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Simulation of Molten Salt Solar Tower CSP Plant Behaviour in Three Cities in Northern Nigeria

Haruna Mohammed Muye*[1]
Mechanical Engineering Department,
Niger State Polytechnic, Zungeru,
Nigeria

Kasim Ibrahim Mohammed [2]
Science Lab. Technology Department,
Niger State Polytechnic, Zungeru,
Nigeria

Garba Aliyu [3]
Electrical Engineering Department,
Niger State Polytechnic, Zungeru,
Nigeria

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. 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, simulation of Molten – Salt Solar Tower Concentrated Solar Power plant behaviour in three cities in Northern Nigeria namely Minna, Kano, and Sokoto was carried out using Solar Advisor Model (SAM). The three cities were selected based on their Direct Normal Irradiation (DNI) values and hours of sunshine per day which are comparable to that of the sites where Concentrated Solar Power (CSP) plants are operating in Southern Spain. The annual electrical energy generation of the CSP Plant was found to be 112 GWh_e, 106 GWh_e and 89 GWh_e with 6,421 hours, 6,105 hours and 5,133 hours of electricity production per year at Sokoto, Kano and Minna sites respectively. The NPV values for the CSP Plant at all the sites are positive implying that the project is economically viable and the project promises more internal rate of return (IRR) than the required 15% internal rate of return. The average cost of electricity from the CSP plant is about 2.64 times more expensive than the electricity from the current available power plants in Nigeria.**

Key Words: Direct Normal Irradiation, Concentrated Power Plant, Annual Electrical Energy, Levelised Cost of Energy, and Capacity Factor.

1. INTRODUCTION

Increasing worldwide demand for electricity coupled with growing concerns about climate change and the need to reduce the environmental impact of conventional fossil-fuel based power plants has led to the development of innovative and more sustainable power generation solutions based on renewable resources *(Arobieke, et al, 2012).*

Nigeria over the years has been faced with acute problems in the supply of electricity to meet up with the demand despite the nation's vast natural resources. The electricity demand in Nigeria far outstrips the supply and the supply is epileptic in nature.

As at 2005, the nation has an installed capacity of approximately 6,538.3 MW. Out of this installed capacity, not more than 4,500 MW is ever produced *(Nwulu & Agboola, 2011)*. In December, 2009, the total grid capacity stood at 8,876 MW. Out of this only 3,653 MW were available. Thus 41% of the installed capacities are unavailable *(Emovon eta al, 2010)*. However, the energy demand has always been on the increasing side. For instance, the energy demand increases from 6,000 MW in 2001 to 13,000 MW in 2013 with energy generation at 4,000 MW.

An analysis of the power generation capacity required to support the Nigeria Vision 20:2020 economic vision shows that, Nigeria will need to generate electricity in the range of about 35,000MW by 2020. This is based on the assumption that the country will take low energy intensity (<0.4) growth path *(Habib, et al, 2012)*.

With the rate of increase in Nigeria population, pressures on the conventional energy infrastructure for the supply of energy demand will continue to increase. Since the quantity of available energy from conventional resources cannot meet up with the ever increasing energy demand , there is urgent need to aggressively pursue the harnessing of the nation's renewable energy resources such as solar, wind and biomass to meet the future demand.

Among the Nigeria renewable energy resources listed, solar energy is the most appropriate to meet up with the current and future energy demand in view of its enormous potentials. 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

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Habib, et al, 2012, while PV is suitable for small or off-grid solutions, CSP showed attractive features to be installed in large scale.

CSP systems are ideal for grid connection, although small off-grid systems can be designed; they are the best suited solar technology that is capable of providing utility scale electricity and are usually used to provide base load power where they exist *(Habib, et al, 2012)*. As at the end of 2012, CSP is contributing about 1700 MW of electricity to global electricity generation *(Olumide and Andrew, 2013)*

2. OBJECTIVES

The main objective of this study is to model a 20 MW turbine capacity Concentrated Solar Power Plant for Minna, Kano and Sokoto in Northern – Nigeria.

The specific objectives include:

i. To assess the technical performance of operating a 20 MW turbine capacity Concentrated Solar Power Plant using the selected technology at the selected sites.
ii. To determine the Financial viability of operating a 20 MW turbine capacity Concentrated Solar Power Plant using the selected technology for the selected sites, And;
iii. To compare the unit energy cost of current source of electrical power supply to the selected sites and that of the CSP plant modeled.

