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Comparative Study of Solar Tower and Parabolic Trough Concentrated Solar Power Technologies in Kano, Northern Nigeria

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Abstract:
Concentrated Solar Power systems are viewed as one of the most promising renewable technologies for producing electricity that will meet up with the increasing energy demand globally. This study is aimed at comparing the performance of Solar Tower and Parabolic Trough Concentrated Solar Power (CSP) plants in Kano, a potential CSP site in Northern Nigeria using the National Renewable Energy Laboratory's (NREL's) Solar Advisor Model (SAM).Molten salt is used as both heat transfer fluid and thermal storage fluid for two the CSP technologies considered. The simulation results shows that Solar Tower CSP Technology is more favoured to be adopted for use in the study site because it has higher annual generation (i.e. the highest overall annual electrical energy output to the grid), higher capacity factor, lower Levelised cost of electricity, and higher Net Present Value that makes it more economical viable project for the site.

1. Introduction

There have been rigorous efforts to meet the global energy demand challenges but relying on the traditional fossil fuels alone is synonymous to taken a great risk of backward trend in modern developmental strategies. An environmental concern over electric power generations from conventional sources has led to widespread public support for renewable energy sources. Renewable energy could provide as much as 35% of the world's energy needs by 2030, given the political will to promote its large scale deployment in all sectors on a global level, coupled with far reaching energy efficiency measures (Arobieke, et al, 2012).

Nigeria has abundant renewable energy resources such as; solar, wind, small hydro, biomass, etc. Among these renewable energy resources solar energy is the most promising because of its presence in almost every part of the country. According to Usman, 2012; Nigeria is endowed with daily sunshine that is averagely 6.25 hours, which is ranging from between 6.25 hours and 3.5 hours in northern region and southern region of the nation respectively.

There exist various types of technologies that have been developed to harvest the power from the sun. Photovoltaic, which is direct conversion from light energy into electricity, and concentrated solar thermal power called also concentrated solar power (CSP), which uses mirror to concentrate light energy are the two known technology types to utilize the solar energy. According to Habib, et al, 2012, while PV is suitable for small or off-grid solutions, CSP showed attractive features to be installed in large scale.

Concentrating Solar Power (CSP) has begun to achieve a growing penetration into global electricity markets. In the last 6 years the installed capacity of CSP has increased from 355 to 2550 MW (IRENA, 2012;CSP world.com) and according to reports from the International Energy Agency is expected to continue increasing up to 1500 GW by 2050 (Philibert, et al, 2010).

The minimum direct normal irradiation of Nigeria is in the range of 4.5 – 7.5 kWh/m^2/day in the Northern Nigeria with the highest in north-east part of the country as shown in Fig 1, which has met the minimum DNI threshold of 4.1 – 5.8 kWh/m^2/day needed for economically viable concentrating solar power project.

