International Journal of Sudan Research
V8, N1
2018

TECHNO-ECONOMIC STUDY OF PHOTOVOLTAICS AND DISH STIRLING ENGINES FOR DECENTRALISED POWER GENERATION IN SUDAN: PART 1: OVERVIEW AND METHODOLOGY

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ABSTRACT

Purpose: This paper presents an overview of the power generation market in Sudan, solar energy potential, introduction to photovoltaics (PV) and the dish Stirling engine (DSE), and proposes a methodology for assessing the feasibility of these two technologies in Sudan's climate.

Methodology: We carried out a detailed literature review of the electricity profile in Sudan, grid access, generation capacity, energy policy and the potential to use solar energy in Sudan for power generation. We also presented a brief technology overview of solar PV and DSE. The principles of economic analysis are discussed. Lastly, we proposed a methodology for carrying a techno economic assessment of PVs and DSEs in Sudan. The second part of this research project will include the outcomes of using this methodology.

Findings: There is a huge potential for solar energy utilisation in Sudan. Average daily solar insolation is 6.1kWh/m^2. Grid access is only 35.9%, and there is heavy reliance on gasoline and diesel generators.

Original value of the paper: We carried out a comprehensive review of the electricity profile and solar energy potential in Sudan (given the scarce data), and presented important graphical results for solar irradiation in Sudan.

Research limitation: There is almost no published data on the status of renewables in Sudan. No ground measurements data for solar radiation were found. This research was conducted in Malaysia; therefore, no onsite surveys or interviews were conducted.

Practical implications: More research work on the technical potential for solar energy is required and this should be peer-reviewed. This implication is relevant to researchers.

Keywords: PV; dish Stirling engines; renewable energy; techno-economic; Sudan; decentralised; power plant

Reference to this paper should be made as follows: *Alhaj, M. A. B. and 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 Research, Vol. 8, No. 1, pp.015–031.*

INTRODUCTION

The problem of electricity access in Sudan is a serious one as only 35.9% of the population have grid access as compared with the global average of 77.6% (The World Bank, 2013). This issue is further escalated by the fact that 66.6% of the population live in rural areas where access to electricity is limited when compared to urban areas. In one of the villages the author visited recently, the electricity is only available for four hours per day in the evening only. Citizens are required to pay a monthly charge for electricity that exceeds the value of the service they get. As a result, many citizens revert to gasoline/diesel generators that are noisy and costly to operate when running at low loads; usually a number of people have to share a single generator (Nayar et al., 1993). The poor access to electricity hinders local development and prevents people from enjoying basic household amenities such as lights and fans. It also affects the education and health sectors.

Using solar energy for rural electrification remains the most promising and fruitful solution for developing countries such as Sudan due to the high levels of solar radiation and the availability of land. Under the current economic conditions, extending the national grid is not a feasible solution, and hence many experts believe that the best alternative is decentralised power systems or micro-grids. The World Bank, United Nations Development Program (UNDP) and other NGOs have implemented numerous projects globally for rural electrification using solar energy technologies such as photovoltaics.

Currently, on a global scale, most rural electrification projects, relying on solar energy, use photovoltaics technology. This is due to the maturity of PVs in decentralised power generation and the decreasing prices of Silicon, the most used semiconductor material in solar cells. Dish Stirling engines (DSE); on the other hand, are still considered to be in the pilot phase of implementation, even though their working mechanism is well understood.

The technical differences between PV and Stirling engines are well known and have been investigated by many researchers. However, the large majority of papers written on this topic considered only large power plants. There have been no publications focusing on the technical and small-scale economics of these two systems when considering the electrification of rural areas.

This paper presents Part 1 of our research project. In this part, we aim to present a detailed review of the status of electricity generation and access in Sudan. Further, we carried out a review of energy policy in Sudan. The potential of solar energy is discussed, and graphical representations of the value of incident solar radiation are shown. The technologies of solar PV and DSE are explained in detail and compared in technical and economic terms. We also discuss the fundamentals of the economic assessment of renewable energies. The paper is then concluded by proposing a methodology for assessing PV and DSE in techno-economic terms. Part 2 of this project will present the outcomes of implementing this methodology.

ELECTRICITY PROFILE OF SUDAN

Sudan is one of the largest and most resource abundant countries in North Africa. Its total area is 1,886,068km^2 and it has a population of 37.2 million (The World Bank, 2013). The major resources in Sudan are livestock, fertile land and oil. These factors indicate that Sudan has the potential to be one of the leading developing countries in the region. However, due to the poor economic conditions, wars and lack of proper policies, many of the country's resources have not been properly utilised. The lack of comprehensive planning and management and the constraints on foreign investment and finance are two key barriers to achieving universal electricity access (Mohammed et al., 2014).

Regarding the power sector, the annual electricity generation was 8.6GWh in 2011 according to The World Bank, of which 6.4GWh (74%) came from hydropower. Other renewables, such as solar and wind energies, make no contribution to annual electricity generation.

Electricity is delivered through two interconnected grids; the Blue Nile grid and the Western grid. However, these grids only cover a small fraction of the country. Moreover, the frequency of power outages is high; 19 days in 2009 (REEEP Policy Database, 2012). Figure 1 shows the grid coverage for Sudan and South Sudan (when it was one country up to 2011).

The poor grid coverage problem has led to a very low electricity access rate of only 35.9% of the total population. Furthermore, 66.6% of the population live in rural areas (The World Bank, 2013), which means it is even more difficult for them to get access to electricity as compared with urban areas. Poor infrastructure and mismanagement of resources are two of the key reasons behind the electricity problem.

A large number of citizens rely on diesel or gasoline generators for basic power needs. In fact in 2009, 41% of the population owned private generators (REEEP Policy Database, 2012). These generators are very popular due to their low capital costs and simple operation. However, they are not reliable in the long term. Gasoline/diesel generators are noisy, pollute the environment and have high operation and maintenance costs.

