1–1 with Generic PV.

acquired from the National Aeronautics and Space Administration (NASA) database (NASA, 2020). Table 3 summarizes the monthly average solar radiation and clearness index for a period of one year. In addition, temperatures were also acquired from the NASA database. Fig. 2 demonstrates, for every month of the year, the daily radiation (kWh/m^2/day) data on the left axis and the clearness index values on the right axis. It can be observed that the clearness index values were nearly the same throughout the whole year (between 0.664 and 0.526). However, the same cannot be said for the solar radiation data: the average daily radiation value was at its peak in April (6.880 kWh/m^2/day) and at a minimum in December (5.350 kWh/m^2/day).

The last stage was to set out the project configurations (i.e., constraints, economics, optimization, and emissions). Starting with the constraints, the solar power output was set at 100% to boost the yield from solar energy, given that it is the sole source of energy investigated in this study. Because the solar system is not supported by any other energy source, the maximum annual capacity shortage was assumed to be 100%. As for the project economics section, a 25-year project lifetime was considered, and the nominal discount rate (a measure of the weighted average cost of capital for electrical energy distribution in the country) was defined to be 6% (Elkadeem et al., 2019a,b). Moving to the optimization configuration, and in order to simulate the solar energy system for every hour for the year, the time step was set at 60 min. Furthermore, and given the fact that no penalties are imposed on emissions in Sudan, emission penalties were set at zero. HOMER project configuration input parameters are summarized in Table 4. After providing all the necessary data and defining the project configurations, HOMER software simulated the operation of the system and calculated the results according to the provided data. HOMER operation flow diagram is summarized in Fig. 3.

In the second part of the study, and considering the same load profile (20 MW), a diesel-powered generator replaced the PV systems to determine the emissions that could be avoided by the use of PV. The capital, replacement and operation and maintenance costs of the diesel generator are summarized in Table 5.

In the third part of the study, the optimal PV identified in the study's first section was simulated operating in the 21 locations identified in Sudan. Each of these locations had a diverse solar radiation (Table 6) and clearness index (Table 7) values. The same project configurations and electric load profile were used as in the first part of the study.

As for the last part of the study, and after identifying the optimal locations that deliver the most solar energy while taking into account the cost of energy (COE), the costs of PV were varied to deliver an understanding of the effect of PV cost on the project economics.

3. Results and discussion

3.1. Determination of the optimal PV

Table 8 demonstrates HOMER simulation results for the 19 different types of solar PV systems having diverse capacities. The net present cost (NPC) for all the PVs was found to be around USD$ 42.8 M. From the results, it can be observed that the highest COE was recorded for types 12 (Schneider Conext CL25000 E with generic PV) and 15 (Schneider Conext CL20000 E with generic PV) at USD$ 0.09871/kWh. On the other hand, types 4 (Studer VarioTrack VT-65 with Generic PV), 5 (Studer VarioTrack VT-80 with Generic PV) and 6 (Schneider ConextCoreXC 630 kW with Generic PV) showed the lowest COE (USD$

