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Improvement of Electric Power Supply to Port Harcourt Refining Company, Rivers State, Nigeria

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Abstract— The study presents an improvement to electric power supply to Port Harcourt Refining Company, Rivers State, Nigeria. A combined Gas-Steam Turbine Power Supply System was proposed and modelled based on typical Rankine and Brayton Cycles used in the operation of gas and steam turbines respectively. MATLAB / SIMULINK, was used to model the gas turbine cycle and the steam turbine cycle with their respective governors to generate data for the analysis within a simulated environment, using tools from the SimPower Systems Toolbox. The model was used to determine the ideal and actual turbine powers, turbine isentropic efficiency and exergy calculation. The performance analysis indicated a linear response with graded increase in MW output power of the turbine for a corresponding increase in ambient temperature. The analysis also showed that the exergy destroyed due to rise in ambient temperature at a specified base inlet temperature of 100^{o}C (373K) decreases for every increase in ambient temperature. The sensitivity analysis indicated reduction in output power with increase in inlet temperature while the exergy destroyed for sensitivity analysis on the other hand exhibited a random fluctuation with several peaks indicating a tendency to increase. At implementation, 2 x 30MW Gas turbine generating plant (Rankine Cycle) was install to run in parallel with the existing 4 x l4MW Steam turbine generating plant (Brayton Cycle). The power generated by the turbines is able to meet the energy demand of the facility as well as its environs.

Index Terms— Demand Energy, Gas-Steam Turbine Power, Rankine and Braxton Cycle, Exergy, Power Generation Expension.

1 Introduction

Since the discovery of electricity in the 18th century and its eventual realization in the 19th century, the need for reliable, cheap, and affordable electricity is still continuously sought through the complete structure of the electric power system[1]. History has it that in many other developing countries just as in Nigeria, large industrial sites resolved to providing power by the use of their own generation units; mainly because of they are located in isolated places, as new industrial sites or due to unreliable power supply by local utility to support their regular production [2]. The foregoing is mostly in the case of energy-intensive industries like refineries or production plants in the Oil & Gas sector, cement plants, brewing plants etc.

In Port Harcourt Refining Company (PHRC), Rivers State, Nigeria today, there is presently insufficient, unstable, ineffective, and unreliable power supply. The power supplied in megawatts is far below the power (energy) demand of the facility; this has led to seeking possible ways for improvement of power supply to the facility. The steam turbine owned and used by the organisation for power generation operates below capacity and cannot generate the present required power of the organisation even when assumed to operate at full capacity. Therefore a generation expansion is envisaged to improve the electric power supply to the facility.

The economic cost in terms of capital as well as the high reliability and flexibility in operation of power generation by gas turbine has made it attractive and a regular option for independent power plant (IPP) project [3]. Another reason is its outstanding ability to quick starting and the use of a wide variety of fuel from natural gas to residual oil or powdered cost [4], [5], [6] & [7]. Due to better materials being made available and with the use of adequate blade cooling, the inlet gas temperature to gas turbine (GT) bladders can now exceed 1200°C as a result of which the overall efficiency of a GT plant can be about 35 percent, almost the same as that of a conventional steam power plant [8]. The gas turbine is widely employed to drive auxiliaries like compressor, blowers and pumps [9].

2 Related Works

Many researchers have investigated the potentials of Gas Tuturbine as a reliable electric energy source for industrial purpose [10], [11], [12]. Subtransmission system expansion planning with distributed generations considering natural gas transmission constraints was presented in [13]. The evaluation and comparative potential of gas turbines as alternative energy production systems was considered in [14]. Analysis in terms of cost and effectiveness of gas turbine systems proved that such systems when implemented are reliable and cost effective [15], [16], [17]. Works relating to risk management, risk avoidance are useful for power systems planning and operation [18], [19], [20], [21]. This work presents possible improvement to an existing power generation scheme that uses steam turbines via the introduction of gas turbine working in parallel with the steam turbine. Similar works on ways to improve the performace of steam turbines are presented in [22], [23], [24], [25], [26] [27]. The thermal performance of these turbine power plants based on exergy analysis using numerical tehniques and software simulation is being reviewed and explored in the papers; gaining wider readership .

3 Methodology

For simplicity, let us consider a modern gas turbine burning natural gas whose exhaust gases are to raise steam, which is then used drive a suitable turbine which drives an alternator. The relevant data for the gas turbine is given in Table 3.2, if the fuel gas has a calorific value of 48 MJ/kg; the fuel-to electricity efficiency of the gas turbine is about 33%.