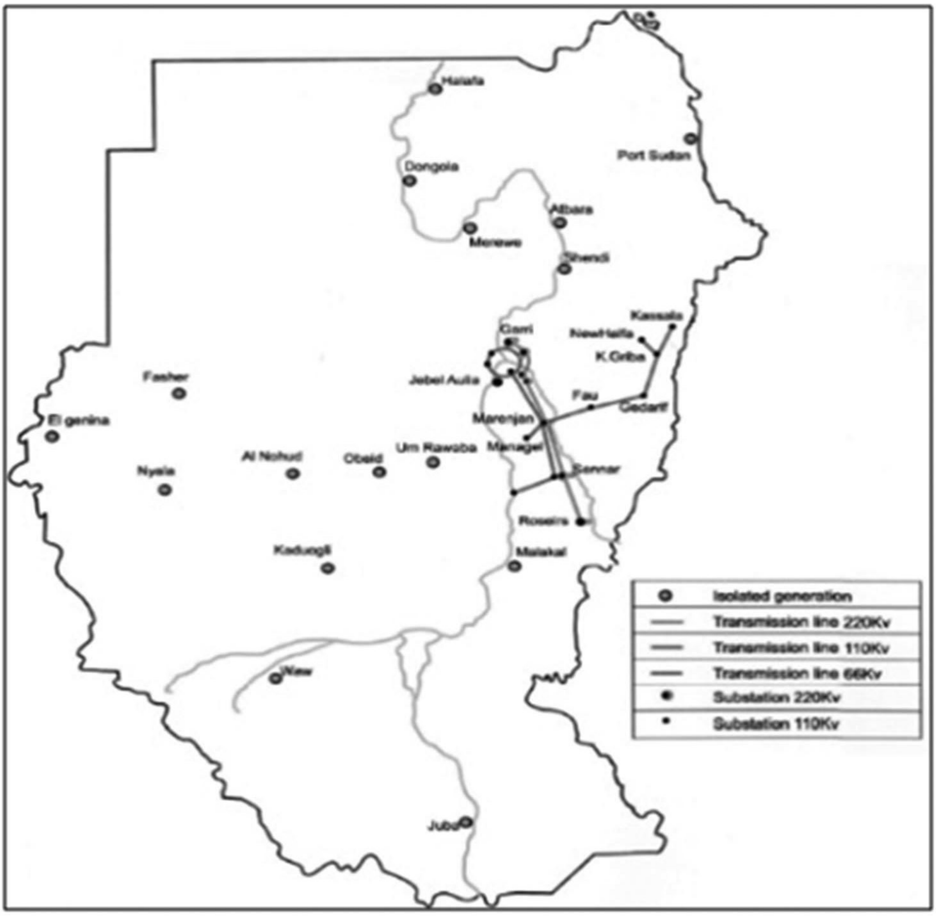

FIGURE 1 National grid coverage in Sudan and South Sudan

Source: Bakhiet, 2008

ENERGY POLICY

In 2001, the investment law was passed that encouraged foreign investment in the electricity sector. This has resulted in the construction of some thermal power plants through Chinese and Malaysian financing (REEEP Policy Database, 2012). This investment was, however, on a small scale.

In 2005, the Renewable Energy Master Plan was drafted with the target of promoting the use of renewable energy (REEEP Policy Database, 2012). A total of $9.1 million was allocated for this plan. One of the key priorities for this plan was the deployment of community scale PV projects.

Moreover, the government also announced an ambitious plan to increase the electricity access rate to 90% in the mid-term (REEEP Policy Database, 2012). However, some experts believed that this will be difficult to achieve because of the large amount of investment needed and the expected rise in consumption. The major focus in increasing electrical capacity, so far, has been on hydro power.

Overall, the energy policy in Sudan did not create the stimulating environment required for sustainable development. The Renewable Energy Master Plan, for example, did not "detail specific regulatory mechanisms for the promotion of sustainable energy" (REEEP Policy Database, 2012). There is a serious need for formulating clear detailed policies that encourage the participation of the private sector, alongside the public sector, in the development of renewable energy and its applications in Sudan.

SOLAR ENERGY POTENTIAL IN SUDAN

Sudan is one of the countries best suited for the deployment of solar energy technologies. The average daily solar insolation is 6.1kWh/m^2 (REEEP Policy Database, 2012). Figure 2 shows the variation of solar radiation in Sudan:

FIGURE 2 Average annual sum of global horizontal irradiation in Sudan in kWh/m2/year

Source: Solar Gis, 2010

In addition, Sudan also has the advantage of the availability of land and low cloud cover, making it ideal for solar thermal and solar PV technologies. The minimum number of daily sunshine hours is 8.5 hours, indicating the potential for the high utilisation of solar energy. Figure 3 shows global and diffuse solar radiation at different months in the year in the capital Khartoum; the figure was generated by the Meteonorm 7 software package:

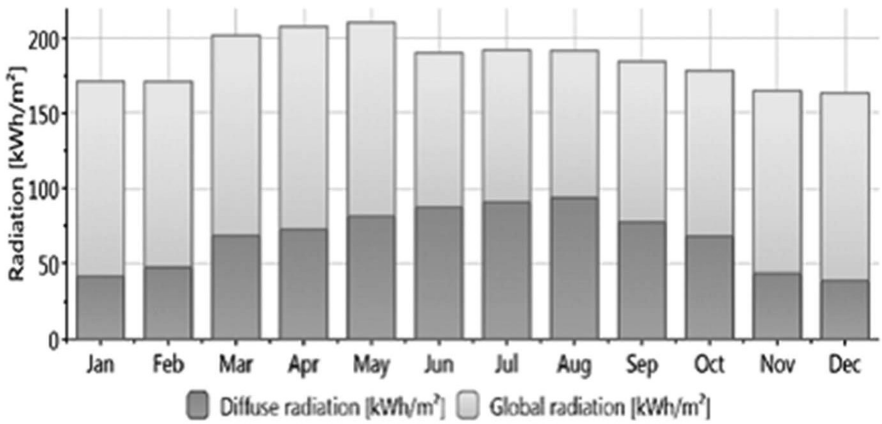

FIGURE 3 Monthly global and diffuse solar radiation in Khartoum

Source: Meteotest, 2016

As Figure 3 shows, Sudan has high levels of global solar radiation throughout the year. Figure 4 shows the average number of sunshine hours throughout the year generated by the same software:

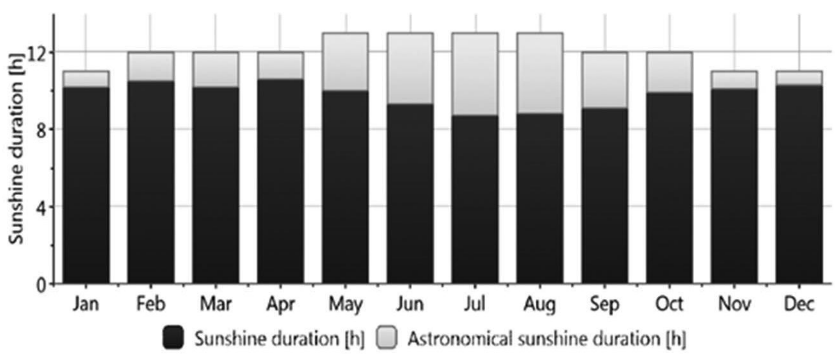

FIGURE 4 Monthly sunshine hours in Khartoum

Source: Meteotest, 2016

However, there are two major obstacles facing solar energy technologies in Sudan; dust and high temperatures. In particular, dust has a major impact on the efficiency of PV modules, and similarly for dish Stirling systems, by reducing the optical efficiency. High temperatures also cause a reduction in the efficiency of PV modules and increase radiation thermal losses. Figure 5 shows monthly ambient temperatures in Khartoum.

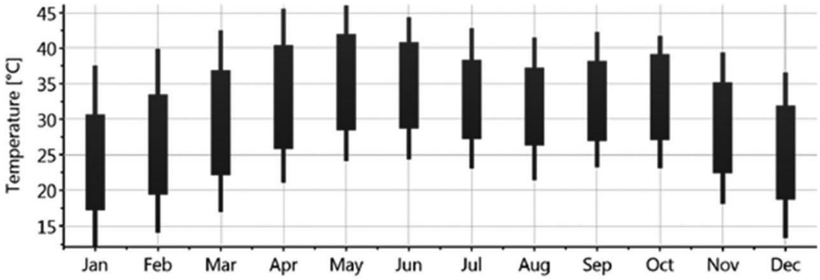

FIGURE 5 Monthly ambient temperature in Khartoum

Source: Meteotest, 2016

SOLAR ENERGY VERSUS GASOLINE/DIESEL GENERATORS

A number of studies have shown that solar energy systems (particularly PV) are economically more competitive that diesel generators. One optimisation study undertaken by the National Renewable Energy Laboratory (NREL), using HOMER software, simulated the performance and life cycle cost for a small PV system in Iraq. The system had a daily load of 31.6kWh. The PV system was compared to a diesel generator. It was found that the PV system had an initial cost of $50,700 compared to $4,500 for the diesel generator. However, in terms of net present cost (or life cycle cost), the PV system cost only $60,375 compared to $353,303 for the diesel generator. Further, the electricity cost per kWh was lower for the PV as compared to the diesel generator; $0.238/kWh compared to $1.332 for the diesel generator (Al-Karaghouli and Kazmerski, 2010). The authors highlighted that the low fuel efficiency of diesel generators is the reason behind the high electricity cost. The fuel efficiency of diesel is usually 2.5—3.0kWh/L at full load (Al-Karaghouli and Kazmerski, 2010). In addition to the low fuel efficiency, the operational life of diesel generators is also low; approximately 15,000 hours (Ramli et al., 2015). In terms of lifetime, a typical 20kVA diesel generator (Caterpillar) would have a lifetime of 13 years (Mahmoud and Ibrik, 2006).

Another study that investigated the economic effectiveness of supplying electricity using solar PV, diesel generators or the electric grid in Palestine found that, compared to diesel generators, solar PV has a higher net present value ($8,012.31 compared to $262.69), lower cost of electricity ($0.60/kWh compared to $0.72/kWh) and a shorter payback period (10.4 years compared to 11.95 years) (Mahmoud and Ibrik, 2006). The authors hence concluded that using solar PV is economically more feasible than diesel generators and grid extension for the electrification of remote villages in Palestine.

A study by Veldhuis and Reinders (2015) on the cost effectiveness of stand-alone PV and diesel generators for rural electrification found that in most of Indonesia, solar PV will yield a lower electricity cost than a 100% diesel generator system. They estimated the cost of electricity for a stand-alone PV system to be $0.76/kWh. The study also highlighted that solar PV systems are likely to become financially more attractive as fossil fuel prices increase (Veldhuis and Reinders, 2015).

On the other hand, very few studies focused on the use of solar dish Stirling engines for rural electrification as an alternative to diesel/gasoline generators. This is because of the high capital costs for these systems at the moment; this results in a high electricity cost, especially for a small number of units.

The motive for switching to solar energy technologies in Sudan is very logical because of

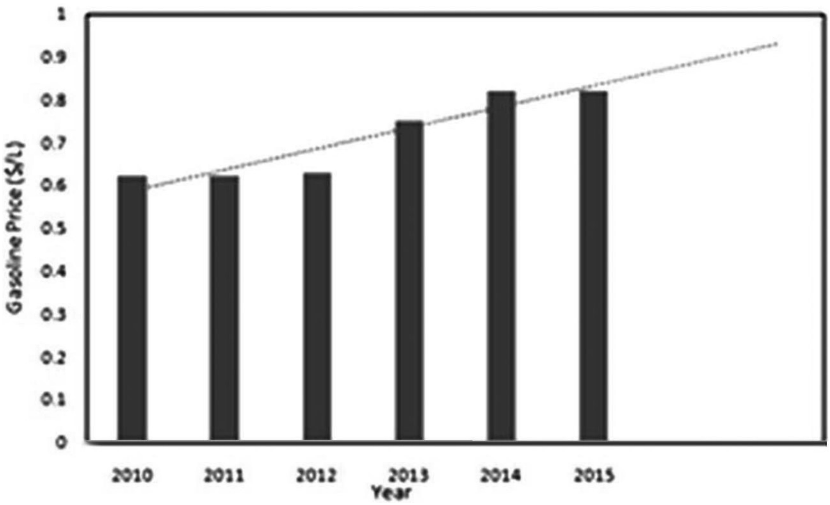

FIGURE 6 Gasoline prices in Sudan

Source: German Federal Ministry of Cooperation and Development, 2011, 2013, 2014; The World Bank, 2014

the increase in gasoline prices; this is shown by Figure 6 that used statistics from the German Federal Ministry of Cooperation and Development and the World Bank.