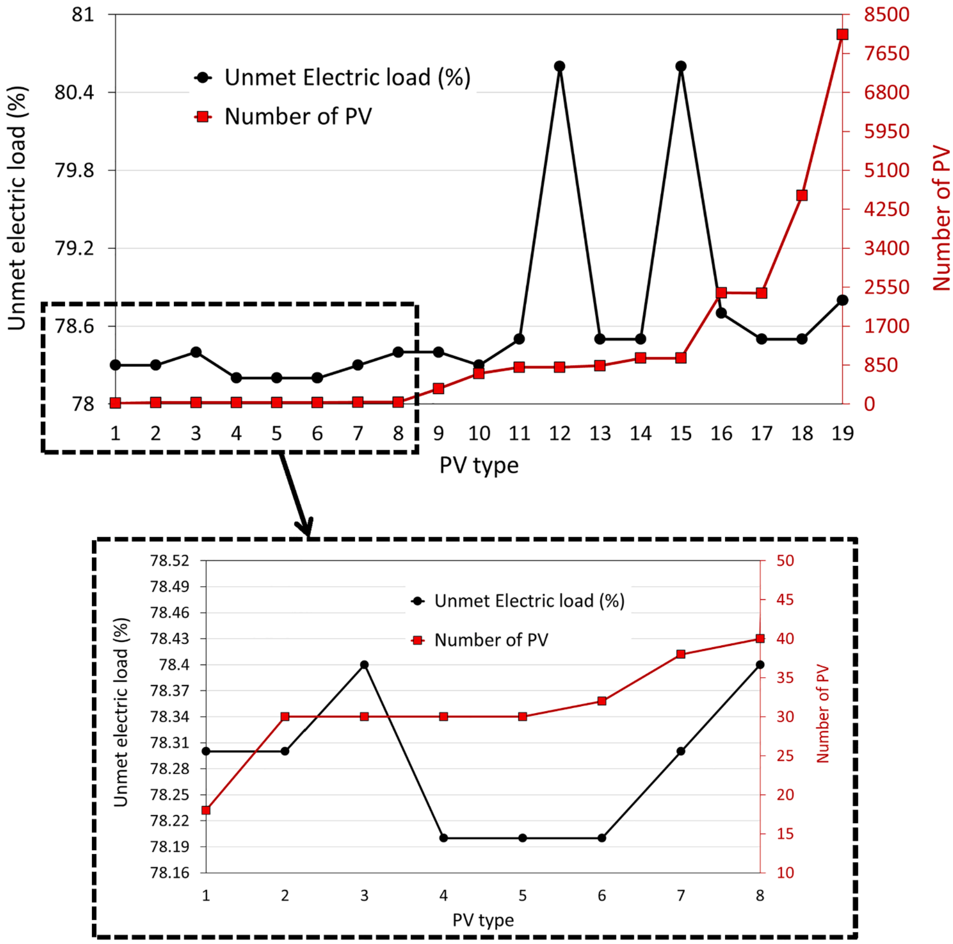

Fig. 5. The unmet electrical load of the examined PVs. 1 Ingeteam (1164kVA) with Generic PV. 2 Schneider ConextCoreXC 680 kW with Generic PV. 3 Studer VarioString VS-120 with Generic PV. 4 Studer VarioTrack VT-65 with Generic PV. 5 Studer VarioTrack VT-80 with Generic PV. 6 Schneider ConextCoreXC 630 kW with Generic PV. 7 Schneider ConextCoreXC 540 kW with Generic PV. 8 SolarMax 500RX A with Generic PV. 9 SMA Sunny Tripower 60-US with Generic PV. 10 Huawei SUN2000 30 kW with Generic PV. 11 Huawei SUN 2000 25 kW with Generic PV. 12 Schneider Conext CL25000 E with generic PV. 13 Fronius Symo 24.0–3-M with Generic PV. 14 Fronius Symo 20.0–3-M with Generic PV. 15 Schneider Conext CL20000 E with generic PV. 16 Fronius Primo 8.2–1 with Generic PV. 17 Fronius Symo 8.2–3-M with Generic PV. 18 Fronius Symo 4.5–3-S with Generic PV. 19 Fronius Galvo 3.1–1 with Generic PV.

Table 9
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%

0.08746/kWh for types 4 and 5 and USD$ 0.08771/kWh for type 6). Figs. 4 and 5 depict the COE and the unmet electrical load of the examined 19 solar PVs, respectively. It can be seen that the unmet electrical load results were nearly the same and varied between 78.2% and 80.6%. However, the same cannot be said for the COE results. The operation and maintenance costs are highly dependent on the number of PV units required for electricity generation to supply the desired demand of 20 MW. The lower the number of required solar PV panels, the lower the operation and maintenance costs. The least number of PV units required was with type 1 (Ingeteam (1164kVA) with Generic PV), whereas the highest was from type 19 (Fronius Galvo 3.1-1 with Generic PV).

Based on the attained results, and considering the fact that it had the lowest COE and a relatively low number of PV units required, the optimal solar PV to meet a 20 MW-demand for a village in Sudan is either type 4 (Studer VarioTrack VT-65 with Generic PV), which was selected for the subsequent analyses, or type 5 (Studer VarioTrack VT-80 with Generic PV). Table 9 summarizes the properties of the selected optimal PV system. This type of system, in comparison to the other types investigated earlier, showed the lowest COE (around USD$ 0.08746/kWh) and it requires only 30 PV panels to supply the desired demand.

3.2. Comparison between the optimal PV and diesel generator

3.2.1. Economics

The costs of electricity for the two systems are: USD$ 0.08746/kWh for solar PV and USD$ 0.9623/kWh for the diesel-powered generator system. In this sense, implementing a solar PV system will contribute COE savings of around USD$ 0.87484/kWh.

This analysis was performed considering a fixed value for diesel fuel price (USD$ 0.159/L). However, this value is anticipated to change through the project lifetime. For instance, if the government decided to decrease the subsidy on the diesel fuel prices, the fuel price will be increased in the future. On the other hand, and in the wake of such events, the Coronavirus (Covid-19) pandemic and global economic recession has diminished global energy demand and collapsed fossil fuel prices (Yoshino et al., 2020). In this regard, and to cover the future fluctuations of the diesel fuel price, a sensitivity analysis was performed, and the price of diesel fuel was varied to deliver an understanding on the effect of diesel fuel price on the COE savings. Fig. 6 illustrates the impact of diesel fuel price on the COE of the diesel-powered generator system. The results clearly show the superior economic performance of the recommended solar PV system over the conventional diesel-powered generator system, implying that the system is sustainable to the fluctuations of diesel fuel price.

3.2.2. Greenhouse gases emissions

Since it produces no emissions, unlike fossil fuels that generate

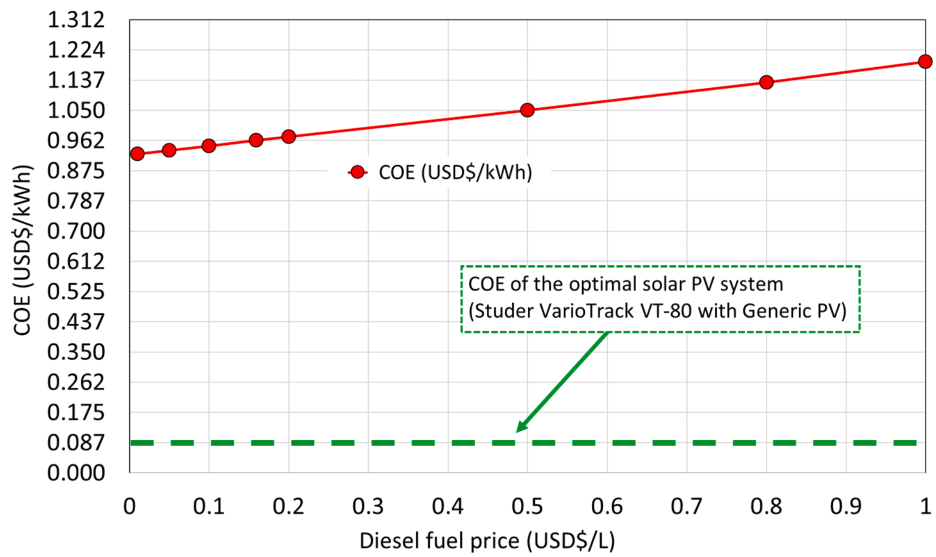

Fig. 6. Effect of diesel fuel price on the COE of the diesel-powered generator system.

Table 10
Greenhouse gas emissions by a diesel generator with a met electric load percentage of 21.8%

Quantity	Emissions (kg/year)
Carbon monoxide (CO)	167,508
Carbon dioxide (CO_2)	26,574,036
Particulate matter (PM)	1015
Unburned hydrocarbons (UHC)	7309
Nitrogen oxides (NO_x)	157,356
Sulfur dioxide (SO_2)	65,074
Total	26,972,298

significant amounts of pollutants, solar PV is considered a clean, environmentally friendly source of energy. Employing solar PVs would prevent greenhouse gas emissions caused by fossil fuel combustion. The currently employed and most widely utilized fossil fuel in Sudan's electricity production in off-grid power plants is diesel. Greenhouse gases have various negative effects on humans and the environment. Starting with the effects on humans, they can cause respiratory problems and prevent delivery of oxygen to the body's tissues and organs, causing dizziness, headaches and impaired visual perception. Environmentally, burning fossil fuels results in atmospheric reactions causing photochemical smog and acid rain (Diab et al., 2016). Table 10 summarizes the amounts of greenhouse gases (carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM), unburned hydrocarbons (UHC), nitrogen oxides (NO_x) and sulfur dioxide (SO_2)) emitted from a diesel generator with a met electric load percentage of 21.8% (similar to the met electrical load of the optimal PV). HOMER simulation results show that the utilization of PV will avoid the generation of a total of 26,972,298 kg/year of pollutants.