Table 1
Basic Parameters for the Gas Turbine of the Combined Cycle Plant

S/N	ITEM	Unit of Measurement
1.	Gas Intel temperature to turbine	1060^0C
2.	Pressure ratio	10.7
3.	Mass flow of fuel/gas	495kg/s
4.	Mass flow of fuel/gas	9.2kg/s
5.	Gas outlet temperature from turbine	533^0C
6.	Electrical power output	144MW

3.1. Single Pressure Cycle

Assuming c, of the exhaust gases from the gas turbine to be 1.114 KJ/Kg k and that the gases are cooled to 107°c (to give a sufficient working margin above dev point temperature), the allowable temperature drop of the exhaust gases is (553-107) or 446 k, and the rate of heat transfer from the exhaust gases to the steam generation.

$$Q_1 = Wc_p\ (T_1 - T_2) = 495 + 9.2) \times 1.114 \times 446 = 251kw \quad (3.1)$$

Assuming a temperature approach (at pinch point) as 20k, the temperature of the emerging steam at point 1 is thus limited to 553-20 = 533°c. The problem then is to estimate the largest pressure and mass flow rate of steam which gives a sufficiently large temperature approach; say at the point x = 5; therefore

$$Ws\ (h_1 - h_4) = W_g\ {}^c p_g\ (T_d - T_a) \quad (3.2)$$

$$Ws\ (h_5 - h_4) = W_g\ {}^c p_g\ (T_x - T_a) \quad (3.3)$$

By trial-and-error estimation from the above two (3.2) and (3.3) and from steam properties we find T_1 = 522°c. The feed water temperature, T_4 = 38 °c, which shows that at a pressure as low as 5 bar the temperature approach, $T_x - T_5$, is less than 20 k and the corresponding mass flow rate of steam is 74 kg/s.

3.2. Dual Pressure Cycle

The HP and LP steam are to be calculated by trial-and-error as before but with added complexity. Employing regenerative feed heating, the steam conditions yielded are: 6.5 bar, 200°c and a flow of about 13.5kg/s for the LP boiler and 80 bar, 520°c and flow of about 66kg/s for the HP boiler.

Assuming a condenser pressure of 0.068 bars; the specific enthalpy drops in the HP and LP turbine are 670 and 570 kJ/kg, respectively. Therefore, the steam turbine power output

$$W_{st} = (13.5 + 66) \times 579 + 66 \times 670 \quad (3.4)$$
$$= 45.3 + 44.2 = 89.5\ MW$$

Thus we have approximately equal power from both LP and HP stages and sufficient for an alternator output of 85 MW, since the heat input to steam plant from the gas turbine exhaust gases has been shown to be 251 MW, the thermal efficiency of the steam cycle is thus 89.5/251 = 0.357 or 35.7%. Since the power output of the gas turbine was about 144 MW, the output from the combined plant is about 144 + 85 = 219 MW electrical. If the calorific failure of fuel is about 48 MJ/kg and the mass flow of fuel consumption is 9.2 kg/s. the fuel-to-electricity efficiency of the combined plant is 219/(9.2 x 48) = 0.4969 or 49.69%.

3.3. Analysis of Gas Turbine Plant

The analysis of Brayton cycle provides the following:

Heat supplied, $Q_1 = m_a\ c_p\ (T_3 - T_2)$ (3.5)

Heat rejected, $Q_2 = m_a\ c_p\ (T_4 - T_1)$ (3.6)

$T_{2s}/T_1 = T_3/T_{4s} = [P_2/P_1)\ 1)\ (y-1)y = r_p\ (y-1)/y$ (3.7)

Where m_a = mass of air and r is the pressure ratio, P_2/P_1.