3. METHODOLOGY

The sites selected for the study was based on the result of the potential CSP capacity of some selected states in the Northern Nigeria as contained in the Nigeria Climate Assessment, preliminary report (World Bank/Lumina Decision) 2011and reported by *Habib et al, 2012.* The CSP Technology employed was based on the meteorological conditions and terrain of the study sites.

System Advisory Model (SAM), one of the CSP plant modelling and analytical techniques was used to simulate a 20 MWe turbine capacity of the selected CSP technology behaviour for the selected sites.

The study sites resource data file in EPW format was acquired from Meteonorm Meteorological Database and was uploaded into the modelling software, SAM.

The CSP Plant specifications for the technology selected was primarily sourced from; Gemasolar CSP Plant NREL/ Solar PACES websites, Study sites conditions and SAM help contents

The financial assumptions for this study were compiled mainly from central Bank of Nigeria and *www.tradingeconomics.com/nigeria.* The market considered was Independent Power Producer.

2. Concept of CSP Technology

The basic concept of CSP technology is relatively simple; it involves the concentration of the sun's Direct Normal Irradiation (DNI), using lenses or mirrors. The sun's energy is amplified to temperatures in the range of 400 - 1000^{0}C. This heat is first transformed to mechanical energy (by conventional steam cycle, Stirling engines or combined cycle engines) then to electrical energy *(OECD and IEA, 2009)*.

The process of generating electricity from CSP is nearly the same with conventional fossil fuel thermal plants with the difference being the fuel source. A typical CSP plant uses reflectors and parabolic mirrors to focus the sun's rays onto a heat collector. Heat transfer fluids such as synthetic oil are used to transfer heat from the collector to heat exchangers where water is super-heated. The super-heated steam runs a turbine which in turn drives a generator to generate electricity *(Habib, et al, 2012).*

At present, there are four categories of CSP, with similar modes of operation but different ways of receiving and amplifying the sun's energy. The four categories include; Parabolic Trough, Linear Fresnel Reflector (LFR), Solar Tower or Central Receiver System (CRS) and Parabolic Dish or Dish Stirling systems. The four categories can be divided into two groups based on how they concentrate irradiance on the receiver. LFR and Parabolic trough designs are classified as line focus system. In this design, collectors track the sun and focus irradiance on a linear absorber (usually stainless steel pipes). The absorber moves in tandem with the collector assembly as it tracks the direction of the sun in the parabolic trough design. The LFR uses a fixed linear downward facing receiver positioned at a common focal point of the reflectors. In Dish Stirling and CRS designs, collectors track the sun and focus irradiance at a single point receiver. Higher temperature is achieved in this design and ease of transportation of collected heat to power block *(Olumide and Andrew, 2013)*.

4. NIGERIA'S CSP POTENTIALS

Solar energy has considerable potential in Nigeria, and could bridge the major energy gaps in rural areas, particularly northern Nigeria *(Newsom, 2012)*. Nigeria is endowed with daily sunshine that is averagely 6.25 hours, which is ranging between about 6.25 hours and 3.5 hours northern region and southern region of the nation respectively *(Bala, et al, 2000)*. On the average, the country has access to energy in excess of 3000 MW i.e. 3 GW daily from the sun *(Arobieke, et al, 2012)*. Studies relevant to the availability of the solar energy resources in Nigeria have fully indicated its viability for practical use *(Bala, et al, 2000; Folayan, 1988; and Sambo, 1986)*.

The minimum direct normal irradiance 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.

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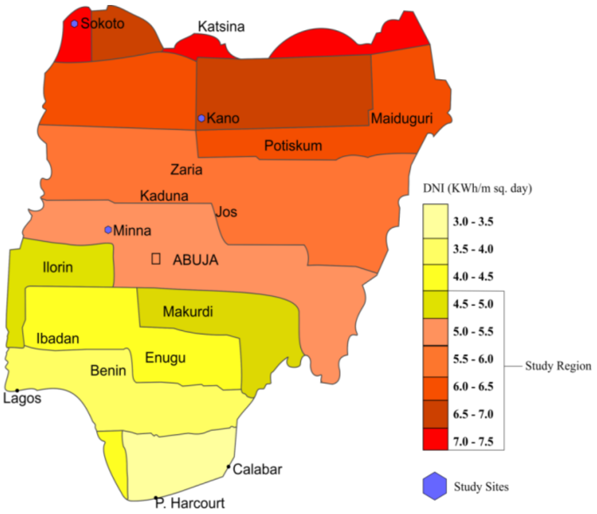

Fig.1: Map showing DNI of towns in Nigeria.