3.3. Performance analysis of the optimal PV system

Table 11 demonstrates the results of HOMER simulation utilizing the optimal solar PV system (Studer VarioTrack VT-65 with Generic PV) for the 21 locations in Sudan. The minimum COE was attained in Wawa (USD$ 0.0812/kWh) followed by Kutum (USD$ 0.08151/kWh), Wadi Halfa (USD$ 0.0821/kWh), Dongola (USD$ 0.08254/kWh) and Al-Goled (USD$ 0.08255/kWh). In contrast, the maximum COE was attained in Al-Damazin, followed by Port Sudan, Kosti, Nyala and Ad-Damar at USD$ 0.09020/kWh, USD$ 0.08916/kWh, USD$ 0.08734/kWh, USD$ 0.08712/kWh and USD$ 0.08573/kWh, respectively. The

Table 11
HOMER simulation results using the best solar PV (Studer VarioTrack VT-65 with Generic PV) for the 21 locations in Sudan.

Location	COE (USD $/kWh)	NPC (USD $)	OC (USD $)	Unmet electric load (%)
Port Sudan	0.08916	42.8 M	1 M	78.6
Omdurman	0.08298	42.8 M	1 M	77
Al-Qadarif	0.08546	42.8 M	1 M	77.6
Kassala	0.08468	42.8 M	1 M	77.4
Kosti	0.08734	42.8 M	1 M	78.1
Al-Obeid	0.08334	42.8 M	1 M	77.1
Dongola	0.08254	42.8 M	1 M	76.9
Al-Junaynah	0.08390	42.8 M	1 M	77.2
Al-Fashir	0.08347	42.8 M	1 M	77.1
Nyala	0.08712	42.8 M	1 M	78.1
Wadi Halfa	0.08210	42.8 M	1 M	76.7
Al-Damazin	0.09020	42.8 M	1 M	78.8
Haiya	0.08491	42.8 M	1 M	77.5
Ad-Damar	0.08573	42.8 M	1 M	77.7
Abu Hamed	0.08319	42.8 M	1 M	77
Merowe	0.08345	42.8 M	1 M	77.1
Kutum	0.08151	42.8 M	1 M	76.6
Salala	0.08525	42.8 M	1 M	77.6
Wawa	0.08120	42.8 M	1 M	76.5
Karima	0.08344	42.8 M	1 M	77.1
Al-Goled	0.08255	42.8 M	1 M	76.9

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

COE for the investigated 21 locations in Sudan is illustrated in Fig. 7, where the five lowest-cost locations are highlighted in red. The unmet electric load ranges between 76.5 and 78.8%; Al-Damazin has the highest percentage of unmet electric load and Wawa has the lowermost percentage. The unmet electrical load for the investigated 21 locations in Sudan is depicted in Fig. 8, where the where the five lowest unmet load locations are shown in red.

Because of the high intensities of solar radiation that characterize these regions, solar photovoltaic systems are ideally suited to electrical power production in remote desert areas. Having said that, dust deposition on PV panels, which is considered a complex phenomenon that mainly takes place at regions with dry weather and is influenced by diverse site-specific environmental and weather conditions, has negative consequences on the PV panels' output. Accumulation of dust on even one panel in an array prevents incident light from reaching the solar PV panel, diminishing their efficiency in energy generation substantially up

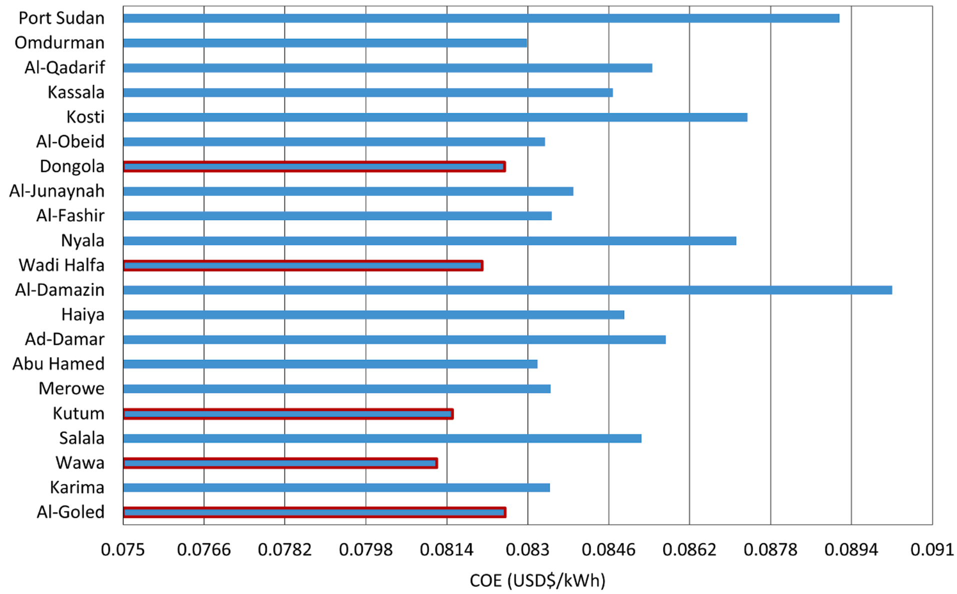

Fig. 7. The Cost of energy (COE) for the 21 locations investigated in Sudan.