The compressor efficiency:

$$n_c = (T_{2s} - T_1)/(T_2 - T_1) \quad (3.8)$$

and the turbine isentropic efficiency:

$$n_T = (T_3 - T_4)/(T_3 - T_4) \quad (3.9)$$

For the ideal cycle I – 2s - 3 - 4s -1,

$$n_{\ cycle} = 1/(r_p{}^{(y-1)/y}) \quad (3.10)$$

$$= 1 - (T_1/T_{4s}).\ r_p\ (y-1)/y \quad (3.11)$$

As r_p increases, $n_{\ cycle}$ increases till Carnot cycle is reached

$$(r_p)max = (T_3/T_1]^{1/2}\ \ (T_{max}/T_{min})^{1/2} \quad (3.12)$$

There is a particular value of r when w, i.e. $W_T - W_C$ becomes maximum:

$$W_{net} = Q_1 - Q_2 = W_T - W_C = m_a\ {}^c p\ [T_3 - T_{2s} - + T_1)W_{net} \quad (3.13)$$

Substituting T_{2s} and T_{4s} in terms ${}^r p$ Equation (3.7) and since $T_3 = (T_{max})$ and $T_1 = (T_{min})$ are fixed on differentiation of W_{net} with respect to ${}^r p$ and making ${}^{dw}{}_{net}/{}^{dr}p$ equal to zero, we get;

$$({}^r p)opt = (T_{max}/T_{min})^{r2(y-1)} \quad (3.14)$$

$$({}^r p)opt = [({}^r p)_{max}]^{1/2} \quad (3.15)$$

On substitution in Equation (3.9);

$$W_{net} = m_a\ {}^c p\ [(T_{max})^{1/2} - (Tmin)^{1/2}]^2 \quad (3.16)$$

$$\text{and } n_{max}\ \text{power} = 1 - [Tmin/Tmax]^{1/2} \quad (3.17)$$

If the compressor and turbine efficiencies are considered;

$$({}^r p)_{out} = (\eta_c \eta_{r\ T} \underline{T}_3/\underline{T}_1]\ \ y/2(y-1) \quad (3.18)$$

And $$(r_p)_{max} = \frac{T_3 T_1}{I + [\{(T_3/T_1) - 1\{1/(\eta_c \eta_T) — 1\}]^{1/2}} \quad (3.19)$$

The work ratio r is defined as the ratio of net work to work done in turbine, i.e.

$$r_w = W_{net}/W_T \ (W_T - W_c)W_T = 1 - (T_1/T_3) r_p^{(y-1)/y} \quad (3.20)$$

4 Results and Discussion

In using the results of simulations from the MATLAB/SIMULINK environment and the results of performance using proposed modelling approach. While all simulations have been interpreted in terms of the power generated and the rate of exergy destroyed. Implementation of the results at the site is also reported.

4.1 Gas Turbine Simulation Results

The gas turbine model is simulated using the developed model to determine the power output; the input parameters are provided in the Appendix. The system is as shown in Figure 1.

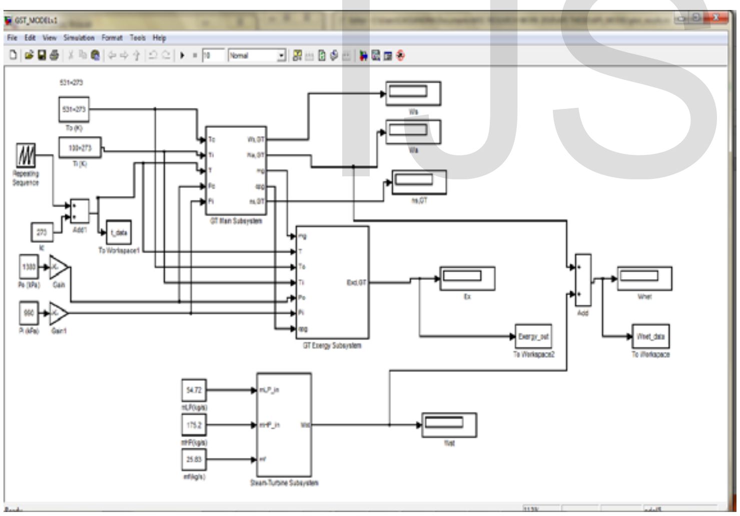

Figure 1: Combined Steam-Gas Turbine Plant Model

Simulations (performance and sensitivity analysis) are performed to determine the effect of ambient temperature and gas turbine inlet temperatures on the combined cycle turbine output

4.2. Performance Analysis with Varying Ambient Temperature for a Fixed Inlet Temperature

This analysis the ambient conditions were set to a range of between 20℃ (293K) and 40℃ (313K) spaced at 5℃ interval while the gas turbine inlet temperature was fixed at 100℃ (373K). Figure 2 shows a line plot of varying values of ambient temperatures with respect to turbine power generated and at a specified gas turbine inlet temperature of 100℃ (373K); this indicates a linear response of the model i.e. there is a graded increase in MW output power of turbine for a corresponding increase in ambient temperature.

