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Investigating the Influence of Incorporation of Solar Aided Power Generation Technology on a Steam Power Plant in Nigeria

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Abstract – One of the ways of meeting the growing energy demand in a developing country like Nigeria is to have a suitable and sustainable means of power generation. Steam power plants have a huge potential to meet these needs but its viability has been hampered by its dependence on conventional fossil fuels. This paper is aimed at evaluation the effect of integrating a solar aided power generation technology (SAPG) into steam power plant. In this study, computer program codes were developed in Microsoft Excel macros for simulation and evaluation of the plant's energy, exergy, environmental and economic analysis of the various models. The performance of four replacement models (Model 1; Model 2; Model 3 and Model 4) was compared with the base case (control) using energy, exergy, environmental and economic parameters. The result showed that Model 2 was the best integration option with a 6% increase in both energy and exergy efficiency; around 14% reduction CO_2 emission with a payback period of 0.77 years. Based on the results of this study, steam powered plants can meet up with the escalating energy demand in a cleaner way if the option of SAPG is considered.

Keywords – Annualized cost of electricity generation, CO_2 emission, energy efficiency, exergy efficiency, levelized cost of electricity.

1. INTRODUCTION

Availability of clean and stable electricity is essential to actualizing Nigeria's pursuit for joining the most industrious nations by the year 2020. The development of every nation depends on largely on having minimum access to electricity for larger percentage of its population [1]. Presently, Nigeria depends on its aged hydro plant installments and petroleum reserves for electricity generation. Despite the importance of electricity in an economy and being so richly endowed with energy resources, Nigeria have not been able to generate adequate and reliable electricity to meet her demand and has been in an energy crisis for decades [2]. The Nigerian electricity sector operates well below its estimated installed capacity of 8,425 MW, with power outages being a frequent occurrence due to the ageing power plants, poor maintenance and natural gas shortage of gas supply resulting from the Niger Delta crisis [3]. The over-dependence on the natural gas in the Nigerian power generation has slowed down the development of alternative fuels. Therefore there is need for the diversification of wider energy supply mix, which will ensure greater energy security for the country.

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The country is blessed with several renewable energy resources (RES) such as wind and solar, which are yet to be exploited. As at the moment the development of solar energy is highly restricted to a few individual homes in urban cities and some public street lighting operations to augment power shortage from the public utility grid. However, the intensity of solar radiation exhibits significant variation from the north to the south of Nigeria with higher percentage towards the northeastern axis. Yet, the entire country has enough solar radiation to sustain the energy requirement of the country with a benchmark of 2,324 Wh/m^2/day as the average domestic load demand [4]. The potential of solar as a renewable source of energy is apparently limitless [5]. According to Akinyele [6] solar technologies can be categorised as solar thermal and solar photovoltaic systems. Many studies have been conducted on the potential analysis of solar energy application in Nigeria and virtually all indicated that vast opportunities for tapping solar energy existed [4]–[10]. Despite this vast solar potential, Nigeria is yet to integrate solar energy into its energy generation mix [11]. Furthermore, the application of solar thermal in the country has not been exploited to the best of authors' knowledge.

Presently, all Nigeria power plant run on natural gas and whenever there is natural gas shortages due to vandals the generation drops. Also, it should be noted that although natural gas is very clean and still releases some level of CO_2 into the environment. Hence, the need for alternative renewable sources of fuel for our power plants for 100% supply cannot be over emphasised. Several studies [11], [12] have been able to present different approach of combining one or two sources energy to run power plant. It is against this backdrop that this study is designed to fill this gap by investigating and to evaluate the effects of integration of SAPG into a natural gas powered steam power plant in

Nigeria using energy, exergy, environmental and economic analysis.

As earlier mention the gas shortages in the country hampers the supply of electricity generation which and several studies have been carried out with a possibility of integrating solar aided power into existing power plant to stand as alternative [12], [13]. In solar thermal power plants, the incoming radiation is tracked by large mirror fields which concentrate the energy towards absorbers. They, in turn, receive the concentrated radiation and transfer it thermally to the working medium. The heated fluid operates as in conventional power stations directly (if steam or air is used as medium) or indirectly through a heat exchanging steam generator on the turbine unit which then drives the generator [14]. There are three different technologies for solar thermal power plants making use of concentrating solar energy systems. These include parabolic troughs, central receivers (towers) and parabolic dishes [12], [13]. Parabolic trough systems use linear concentrators of parabolic shape with highly reflective surfaces, which can be turned in angular movements towards the sun's position and concentrate the radiation onto a long-line receiving absorber tube. The absorbed solar energy is transferred by a working fluid, which is then piped to a conventional power conversion system [14].