Source: Adapted from Habib, et al, 2012

There are large numbers of solar energy devices that were developed by Nigerian researchers in different part of the country and these devices are ready for adoption into the economy especially in rural remote areas *(Usman, 2012).* Few amongst the devices include; solar dryers, solar cookers, solar stills, solar water heaters, water pumping, vaccines and drug storage, and streets and traffic control. According to *Arobieke, et al, 2012* only one CSP plant is in operation in Nigeria. The CSP is a 2.5 kW Big Parabolic dish.

Many studies have been conducted to ascertain the potential of operating CSP plants in Nigeria. These studies have fully indicated large scale CSP plants can be deployed to the Northern part of the country for sustainable electric power generation *(Habib, et al, 2012; Usman, 2012; Olumide and Andrew, 2013).*

5. COLLECTOR CHOICE FOR STUDY SITES

The major parameters to consider in making a choice of CSP Technology for any site are meteorological conditions and terrain of the site. The calculated average annual direct solar radiation of the selected cities in Northern Nigeria ranges between 5.02 kWh/m^2/day (Minna site) and 6.20 kWh/m^2/day (Sokoto site). This range of value is high enough compared to some sites in Spain and USA, and due to the high temperature needed to generate steam of very high quality for the operation of the power cycle, a CSP technology which is capable of working at the highest temperature to achieve higher efficiencies in electricity production will be more appropriate for the conditions in the study sites.

The in ability of Parabolic Troughs, Linear Fresnel collectors, and Dish collectors to generate very high temperature as compared to Solar Tower for quality steam generation makes them less suitable for the meteorological conditions of the study sites. The high temperature generated by the Solar Tower System has a good prospect for high conversion efficiencies which impacts on the overall efficiency of such plants. Based on the aforementioned advantage of Solar Tower System over other CSP Systems and since high overall efficiency is needed in accessing the profitability of a plant, the Solar Tower System is the most favoured technology for the study sites.

The CSP plants operating based on the CSP Technology selected for this study is the GEMASOLAR plant in Southern Spain. Gemasolar CSP plant, located in Fuentes de Andalucía, Spain, about 40 miles east of Sevilla with an average annual direct solar radiation of 4.85 kWh/m^2/day, is the first commercial-scale plant in the world to apply solar tower receiver and molten salt heat storage technology. The plant has a capacity of 19.9 MWe (gross), an annual water usage of 368,347 m^3, and annual electrical output of 107.4 MWh/yr which equates to a capacity factor of 74% *(http://www.sener-power-process.com/ENERGIA/ProjectsI/gemasolar/en).*

The estimated average annual direct solar radiation of the study sites and the daily sunshine hours of about 6.5 hours in the study sites are comparable the Sevilla site in Spain where Gemasolar CSP Plant is operating.

6. DATA ACQUISITION AND SIMULATION PROCESS

This study used the Minna, Kano, and Sokoto EPW climate file from Meteonorm 7 database which was uploaded into SAM software. The basic topography information of the study sites are given in table 1.

Table 1: Basic Topography and Meteorological Conditions of Study Sites

Parameters	Study Sites Values		
	Minna	Kano	Sokoto
Latitude (oN)	9.62	12.05	13.05
Longitude (oE)	6.53	8.53	5.21
Altitude (m)	260	477	265
DNI (kWh/m2/year)	1164	1608	1912
Ambient Temp. (°C)	28.3	29.5	29.7
Average Wind Speed(m/s)	3.2	3.5	3.3

Source: Meteonorm V7.0.22.8

The temperature and radiation periods of the data are between 2000 – 2009 and 1986 – 2005 respectively.

The simulation process adopted for this study includes;

i. Configuration of receiver and collector components,
ii. Selection of HTF and specifying of the operating temperatures,
iii. Sizing/Configuration of solar field
iv. Specifying of power cycle design point,
v. Specifying of the thermal storage parameters,
vi. Specifying of the financial parameters, and;
vii. Optimization of solar multiple and TES capacity

In sizing of the solar field, the mass flow rate of the heat transfer fluid (HTF) in the receiver need to be modulated so as to achieve the desired outlet temperature of the HTF from the receiver. In this study, the mass flow rate was calculated by the modelling software based on the

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set HTF outlet temperature from the receiver and the maximum temperature of the HTF to the receiver.