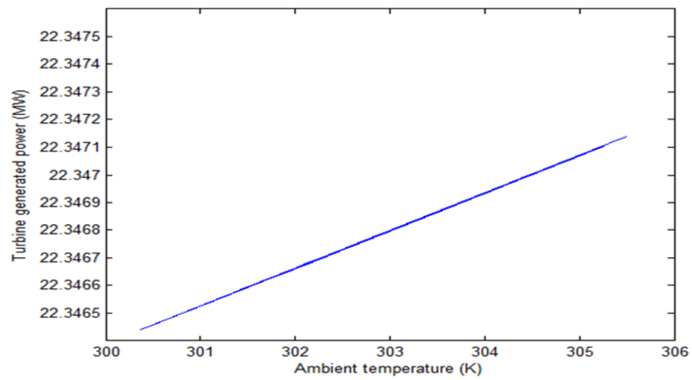

Figure 2: Graphical Presentation of Generated Power from Gas-Turbine Plant for a Range of Ambient Temperatures

The exergy destroyed due to ambient temperature rise and at the specified base inlet temperature of 100℃ (373K) is as shown in Figure 3. The graph shows that exergy destroyed will decrease for every increase in ambient temperature.

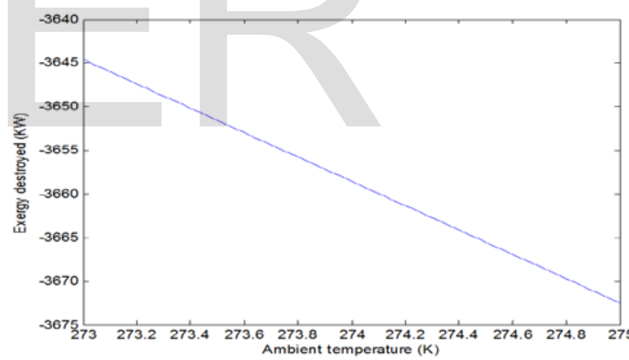

Figure 3: Graphical Presentation of Destroyed Exergy for a Range of Ambient Temperatures

4.2 Sensitivity Analysis by Varying Turbine Inlet Temperature

The gas turbine inlet temperature was adjusted slightly in steps of 20℃ from 100℃ (373K) to 160℃ (433K) and the model simulated. The same ambient conditions were used but with the ambient temperature modeled as a random source block with a mean of 30℃ and unit variance. The turbine generated power and destroyed exergies response were simulated for a hundred data points and are as shown in Figures 4 and Figure 5 respectively. The plot in Figure 4 indicates a reduced power output with increase in inlet temperatures. The exergies destroyed on the other hand exhibited a random fluctuation with several peaks at around 20th, 30th and 90th points indicating a tendency to increase (see Figure 5).

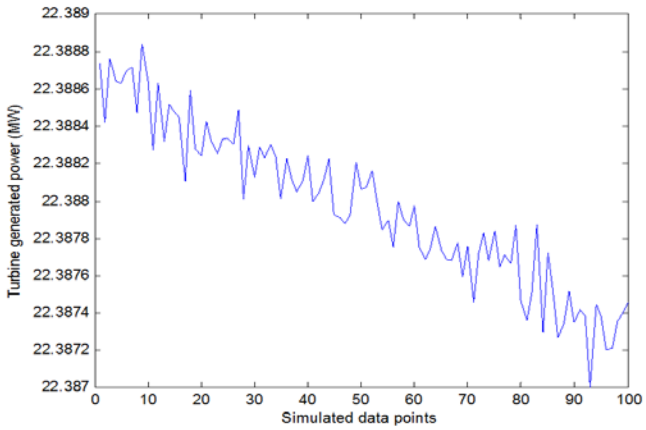

Figure 4: Graphical Presentation of Generated Power of Gas-Turbine Plant for Varying Amounts of Inlet Temperatures for 100 Data Points