This solar power generation technology has been incorporated into different power generation systems either as a total replacement or as an aid on the basis of SAPG. In SAPG, solar-thermal energy at various temperature ranges is used to replace the bled-off steam to pre-heat feedwater in different positions thereby having the several advantages as stated by Yang *et al.* [16]. The major benefits of SAPG to power generation stations are; (i) additional power generation with the same fuel consumption (solar boosting mode) and (ii) Fuel and emission reduction while maintaining the same generating capacity. Xu, *et al.* [17], established the renewable electricity contribution from solar thermal power systems based both energy and exergy analysis. You and Hu [18] investigated the effect of incorporating two types of solar collector in regenerative steam power plant. Case 1: incorporating a flat plate solar collector with 110^{o}C and Case 2: incorporating an advanced solar collector with 286^{o}C. Their result showed that the thermal efficiency of the Case 1 and Case 2 increased by 8.69% and 25.64% while their exergetic efficiency increased by 1.27% and 13.5%, respectively. You and Hu [19] carried out an analysis of a solar reheat-regenerative power plant from energy and exergy view point and optimized the boiler saturation temperature. Their result showed that the optimum saturation temperature in the boiler was about 201^{o}C, and the thermal efficiency and the exergetic efficiency of the system was 17.9% and 25.12% respectively. The advantages of SPAG in coal-fired power plants have been presented by Suresh *et al*. [12] using 3-Es (energy, exergy, and environment). While Suresh *et al*. [13] performed a 4-E (Energy, Exergy, Environment, and Economic) analysis by assuming operation of coal-fired power plants with Solar Aided Feed Water Heater (SAFWH) for 8 h/day in either fuel conservation or power boosting mode. They observed an instantaneous reduction of about 14–19% in coal consumption by substituting turbine bleed streams to all the feedwater heaters including deaerator with SAFWH in "fuel conservation mode". According to them, the substitution resulted in about 5–6% improvement in coal consumption and additional power generation. This paper therefore is aimed at investigating the best position to integration SAPG into a natural gas powered steam power plant in Nigeria using energy, exergy, environmental and economic analysis.

2. DESCRIPTION OF THE PLANT

Egbin power plant has a total installed power capacity of 1,320 MW with six installed units each having a capacity of generating 220 MW. It is located at Ikorodu area of Lagos State, Nigeria. The plant boilers are designed for dual firing of Natural Gas and Low /High Pour Fuel Oil (LPFO/HPFO). The plant uses natural gas. The schematic diagram of one of the 220 MW is shown in Figure 1. This unit employs regenerative feed water heating system. The feed water heating is executed in two stages of high pressure heaters (HPH6, HPH5) and three stages of Low Pressure heaters (LHP1, LPH2, LPH3) along with one deaerating heat exchanger. The boiler unit feeds dry steam to the turbine. The turbine comprises of low pressure turbine (LPT), intermediate pressure turbine (IPT) and high pressure turbine (HPT) mounted on a single shaft. The turbine exhaust is sent to the condenser, submerge in the Lagos lagoon. Then the circle starts over again.

2.1 Description of the SAPG Models

In this work, the steam bleed-off from the turbine was used to pre-heat the boiler feed water. In the SAPG, the bled-off steam was partly or totally replaced by solar heat carried by thermal oil or other heat carrier (12, 19, 23 and 24). The plant model consists of a steam turbine sub-model, condenser sub-model, feedwater heater sub-model, deaerator sub-model and boiler sub-model, and can be used to simulate different operation conditions. Then the system model can integrate with developed solar collector model. The modelled solar aided power generation system is then used to analyse the best position to site the solar input. In this plant, there are seven stages of bled off (i.e. A- G) and six feed water heaters. The deaerator C is the only open type of feed water heater. Table 1 lists the solar integration options (models) in this study. The temperatures used in the table were chosen based on the maximum temperature the stream can cope with based on literature. The plant system has been modelled and validated with the design values. Figure 2 shows bled-off points on the flow diagram where the SPAG can be integrated while Figure 3 show a typical solar collector ready for injection.

Table 1. Integration options of solar troughs.

Cases	Replacing Option	Solar Collector Maximum Temperature Output (^{o}C)
Model 1	Replacing the bled-off steam A to HPH5	300
Model 2	Replacing the bled-off steam B to HPH6	300
Model 3	Replacing the bled-off steam D and E to LPH1	200
Model 4	Integrating of Solar panels on stream 43	300

