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Energetic and exergetic analysis of a triple-pressure reheat combined cycle power using different primary movers

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Abstract In this work, actual operating data for Sabiya combined cycle power plant located in Kuwait were used to conduct the performance evaluation based on the energetic and exergetic analysis. The proposed system consist of an advanced gas turbine engines, with two triple pressure reheat heat recovery steam generator, and one steam turbine. Three types of primary movers were selected carefully, in order to cover different types, sizes and technologies. The movers are gas turbine engine frame 9FA, LM6000 and GT26. The proposed models have been developed using specialised software and validated with the manufacturer's data featuring a high level of compatibility. The performance of a combined cycle power plant was investigated for different operating conditions. The result shows that the highest exergy destruction takes place in 9FA engine due to high irreversibility in combustion chamber because of low-pressure ratio, which causes low inlet temperature of compressed air to the combustion chamber. The 9FA engine also has the highest exergy loss due to high exhaust gases temperature, which is caused high useful work from a steam turbine. The GT26-reheat gas turbine engine constitute the best choose as primary mover due to low waste exergy, which is equal to 43.93% whereas 9FA and LM6000 equal to 47.27% and 45.17%, respectively. LM6000 aeroderivative gas turbine is considered the second best choice but the combined cycle power plant will consist of a large number of engines compared to other industrial gas turbine engine, and that may increase the number of auxiliary equipment, capital and maintenance cost.

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Keywords: Exergy; Aeroderivative; Gas turbine; Reheat and waste exergy

Nomenclature

$\dot{E}$ – exergy rate
$\overline{e}_k^{ch}$ – molar chemical exergy
h – enthalpy
$\overline{LHV}$ – low heating value in molar basis
$\dot{m}$ – mass flow rate
P – pressure
R – gas constant
$\overline{R}$ – universal gas constant
S – entropy
T – temperature
V – velocity
y – mole fraction

Greek symbols

η_{ex} – exergetic efficiency
Δ – difference

Subscripts

ch – chemical
d – destruction
e – outlet
i – inlet
k – component
ke – kinetic energy
L – loss
o – reference state
ph – physical
pe – potentials
st – stoichiometric
x – total

Abbreviations

AC – axial compressor
CC – combustion chamber
CCPP – combined cycle power plants
Comp. – compressor

EC – economizer
EV – evaporator
G – electric generator
GT – gas turbine
HRSG – heat recovery steam generator
HP – high pressure
HPC – high-pressure compressor
HPT – high-pressure turbine
IP – intermediate pressure
LP – low pressure
LPC – low-pressure compressor
LPT – low-pressure turbine
RH – reheater
SH – superheater
S – state
st – stoichiometric
x – total

1 Introduction

Population growth and modernisation across the world has increased the requirements for electrical power, and this has led to higher consumption of fossils fuels and raised levels of pollution emissions as well as greenhouse gases. Non-renewable energy resources have become rarer, and prices have risen due to the reduced supply and increased demand. This encourages research to focus on renewable energy resources or the improvement of existing energy-conversion efficiency for non-renewable resources. Thermal energy systems consume huge amounts of natural and economical resources, which contribute significantly to the climate change problem.Thus, these systems must be designed and operated in an efficient manner in order to reduce their environmental impact. Initially, a proper diagnostic using thermal analysis tools is performed to determine the locations, magnitudes and types of wastes and losses within these systems. Identifying the sizes and locations of any deficiencies will assist in modifying or improving the system. The primary analysis and assessment tools used for optimizing thermal energy systems are energy and exergy analysis [1–3].

Exergy plays an important role in sustainable development, due to the diversity of energy resources, and the concerns about the quality and quantity of energy. Exergetic efficiency is considered to be an important factor in sustainability as it increases as resource depletion reduces. The exergy principle has a significant effect on energy, the environment and on sustainable development. The greatest impact on sustainable development is energy conversion efficiency. The aim of improving energy conversion efficiency or future thermal power plants is to decrease fuel consumption, pollution and product costs. Sustainable development is necessary to delay the depletion of non-renewable resources by reducing fossil fuel consumption. Natural gas is considered apart from of sustainable energy in comparison to other fossil fuels because it has a more appropriate environmental quality.