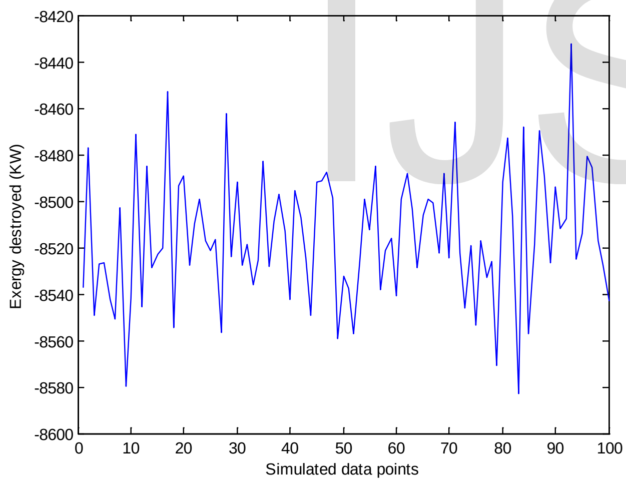

Figure 5: Graphical Presentations of Destroyed Exergies of Gas-Turbine Plant for Varying Amounts of Inlet Temperatures 100 Data Points

4.3 Implications of Study

The project involves the procurement and installation of two (2) natural gas turbine driven power generating sets (30MW, 50Hz site rating each) required to provide the electric power requirement of PHRC Process Plants, PPMC Truck loading and Jetty Site.

The total PHRC complex power demand can be met by running the generating set in synchronous mode while the other will be on spinning spare or standby. The scope of supply and installation shall include Engineering, Procurement and Construction and Installation of the followings:

1. Two (2) sets of AC Electric Power Generator sets, each comprising of:

- Alternator
- Exciter
- Automatic/Manual voltage regulator (panel mounted as part of the Gas Turbine control panel).
- Single shaft gas Turbine with turning gear and compressor cleaning system. Diesel starter system. Fuel gas filter and gas regulating system.
- Temperature, pressure, speed and vibration monitoring systems.
- Acoustic enclosure, gas/fire detection system, instrumentation including local instrument panels. Gas control panels, common base plate for turbine, gear and electric power generator.
- Fuel gas treatment system including fuel gas scrubber
- Testing, painting, installation operating and maintenance manuals

2. Two (2) sets of waste heat boilers.

3. Operating spare parts, commissioning spares, special tools and capital spares comprising of one spare set of coupling, generator rotor, gear rotors, compressor/ turbine rotor !stator assemblies each.

4. Interconnecting piping, station control panel, Generator switch-gear, auxiliary switch gear.

5. Applicable codes / standards: API 616, 614, 671, 613 and ISO 2314

5 Conclusion

It can be seen from this dissertation, that it is important for Port Harcourt Refining Company (PHRC) Management to install 2 new gas turbines of 30MW each. This is expected to boost power plant capacity and reliability for sustained plant operations while reducing steam demand for power generation.

The use of Gas Turbine for generation of electricity is most economical and technically viable; this is because it is cost friendly as far as cost generation is concerned. It is more reliable.

The project is estimated to cost $60.00 million which shall include Business Plan with a provision of $17.24 million Capital Budget.

The government and other private agencies should encourage the building of Gas Turbine for generation of electricity nation-wide; this would also rapidly increase the installed electricity generation capacity of the country and put less pressure on the national grid.

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Table 2
Project Economic Evaluation for Construction of 2 X 30MW Gas Turbines