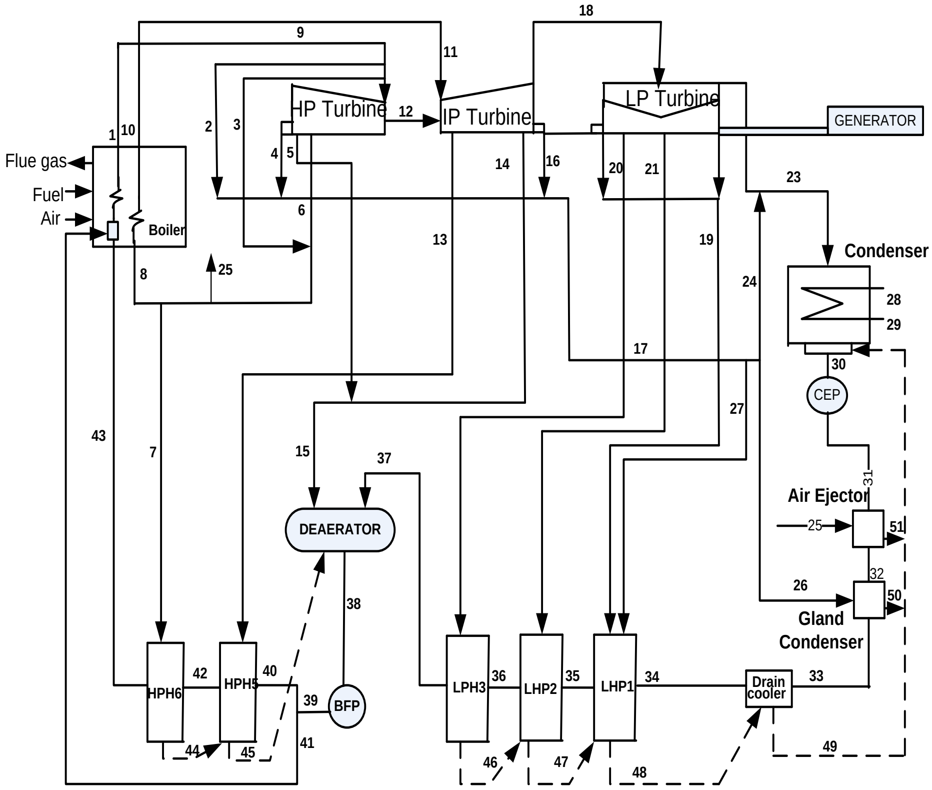

Fig. 1. Flow chart of Egbin power plant.

(Key HP Turbine = High Pressure Turbine , IP turbine = Intermediate Pressure Turbine LP Turbine = Low pressure turbine, CEP = Condensate Extraction Pump, LPH1 = Low Pressure Heater 1, LPH2 Low Pressure Heater 2, LPH3 Low Pressure Heater three, HPH 5 High Pressure Heater 5 and High Pressure Heater 6 and BFP= Boiler Feed Pump).

3. METHODOLOGY

3.1. Plant Simulation

In this study, the process operating data were employed. The plant was arranged into work modules. The inlets and outlets streams from the components in each arrangement as well as the various solar integration options properties were extracted and input into the Microsoft excel worksheet. Computer program codes were developed and written in Microsoft excel macros for the simulation.

3.2 Energy and Exergy Analysis

The following assumptions are adopted for this study:

i. The system is in a steady state flow conditions.
ii. Kinetic and potential energy are negligible.
iii. The temperature and pressure at the reference state is:

T_o=25^{o}C = 298.15 K and P_o= 101 kPa, respectively.

Each component in the plant shown in Figure 1 constitutes a control volume and the associated equations of mass balance, energy balance and exergy balance are given as [20].

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

Where: $\dot{m}$ is the mass flow rate and the subscripts i and e refer to the inlet and exit conditions, respectively. The energy balance is given as [21]:

$$\sum_i \dot{m}_i h_i + \dot{Q} = \sum_e \dot{m}_e h_e + \dot{W} \tag{2}$$

Where: $\dot{Q}$ is the heat transfer rate to the control volume, $\dot{W}$ is the work given out per unit time and h is the enthalpy. Applying the steady state equation to the control volume of the plant neglecting the potential and kinetic exergy, the exergy balance is given by:

$$\sum\left(\dot{Q}(1-\frac{T_o}{T})\right)_i+\sum(\dot{E}x)_i=\sum\left(\dot{Q}(1-\frac{T_o}{T})\right)_e \qquad (3)$$

$$+I_{total}\pm W+\sum(\dot{E}x)_e$$

Where: $\sum(\dot{E}x)_i$ – sum of all exergy of streams making up the input, $\sum(\dot{E}x)_e$ – sum of all exergy transfers making up the output, I_{total} – Total irreversibility's in the system and T is the absolute temperature and the subscripts o refers to the surface and environmental conditions. $\sum\left(\dot{Q}(1-\frac{T_o}{T})\right)_i$, $\sum\left(\dot{Q}(1-\frac{T_o}{T})\right)_e$ – Exergy related to heat transfer.

The exergy of a stream or constituent of a mixture is generally the sum of the physical and chemical exergies. The chemical exergy is generally important when dealing with a chemical process. Therefore the total exergy transfer rate, $\dot{E}x$ is given by [20]:

$$\dot{E}x=\dot{E}x_{ph}+\dot{E}x_{ch} \qquad (4)$$

Where: the subscript ph and ch represent physical and chemical respectively.

The energy and exergy performance criteria of the components of the power plant are obtained by applying both energy and exergy balance to the components and treating each of them as a control volume as presented [23].