The configurations, selections, definitions, and estimated values of the system technical characteristics of the considered CSP plant are given in Table 2. The values of the financial assumptions made for this study are given in Table 3.

Table 2: System Characteristics/Specifications

Parameters/ Variables	Values
Heliostat Field	
Number of Heliostat	8,929
Heliostat width	10.9 m
Heliostat height	10.9 m
Tower and Receiver/Solar field	
Receiver height	14.22 m
Receiver diameter	8.89 m
Tower height	140 m
Number of panels	16
Receiver fluid/Solar field fluid	Molten Salt
Solar multiple	2
Max flow rate to receiver	281.3 kg/s
Power Cycle	
Design Turbine Capacity (Gross)	20.0 MW
Rated cycle conversion efficiency	0.412
Design HTF inlet temperature	565^0C
Design HTF outlet temperature	290^0C
Condenser type	Evaporative
Ambient temp at design	20^o C for Minna and Sokoto; and 18^o C for Kano
Fossil Backup Type	Natural gas
Backup Percentage	15%
Fossil Dispatch mode	Supplemental operation
Thermal Storage	
Tank height	20m
Storage type	2 tank
Full load hours of TES	8
Storage fluid	Molten Salt
Cold tank heater set point temp.	280^0C
Hot tank heater set point temp.	500^0C
Dispatch schedule	Uniform dispatch

Table 3: Financial Assumptions for the study

Parameters	Values
Inflation Rate	8.5%
Debt fraction	50 for Sokoto 49 for Kano 52 for Minna
Loan/Debt interest rate	12%
Income Tax rate	30%
Sales tax (VAT)	5%
Discount rate	4.25%
Annual Insurance rate	0.75%
Minimum Required IRR	15 %
PPA Escalation Rate	1.2%
Depreciation(Federal)	25 years
Incentives	0%
Up-front Fee	2.5%

7. RESULTS AND DISCUSSION

7.1 Technical Results and Discussion

The technical/performance results as generated by SAM 2014.1.14 are presented in table 4 for all the sites for the CSP technology considered.

Table 4: Performance Results of CSP Technology at Sites

Sites	Variables	Values
Minna		
Resource	Annual DNI kWh/m^2/year	1164
Key Metrics	Annual Generation GWh$_e$	89
	Capacity Factor %	58.60
	Annual Water Usage m^3	395,569
	Total Land Area acres	1152.55
Kano		
Resource	Annual DNI kWh/m^2/year	1608
Key Metrics	Annual Generation GWh$_e$	106
	Capacity Factor %	69.70
	Annual Water Usage m^3	427,776
	Total Land Area acres	1152.55
Sokoto		
Resource	Annual DNI kWh/m^2/year	1913
Key Metrics	Annual Generation GWh$_e$	112
	Capacity Factor %	73.30
	Annual Water Usage m^3	443,470
	Total Land Area acres	1152.55

7.1.1 Annual Electric Energy Generation

From table 4, it is observed that the value of annual electrical energy generation is higher at Sokoto site compare to the other two sites. The annual electrical energy generation is 112 GWh$_e$ at Sokoto site with the highest value of DNI of 1912 kWh/m^2, followed by Kano site with annual electrical energy generation of 106 GWh$_e$ and DNI of 1608 kWh/m^2, and then Minna site with annual generation of 89 GWh$_e$ and DNI of 1164 kWh/m^2. This trend is in agreement with the statement made by *Kaushal & Richard in 2010* that “the meteorological parameter that has the strongest influence on performance of a CSP plant is clearly Direct Normal Irradiance (DNI)”. From this result it can be said the Performance of CSP Plant is directly proportional to the DNI of the site/location at which it’s operating. *Garcia, 2007* also testified to this statement.

7.1.2 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 Technology considered are 58.6%, 69.70% and 73.30% at Minna, Kano and Sokoto sites respectively. The results indicate that Sokoto site has the highest capacity factor of 73.3%, implying that the plant will produce electricity for 6,421 hours per year at Sokoto site as compare to 6,105

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hours and 5,133 hours per year of electricity production at Kano and Minna sites respectively.