Year No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Total Investment N' Million)	(8,700.00)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$'m	60,00															
N'm	0.00															
Profit before Tax & Deprecia-tion		3,959.96	4,197.56	4,428.43	4,649.85	4,882.34 `	5,126.46	5,382.78	5,651.92	5,934.52	6,542.81	6,869.95	7,213.44	7,213.44	7,574.12	7,952.82
Escalation Factor (12%)	1.065	1.06	1.055	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05`	1.05	1.05
Depreciation (Linear) Inv/life)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)	(580.00)
Maintenance cost (10% of Inv.)		870.00	922.20	972.92	1,021.57	1,072.65	1,126.28	1,182.59	1,241.72	1,303.81	1,369.00	1,437.45	1,509.32	1,584.79	1,664.03	1,747.23
Profit before Tax	0.00	2,509.96	2,695.36	2,875.51	3,048.28	3,229.70	3,420.18	3,620.19	3,830.20	4,050.71	4,282.25	4,525.36	4,780.63	5,048.66	5,330.09	5,625.60
Taxes (35%)	0.00	878.49	943.38	1,006.43	1,066.90	1,130.39	1,197.06	1,267.07	1,340.57	1,417.75	1,498.79	1,583.88	1,673.22	1,767.03	1,865.53	1,968.96
Net Profit	0.00	1,631.48	1,751.99	1,869.08	1,981.38	2,099.30	2,223.12	2,353.12	2,489.63	2,632.96	2,783.46	2,941.48	3,107.41	3,281.63	3,464.56	3,656.64
Net Cash Flow	(9,280.00)	1,929.96	2,115.36	2,295.51	2,468.28	2,649.70	2,840.18	3,040.19	3.250.20	3,470.71	3,702.25	3,945.36	4,200.63	4,468.66	4,750.09	5,045.60
NPV:																
Discounted @ 10%	(9,280.00)	1.754.51	1,748.23	1,724.65	1.685.87	1,645.25	1,603.21	1,560.10	1,516.24	1,471.92	1,427.38	1,382.82	1,338.45	1,294.41	1,250.85	1,207.88
Total	13,331.77															
Discounted @ 15%	(9,280.00)	1,678.23	1,599.52	1,509.33	1,411.25	1,317.37	1,142.92	1,142.92	1.062.50	986.59	915.14	848.03	785.13	726.28	671.32	620.08
Total	7,221.57															
Discounted @ 20%	(9,280.00)	1,608.30	1,469.83	1,328.42	1,190.34	1,064.85	848.46	848.46	755.89	627.65	597.93	531.00	471.13	417.13	369.97	327.49
Total	3,324.26															
Discounted @ 25%	(9,280.00)	1,543.97	1,353.83	1,175.30	1,011.01	868.25	637.57	637.57	545.29	465.83	397.83	338.90	288.66	245.67	208.91	177.53
Total	722.80															
Exchange rate (N/S)	145.00	140.00	135.00	135.00	135.00	135.00	135.00	135.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

NPV @ 15%	7,221.57
DCF-IRR	15.27%
IRR	26.80%
PAY-OUT (YEARS)	4.51
NCR	38,267.24

15% CAPITAL INCREASE	20% CAPI-TAL IN-CREASE	25% CAPI-TAL IN-CREASE
3,828.74	2,697.80	1,566.86
9.69%	8.07%	6.54%
20.66%	18.87%	17.19%
6.16	6.85	7.65

Table 3

Data used for the Dynamic Simulations

Plant unit	Parameter	Symbol	Units	Value
Operating data of the existing CCPP [27]				
Compressor	Inlet temperature	T_1	°C	31
	Inlet pressure	P_1	kPa	99
	Volume flow rate	V_1	m^3/s	1287
	Outlet pressure	P_2	kPa	1380
Combustion chamber	Fuel inlet temperature	T_f	°C	60.2
	Fuel inlet pressure	P_f	kPa	2650
	Fuel mass flow rate	$\dot{m}_f$	kg/s	25.83
	Fuel lower heating value	LHV	kJ/kg	52580
Gas turbine	Outlet temperature	T_4	°C	531
	Net power output	$\dot{W}_{net,GTC}$	MW	447
HRSG	Flue gas mass flow rate	$\dot{m}_g$	kg/s	1509.3
	Stack exhaust temperature	T_5,T_6	°C	126
Steam turbine	Net power output	$\dot{W}_{net,STC}$	MW	202
	Inlet steam high pressure (HP)	HPST	kPa	10020
	Inlet steam low pressure (LP)	LPST	kPa	537
	Mass flow rate of HP steam	$\dot{m}_{Hp}$	kg/s	175.2
	Mass flow rate of LP steam	$\dot{m}_{LP}$	kg/s	54.72
	Inlet temperature of HP steam	T_7	°C	512
	Inlet temperature of LP steam	T_9	°C	257.2
Air cooled condenser	Outlet water temperature	T_{11}	°C	60.7
	Outlet water pressure	P_{11}	kPa	21
	Air mass flow rate	$\dot{m}_{acc}$	kg/s	160680
Other thermodynamic specifications				
	Combustion efficiency [28]	η_{CC}	–	0.98
	Flue gas constant	R_g	kJ/kg K	0.285
	Steam turbine isentropic efficiency [16]	$\eta_{s,ST}$	–	0.82
	Feed pump isentropic efficiency	$\eta_{s,FWP}$	–	0.90
	Pinch temperature difference in the ORC evaporator [29]	ΔT_e	K	10
	Condenser temperature [30]	T_{16}	K	313
	ORC turbine isentropic efficiency [31]	η_E	–	0.87
	ORC pump isentropic efficiency	η_P	–	0.85
	Electric generator efficiency	η_G	–	0.90

Source: Oko & Njoku, (2017)