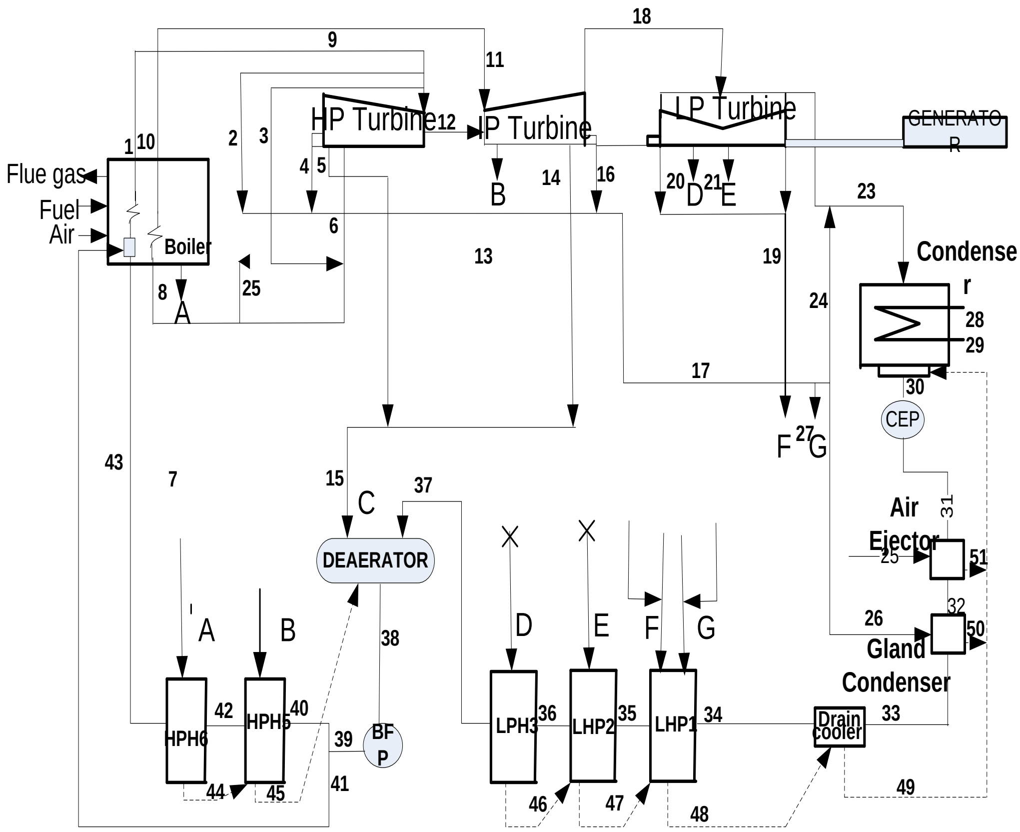

Fig. 2. Flow diagram of bled–off point for integration.

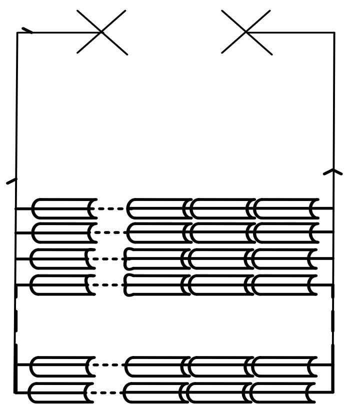

Fig. 3. Diagram of solar collectors for integration.

Energy of stream,

$$\dot{E}_j = m_j h_j \tag{5}$$

where: $\dot{E}_j$ – Energy of stream j (kg/h)
h_j – Enthalpy of stream j (kJ/kg)
$\dot{m}_j$ – Mass flow rate of stream j (kg/h)

Physical exergy of stream;

$$Ex_{ph\,j} = m_j\left[(h_j - h_o) - T_o(s_j - s_o)\right] \tag{6}$$

where: h_o is ambient enthalpy (kJ/kg), s_o, is specific ambient entropy (kJ/kgK), s_j is- specific entropy of stream (kJ/kgK). For the stream of water, the chemical exergy is zero. Therefore the exergy of the stream of water is the same as the physical exergy as given by equation (5). The mass flow rate, enthalpy, temperature and pressure values of each stream of water were obtained from the plant flow chart diagram obtained from the plant while their corresponding entropy values were determined using Water and Steam Properties for Windows (WASP) Software [24].

3.3 Evaluation of Models

1) Solar Collector Area: The estimated energy input to the solar collector was calculated from [8];

$$\dot{Q}_s = \frac{\dot{Q}_c}{\eta_c} \tag{7}$$

Where: η_c is the collector efficiency. For this study, it was assumed that the parabolic trough being used as the solar thermal energy collector has a collection efficiency of 60% [23], [24]. Q_c is the energy output of the solar collector field (MW_{th}) given as [13]:

$$\dot{Q}_c = \dot{m}\Delta h \tag{8}$$

Where: $\dot{m}$ is the mass flow rate of the feed water (kg/s), and Δh is the specific enthalpy gain of the feed water across the feed water heater (kJ/kg).

Hence, the solar collector area (A_c) required transferring the energy output as calculated from [12], [13]:

$$A_c = \frac{Q_c}{S_d \eta_c} \tag{9}$$

Where: S_d is the direct irradiation in W/m^2.