Figure 6 shows that there is a trend of increasing gasoline prices that indicates that the use of gasoline generators is likely to become economically unsustainable in the future. Diesel prices also have a similar trend. In addition, the cost of fuel transport is also a major obstacle when considering remote areas.

Another motive for the transition to solar energy is the environmental commitment that mandates that we reduce CO_2 emissions as much as possible. Solar energy technologies, like all renewables, have very few emissions as compared to fossil fuels. A study by Bravo et al. (2012) found that for a 10kW dish Stirling engine power unit and a similar PV one, the CO_2 emissions are almost the same. Further, their study indicated that dish Stirling engines are in "good accordance" with other renewables in terms of environmental impact (Bravo et al., 2012).

All of these points indicate that the use of solar energy technologies is an excellent alternative to gasoline/diesel generators for decentralised power generation in Sudan.

PHOTOVOLTAIC TECHNOLOGY

PV modules are made of semiconductor material solar cells that directly convert incident solar radiation to dc current. This is achieved when the electrons are excited and moved from the valence band to the conduction band. The most common types of semiconductor materials used in solar cells are mono and polycrystalline Silicon and amorphous Silicon. Between 85—90% of the global market uses wafer based crystalline Silicon (Chu, 2011). The current efficiency of commercial solar cells is in the range 14%—16% and some commercial panels have even reached 20%. PV modules are one of the most reliable and mature solar energy technologies, and have contributed greatly to the electrification of thousands of homes around the globe. Another key feature about PV modules is their ability to convert both direct and diffuse radiation, unlike concentrated solar power (CSP) technologies that only utilise the direct radiation. Hence, they can produce electricity even on cloudy days.

The following figure shows a schematic of a grid connected PV power system:

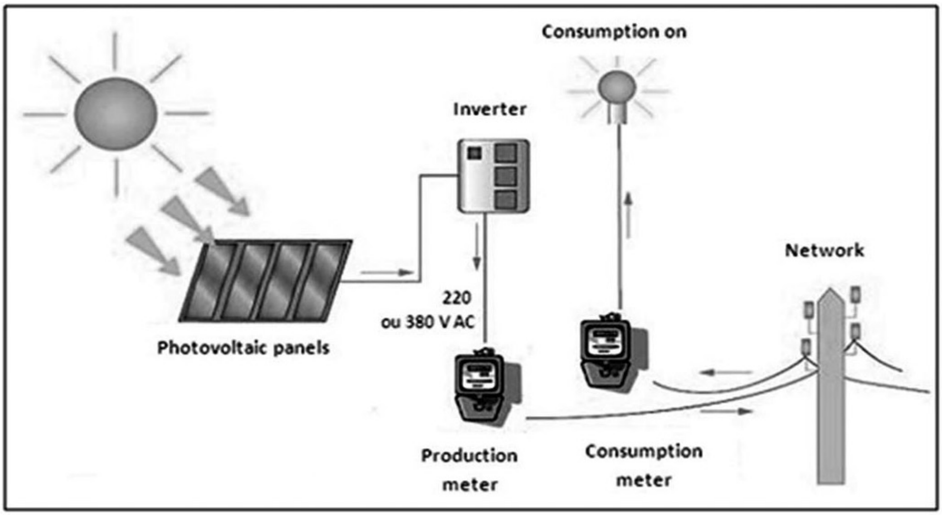

FIGURE 7 PV grid connected system

Source: Agence de l'Environnement et de la Maîtrise de l'Energie (no date)

The main challenge, however, facing PV modules is the high initial cost, as well as the degradation of efficiency due to dust and high temperatures. These two factors are critical when considering a power system implemented in a country such as Sudan that has high temperatures and large amounts of dust.

FACTORS AFFECTING PV MODULE PERFORMANCE

A number of factors affect the performance of PV modules. One of the most significant is dust accumulation over the panels: this is also referred to as soiling. Many researchers have conducted experiments to quantify the drop in performance due to dust. In one study, a degradation in performance of 40% was reported in a test period of six months in Saudi Arabia (Nimmo and Said, 1979). The accumulation of dust leads to an exponential reduction in performance (Mekhilef et al., 2012). Furthermore, when the wind speed increases, the rate of dust accumulation increases, causing more losses.

Other factors that affect the output power (P) of PV modules include temperature, optical efficiency and type of tracking used. These factors are shown in the following equation (Duffie and Beckman, 1980) :

$$P\,(T,\theta)=[\eta_{0b}K_b(\theta)I_b+\eta_{0b}K_dI_d]\,[1+(T_c-T_r)\alpha] \qquad (1)$$

Where:

η=Optical efficiency

$K_{b,d}(\theta)$=Incidence angle modifier for direct/diffuse radiation.

$I_{b,d}$=Direct/diffuse solar radiation

T_c=Cell temperature

T_r=Reference temperature: 25°C

α=Power temperature coefficient. It has a negative value because power is inversely related to temperature.

The first term in this equation indicates the power produced at the reference temperature, while the second term indicates the power loss due to the ambient temperature effect. The cell temperature can be found using the following equation (Campana et al., 2013):

$$T_c = T_a + [NOCT - 20/800]\ I_{tot} \tag{2}$$

Where:

T_c = PV cell temperature

T_a = Ambient temperature

NOCT = Nominal operating cell temperature at standard test conditions

I_{tot} = Global solar radiation

The NOCT is the cell temperature under standard test conditions. The reason it is used is because at standard test conditions (I_{tot} = 1000W/m^2, T_a = 25°C), the cell's temperature is actually higher than the ambient temperature. For very efficient cells, NOCT is 33°C. Typical cells have a NOCT of 48°C. The NOCT is fixed for a given PV cell and depends on the cell's material and the rear packing of the PV module. Using equation 2, the following graph was plotted for T_{cell} vs T_{amb}:

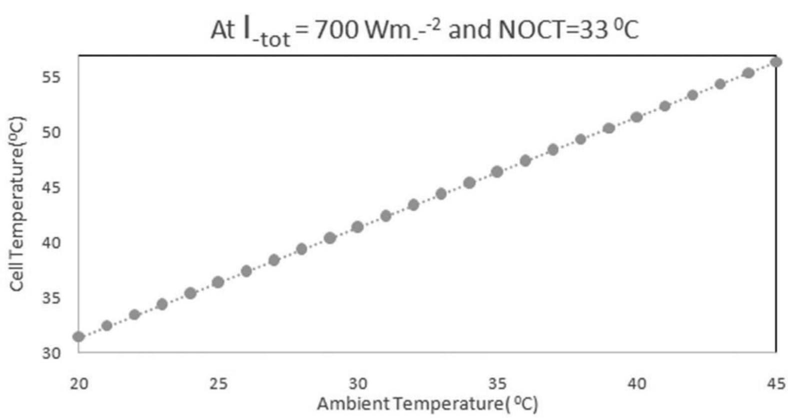

FIGURE 8 Variation of cell temperature with ambient temperature

Source: Devised by author

It is evident from the above graph that the relationship between the cell temperature and the ambient temperature is a linear one. However, the effect of temperature is mostly dominant in mono-crystalline Silicon solar cells and is less significant in poly-crystalline cells (Sharma and Chandel, 2013).

DISH STIRLING ENGINE TECHNOLOGY

Dish Stirling systems are one of the many types of CSP technologies. CSP refers to the utilisation of solar thermal energy by means of concentration using mirrors or lenses. The purpose of this technology is to use the heat in solar radiation to either generate electricity or for space heating and other residential and industrial purposes. Some types of CSP technologies are parabolic troughs and linear Fresnel reflectors.

Since solar radiation in CSP has to be focused or concentrated, CSP systems operate best when there are high levels of direct normal irradiance (DNI). This is because direct radiation has more intensity than diffuse radiation that has been scattered by the atmosphere.

The Stirling engine, invented in 1826 by Robert Stirling, is an external combustion heat engine that operates using the Stirling cycle, which is considered to be the most efficient thermodynamic cycle. This cycle consists of two isothermal and two adiabatic processes. The Stirling engine converts the concentrated solar thermal energy to mechanical energy and then to electrical energy by means of an AC generator. Since this engine is a heat engine, it has to exchange heat between two reservoirs, the concentrated radiation and a cold reservoir. Figure 9 shows how mechanical motion is generated by the engine:

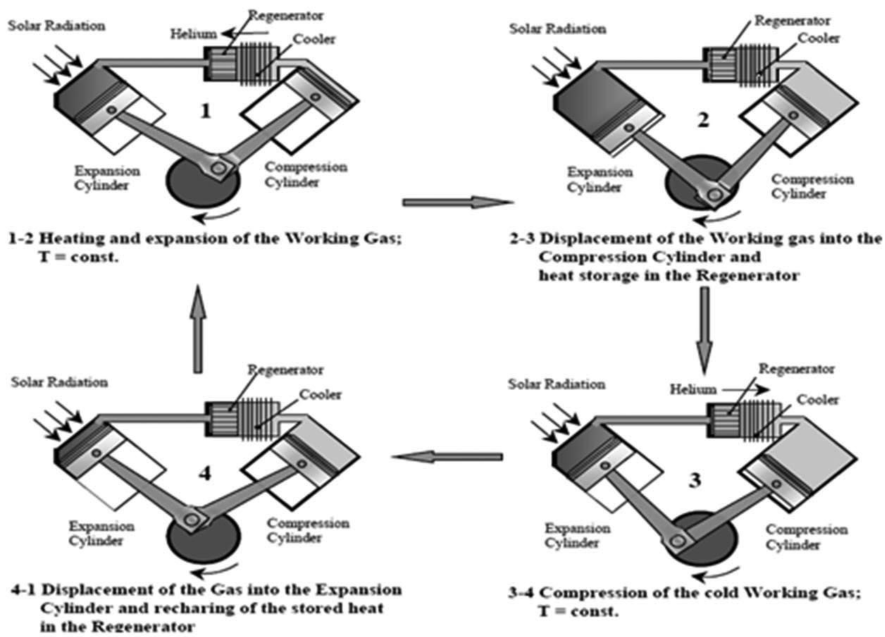

FIGURE 9 Working mechanism of the Stirling engine

Source: Bergermann and Partner, 2001

Dish Stirling engines use a parabolic shaped dish to reflect and concentrate solar radiation to the Stirling engine placed at the focal point of the dish. The conversion of thermal energy to mechanical energy is achieved by the use of a heat transfer fluid (HTF) inside the engine, which is usually Helium operating at temperatures in excess of 500°C and at a pressure of up to 150 bars. As Figure 9 shows, the continuous heating and cooling of the HTF drives the flywheel. Figure 10 shows a complete solar dish Stirling engine system.

Stirling engines have a number of advantages that make them very suitable for decentralised power generation, especially in hot arid climates. Firstly, their concentration factor is the highest among CSP technologies; 1000—3000 (Müller-Steinhagen and Trieb, 2004). This results in high temperatures of the HTF, and according to the Carnot efficiency law, the higher the temperature of the heat source in a heat engine, the higher the engine's efficiency. Secondly, dish Stirling engines produce alternating current, thus eliminating the need for an inverter. Moreover, dish Stirling engines have the highest solar to electric efficiency among solar energy technologies: 31.25% recorded by Sandia National Laboratories in 2008.