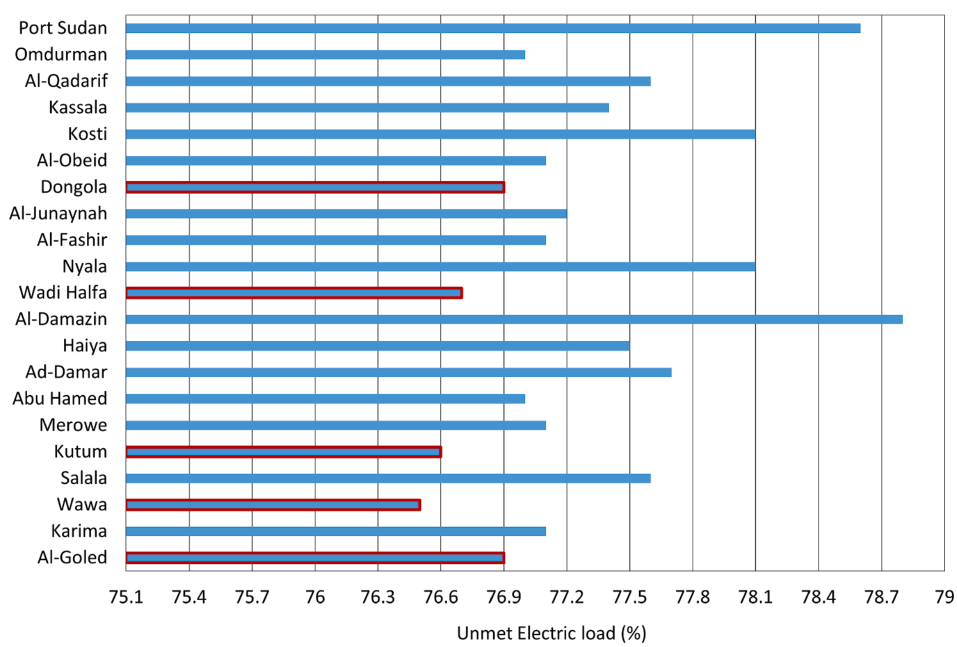

Fig. 8. The unmet electrical load for the 21 locations investigated in Sudan.

to 40% (Ibrahim, 2011; Mondal and Bansal, 2015).

Another crucial factor in solar photovoltaic system underperformance is humidity. When the incident light hits a water layer, refraction, reflection or diffraction occur, which affect the reception levels and diminish the light's intensity (Mondal and Bansal, 2015). This, in turn, reduces the PV panel's efficiency.

In this regard, and for better solar energy production, solar photovoltaic systems should be used in regions with high intensities of solar radiation and clearness index values, and lower levels of dust and humidity.

Wawa, Kutum, Wadi Halfa, Dongola and Al-Goled stood out distinctively as the finest sites for solar energy production. Not only are these located in arid desert with lower amounts of dust; they are endowed with the highest levels of solar radiation (Fig. 9) and clearness indices (Fig. 10), and longer durations of sunshine hours. Kutum and Wawa have the maximum level of solar radiation in Sudan followed by Al-Goled, Dongola and Wadi Halfa (Fig. 9). With regard to clearness index (Fig. 10), Wawa has the maximum clearness index followed by Wadi Halfa, Dongola, Al-Goled and Kutum. These locations also had the lowest energy costs compared to the other sites in Sudan. The lowest was attained in Wawa, followed by Kutum, Wadi Halfa, Dongola and Al-Goled at a COE of USD$ 0.08120/kWh, USD$ 0.08151/kWh, USD$ 0.08210/kWh, USD$ 0.08254/kWh and USD$ 0.08255/kWh, respectively. All these factors indicate the potential for high utilization of solar energy at these locations, particularly at Wawa, Kutum and Wadi Halfa. Expanding on this, Fig. 11 shows the monthly average electric production from Wawa, Kutum and Wadi Halfa. For the three locations, the results show that the highest solar electricity generation levels take place between March and April, with higher levels occurring in March. During this period, these locations experience the highest levels of solar

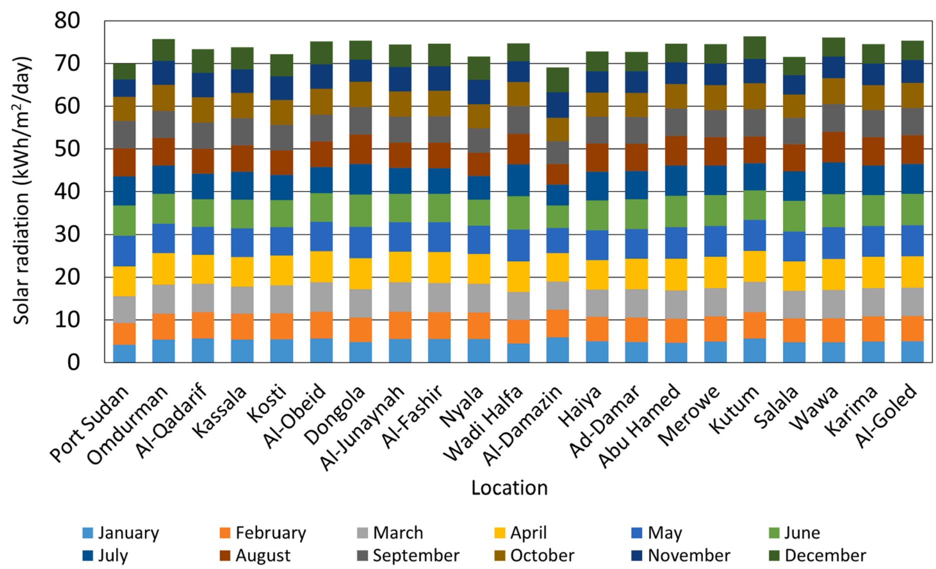

Fig. 9. Solar radiation values for the 21 locations investigated in Sudan.