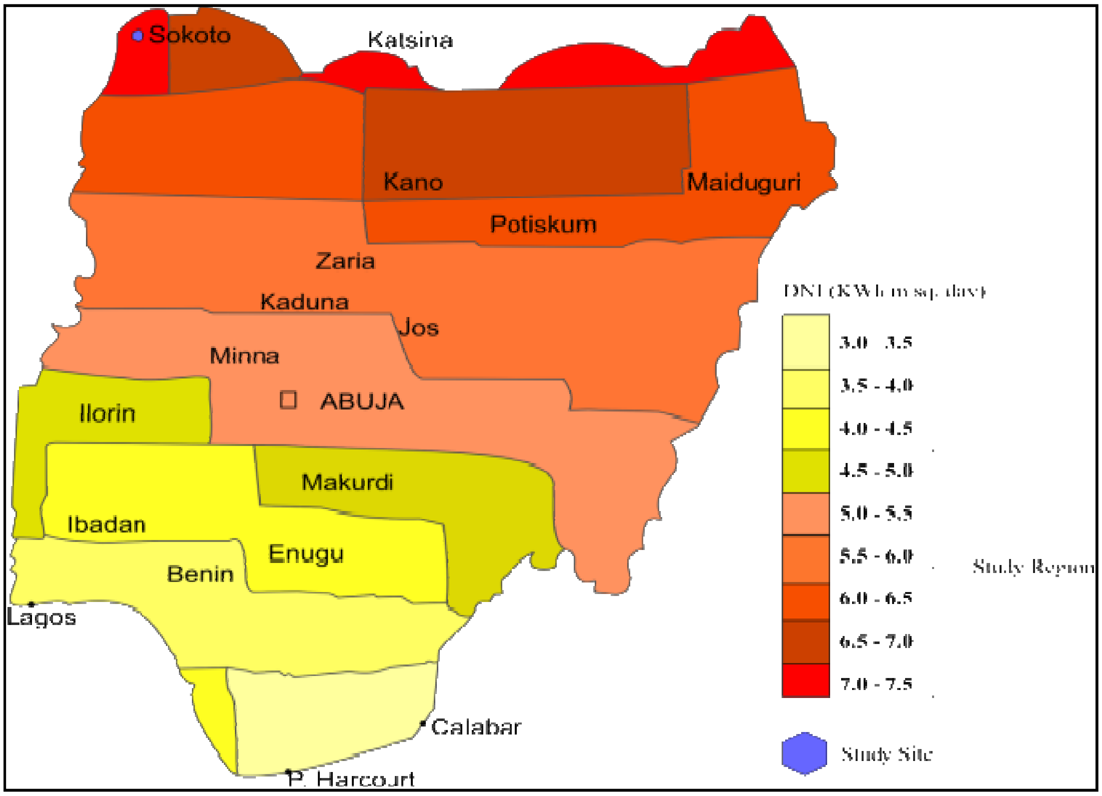

Figure 1: Map showing DNI of towns in Nigeria.

The three common deployed CSP technologies namely; Solar Towers, Parabolic Troughs and Linear Fresnel plants are in operation in Southern Spain and the data that have been obtained by these plants allow one to study there potential for application in different locations. In this study, Solar Tower and Parabolic Trough Concentrated Solar Power Technologies behaviour is simulated for Kano in Northern – Nigeria using National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM) software.

2. Objectives

The objectives of the study include;

i. To assess the performance of operating a given 100 MWe turbine capacity Concentrated Solar Power Technologies namely; solar tower and parabolic trough at the selected site,
ii. To compare the performance and financial viability of the CSP technologies at the selected site

3. Methodology

In this study, the National Renewable Energy Laboratory's (NREL's) System Advisory Model (SAM), one of the CSP plant modelling and analytical techniques was used to model 20 MW turbine capacity molten salt solar tower and molten salt parabolic trough CSP technologies using the resource data file in EPW format from Meteonorm Meteorological Database describing ambient weather conditions of Sokoto been one of the potential site for CSP in Nigeria..

4. Solar Tower and Parabolic Trough CSP Technologies Description

Solar towers (often called solar central receiver power plants) generate electric power from sunlight by focusing concentrated solar irradiation using mirrors on a tower-mounted heat exchanger (Andreas, et al, 2013). The collector field consists of an array of heliostats (mirrors) at the centre of which a tower is installed (Poullikkas, et al, 2009). At the top of the tower is a central receiver designed to collect the heat from the sun. The energy concentrated can be as much as 1,500 times the energy coming in from the sun. Energy losses from thermal energy transport are minimized as solar energy is being directly transferred by reflection from the heliostats to the central receiver, rather than being moved through a transfer medium to one central receiver, as with parabolic trough plants(Andreas, et al, 2013). In the receiver, the solar energy is absorbed by a heat transfer fluid (molten salt, water, liquid sodium or air) which is heated up to temperatures of 500 – 1000 ^{o}C, then used to generate steam to power a conventional turbine which converts the thermal energy into electricity (Kalogirou, 2010). These plants are best suited for large utility-scale applications in the 30 MW to 400 MW range (Andreas, et al, 2013).