Industrial and aeroderivative gas turbines (GTs) are an attractive choice for power generation worldwide due to low installation cost, short installation time, operational flexibility and ability to integrate with other thermal energy systems. The gas turbine engine will determine the shape of the energy of the future, especially up to 2050. Developments in gas turbine technologies are considered great challenges facing researchers and manufacturers. There are two ways to improve this technology, either by developing the gas turbine or by a thermal integrated system such as steam turbines, desalination, cooling and heating.

Gas turbine units suffer from efficiency limitations and substantial energy loss through stack. The combined cycle adds a steam turbine in order to boost power output and efficiency by capitalizing energy loss from the simple cycle. The main components in a combined power plant are a gas turbine unit, a heat recovery steam generator (HRSG) and a steam turbine. The HRSG utilizes heat energy in exhaust gases to convert water to steam, producing more power with the steam turbine while using the same fuel. The expected increase in power output is about 50% of gas turbine units capacity. The combined cycle power plants (CCPP) have higher thermal efficiency compared to separated gas turbine and steam power plants. In last four decades the use of CCPP has increased dramatically worldwide. Many researchers have studied CCPP processes based on exergy analysis such as Kotas [4], Facchini *et al.* [5], Moran and Shapiro [6]. All concluded that the maximum exergy losses occur in combustion chambers, due to chemical reactions. Rahim performed sensitivity analysis for all types of heat recovery steam generators without reheat system in a CCPP [7]. The evaporator pinch point, steam pressure and economiser approach were selected as a design parameters to evaluate the plant performance. The main outcomes were: net power increment increases with the number of stages at a specified steam pressure, and adjusting the pinch point and approach temperatures to a minimum level is highly recommended in order to improve performance of the heat recovery steam generation and entire plant. Sanjay conducted an exergy analysis of a CCPP with different HRSG configurations [8]. The generating steam capacity depended on the number of stages, desired steam pressure level and temperature. A triple pressure HRSG achieved the highest capacity of generated steam with higher performance and lower exergy destruction compared to the others. Bassily carried out comprehensive thermodynamic modelling of a triple pressure reheat CCPP [9]. The results showed that reducing the irreversibilities in the HRSG enhances both efficiency and power output for the CCPP. Furthermore, increasing the gas turbine inlet temperature and optimisation were considered the main methods to improve plant efficiency. Deng and Chuang conducted an exergy study to evaluate plant performance and energy utilisation in CCPPs at part load using different ambient temperatures and preheated fuel [10]. CCPP efficiency, operating at 50% load was found to be 2.4% lower than at full load though plant performance can be improved by increasing the pressure stages in the HRSG, pre-cooling the inlet air, and preheating the fuel. Amer *et al.*, presented an exergy analysis of a 420 MW combined cycle power plant in Iran using a dual pressure HRSG [11]. The results showed that the HRSG was the second greatest source of irreversibilities after the combustors and, thus, exergy loss is affected significantly by HRSG optimisation. A supplementary duct burner added to the HRSG had an adverse effect on the plant's overall performance, despite an increase in power output by the steam turbine. Ersayin and Ozgener recently carried out an exergy analysis of an operating CCPP located in Turkey using data obtained from the power plant control unit [12]. The plant consisted of two LM6000 aeroderivative GT engines, a once-through steam generator (OTSG), an HRSG and a steam turbine. The effect of ambient temperature on all plant components was investigated, and a part of the results, which were related to the topping cycle rotating equipment, contradicted the results of Rahim [7]. The study proposed modifications to improve plant performance. Sharma and Singh studied the effect of varying reference state temperature on the exergy parameters of a dual pressure HRSG [13]. They introduced useful information to enhance the entire system performance, and also have showed the sensitivity of the system to steam pressure. Dev and Attri presented exergetic and energetic analysis for a CCPP using a computer programming tool (Engineering Equation Solver – EES) [14] to evaluate the impact of pressure ratio variation on system efficiency [15]. The exergy destruction decreased in the combustor, steam turbine, condenser and feed water heater with increase in the pressure ratio. In contrast, the exergy destruction is increased in the compressor, gas turbine and intercooler. Soo and Yong Lee proposed a new approach to maximising the efficiency of the steam cycle of a single pressure HRSG by optimising the heat transfer process within the HRSG system and thus minimising the waste exergy [16].