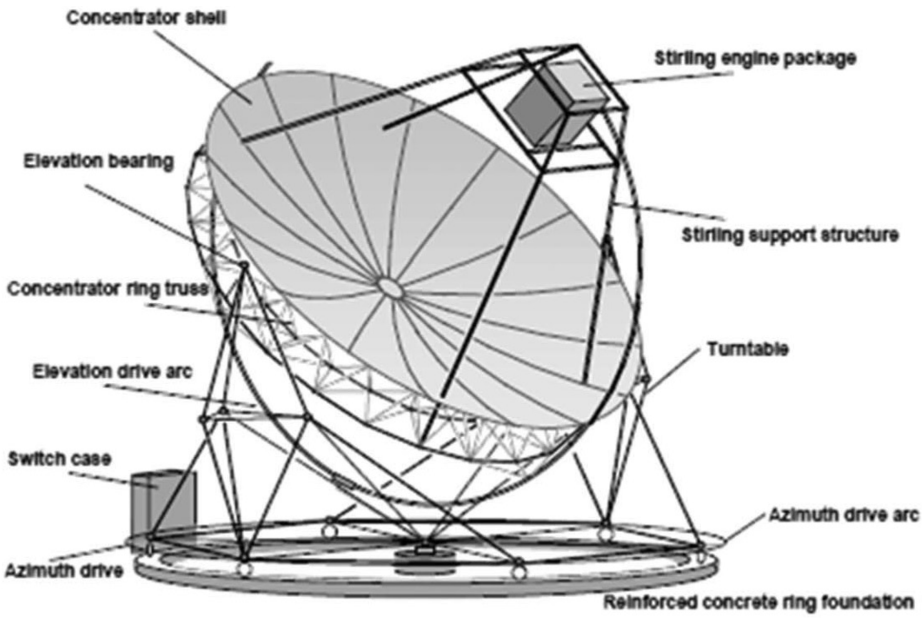

FIGURE 10 A Dish Stirling Engine system

Source: Bergermann and Partner, 2001

A recent report published by the Department for International Development, a UK government organisation, in 2010 analysed in great detail the market potential for dish Stirling systems and identified them as having the "appropriate size for a developing world village" (Department for International Development, 2010).

FACTORS AFFECTING DISH STIRLING ENGINES PERFORMANCE

The main factors that affect the performance of dish Stirling systems are DNI levels, ambient temperature, dust and system components. A number of experimental studies were undertaken to analyse the performance of dish Stirling systems. In a study performed in Algeria to compare the output of a small 10kW dish Stirling system in four locations, the highest electrical output was at a DNI of 900W/m^2 (Abbas and Boumeddane, 2009). In the same study, it was found that the system efficiency varies throughout the day, with the maximum being 18% at a DNI of 800W/m^2. Figure 11 shows the results obtained for the testing of the system in one of the four sites.

The solar-to-electric efficiency of solar dish Stirling engines is directly related to the DNI levels. This implies that for countries such as Sudan where there is little cloud cover, we expect the dish Stirling engine to have high efficiency. At very high ambient temperatures the heat loss from the receiver (a component of the Stirling engine that absorbs the reflected radiation) in the dish will increase due to radiative heat transfer. As a result of this heat loss, the thermal efficiency of the receiver will drop. If the operating temperature of the receiver is reduced, the thermal efficiency will increase (Stine and Diver, 1994).

Abraham Kribus (2002) investigated the effect of the receiver temperature on the dish system solar to electric conversion efficiency and found that the maximum efficiency was 30%; this was achieved at a receiver temperature of 1000K for a receiver diameter of 0.5m. Their

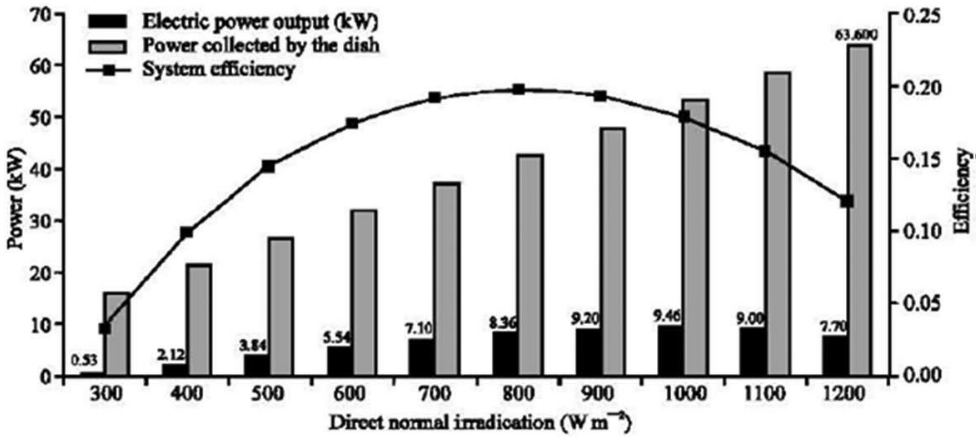

FIGURE 11 Dish Stirling Engine power and efficiency variation with DNI

Source: Abbas and Boumeddane, 2009

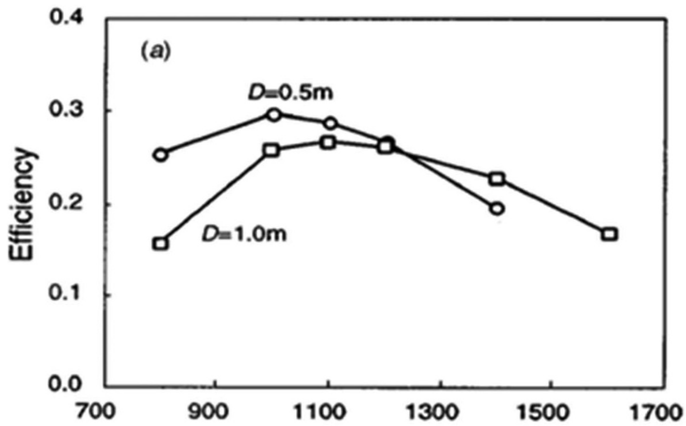

FIGURE 12 Dish Stirling Engine system efficiency versus receiver temperature

Source: Kribus, 2002

results showed that if the receiver temperature exceeds 1000K, the system efficiency starts to decrease, as shown in Figure 12.