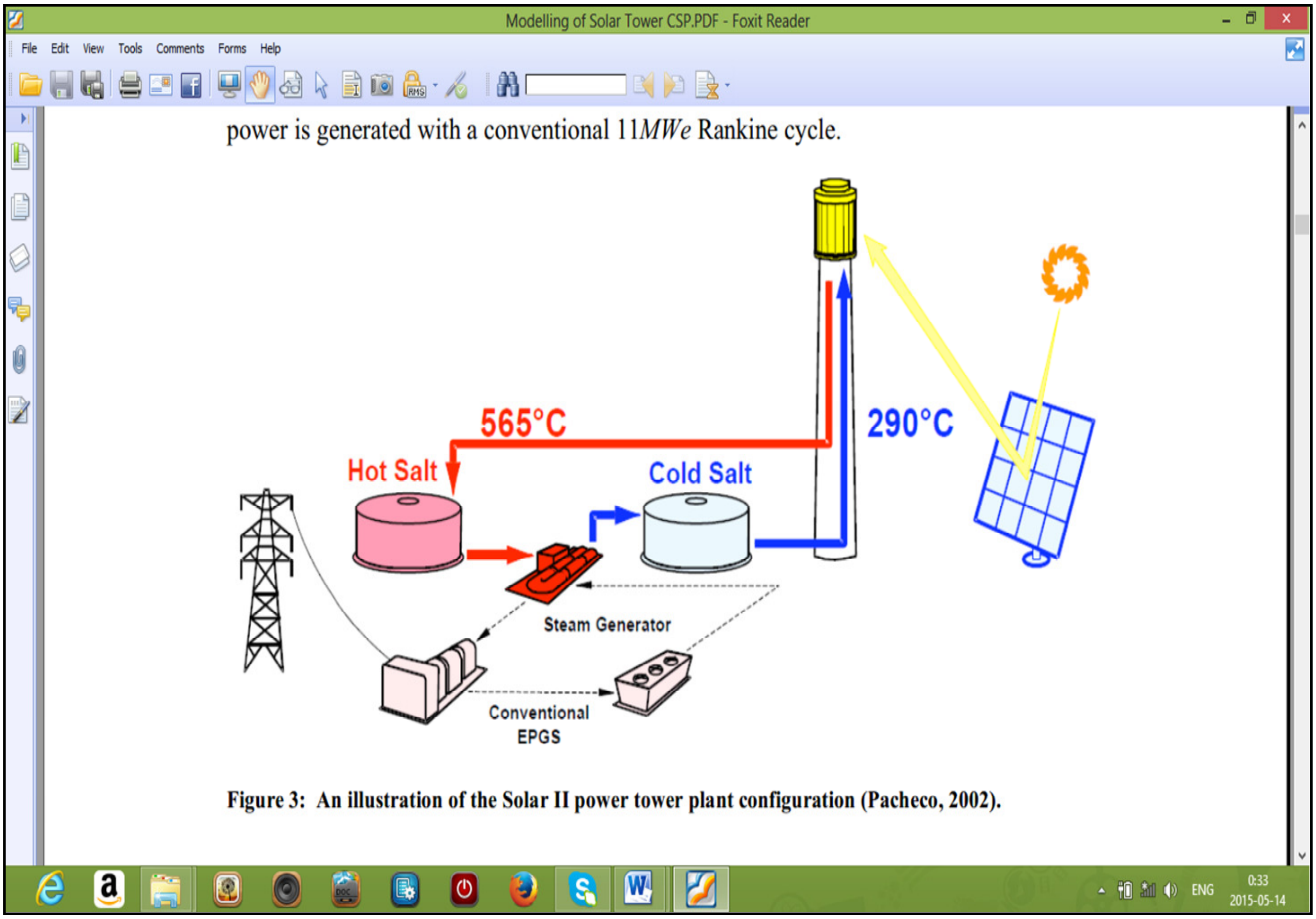

Figure 2: Simplified schematic of a solar power tower system using molten salt thermal storage.

Parabolic troughs has solar field consisting of a large field of single-axis tracking solar collectors. The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned with their long axes oriented north to south and mounted on supports that allow them to track the sun from east to west across the sky. Each solar collector has a linear parabolic shaped reflector that focuses the sun's direct beam irradiation on a linear receiver (or absorber tube) positioned along the length of the parabolic reflector at its focus (Poullikkas, et al, 2009). In order to collect the concentrated heat, a heat collection fluid is pumped through the linear receiver. The heat collecting fluid is typically synthetic oil, similar to engine oil, capable of operating at high temperature. During operation it is likely to reach between 300ºC and 400ºC. After circulating through the receivers the oil is passed through a heat exchanger where the heat it contains is extracted to raise steam in a separate sealed system. The generated steam is then used to drive a steam turbine generator to produce electricity. Typical steam conditions reached at the turbineinlet are 370°C - 395°C at 100 bar. The spent steam from the turbine is condensed in a condenser and returned to the heat exchanger via condensate and feed water pumps to be transformed back into steam. Condenser cooling is typically provided by mechanical draft wet cooling towers, although, dry cooling is also an alternative option in areas isolated from water sources. The heat collecting fluid is then cycled back through the solar collector field to collect more heat(Andreas, et al, 2013).