Although numerous studies are available in the literature for CCPPs, none have explored a triple pressure reheat HRSG using a real set of data based on exergy analysis. Furthermore, no attempts were found in the literature to assess CCPP using different primary movers using exergy analysis.

2 Case study

Sabiya combined cycle power plant is the largest in the Arabian Gulf region and is entirely compatible in design with the current study model. Therefore, it was selected as a case study, in order to achieve more accurate outcomes based on real industry data. In 2009, the ministry of electricity and water (MEW) in Kuwait signed a contract agreement with General Electric (GE) for engineering, procurement, and construction (EPC) of the Sabiya power plant. This agreement included seven-year operation and maintenance work starting from the commercial operation of the last generating unit. The Sabiya CCPP consisted of three blocks, each block contains two advanced GE gas turbine frame 9FA, with two triple pressure reheat HRSG, and one steam turbine, as illustrated in Fig. 1. The first phase of the agreement was accomplished on June, 2011, based on a simple cycle mode, and it added nearly 1.400 MW to the national grid. The second phase boosted the plant's power output and efficiency without any increase in the fuel consumption, to more than 2000 MW, and 54.5%, respectively. The primary mover of the Sabiya Power Plant is a 9FA industrial gas turbine, which has its merits of having high power output, low heat rate, and low emissions. All manufactures have great concern for the environmental impact of their products, which was reflected by their continuous development in combustors, and in the use of the robust Dry Low NOx technology. The gas turbines environmental impact can be limited by controlling the fire temperature, the availability of oxygen in the combustion zone, and the duration of the combustion process. However, the current study extended to investigate different primary movers, which are LM6000 and GT26 gas turbines as shown in Figs. 2 and 3 respectivly. The selected engines are inspired by actual engines with different technologies since the first represents an aero-derivative and the second represents a reheat industrial gas

