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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 CO₂ 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 (Jager-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 Garmi and Awasthi, 2017). The World Energy Outlook 2019 stated that the only way to meet the previous zero CO₂ 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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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 lowest cost 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 (Murdoch 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 (Murdoch 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).

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, INSER, 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)).

| 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       | 20.216        |
| 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-Dammar    | 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        |
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) 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 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 2
The capital, replacement, and operation and maintenance costs for solar PV in countries near Sudan.

| Reference             | Country   | 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                                 |
| Izak (2018)           | Chad      | 3000              | 2000                  | 1                                     |
| Gebrehiwot et al. (2019) | Ethiopia  | 1500              | 1000                  | 50                                    |
| Abdul-Wahab et al. (2019) | Oman      | 1504              | 1316                  | 19                                    |

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

| Month   | Radiation (kWh/m²/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| 5.74                  | 0.565           |
| October | 5.79                   | 0.613           |
| November| 5.63                   | 0.652           |
| December| 5.35                   | 0.65            |
and the possibilities of increased load. The results indicated that systems of 61, 76, and 68 kWp 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

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       |

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

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          |
the application of renewable energy systems constitutes an important exam-ined with various economic scenarios. The study concluded that agriculture and irrigation site in Dongola, situated in the north of Sudan.

isolated hybrid renewable energy system to generate electricity for an enough energy to cover the full load. Using HOMER, different cases were

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

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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 investi-gated 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 re-sources 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

| 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| 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  | 7.22  | 6.56| 6.42| 5.84| 5.74   | 5.98      | 5.85    | 5.50     | 5.22     |          |
| Al-Obeid       | 5.67    | 6.26     | 6.84  | 7.97  | 6.94| 6.72| 6.08| 5.98   | 5.62      | 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  | 5.99  | 6.66| 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-Damur       | 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| 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| 7.24| 6.99| 6.73   | 6.34      | 5.94    | 5.29     | 4.59     |          |
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 electric load of 20 MW (\( \text{No. of PV units} = \frac{\text{Capacity of the selected PV type}}{\text{Capacity of the selected PV type}} \)).

### Table 8

| 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 |
|-----|------|---------------|---------------|------------|------------------------|-------------------------------------------------------------|
| 1   | Ingeteam (1164kVA) with Generic PV | 1164 | 0.08792 | 42.8 M | 78.3 | 18 |
| 2   | Schneider ConnectCoreXC 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 ConnectCoreXC 630 kW with Generic PV | 630 | 0.08771 | 42.8 M | 78.2 | 32 |
| 7   | Schneider ConnectCoreXC 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.

### 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...
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/m²/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/m²/day) and at a minimum in December (5.350 kWh/m²/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 ConextCL25000 E with generic PV) and 15 (Schneider ConextCL20000 E with generic PV). 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$
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...
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 (CO₂), particulate matter (PM), unburned hydrocarbons (UHC), nitrogen oxides (NOₓ) and sulfur dioxide (SO₂)) 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 in USD$ 0.0812/kWh, Wadi Halfa in USD$ 0.0821/kWh, Dongola in USD$ 0.0825/kWh and Al-Goled in USD$ 0.08255/kWh. In contrast, the maximum COE was attained in Al-Damazin in USD$ 0.0902/kWh. 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 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. However, dust deposition on PV panels, which is 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

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**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 (CO₂)      | 26,574,036          |
| Particulate matter (PM)   | 1015                |
| Unburned hydrocarbons (UHC)| 7309               |
| Nitrogen oxides (NOₓ)     | 157,356             |
| Sulfur dioxide (SO₂)      | 65,074              |
| Total                     | 26,972,298          |

**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-Obeyd      | 0.08334         | 42.8 M      | 1 M        | 77.1                   |
| Dongola       | 0.08254         | 42.8 M      | 1 M        | 76.9                   |
| Al            | 0.08390         | 42.8 M      | 1 M        | 77.2                   |
| Junaynah      | 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 lowest percentage. The unmet electric 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.

**Fig. 6.** Effect of diesel fuel price on the COE of the diesel-powered generator system.
Another crucial factor in solar photovoltaic system under-performance 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

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; Adeb 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.
The 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.

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