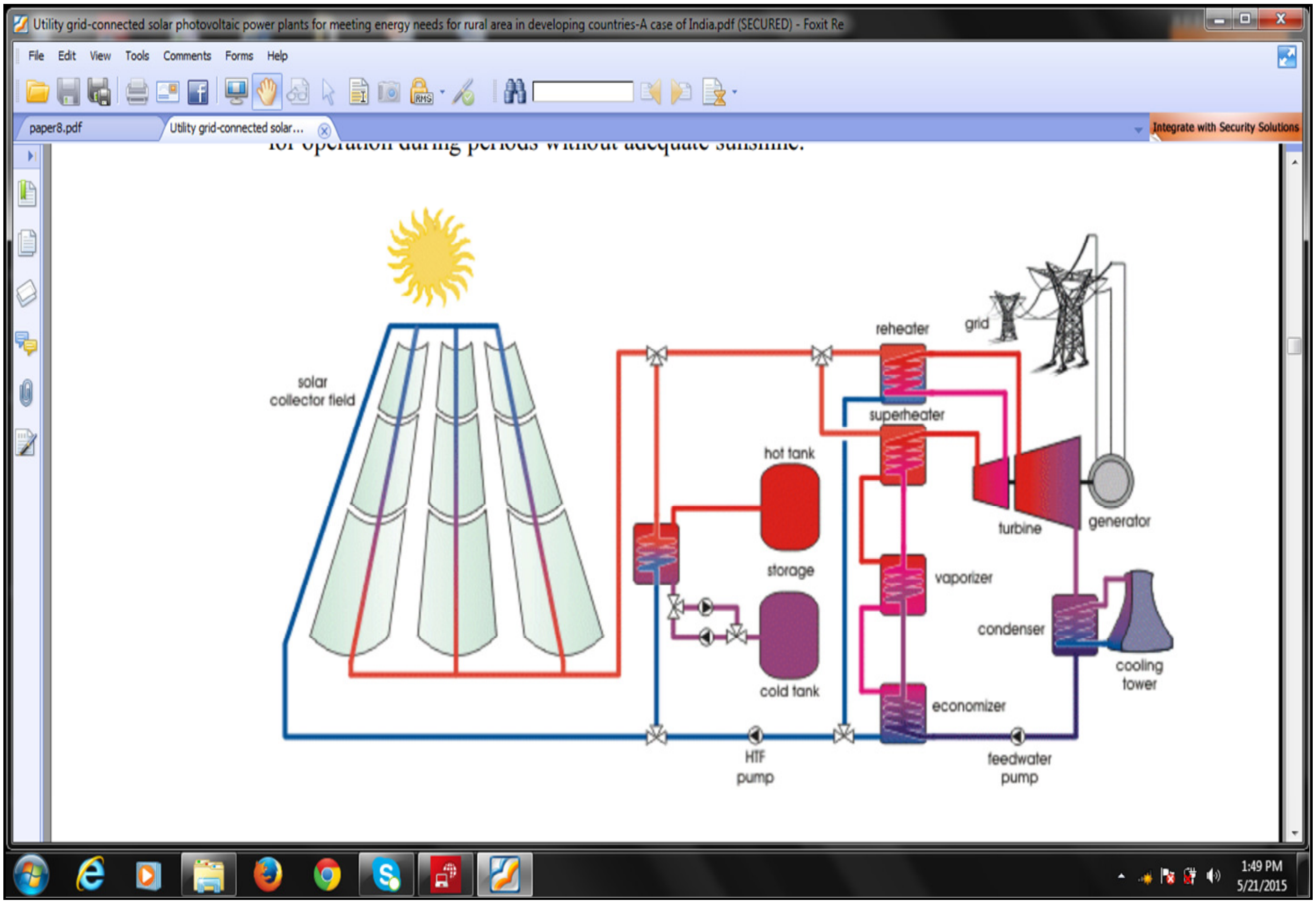

Figure 3: Simplified schematic of a parabolic trough system

5. Data Acquisition

This study used the KanoEPW climate file from Meteonorm 7 database which was uploaded into SAM software. The basic topography and ambient weather conditions of the study site are given in Table 1.The temperature and radiation periods of the data are between 2000 – 2009 and 1986 – 2005, respectively.