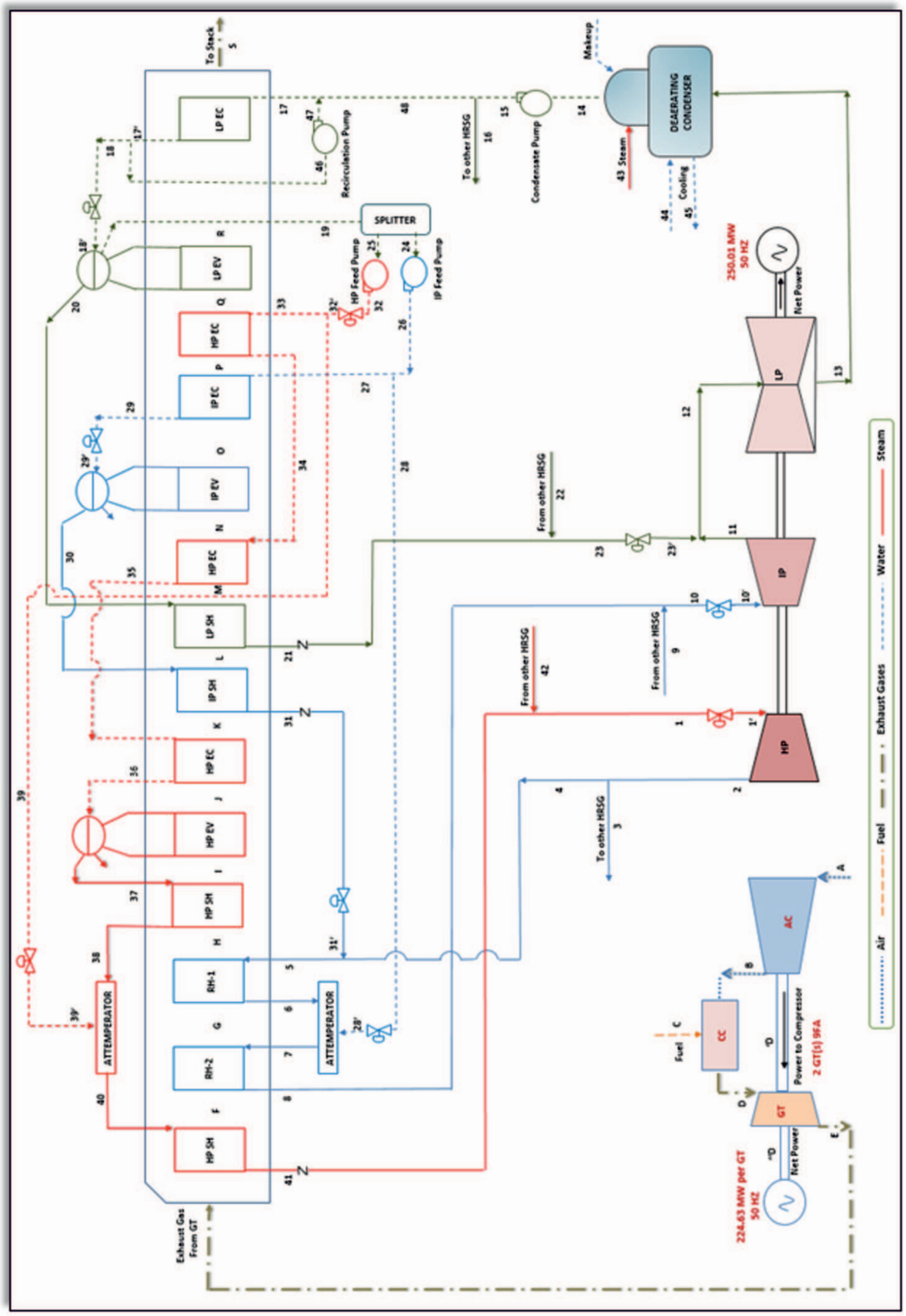

Figure 1: Schematic diagram of Sabiya combined cycle power plant [18].

turbine. The LM6000 engine will integrate by a triple pressure HRSG, without a reheating system, due to low gases exhaust temperature.

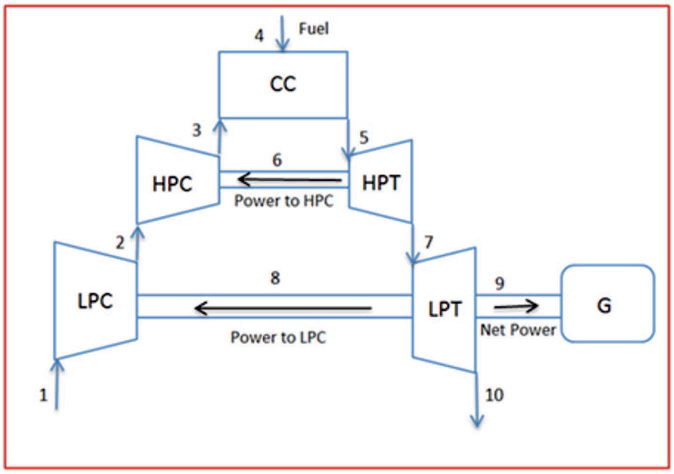

Figure 2: Schematic diagram of LM6000 gas turbine engine.

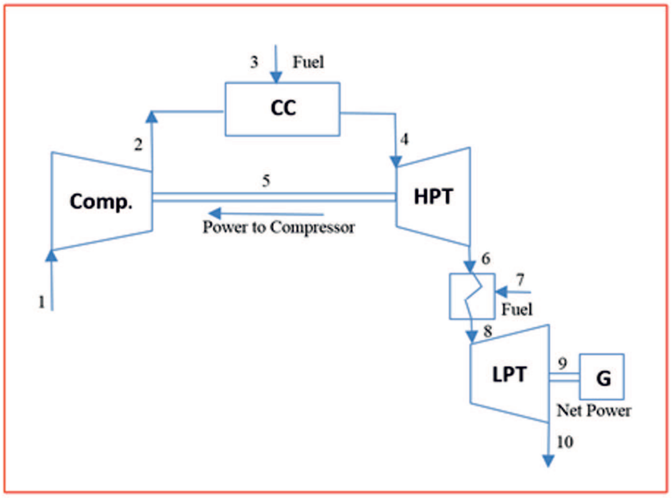

Figure 3: Schematic diagram of GT26 gas turbine engine.

3 Exergy analysis methodology

In the present study, comparison study for different primary mover were conducted based on exergy analysis. The environmental state was selected at a temperature of 288 K and an ambient pressure of 0.101 MPa. Some assumptions that were made about the gas turbine model included the following:

- The gas turbine model operated at a steady state.
- An ideal gas mixture concept was applied in both air and combustion products.
- Gas leakage was negligible.
- The kinetic and potential exergies of fluid streams were negligible.
- The combustion reaction was complete and N_2 was inert.
- Heat transfer from the combustor was 2% of the natural gas lower heating value (LHV).
- Natural gas was supplied to the system as fuel (the composition is given in Tab. 1).