2) Energy and Exergy Efficiency: The unit heat consumption rate needed in the boiler per kWh electricity generated was estimated from;

$$q = \frac{Q}{w} \tag{10}$$

Where: Q is the total heat load in the boiler per hour, kJ and W is the electrical output of the plant, kWh.

The performance of steam power plants with SAPG was evaluated in terms of plant energy and exergy efficiencies. The equations used to determine plant efficiencies are as follows:

$$Energy\,(Thermal)\,Efficiency, \eta = \frac{Net\,electricity\,output}{m_f \times LHV} \tag{11}$$

Where: $\dot{m}_f$ is the mass flow rate of fuel and LHV is the lower heating value of the fuel.

$$Exergy\,Efficiecny, \varepsilon = \frac{Net\,electricity\,output}{m_f \times Specific\,exergy\,of\ fuel} \tag{12}$$

3) Environmental parameters: Steam power plants release some pollutants like CO_2, CO, SO_x, NO_x, and some trace hydrocarbons into the atmosphere which could be obnoxious and negatively affect the environment. The CO_2 emissions from combusted fuel are evaluated based on Intergovernmental Panel on Climate Change (IPCC) guideline [25]. The IPCC established Carbon Emission Factor (CEF) values which is used for the carbon content of fuel used for combustion purpose. The energy inputs per unit operation were converted into Joule using appropriate conversion factor. The fraction oxidised is used to take into account the carbon content which is not oxidised. In this study, the CO_2 emissions generated from the fuel used are determined based on IPCC emission factors for natural gas (15.3 kgC/GJ). The carbon emission (CE_{fuel}) due to fuel (natural gas) consumed by the power plant is thus evaluated as [26]:

$$CE_{fuel} = 3.67 \times FC \times CEF \times FO \tag{13}$$

Where: FC is the fuel consumed and FO is the fraction oxidised.

The specific CO_2 emission (kg of CO_2/kWh) was calculated to determine the impact of solar thermal aided steam power plants for the four models on the environment. Other pollutants were considered negligible when compared to the amount of CO_2 generated.

4) Economic Analysis: The annualized cost of electricity generation (ACoE) and levelized cost of electricity generation (LCoE) were used as economic indicator. The procedure used to calculate ACoE was modified to make up for the escalation of annual fuel and operation and maintenance cost using a levelizing factor. The steps involved in the calculation of ACoE and LCoE ($/kWh) are listed as [13]; the first cost is the total cost of the equipment.

a. Auxiliary Consumption (AC) = 10% of generation (14)

b. $$Total\ energy\ generated\ annually\ (P_{net})\ kWh/kW = 8000 \times PVF \times (1 - AC) \tag{15}$$

Where: PVF is the present value factor. In the discounting equation it is expressed as $(1+i)^{-n}$

c. $$Fixed\,Cost\,Capital\ (FCC) = \frac{ACC}{P_{net}} \quad (16)$$

Where: ACC is given as; ACC=CC×CRF and CC is the capital cost.

d. $$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (17)$$

Where: n is the life of the power plant and i is the interest rate.

e. $$Fixed\,O\,\&\,M\ Cost\ (FOM) = 2.5\%\ of\ PEC \quad (18)$$

Where: PEC is the purchase equipment cost.

f. $$Fixed\,O\,\&\,M\ cost\ per\ unit\ (CFOM) = \frac{FOM}{P_{net}} \quad (19)$$

Variable O&M Cost per unit (C_{VOM})=$0.0018/kWh

g. $$FuelCostperUnit(CC_F),\$/kWh = \frac{C_F \times LHV}{HR} \quad (20)$$

h. $$Total\ variable\ cost\ per\ unit\ \ (C_v),\$/kWh = CC_f + C_{VOM} \quad (21)$$

i. $$\text{Annualized Cost of Electricity(ACoE)} = \text{FCC} + \text{CFOM} + \text{C}_\text{v} \quad (22)$$

j. Escalation rate e =10%

k. Equivalent interest rate with escalation

$$d = \frac{i-e}{i+e} \quad (23)$$

l. Levelizing Factor (LF), ($/kW)

$$LF = \left[\frac{(1+d)^n - 1}{d(1+d)^n}\right]\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (24)$$

m. Levelizing Fuel and O&M Cost (C_L), $/kWh

$$= LF \times (CFOM + C_V) \quad (25)$$

n. $$Levelizing\ Cost\ of\ Electricity\ generation\ (LCoE), (\$/kWh) = FCC + C_L \quad (26)$$

The payback period is the length of time taken to recover the money spent on an investment. It was calculated as [22]:

$$\text{Payback Period} = \frac{Fixed\ capital\ cost}{cost\ saving\ achieved} \quad (27)$$

Table 2. Energy and exergy of streams of Egbin power plant.