Parameters	Values	Source
Latitude (^{o}N)	12.1	Meteonorm V7.0.22.8
Longitude (^{o}E)	8.5	Meteonorm V7.0.22.8
Altitude (m)	481	Meteonorm V7.0.22.8
Ambient Temperature (^{o}C)	29.5	Meteonorm V7.0.22.8
Overall Mean wind speed (m/s)	3.5	Meteonorm V7.0.22.8
Direct Normal Irradiation (KWh/m^2/day)	5.94	*SolarelectricityHandbook.com/Solar Irradiance.html*

Table 1: Basic Topography and ambient weather conditions of Study Site

The system/Plant specifications for the two technologies considered were primarily sourced from "Gemasolar" NREL/ Solar PACES website for Solar Power technology, "Andasol-1" NREL/Solar PACES website for Parabolic Trough technology, Study site conditions and SAM help contents. Molten salt is used as both heat transfer fluid and thermal storage fluid for two the CSP technologies considered. The market considered for this study is Independent Power Producer. The financial assumptions for this study were compiled mainly from Central Bank of Nigeria and www.tradingeconomics.com/nigeria.

The values of the system specifications for solar tower and parabolic trough Concentrated Solar Power technologies are given in Table 2 and Table 3 respectively. The values of the financial assumptions made for this study are given in Table 4.

Parameters/Variables	Values	Remark / Source
Heliostat Field		
Solar multiple	2	User defined
Number of Heliostat	8,038	Optimised
Solar Field Aperture (m^2)	118.81 m^2	Optimised
Heat Transfer Fluid/ Receiver Fluid	Molten Salt	The operating temperatures are higher than synthetic oil HTF and are similar with usual steam turbines, and it is non-flammable and non-toxic. It also has lower cost than oil.
Irradiation at design	800 W/m^2	For systems with horizontal collectors and a field azimuth angle of zero. *www.nrel.sam/help*
Tower and Receiver		
Receiver type	External	Gemasolar CSP Plant's condition
Receiver height	19.24 m	Optimised
Receiver diameter	12.03 m	Optimised
Tower height	164.4 m	Optimised
Power Cycle		
Design Turbine Capacity (Gross)	100 MW	User defined
Design HTF inlet temperature	565 ^oC	Typical for Molten salt HTF
Design HTF outlet temperature	290 ^oC	Typical for Molten salt HTF
Freeze protection temperature	260^0C	Always set above HTF freezing temperature
Condenser type	Air Cooled	User defined
Ambient temp at design	28.5 ^{o} C	It is always taken as dry bulb ambient temperature value of site for the air cooled condenser options.
ITD at design point	16 ^{o} C	Modulated by SAM
Fossil dispatch mode	Supplemental operation	This mode assumes a safety reserve as a percentage of maximum capacity of system. *www.nrel.sam/help*
Thermal Storage		
Full load hours of TES	8	User defined
Initial hot HTF temp.	565 ^{o} C	Typical for Molten salt HTF
Dispatch schedule	Uniform dispatch	User defined
Tank height	20 m	User defined
Storage fluid	Molten Salt	It is liquid at atmospheric pressure, provides a low-cost medium to store thermal energy, its operating temperatures are compatible with today's steam turbines

Table 2: System Specification inputs for Solar Tower CSP Plant

Parameters/Variables	Values	Remarks
Receiver/Collector/ Solar Field		
Receiver Type	Schott PTR 70	Most used for CSP Plant. It has transmissivity ≥ 96%, absorptivity ≥ 95% and emissivity≤ 10% at 400^0C.
Collector Type	Euro Trough (ET 150)	It has low cost, rigid structure, high optical performance, less specific weight, and very easy to install.
Collector tilt angle	12.1 ^{o}	Absolute value of the latitude of the sites. This is the slope which in general maximises the annual solar radiation in the plane of the solar collector. www.retscreen.net
Collector azimuth angle	0 ^{o}	The array of the collectors are assumed to orient north-south (due south)
Solar Multiple	2	User defined
Number of Collectors	1,248	Andasol CSP Plant's condition
Solar Field Aperture (m^2)	510,120	Andasol CSP Plant's condition
Irradiation at design	800 W/m^2	For systems with horizontal collectors and a field azimuth angle of zero. www.nrel.sam/help
Heat Transfer Fluid/Receiver fluid	Molten Salt	The operating temperatures are higher than synthetic oil HTF and are similar with usual steam turbines, and