Table 1: Molar fraction of the natural gas components.

Component	Molar fraction [%]
Methane (CH_4)	93.340
Ethane (C_2H_6)	0.211
Propane (C_3H_8)	0.029
Nitrogen (N_2)	6.420

The fuel is provided to the combustor at a high pressure with different values of mass flow rate, depending on load variations and inlet temperature to the annular combustor. The air stream mass flow rate varies, as well, in the cold section. The composition is given in Tab. 2.

Exergy is also known under the name of availability or available energy. Exergy is the maximum amount of useful work that may be produced by

Table 2: Molar fraction of air.

Component	Molar fraction [%]
Nitrogen (N_2)	77.48
Oxygen (O_2)	20.59
Water (H_2O)	1.90
Carbon dioxide (CO_2)	0.03

a system at reversible operation. The total exergy ($\dot{E}_x$) of stream is defined as

$$\dot{E}_x = \dot{E}_{ph} + \dot{E}_{ke} + \dot{E}_{pe} + \dot{E}_{ch}\,, \tag{1}$$

where $\dot{E}_{ph}$, $\dot{E}_{ke}$, $\dot{E}_{pe}$, and $\dot{E}_{ch}$ are physical exergy, kinetic exergy, potential exergy and chemical exergy respectively. Specific exergy of stream equal to total exergy divided by mass flow

$$e_x = \frac{\dot{E}_x}{\dot{m}}\,. \tag{2}$$

Therefore, the specific exergy of defined stream is equal to the sum of specific exergies and it is given by the expression

$$e_x = e_{ph} + e_{ke} + e_{pe} + e_{ch}\,. \tag{3}$$

In the present study, specific kinetic exergy, e_{ke}, and specific potential exergy, e_{pe}, are omitted due to insignificant effects.

Physical exergy is a maximum useful work that can be extracted from a unit mass of substance passing through a specified state (T_s, p_s) to the environmental or reference state (T_o, p_o) in purely physical processes [17]. The physical exergy consists of two parts: mechanical and thermal exergy and it is given by the expression

$$\dot{E}_{ph} = \dot{m}\left[\,(h_s - h_o) - T_o\,(s_s - s_o)\,\right]. \tag{4}$$

Once the specified temperature is equal to the reference temperature, $T_s = T_o$, with the ideal gas relation Eq. (4) takes the form

$$\dot{E}_{ph} = \dot{m}_e R T_o \ln \frac{P_e}{P_o}\,. \tag{5}$$

Chemical exergy is associated with mass flows from an environmental state to a dead state due to differences in concentration and molecular structure. The maximum useful energy that can be extracted during this process represents chemical exergy. The chemical exergy of gas mixture can be calculated by

$$\dot{E}_{ch} = \dot{n}\Big[\sum y_k \overline{e}_k^{ch} + \overline{R}T_o \sum y_k \ln y_k\Big], \tag{6}$$

where $\dot{n}$ represent the number of mole and $\overline{e}_k^{ch}$ is molar chemical exergy for component k in the mixture, it can be selected from standard chemical exergies table, as presented in [10]. The chemical exergy for fuel stream is given by

$$\dot{E}_{ch} = \dot{n}_f \overline{LHV}\,. \tag{7}$$

In all system components the rate of exergy outlet is less than the rate at inlet due to exergy destruction and exergy loss. These quantities in steady state can be related by the following:

$$\dot{E}_i = \dot{E}_e + \dot{E}_d + \dot{E}_L\,, \tag{8}$$

where $\dot{E}_d$ and $\dot{E}_L$ represent rates of exergy destruction and exergy loss. The exergy destruction during a process is proportional to entropy generation due to irreversibilities within each component in the process. Exergy destruction can be calculated from the difference in exergy values across the component

$$\dot{E}_d = \dot{E}_i - \dot{E}_e\,. \tag{9}$$

Exergy loss is associated with the rejection of energy to the environment at the end of a process such as exhaust gases and water.