Stream	Flow (kg/s)	T (^{o}C)	P (kPa)	Energy (kJ/s)	Exergy (kJ/s)
1	179.86	541	12913	619444.4	268087.8
2	0.11	538	12500	371.13	159.94
3	0.35	538	12500	1192.79	514.04
4	0.49	351.9	3343	1524.42	551.78
5	1.02	351.9	3343	3179.49	1150.86
6	174.81	351.9	3343	544444.4	197078.3
7	13.97	352.2	3209	43533.19	15683.17
8	161.03	351.2	3289	502777.8	180286.8
9	179.86	538	12500	619444.4	266915.1
10	161.03	541	3129	572222.2	219896.2
11	161.03	538	3076	569444.4	218876.9
12	3.09	469.1	3343	10437.19	3928.97
13	8.32	437	1539	27744.59	9493.4
14	6.28	332.2	694.1	19625.79	5775.42
15	7.3	333	794.1	22805	6841.82
16	0.3	332.2	694.1	619444.4	276.33
18	149.23	332.2	694.1	466666.7	137327.5
19	9.65	105.7	76.49	25962.58	4327.62
20	6.2	257.1	365.4	18487.17	4690.27
21	5.82	180.1	174.2	16481.28	3501.29
22	127.55	105.7	123.8	305555.6	14396.51
23	127.84	106.2	29.4	308333.3	14710.37
24	0.29	345.7	495.1	912.43	256.76
25	0.15	352.2	3201.4	467.28	168.34
26	0.26	345.7	495.1	833.47	234.54
27	0.34	345.7	446.1	1089.12	301.74
28	9072.22	30	4.2	1138889	796.86

29	9072.22	32.6	4.9	1238889	2847.59
30	150.27	42.1	8.24	26478.26	281.11
31	150.27	42.1	9	26478.41	281.26
32	150.27	42.62	9	619444.4	295.05
33	150.27	43.7	9	27575.26	334.18
34	150.27	69.18	30	43490.77	1845.15
35	150.27	86.7	71.88	54609.53	3608.8
36	150.27	110	163.7	69396.48	6580.9
37	150.27	134.2	343.4	84829.61	10279.82
38	179.86	163	666.4	123817.2	18908.58
39	179.86	165.5	709.5	127198.6	19962.63
40	174.31	165.5	709.5	123269.7	19346.02
41	5.56	165.5	709.5	3928.89	616.6
42	174.31	196.6	1447	146888.2	27581.6
43	174.31	236.6	3209	178368	40128.88
44	13.97	202.6	1641.7	12082.3	2326.06
45	22.29	171.5	821.2	16181.52	2611.83
46	6.2	118	186.3	10279.82	315.12
47	12.02	94.7	83.6	619444.4	352.46
48	22.02	90.7	72	20696.97	2804.91
49	22.02	51.7	13.4	4766.91	104.65
50	0.26	99.1	495.1	109.61	8.84
51	0.15	99.1	3201.4	62.61	5.42

Table 3. Area and cost implication of the models.

	Model 1	Model 2	Model 3	Model 4
Solar irradiation (W/m^2)	900	900	900	900
Collector efficiency (%)	0.6	0.6	0.6	0.6
Required Area (m^2)	203,928	342,857	260,901	172,800
Cost (US$)	40,785,608	68,571,382	52,180,289	34,560,063

Table 4. Thermodynamics property of the models.

Parameters	Base Case	Model 1	Model 2	Mode1 3	Model 4
Fuel rate (kg/s)	11.9	10.6	9.8	11.4	10.6
Unit heat rate (kJ/kWh)	9,406.20	8,334.00	7,730.60	8,972.60	8,334.00
Quantity of heat supplied to boiler (kWh)	505.8	448.2	415.7	482.5	448.2

4. RESULT AND DISCUSSION

In Table 2, the temperature, pressure, mass flow rate, enthalpy, entropy exergy and energy are presented according to their stream numbers as specified in Figure 2. Each node is treated as a stream entering or leaving a control volume, and their respective properties are used to calculate the energy and exergy values.

4.1. Simulation Result

The result of integrating solar in steam power plant, with Model 1, Model 2, Model 3 and Model 4 is presented in Table 3. It showed that with an average direct solar irradiation of 900 W/m^2 at the plant location, a parabolic solar trough efficiency of 60% was observed. Model 2 conspicuously required the highest area due to relatively large temperature difference across the parabolic solar trough.

4.2 Effect of Integrating Solar into Steam Power Plant

1) Thermodynamic Variation: The mass flow rate, unit heat rate and quantity of heat supplied to the boiler of steam power plant result are presented in Table 4. It was observed that the lowest fuel flow rates, unit heat rates and the quantity of heat supplied by the boiler occurred on Model 2. This may be due to the high temperature and pressure gained in the incorporation of the parabolic solar troughs.

2) Thermal and Exergetic Efficiencies: The thermal efficiency and exergetic efficiency of the models are presented in Figures 4 and 5, respectively. From Figure 4, it is obvious that the model with the best cycle efficiency was Model 2 with a value of 46.6% efficiency against the base cases of 38.2%, this shows a significant improvement. This is as a result of the high temperature and pressure of the bleed-off used.