		it is non-flammable and non-toxic. It also has lower cost than oil.
Power Cycle		
Capacity - Design gross output	100 MW	User defined
Design HTF inlet temperature	565 ^oC	Typical for Molten salt HTF
Design HTF outlet temperature	290 ^oC	Typical for Molten salt HTF
Freeze protection temperature	260^0C	Always set above HTF freezing temperature
Fossil dispatch mode	Supplemental operation	This mode assumes a safety reserve as a percentage of maximum capacity of system. ***www.nrel.sam/help***
Fossil Backup Type	Natural gas	Andasol CSP Plant's condition
Backup Percentage	12%	Andasol CSP Plant's condition
Condenser type	Air Cooled	User defined.
Ambient temperature at design	28.5 ^oC	Dry bulb ambient temperature value of site since air cooled condenser is to be used.www.nrel.sam/help
ITD at design point	16 ^oC	Modulated by SAM
Thermal Storage		
Full load hours of TES	8 hours	User defined
Initial hot HTF temp.	565 ^oC	Typical of Molten salt HTF
Tank height	20 m	User defined
Dispatch schedule	Uniform dispatch	User defined.
Storage fluid	Molten Salt	Great capability of storing energy for long periods of time with insignificant losses.
Performance Adjustment		
Year - to - year decline in output	0.5	Andasol CSP Plant's condition

Table 3: System Specification inputs for Parabolic Trough CSP Plant

Parameters	Values	Remarks
Inflation Rate	8.5%	www.cenbank.org. Retrieved on 12th October, 2014
Debt fraction	50%	User defined. www.nrel.sam/help
Loan/Debt interest rate	12%	www.tradingeconomics.com/nigeria/interest-rate. Retrieved on 12th October, 2014
Income Tax rate	30%	www.tradingeconomics.com/nigeria/co-operate -tax-rate. Retrieved on 12th October, 2014
Sales tax (VAT)	5%	www.tradingeconomics.com/nigeria/sales-tax-rate. Retrieved on 12th October, 2014
Discount rate	4.25%	www.cenbank.org/dicount - rate. Retrieved on 12th October, 2014
Annual Insurance rate	0.75%	www.tradingeconomics.com/nigeria/insurance-rate. Retrieved on 12th October, 2014
Minimum Required IRR	15 %	Desired target. www.nrel.sam/help
PPA Escalation Rate	1.2%	Desired target. www.nrel.sam/help
Depreciation(Federal)	25years	www.nrel.sam/help
Incentives	0%	www.nrel.sam/help
Up-front Fee	2.5%	To be added to the interest amount for the construction loan to help calculate the total construction financing cost. www.nrel.sam/help

Table 4: Financial Assumptions for the study

6. Results and Discussion

6.1. Technical Results and Discussion

The technical/performance results as generated by SAM 2014.1.14 are presented in Table 5 for all the sites and technologies considered.

	Variables	CSP Technologies/Values	
		Solar Tower	**Parabolic Trough**
Key Metrics	Annual Generation GWh	342.64	97.88
	Capacity Factor %	43.50	12.40
	Annual Water Usage m^3	70,547	56,908

Table 5: Performance Results of CSP Technologies at Site

The solar power system parameters used for the analysis of the performance of the CSP technologies considered in this study are the total energy yield (annual system electrical energy generation) and the capacity factor.

6.1.1. Annual Electrical Energy Generation

From the Table 5, it is observed that solar tower CSP technology has the highest annual electrical energy generation of 343 $GWh_e$with parabolic trough CSP technology having a value of 98GWh_e. This result indicates lower gross to net efficiency of the parabolic trough CSP concept (250 %).