7.1.3 Monthly Net Electric Energy Output

Figure 2 shows the Monthly Net Electrical Energy output from the CSP Technology considered at Minna, Kano, and Sokoto sites respectively.

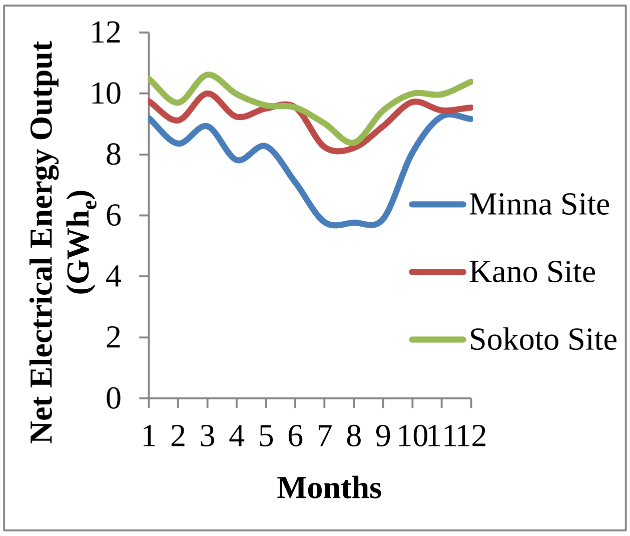

Fig. 2: Monthly Net Electrical Energy Output from the CSP Technology at Study Sites

From each of the line graph in Fig 2, it can be noticed that that the net electrical energy output is not constant through the months of the year for all the sites.

At Minna site, it is observed that the lowest net electrical energy output occur in the eight month, i.e. August. This trend is also noticed at Kano and Sokoto sites. This scenario is due to the fact that usually August is the month of peak rain in most cities in Northern Nigeria as such the number of sunshine hours will be reduce as most of the days in the month will be cloudy and consequently low irradiance will be received by the collectors as shown in Fig 3.

The highest value of net electrical energy output occurs in the month of November at Minna and Kano sites (Fig 2). However, at Sokoto site (Fig. 2) the highest net electrical energy output occurs in the month of March. The above scenario is due to the fact that dry season begins later part of the year (usually from the month of October) and last up to the first quarter of the preceding year (usually up to the month of April) in the Northern part of Nigeria.

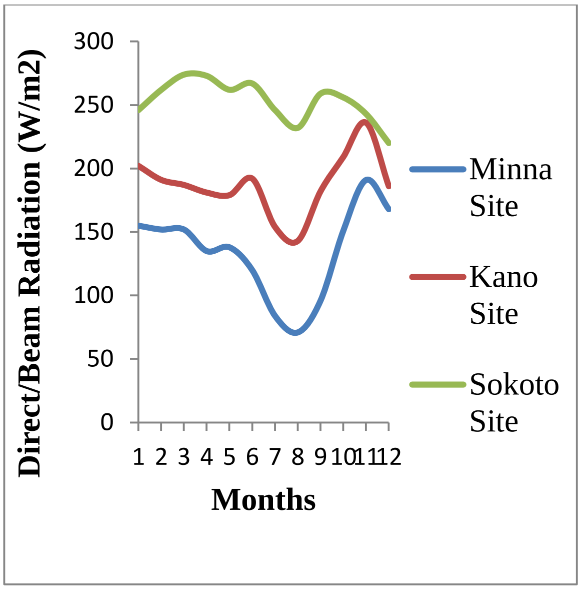

Fig 3: Monthly Direct Normal Irradiation at study sites

7.2 Financial Results and Discussion

The financial results as generated by SAM 2014.1.14 on Thursday, October 21, 06:22:04, 2014 is presented in table 5 for all the sites and technologies considered.

Table 5: Financial Results of the CSP Technology at Sites

Sites	Variables	Values
Minna		
Key Metrics	LCOE(Nom) ¢/kWh	56.60
	LCOE(Real) ¢/kWh	27.21
	IRR %	15
	Net Present Value $	12,826,678
Cost	Total Installed $	378 million
Kano		
Key Metrics	LCOE(Nom)¢/kWh	46.15
	LCOE(Real) ¢/kWh	22.07
	IRR %	15
	Net Present Value $	13,244,239
Cost	Total Installed $	378 million
Sokoto		
Key Metrics	LCOE(Nom) ¢/kWh	42.50
	LCOE(Real) ¢/kWh	22.00
	IRR %	15
	Net Present Value $	13,454,067
Cost	Total Installed $	378 million

The 20 MWe turbine capacity Molten Salt Solar Tower CSP Technology at the three study sites; Minna, Kano, and Sokoto was analyzed for financial viability. There are various criteria for determining the financial attractiveness of a project, namely Payback Period and Net Present Value. However, the NPV criterion that is the most widely accepted by financial analyst, economist and accountants as the only one that yields correct project choice in all circumstances was used in this study.