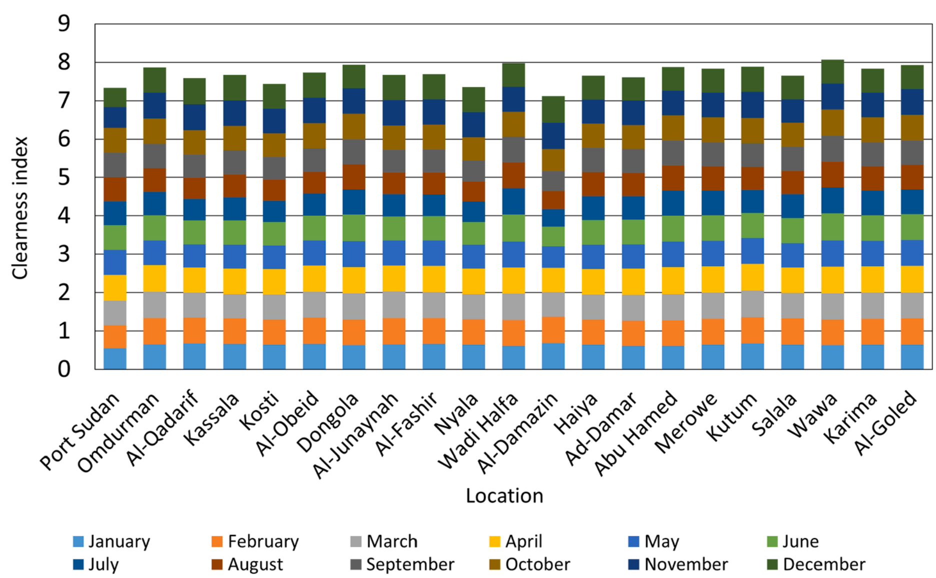

Fig. 10. Clearness index values for the 21 locations investigated in Sudan.

radiation and clearness indices in comparison to the remaining months thus explaining the high electricity generation levels. Also, it can be seen that the electric production tends to decrease from the month of April and continues this gradual decline until July. This can be attributed to the temperature effects on the PV array operation. It has been widely reported in the literature that temperature affects the power output of PV systems inversely in which high temperatures reduce the PV cell's voltage and consequently the power output of the PV system. (Kaltschmitt et al., 2007; Al-Badi et al., 2012; Dubey et al., 2013; Olukan and Emziane, 2014; Adeeb et al., 2019). An increase in PV cell's temperature by 1 °C can decrease the PV system's power output by 0.5–0.6% (Al-Badi et al., 2012; Hajiah et al., 2012; Kazem and Khatib, 2013). As can be observed from Fig. 11, the temperature notably rises as the country approaches summer season (extends from the end of March to the end of June). This causes the efficiency of PV to decrease, resulting in lower electric generation levels.

In contrast, numerous factors make Al-Damazin, Port Sudan, Kosti, Nyala, Ad-Damar, Al-Qadarif and Salala less appealing sites for solar energy utilization. For instance, locations such as Port Sudan and Salalah are on the coast and have high levels of humidity. In terms of solar radiation (Fig. 9), Al-Damazin has the lowest level of solar radiation in Sudan, followed by Port Sudan, Salala, Nyala, Kosti, Ad-Damar and Al-Qadarif. In terms of clearness index (Fig. 10), Al-Damazin also exhibited the lowest clearness index, followed by Port Sudan, Nyala, Kosti, Al-Qadarif, Ad-Damar and Salala. In addition to the aforementioned factors, these locations have the highest COE values in comparison with the COE for other locations in Sudan (Al-Damazin (USD$ 0.09020/kWh) followed by Port Sudan (USD$ 0.08916/kWh), Kosti (USD$ 0.08734/kWh), Nyala (USD$ 0.08712/kWh), Ad-Damar (USD$ 0.08573/kWh), Al-Qadarif (USD$ 0.08546/kWh) and Salala (USD$ 0.08525/kWh)).

3.4. Impact of PV cost on the renewable energy project economics

Having identified the optimal locations that deliver the most solar energy, taking into account the cost of energy (COE), and given the very rapid decline in PV pricing realized to date and the prospect of continued declines, the costs of PV were varied to deliver an understanding on the