FUNDAMENTALS OF ECONOMIC ANALYSIS

A number of terminologies are used to analyse the economic feasibility of renewable energy power plants in the decision making process. The major economic parameters used in decision-making are net present value, internal rate of return and levelised cost of energy. It is important to develop a sound understanding of these terminologies.

a) *Net present value, NPV*: This is one of the most important parameters when assessing the economic feasibility and financial benefit of a project. The NPV is the difference between the cash inflows (revenues) and the cash out flows (investment costs, operation), taking into account the discount rate. NPV can be calculated using the following equation taken from the equations database in SAM software (NREL, 2016):

$$NPV = \sum_{n=0}^{N} \frac{C_{After\ tax,n}}{(1 + d_{cominal})^n} \quad (3)$$

Where:

N=year at end of analysis

$C_{After\ Tax,n}$=After tax cash flow in year n

$d_{nominal}$=discount rate

In general, a positive NPV indicates that the project is economically feasible, while a negative NPV indicates that the project is not economically feasible. NPV analysis is particularly useful when investigating investment features for mutually exclusive projects (Short and Packey, 1995).

c) *Internal rate of return, IRR*: This is the discount rate that will ensure that a given project has a zero NPV, and is used to indicate how fast a project will return the investment. Therefore, a project with a high IRR may be more favourable for the investor and is also considered less risky. However, the choice of a project must not depend only on IRR, because a project may have a high IRR but a low NPV. It is necessary, when comparing two projects, to consider both the IRR and the NPV. The IRR is calculated from the NPV equation by setting NPV to zero.

d) *Levelised cost of energy, LCOE*: This is one of the most important parameters when comparing two energy projects. LCOE is the cost of the energy in $/kWh. It takes into account investment cost, operation and maintenance costs, quantity of energy produced by the project, taxes and selling price. The LCOE can be either nominal, using current dollars, or real, using constant dollars and taking inflation into account. For short term analyses, it is normal practice to use the nominal LCOE for comparison purposes (Short and Packey, 1995). The LCOE is found from equation 4 (NREL, 2016):

$$\text{Levelised cost (real)} = \frac{-C_0 - \dfrac{\sum_{n=1}^{N} C_n}{(1 - d_{nominal})^n}}{\dfrac{\sum_{n=1}^{N} Q_n}{(1 - d_{real})^n}} \quad (4)$$

Where:

Q_n (kWh)—Electricity generated by the system in year n.

N—Analysis period in years.

C_0—The project's equity investment amount.

C_n—The annual project costs in Year n.

d_{real}—The real discount rate.

$d_{nominal}$—The nominal discount rate.

THE ASSESSMENT METHODOLOGY

The methodology proposed is to carry a techno-economic study on PVs and DSEs using the System Adviser Model (SAM) software package. The scope of the study is a 2MW power plant. We will assume that electricity is sold to the consumer under a power purchase agreement (PPA) contract.

There are two objectives for this research project:

1. To investigate the performance and electric output of PV and DSE under the climate conditions of Sudan;
2. To investigate the economic feasibility of implementing these technologies for decentralised power generation.

The parameters investigated under the first objective are system efficiency and energy (in kWh) produced over a period of 25 years. The parameters investigated in the second objective are system capital costs, operation and maintenance costs, LCOE, NPV and energy selling price.

Figure 13 shows the methodology flow chart. The chart starts with inputting the data (weather, power plant specifications and cost data) into SAM. Then SAM computes and

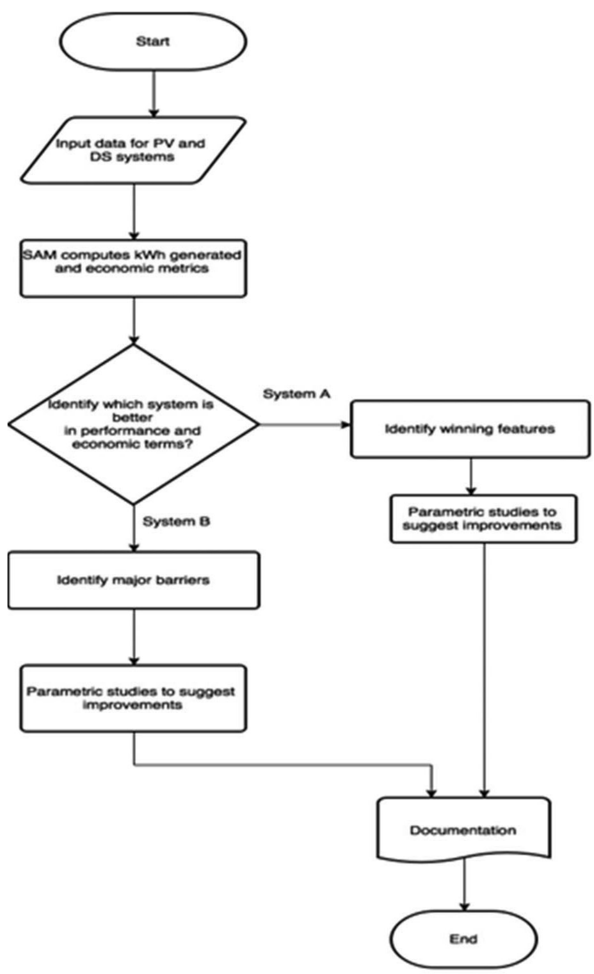

FIGURE 13 Methodology flow chart

Source: Devised by author

simulates the performance of each system for 25 years. After this, the decision making process comes where we have to select which of the two systems has better performance and is economically more competitive. This will be followed by a number of parametric studies to suggest improvements to both systems. System A in the flow chart represents the system with better overall technical and economic results while System B is the lesser one.

CONCLUSIONS

This paper presented Part 1 of a research project that assesses in technical and economic terms PVs and DSE for decentralised power generation in Sudan. An overview of the power generation market, power generation capacity, grid access and energy policy in Sudan is given. The technical potential for solar energy technologies was discussed, and it was found that Sudan has high solar irradiation and is, therefore, very suitable for the utilisation of solar energy for power generation. The technologies of PVs and DSEs are explained and factors affecting their performance are briefly discussed. The paper is concluded by proposing a methodology for comparing PVs and DSEs when implemented as a 2MW power plant for decentralised power generation. In Part 2, we will present the details of the methodology and the results of this project.

REFERENCES

Abbas, M., Boumeddane, B., Said, N. and Chikouche, A. (2009), 'Techno Economic Evaluation of Solar Dish Stirling System for Stand Alone Electricity Generation in Algeria', *Journal of Engineering and Applied Science*, Vol. 4, No. 4, pp. 258—267.