6.1.2. Capacity Factor

Capacity factor is the number of hours per year that Concentrated Solar Power plant can produce electricity. From Table 4, the capacity factors of the CSP Technologies considered are 43.5% and 12.4% for Solar Tower and Parabolic CSP plants respectively. The results indicate that solar tower CSP plant capacity factor is about 31 % higher that than of the parabolic trough plant. This is because of the good performance of the solar tower CSP plant in terms of electrical energy output

6.1.3. Annual Water Usage

Currently, the issue of water scarcity is one of the most important issues faced by the CSP industry. Azoumah, et al, 2010 noted that water is one of the key parameters required to meet the technical requirements for the implementation of a CSP plant. The cost of water and of water transportation (related to the distance of the CSP plant from the water source) has started to play an important role in the estimation of overall CSP plant economics (Andreas, et al, 2013).

From Table 4, the annual water usage of molten salt parabolic trough CSP technologies is about 24% lower than that of the molten salt solar tower CSP technology. This is because the parabolic trough plant generates less energy than the solar tower plant. Thus shall require less water for cooling process during operation.

6.2. Financial Results and Discussion

The financial results as generated by SAM 2014.1.14 are presented in Table 6 for the CSP technologies considered at the study site.

	Variables	CSP Technologies/Values	
Key Metrics		**Solar Tower**	**Parabolic Trough**
	LCOE(Nominal) $/kWh	0.286	1.081
	LCOE(Real) $/kWh	0.137	0.525
	FIT for Solar Energy Generation as at 2015 in Nigeria $/kWh	0.524	0.524
	IRR %	18.48	0.22
	Net Present Value M$	58.99	- 270.63

Table 6: Financial Results of CSP Technologies at Study Site

Net Present Value (NPV), the most widely accepted criteria for the determining the financial attractiveness of a project by financial analyst, economist and accountants was used in this study.

6.2.1. Net Present Value

Net Present Value (NPV) of a project is the total present value of a time series of cash flow of the project. In other words, NPV of a project is the difference between the discounted cash flows (inflow and outflow) of the project.

From Table 6, the Net Present Value (NPV) of the CSP Technologies considered is$M58.99and - $M270.63 for Solar Tower and Parabolic Trough Technologies respectively. The result indicates that the molten salt solar tower CSP project is economically viable while the molten salt parabolic trough CSP project is not. The viability of the molten salt solar tower CSP plant also implies that it will give more internal rate of return (IRR) than the required 15% internal rate of return as indicated from the result (18.48 %).

6.2.2. Levelised Cost of Electricity

Levelised Cost of Electricity (LCOE), an economic assessment of the cost of energy from a generating system is the price at which electricity must be generated from a specific source to break even over the life time of the project. In other words, it simply the cost of electricity produced by a generator. Since the analysis is for a long-term based situation, real LCOE will be more appropriate to be used for any discussion.

From Table 6, parabolic trough CSP plant has the highest real LCOE value of 0.525 US$/kWh with Soar Tower CSP Plant having a value of 0.137 US$/kWh. This simply means that the cost of producing electricity from molten salt parabolic trough CSP plant is about 74% higher than that from molten salt solar tower CSP plant. Also, the LCOE of molten salt solar tower plant is lower compared to the current Feed – in Tarriffs (FIT) for solar energy generation in Nigeria (0.524 US$/kWh). The LCOE of molten salt parabolic trough is a little above the FIT. This also indicates that the molten salt parabolic trough plant is not going to be economically viable at the study site.

7. Conclusions

From the performance and financial results of this study, Molten Salt Solar Tower CSP plant has the highest annual electrical energy generation, highest capacity factor, highest Net Present Value, Lower Levelised Cost of Energy, and higher cost selling energy at the study site. From the above findings, solar tower CSP plant is more favoured to be adopted for use in the study site.

If CSP plants are made to operate in all rural and urban areas of Northern Nigeria, there is assurance of availability of affordable and clean electricity that will have a significant input in reducing the level of carbon emission arising from fossil fuel reliance in the energy sector, thereby leading to improvement in the quality of life of the citizenry. Moreover, CSP technology will improve the industrial activities in the region; in addition to power supply, industrial activities which require higher temperatures can derive their heat energy from the CSP plants. Industries such as textile, food, metal, plastics, dairy and leather works found in this region can use heat energy from CSP plants for their industrial operations. If Nigeria can effectively harness its solar potential for thermal power plants, it can transform from being an oil-rich to solar-rich nation.

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