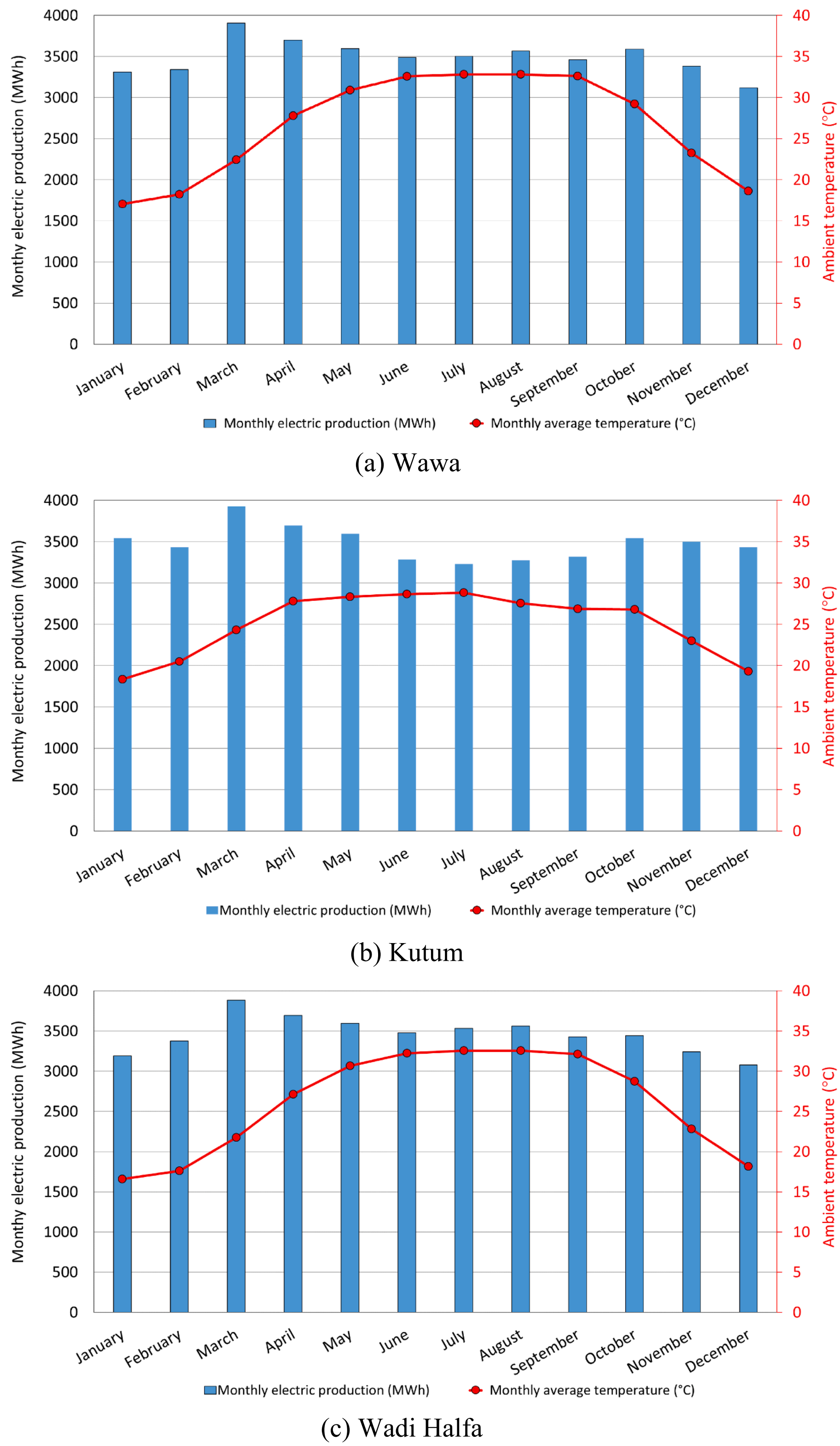

Fig. 11. Monthly average electric production and ambient temperature profile for Wawa, Kutum and Wadi Halfa.

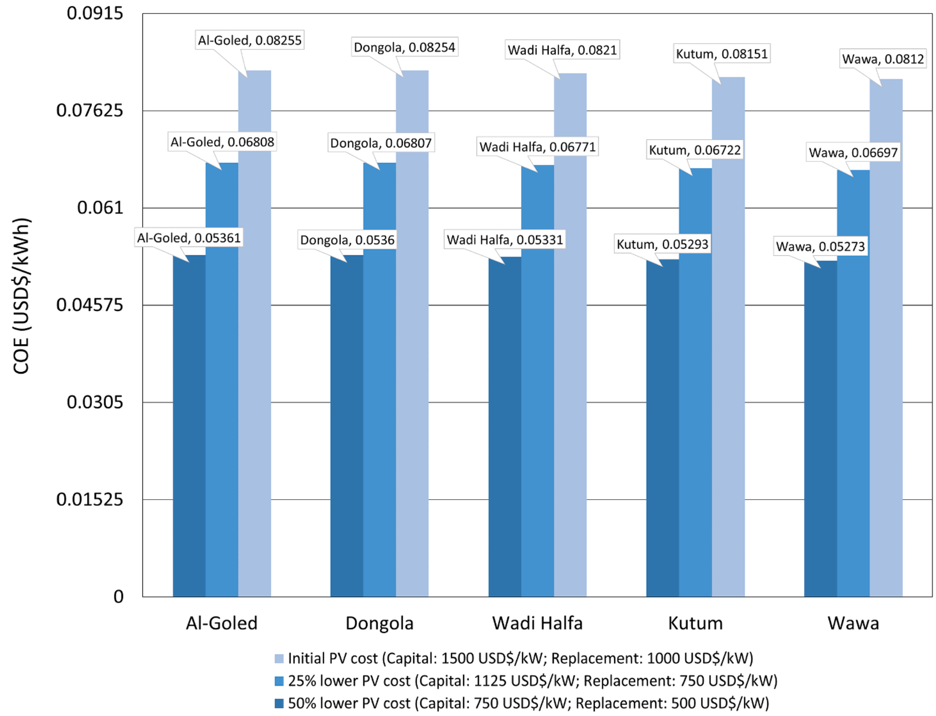

Fig. 12. Impact of PV cost on the COE for the top five locations in Sudan.

effect of PV costs on the project economics. Fig. 12 demonstrates the impact of PV cost variation on the COE for the top five locations with the lowest COE. It is apparent from the results that reducing the PV costs by about 25% (Capital cost = 1125 USD$/kW, Replacement cost = 750 USD$/kW) has a significant influence, and the cost of energy produced from these PV plants reduces to USD$ 0.06697/kWh, USD$ 0.06722/kWh, USD$ 0.06771/kWh, USD$ 0.06807/kWh and USD$ 0.06808/kWh for Wawa, Kutum, Wadi Halfa, Dongola and Al-Goled, respectively. A further decrease in the PV costs (up to 50% of the initial costs) drastically decreases the cost of energy, ranging between USD$ 0.05273/kWh and USD$ 0.05361/kWh in the top five locations in Sudan. This demonstrates the opportunity for PV to serve as a central contributor to all segments of the global energy system in a cost-effective and environmentally sound manner.

4. Conclusion

This study was carried out, with the help of HOMER software, to identify the optimal type of solar PV to utilize to meet an electric load of 20 megawatts (MW) for a town in Sudan. Based on the results obtained, and considering the fact that it has the lowest COE and a relatively low number of PV units required, the optimal solar PV to meet the targeted demand is the Studer VarioTrack VT-65 with Generic PV. Moreover, HOMER simulation results showed that implementing a solar PV system instead of a diesel generator will contribute in COE savings of around USD$ 0.87484/kWh and avoid the generation of a total of almost 27 million kg/year of pollutants. The identified optimal solar PV system was then simulated operating in 21 diverse locations in Sudan to discover which location would most efficiently yield the best amount of solar energy for Sudan. Due to the relatively low COE, the high intensity of solar radiation and the clearness indices that characterize these regions, the software-based analyses revealed that Wawa, followed by Kutum, Wadi Halfa, Dongola and Al-Goled stood out distinctively as the finest sites for solar energy utilization. After identifying the optimal locations that deliver the most solar energy while taking into account the COE, and taking into consideration the rapid decrease in PV pricing realized to date and the predictions for continued declines, the costs of PV were varied to investigate the impact of PV costs on the project economics. It was found that reducing the PV costs by about 25% of its initial value had a significant impact, and the cost of energy produced from the PV plant reduced in the range of USD$ 0.06697/kWh and USD$ 0.06808/kWh. A further reduction in the PV costs of up to 50% significantly reduced the cost of energy, ranging between USD$ 0.05273/kWh and USD$ 0.05361/kWh in all the top five locations in Sudan.