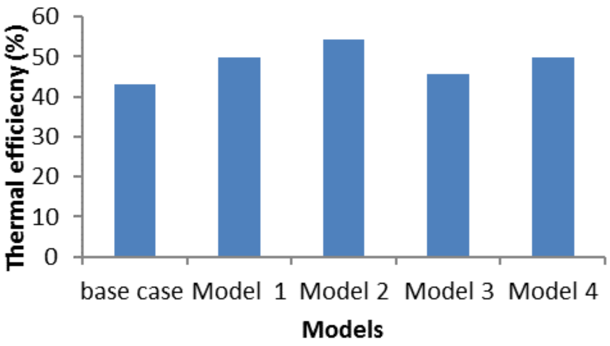

Fig. 4. Thermal efficiency of the models.

Figure 5 presents the exergetic efficiency of the models. The highest exergetic efficiency occur on the Model 2 with a value of 44.7% as against 36.7% recorded on the base case (Figure 5). This is as a result of the high exergy associated with the bled-off stream incorporated.

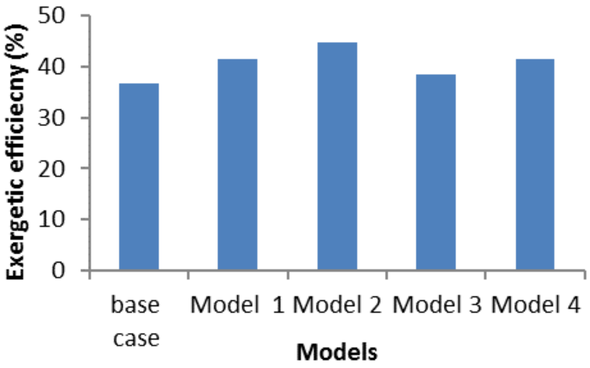

Fig. 5. Exergetic efficiency of the models.

3) Environmental Effect and Fuel Economy: The models specific CO_2 emission and specific fuel consumption is presented in Figure 6. The specific CO_2 emission for base case, Model 1, Model 2, Model 3 and Model 4 are 1.2, 1.17, 1.16, 1.19 and 1.17 kg/kWh, respectively, while the specific fuel consumption of the models are 1.16, 1.03, 0.95, 1.11 and 1.03 kg/kWh, respectively. The highest emission and specific CO_2 emission was observed on the base case while Model 3 has the lowest value. This figure shows the relationship between fuel consumption and CO_2 emission. It was observed that the solar thermal aided plant resulted in a significant reduction in fuel consumption as well as a lower emission in all the models considered. The specific fuel consumption and CO_2 emission of Model 2, is 0.16 kg/kWh and 0.96 kg/kWh, respectively gave the best option in terms of specific fuel consumption and CO_2 emission. Chakraborty *et al*. [27] studied power plants in India, and reported that the specific fuel emission of power plant ranges between 0.776 – 0.8241 kg/kWh and 0.37 - 1.49 kg/kWh for a capacity of 20-60 MW and 210-250 MW, respectively.

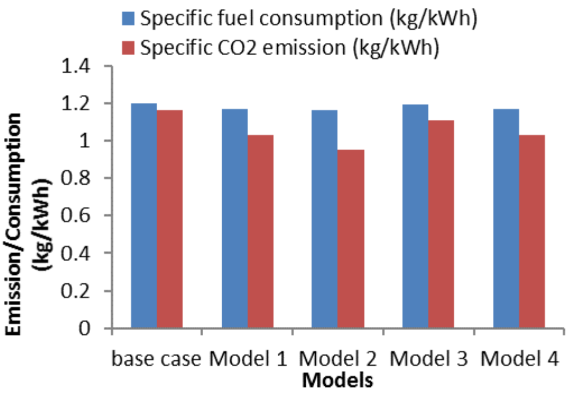

Fig. 6. Models specific fuel and CO_2 emission.

The annual fuel consumption saved in the models is presented in Figure 7. The annual plant consumption of the base case was found to be 342.72×10^6 kg.While the result of the fuel consumption saved for Model 1, Model 2, Model 3 and Model 4 are 3,174,849, 4,941,306, 1,305,681 and 3,174,849 kg respectively. As it can be seen, Model 2 has the highest annual consumption saved, which implies Model 2 is better choice for our environment.

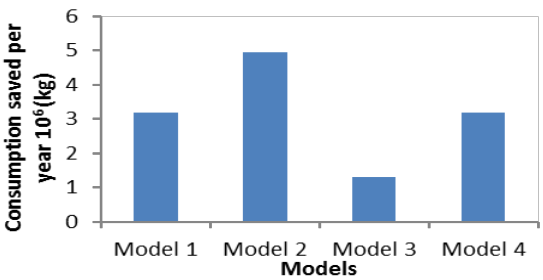

Fig. 7. Annual fuel consumption saved by models.