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7.2.1 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 5, the Net Present Values (NPV) of the CSP Technology considered at Minna, Kano and Sokoto sites are $12,826,678, $13,244,239 and $13,454,069 respectively. Since the NPV values for the CSP Technology considered at all the sites are positive, it implies that all the projects are economically viable and the projects promises more internal rate of return (IRR) than the required 15% internal rate of return.

7.2.2 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 a long-term based, real LCOE will be more appropriate to be used for any discussion.

From table 5, the real LCOE values for the CSP Technology considered at Minna, Kano and Sokoto sites are 27.21US ¢/kWh, 22.07US ¢/kWh, and 22US ¢/kWh respectively. As at the end of 2014, the charge of electricity from the existing power plants in Nigeria is 9US ¢/kWh. Comparatively, the average cost of electricity from the CSP plant in the study sites is between 3.02 and 2.44 times more expensive than the electricity which is currently available for Nigeria citizens. However, there is evidence that significant amount of electricity is produced by private generators in the country, so it is really difficult, nearly impossible to determine the current cost of electricity in reality. In view of the fact that the current power plants in the country (mainly Hydro and thermal) cannot supply the current existing electricity demand, consumers would be ready to pay for the relatively high cost of electricity from the CSP plant. Also, since CDM is supporting projects like solar energy plants, it is expected the price for electricity produced by the plants would be lower than the calculated values.

7.2.3 Total Cost of Installation

The total cost of installation of CSP plant consists of the site, storage, balance of plant, heliostat, tower, receiver, power plant/block, contingency, and indirect costs. From table 5, it can be noticed that the total cost of installation for the CSP Technology considered is the same at all the sites.

From literature, the most significant capital cost difference between the plants located in the USA and Spain lies in the category of power block and balance of plant (BOP) costs, which may cover between 19% to 25% of the total direct capital costs of a CSP plant excluding O&M, contingency and other indirect costs such as, system design, procurement, construction management and project engineering costs *(Bensebaa, 2010; Viebahn, et al, 2011).*

For this study, power block, balance of plant, heliostat, tower, receiver, power plant/block, contingency, and indirect costs of the CSP Technology considered are the same at all the sites because at the SAM solar field input page, the same value of solar field aperture of 118.81m^2 was entered for all the sites. This will obviously give the same number of heliostat or mirrors or reflectors or collectors as the case may be and the same land area at all the sites.

In view of paragraph two and three above, it is obvious that the total capital cost of the CSP technology considered will be same at all the site because the power block and balance of plant costs are the same.

8. CONCLUSION

The study results show that Molten Salt Solar Tower CSP plant behaviour is favourable at all the study sites. The annual electrical energy generation of the CSP Plant is 112 GWh$_e$, 106 GWh$_e$ and 89 GWh$_e$ with 6,421 hours, 6,105 hours and 5,133 hours of electricity production per year at Sokoto, Kano and Minna sites respectively. The NPV values for the CSP Plant at all the sites are positive implying that the project is economically viable and the project promises more internal rate of return (IRR) than the required 15% internal rate of return. The real cost of electricity from the CSP plant is 27.21US ¢/kWh, 22.07US ¢/kWh and 22US ¢/kWh at Minna, Kano and Sokoto sites respectively. Even though the costs are higher compared to the cost of electricity from the current existing power plant to the sites, it is expected that consumers would pay since the current power plants cannot supply the electricity demand and there is guarantee of steady supply of electricity from the CSP plant.

9. RECOMMENDATIONS

The recommendations of this study are as follows:

i. In order to facilitate the off-grid electricity extension especially to the rural and remote areas in Northern Nigeria, there is urgent need to embark on aggressive solar electrification projects using CSP plants,

ii. Provision of tax credits for solar energy is necessary so as to boost the market in the country.

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