The development of such a project will be a major milestone in the renewable energy sector in Sudan, not only adding new capacity but also increasing energy security and addressing environmental concerns. The findings of this study are of high significance and should encourage policymakers, investors and actors in the field of solar energy to undertake more investment in solar energy in Sudan. This in turn will generate employment opportunities that will alleviate poverty and provide a visionary approach towards achieving a cleaner, more sustainable energy future not only for Sudanese, but also for others around the world, considering that Sudan has the potential to become a major exporter of renewable energy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Al-Badi, A.H., Al-Toobi, M., Al-Harthy, S., Al-Hosni, Z., Al-Harthy, A., 2012. Hybrid systems for decentralized power generation in Oman. Int. J. Sustain. Energ. 31 (6), 411–421.

Al Garni, H., Awasthi, A., 2017. Techno-economic feasibility analysis of a solar PV grid-connected system with different tracking using HOMER software. In: IEEE International Conference on Smart Energy Grid Engineering (SEGE), 217–222.

Abdul-Wahab, S., Charabi, Y., Al-Mahruqi, A.M., Osman, I., Osman, S., 2019. Selection of the best solar photovoltaic (PV) for Oman. Sol. Energy 188, 1156–1168.

Adeeb, J., Farhan, A., Al-Salaymeh, A., 2019. Temperature effect on performance of different solar cell technologies. J. Ecol. Eng. 20 (5), 249–254.

Adenle, A.A., 2020. Assessment of solar energy technologies in Africa-opportunities and challenges in meeting the 2030 agenda and sustainable development goals. Energy Policy 137, 111180.

Akinyele, D., 2017. Analysis of photovoltaic mini-grid systems for remote locations: A techno-economic approach. Int. J. Energy Res. 42, 1363–1380.

Alhaj, M.A.B., Sopian, K., 2018. Techno-economic study of photovoltaics and dish Stirling engines for decentralised power generation in Sudan: Part 1: Overview and methodology. Int. J. Sudan Res. 8 (1), 15–31.

Core International Inc., 2003. Issues and options for rural electrification in SAPP member countries and rural electrification planning in Lesotho–USAID Energy and Environment Training Program Desk Study Report. Retrieved from <https://pdf.usaid.gov/pdf_docs/PNADD466.pdf>.

Diab, F., Lan, H., Zhang, L., Ali, S., 2016. An environmentally friendly factory in Egypt based on hybrid photovoltaic/wind/diesel/battery system. J. Cleaner Prod. 112 (5), 3884–3894.

Dubey, S., Sarvaiya, J.N., Seshadri, B., 2013. Temperature dependent Photovoltaic (PV) efficiency and its effect on PV production in the world – A review. Energy Procedia 33, 311–321.

Elkadeem, M.R., Wang, S., Atia, E.G., Shafik, M.B., Sharshir, S.W., Ullah, Z., Chen, H., 2019a. Techno-economic design and assessment of grid-isolated hybrid renewable energy system for agriculture sector. In: 14th IEEE Conference on Industrial Electronics and Applications (ICIEA), 1562–1568.

Elkadeem, M.R., Wang, S., Sharshir, S.W., Atia, E.G., 2019b. Feasibility analysis and techno-economic design of grid-isolated hybrid renewable energy system for electrification of agriculture and irrigation area: A case study in Dongola, Sudan. Energy Convers. Manage. 196, 1453–1478.

Fatih, B., 2019. World Energy Outlook 2019. International Energy Agency Publication: Paris, France.

Gabra, S., Miles, J., Scott, S.A., 2019. Techno-economic analysis of stand-alone wind micro-grids, compared with PV and diesel in Africa. Renew. Energy 143, 1928–1938.

Gebrehiwot, K., Mondal, M.A.H., Ringler, C., Gebremeskel, A.G., 2019. Optimization and cost-benefit assessment of hybrid power systems for off-grid rural electrification in Ethiopia. Energy 177, 234–246.

GlobalPetrolPrices.com, 2020. Sudan Diesel prices. Global Petrol Prices. Retrieved from <https://www.globalpetrolprices.com/Sudan/diesel_prices/> (accessed July 2020).

Hajiah, A., Khatib, T., Sopian, K., Sebzali, M., 2012. Performance of grid-connected photovoltaic system in two sites in Kuwait. Int. J. Photoenergy 178175.

Hossain, M.S., Rahman, F., 2020. Hybrid solar PV/biomass powered energy efficient remote cellular base station. Int. J. Renew. Energy Res. (IJRER) 10 (1), 329–342.

Huang, R., Low, S.H., Topcu, U., Chandy, K.M., Clarke, C.R., 2011. Optimal design of hybrid energy system with PV/wind turbine/storage: A case study. In: IEEE International Conference on Smart Grid Communications (SmartGridComm), 511–516.

Ibrahim, A., 2011. Effect of shadow and dust on the performance of silicon solar cell. J. Basic Appl. Sci. Res. 1 (3), 222–230.

Ibrahim, S.H.A., Agab, E.B., Shukri, M.I., 2020. Design and analysis of PV-Diesel hybrid power system case study Sudan, El Daein (East Darfur). Int. J. Eng. Res. General Sci. 8 (3), 56–65.

Issak, M.B., 2018. Analyzing the Cost of Electricity for SolarPV-Diesel Hybrid Generation for Sub-regional Hospital Electrification in Dourbali District, Chad. Master's thesis, Pan-African University: Institute for Water and Energy Sciences (PAUWES), Algeria. Retrieved from <http://repository.pauwes-cop.net/bitstream/handle/1/250/Mahamat%20Bichara.pdf?sequence=1&isAllowed=y>.

Jäger-Waldau, A., 2020. Snapshot of Photovoltaics—February 2020. Energies 13 (4), 930.

Kabir, E., Kumar, P., Kumar, S., Adelodun, A.A., Kim, K.H., 2018. Solar energy: Potential and future prospects. Renew. Sustain. Energy Rev. 82, 894–900.