4) Economic Effect: The result of the economic analysis of the solar integration in the plant is presented in Table 4. The total levelised cost of solar aided for each of the Model 1, Model 2, Model 3 and Model 4 was \$185.40/kW, \$311.7/kW, \$237.2/kW and \$157.1/kW respectively. Also the annualized capital cost for Model 1, Model 2, Model 3 and Model 4 was found to be about \$4,493,271.81, \$7,554,376.95, \$5,748,601.8 and \$3,807,415.5 respectively. From the table it was observed that the levelized cost of electricity generation (LCoE) for the Model 1, Model 2, Model 3 and Model 4 were \$1,238.39/kWh, \$1,710.78/kWh, \$1,432.11/kWh and \$1,132.54/kWh respectively, while the payback period (PP) for Model 1, Model 2, Model 3 and Model 4 were 1.06, 0.77, 0.92 and 1.16 years respectively. The LCoE with the best option is Model 2 with a value of \$1,710.78/kWh. The payback period also corroborated what the LCoE pointing to the fact that Model 2 has the lowest payback period with a value of 0.77 years. Conclusively, solar assistance of the models has no doubt appears cost effective based on the cost of energy and payback period, the cost of CO_2 avoided is far higher than the cost associated with the environmental pollution in most advanced country of the world. Therefore, the cost of fuel saved which indicates the cost effectiveness of additional investment of the solar aided model were determined to be \$2.80/kg, \$5.22/kg, \$3.79/kg and \$2.26/kg for: Model 1, Model 2, Model 3 and Model 4 respectively. Therefore, the best Model option that can be adopted was found to be Model 2. The cost of fuel saved was observed to be about 65 times the cost of purchased fuel \$0.085/kg as well as the ease of incorporating the solar thermal.

Table 5. Economic analysis of solar integration.

Parameters	Base Case	Model 1	Model 2	Model 3	Model 4
Collector Area (m^2)	-	203,928	342,857	260,901	172, 800
Cost of Solar (CC) (\$)	32,049,451	40,785,608	68,571,382	52,180,289	34,560,063
Total levelised cost (TLC) \$/KW	145.68	185.39	311.69	237.18	157.09
Life of plant (year)	25	25	25	25	25
Interest rate (i)	0.1	0.1	0.1	0.1	0.1
capital recovery factor (CRF)	0.11	0.11	0.11	0.11	0.11
Annualized capital cost (ACC)	3,530,826	4,493,272	7,554,377	5,748,602	3,807,415
Plant capacity factor	0.9	0.9	0.9	0.9	0.9
Auxiliary consumption	0.1	0.1	0.1	0.1	0.1
Net energy generated annually (Pnet) (kWh/kW)	6,480	6,480	6,480	6,480	6,480
Fixed capital cost (FCC)(\$/kWh)	544.88	1,238.29	1,710.68	1,432.01	1,132.44
Fixed O&M cost (FOM) \$/kW	-	4.63	7.79	5.93	3.93
Fixed O&M cost per unit (CFOM) \$/kW (Assumed 2.5%)	-	0.0007	0.0012	0.0009	0.0006
Fuel cost (FC) (\$)	0.08	0.08	0.08	0.08	0.08
Heating value of fuel (LHV) (kJ/kg)	48,098.70	48,098.70	48,098.70	48,098.70	48,098.70
Heat rate (net) (HR) (kJ/kWh)	-	8,334.00	7,730.60	8,972.60	8,334.00
Fuel cost per unit (CF) (\$/kWh)	-	0.01	0.01	0.01	0.01
O&M cost per unit—variable (CVOM) (\$/kWh)	0.002	0.002	0.002	0.002	0.002
Total variable cost per unit (CV) (\$/kWh)	0.002	0.082	0.082	0.082	0.082
Annualized cost of electricity generation (ACoE)(\$/kWh)	-	1,238.37	1,710.76	1,432.09	1,132.53
Escalation rate (fuel/O&M—fixed&variable)	0.019	0.019	0.019	0.019	0.019
Equivalent discount rate with escalation (d′)	0.079	0.079	0.079	0.079	0.079
Levelizing factor (LF)	1.186	1.186	1.186	1.186	1.186
Levelized fuel and O&M cost (CL) (\$/KWh)	165.2	0.1	0.1	0.1	0.1
Levelized cost of electricity generation (LCoE) (\$/kWh)	-	1,238.38	1,710.78	1,432.11	1,132.54
Mass flow rate of fuel (kg/h)	12	10.6	9.8	11.4	10.6
Annual Cost of Fuel (\$/kWh)	27,571,200	17,516,617	17,515,972	17,517,299	17,516,617
Cost of Fuel saved per annum (\$)	-	10,054,583	10,055,228	10,053,901	10,054,583
Payback Period (PBP) (years)	--	1.06	0.77	0.92	1.16
Cost of saved fuel (\$/kg)	-	2.8	5.22	3.79	2.26

5. CONCLUSION

The effects of integrating different models of solar aided power generation (SAPG) into a steam power plant has been clearly investigated and evaluated considering their performance in terms of energy, exergy, environmental and economic viability. The four models showed better performance than the base case. However, Model 2 (Replacing the bled-off steam B to HPH6) was found to give better results, this paper also reveals that regardless the level and type of integration, it is better than the base case. Basically, this paper further reiterates the advantages of SAPG integration into conventional power generation systems.

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