Agence de l'Environnement et de la Maîtrise de l'Energie (no date), *PV grid connected*. Available at: http://www.ademe-poitou-charentes.fr/domaines-dintervention/energies-et-matieres-renouvelables/solaire-photovoltaique (Accessed: 19 February 2016).

Al-Karaghouli, A. and Kazmerski, L. L. (2010), 'Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software', *Solar Energy*, Vol. 84, No. 4, pp. 710—714, Elsevier Ltd. doi: 10.1016/j.solener.2010.01.024.

Bakhiet, A. G. (2008), *Investigation of agricultural residues gasification for electricity production in Sudan as an example for biomass energy utilization under arid climate conditions in developing countries*. University of Dresden.

Bergermann, S. and Partner, G. (2001), *Eurodish-Stirling Brochure*. Germany.

Bravo, Y., Carvalho, M., Serra, L. M., Monne, C., Alonso, S., Moreno, F. and Munoz, M. (2012), 'Environmental evaluation of dish-Stirling technology for power generation', *Solar Energy*, Vol. 86, No. 1, pp. 2811—2825. doi: 10.1016/j.solener.2012.06.019.

Campana, P. E., Li, H. and Yan, J. (2013), 'Dynamic modelling of a PV pumping system with special consideration on water demand', *Applied Energy*, Vol. 112, No. 1, pp. 635—645, Elsevier Ltd. doi: 10.1016/j.apenergy.2012.12.073.

Chu, Y. (2011), *Review and Comparison of Different Solar Energy Technologies*. San Diego, California, USA. Available at: http://www.geni.org/globalenergy/research/review-and-comparison-of-solar-technologies/Review-and-Comparison-of-Different-Solar-Technologies.pdf.

Department for International Development (2010), 'A potential role for an AMC in supporting dish/Stirling Concentrating Solar Power, Case Study Annex', *Advance market commitments for low-carbon development*.

Duffie, J. A. and Beckman, W. A. (1980), *Solar Engineering of Thermal Processes*. 2nd Edn. New York: John Wiley and Sons Inc.

German Federal Ministry of Cooperation and Development (2011), *International Fuel Prices 2010/2011*.

German Federal Ministry of Cooperation and Development (2013), *International Fuel Prices 2012/2013*.

German Federal Ministry of Cooperation and Development (2014), *International Fuel Prices 2014*.

Kribus, A. (2002), 'Thermal Integral Micro-Generation Systems for Solar and Conventional Use', *Journal of Solar Energy Engineering*, Vol. 124, No. 2, p. 189. doi: 10.1115/1.1464879.

Mahmoud, M. and Ibrik, I. (2006), 'Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid', *Renewable and Sustainable Energy Reviews*, Vol. 10, No. 2, pp. 128−138. doi: 10.1016/j.rser.2004.09.001.

Mekhilef, S., Saidur, R. and Kamalisarvestani, M. (2012), 'Effect of dust, humidity and air velocity on efficiency of photovoltaic cells', *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 5, pp. 2920−2925. Elsevier Ltd. doi: 10.1016/j.rser.2012.02.012.

Meteotest (2016), Meteonorm ver 7.1.8.

Mohammed, Y. S., Mustafa, M. W. and Bashir, N. (2014), 'Hybrid renewable energy systems for off-grid electric power: Review of substantial issues', *Renewable and Sustainable Energy Reviews*, Vol. 35, No. 1, pp. 527−539, Elsevier Ltd. doi: 10.1016/j.rser.2014.04.022.

Müller-Steinhagen, H. and Trieb, F. (2004), 'Concentrating solar power', *A review of the technology. Ingenia Inform QR Acad Eng*, Vol. 18, pp. 43−50.

Nayar, C. V., Phillips, S. J., James, W. L., Pryor, T. L. and Remmer, D. (1993), 'Novel wind/diesel/battery hybrid energy system', *Solar Energy*, Vol. 51, No. 1, pp. 65−78. doi: 10.1016/0038-092X(93)90043-N.

Nimmo, B. and Said, S. (1979), 'Effects of dust on the performance of thermal and photo- voltaic flat plate collectors in Saudi Arabia—preliminary results', in *Dec. 10−13. Proceedings of the 2nd Miami International Conference on Alternative Energy Sources*, pp. 223−5.

NREL (2016), System Adviser Model (SAM).

Ramli, M. A. M., Hiendro, A. and Twaha, S. (2015), 'Economic analysis of PV/diesel hybrid system with flywheel energy storage', *Renewable Energy*, Vol. 78, No. 1, pp. 398−405. doi: 10.1016/j.renene.2015.01.026.

REEEP Policy Database (2012), *Sudan (2012)*. Available at: http://www.reegle.info/policy-and-regulatory-overviews/SD (Accessed: 19 February 2016).

Sharma, V. and Chandel, S. S. (2013), 'Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review', *Renewable and Sustainable Energy Reviews*, Vol. 27, No. 1, pp. 753−767, Elsevier Ltd. doi: 10.1016/j.rser.2013.07.046.

Short, W. and Packey, D. J. (1995), *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*, Golden, Colorado, USA. Available at: http://www.nrel.gov/docs/legosti/old/5173.pdf.

Solar Gis (2010), *Global Horizontal Irradiation– Sudan*. Available at: http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-Sudan-en.png (Accessed: 19 February 2016).

Stine, W. B. and Diver, R. B. (1994), *A Compendium of Solar/Dish Stirling Technology*. Albuquerque, New Mexico and Livermore, California. Available at: https://www.osti.gov/scitech/servlets/purl/10130410.

The World Bank (2013), *Online Database-World Development Indicators*. Available at: http://databank.worldbank.org/data/reports.aspx?source=2&country=SDN&series=&period=(Accessed: 19 February 2016).

The World Bank (2014), *World Development Indicators*. http://databank.worldbank.org/data//reports.aspx?source=2&country=QAT&series=&period=#. doi: http://databank.worldbank.org/data//reports.aspx?source=2&country=QAT&series=&period=#.

Veldhuis, A. J. and Reinders, A. H. M. E. (2015), 'Reviewing the potential and cost-effectiveness of off-grid PV systems in Indonesia on a provincial level', *Renewable and Sustainable Energy Reviews*, Vol. 52, No. 1, pp. 757−769. doi: 10.1016/j.rser.2015.07.126.

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