Kaltschmitt, M., Streicher, W., Wiese, A., 2007. Renewable energy: Technology, economics and environment, 1st Ed. Springer-Verlag, Berlin Heidelberg.

Kazem, H.A., Khatib, T., 2013. Techno-economical assessment of grid connected photovoltaic power systems productivity in Sohar, Oman. Sustain. Energy Technol. Assess. 3, 61–65.

Kebede, K.Y., 2015. Viability study of grid-connected solar PV system in Ethiopia. Sustain. Energy Technol. Assess. 10, 63–70.

Khormali, S., Niknam, E., 2019. Operation cost minimization of domestic microgrid under the time of use pricing using HOMER. In: IEEE 20th International Scientific Conference on Electric Power Engineering (EPE), 1–6.

Leading Edge, 2019. Leading Edge–Sudan 2019. Leading Edge Investment Guides, London, United Kingdom. Retrieved from <http://www.leadingedgeguides.com/LE_guides/LeadingEdge_Sudan2019.pdf>.

Lewis, N.S., Nocera, D.G., 2006. Powering the planet: Chemical challenges in solar energy utilization. Proc. Natl. Acad. Sci. 103 (43), 15729–15735.

Maammeur, H., Hamidat, A., Loukarfi, L., Missoum, M., Abdeladim, K., Nacer, T., 2017. Performance investigation of grid-connected PV systems for family farms: Case study of North-West of Algeria. Renew. Sustain. Energy Rev. 78, 1208–1220.

Maatallah, T., Ghodhbane, N., Nasrallah, S.B., 2016. Assessment viability for hybrid energy system (PV/wind/diesel) with storage in the northernmost city in Africa, Bizerte, Tunisia. Renew. Sustain. Energy Rev. 59, 1639–1652.

Mondal, A.K., Bansal, K., 2015. A brief history and future aspects in automatic cleaning systems for solar photovoltaic panels. Adv. Rob. 29 (8), 515–524.

Murdock, H.E., Gibb, D., André, T., 2019. Renewables 2019 global status report. REN21 Secretariat, Paris, France.

Nordrum, A., 2019. At last, a massive solar park for Egypt: A 1.8-GW, $4 billion solar power plant is coming on line in the Sahara-[News]. IEEE Spectr. 56 (11), 8–9.

NASA, 2020. Surface Meteorology and Solar Energy. Available at: http://eosweb.larc.nasa.gov/ (accessed May 2020).

Nassar, I.A., Saleh, A.A.Z., 2015. Simulations of grid-connected photovoltaic system in Qena Al-Gadida City. Int. J. Innov. Res. Electr., Electron., Instrument. Control Eng. 3 (3), 129–136.

Olatomiwa, L., Mekhilef, S., Huda, A.S.N., Sanusi, K., 2015. Techno-economic analysis of hybrid PV–diesel–battery and PV–wind–diesel–battery power systems for mobile BTS: The way forward for rural development. Energy Sci. Eng. 3 (4), 271–285.

Olukan, T.A., Emziane, M., 2014. A comparative analysis of PV module temperature models. Energy Procedia 62, 694–703.

Omar, A.S., Mohamed, A.A.A., Senjyu, T., Hemeida, A.M., 2019. Multi-objective optimization of a stand-alone hybrid PV/wind/battery/diesel micro-grid. In: IEEE Conference on Power Electronics and Renewable Energy (CPERE), 391–396.

Oulis Rousis, A., Tzelepis, D., Konstantelos, I., Booth, C., Strbac, G., 2018. Design of a hybrid AC/DC microgrid using HOMER Pro: Case study on an islanded residential application. Inventions 3 (3), 55.

Ramli, M.A., Hiendro, A., Al-Turki, Y.A., 2016. Techno-economic energy analysis of wind/solar hybrid system: Case study for western coastal area of Saudi Arabia. Renew. Energy 91, 374–385.

Rashad, M., El-Samahy, A.A., Daowd, M., Amin, A.M., 2015. A comparative study on photovoltaic and concentrated solar thermal power plants. Recent Adv. Environ. Earth Sci. Econ. 167–173.

Saeed, T.M., Tayeb, E.B.M., Osman, G., 2019. Sustainable energy potential in Sudan. SUST J. Eng. Comput. Sci. (JECS) 20 (3), 1–10.

Salehin, S., Zhang, H., Martinez, T.L., Papakokkinos, G., Upadhyay, G., Bowler, E., Van Kasteren, J.M.N., 2011. Designing of an emergency energy module for relief and refugee camp situations: Case study for a refugee camp in Chad-Sudan border. In: IEEE World Congress on Sustainable Technologies (WCST), 9–14.

Salih, T., Wang, Y., Adam, M.A.A., 2014. Renewable micro hybrid system of solar panel and wind turbine for telecommunication equipment in remote areas in Sudan. Energy Procedia 61, 80–83.

Sinha, S., Chandel, S.S., 2014. Review of software tools for hybrid renewable energy systems. Renew. Sustain. Energy Rev. 32, 192–205.

Szabo, S., Bódis, K., Huld, T., Moner-Girona, M., 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ. Res. Lett. 6 (3), 034002.

Tamir, K., 2011. Identifying and addressing drivers and barriers to renewable energy development in the rural electrification of Mongolia, Master of Science dissertation, Murdoch University, Australia.

Timilsina, G.R., Kurdgelashvili, L., Narbel, P.A., 2011. A review of solar energy: Markets, economics and policies. The World Bank Development Research Group, Environment and Energy Team, Policy research working paper No. 5845.

Whitley, S., van der Burg, L., 2015. Fossil fuel subsidy reform: From rhetoric to reality. The New Climate Economy, London and Washington, DC. Retrieved from <http://newclimateeconomy.report/misc/working-papers>.

Yahiaoui, A., Benmansour, K., Tadjine, M., 2016. Control, analysis and optimization of hybrid PV-Diesel-Battery systems for isolated rural city in Algeria. Sol. Energy 137, 1–10.

Yoshino, N., Taghizadeh-Hesary, F., Otsuka, M., 2020. Covid-19 and optimal portfolio selection for investment in sustainable development goals. Finance Res. Lett. 101695.