In thermal system efficiency is a significant parameter used to measure the level of energy conversion. Thermal efficiency shows how much work output can be extracted from a specified input fuel, whereas exergetic efficiency indicates how much can be extracted from maximum available work. The exergetic efficiency is defined as the ratio of total exergy output to total exergy input or the ratio of produced exergy to fuel exergy supplied to the system, i.e.,

$$\eta_{ex} = \frac{\dot{E}_e}{\dot{E}_i} = \frac{\dot{E}_p}{\dot{E}_f} = 1 - \frac{\dot{E}_{d+}\dot{E}_l}{\dot{E}_f}\,. \tag{10}$$

The exergetic efficiencies for different component in gas turbine at steady state condition are defined as:

compressor

$$\eta_{ex} = \frac{\dot{E}_e - \dot{E}_i}{\dot{W}_c}\,, \tag{11}$$

combustor

$$\eta_{ex} = \frac{\dot{E}_e}{\dot{E}_{i1} + \dot{E}_{i2}}\,, \tag{12}$$

turbine

$$\eta_{ex} = \frac{\dot{W}_t}{\dot{E}_i - \dot{E}_e}\,. \tag{13}$$

4 Results and discussion

In this section, results of exergy analysis are presented for the proposed systems. The input data of the exergy analysis study came from a gas turbine model developed using IPSEpro – commercial power plant design and analysis software [19] and was validated with manufacturer-published data. Exergy analysis is a useful tool that can assist in determining the locations and magnitudes of inefficiencies and the types of wastes and losses in an energy system. Improving energy conversion systems is required and represents an essential objective in order to reduce product cost as well as environmental impact, and to achieve sustainable development, especially when fossil fuels are employed.

Tables 3 and 4 shows thermodynamic data including exergy analyses for the bottoming cycle and topping cycle in original proposed CCPP at ISO condition. Similarly analyses were performed for the other primary movers. Figure 4 uses a Grossman diagram to illustrate the exergy flow and exergy destruction across a single block of the Al Subiya plant under ISO conditions, for the different primary movers. The GT engines produce the highest useful work in all cases and the maximum value occurs with the LM6000. The lowest value for useful work produced by the steam turbine occurred for the same engine, and may be attributed to number of GTs, high pressure ratio and low exhaust gases temperature compared to the other engines. The highest exergy destruction takes place in 9FA engine due to the high level of irreversibility in the combustion chamber because of the low-pressure ratio, which meant low inlet temperatures of the compressed air into the combustion chamber. The 9FA engine also has the highest exergy loss due to high exhaust gases temperatures, which is caused high useful work from steam turbine.

Table 3: Exergetic data for bottom cycle in Sabiya CCPP.

Point	Substance	Mass [kg/s]	Temp. [K]	Pressure [MPa]	Enthalpy [kJ/kg]	Entropy [kJ/kgK]	Exergy [MW]
1	Steam	149.65	838.35	11.990	3520.81	6.70	238.64
1’	Steam	149.65	837.97	11.890	3520.81	6.71	238.48
2	Steam	149.65	625.74	2.789	3126.73	6.79	175.73
3	Steam	72.00	625.74	2.789	3126.73	6.79	84.54
4	Steam	77.65	625.74	2.789	3126.73	6.79	91.19
5	Steam	88.36	620.55	2.731	3115.95	6.79	102.76
6	Steam	88.36	785.00	2.581	3488.13	7.34	121.46
7	Steam	88.36	765.00	2.581	3443.52	7.29	118.98
8	Steam	88.36	838.00	2.461	3607.90	7.51	127.71
9	Steam	78.00	838.00	2.515	3607.43	7.50	113.17
10	Steam	166.36	837.86	2.451	3607.68	7.51	240.32
10’	Steam	166.36	837.66	2.400	3607.68	7.52	240.29
11	Steam	166.36	605.13	0.460	3131.57	7.61	156.99
12	Steam	184.31	602.99	0.460	3127.14	7.61	173.50
13	Steam	184.31	324.34	0.013	2515.88	7.82	49.62
14	Water	192.99	322.19	0.013	205.30	0.69	1.96
15	Water	192.99	322.33	2.231	207.81	0.69	2.40
16	Water	96.49	322.33	2.231	207.81	0.69	1.21
17	Water	193.05	367.77	1.826	397.73	1.24	8.36
17’	Water	193.05	411.17	1.226	581.20	1.72	17.46
18	Water	96.55	411.15	1.226	581.20	1.72	8.74
18’	Water	96.55	411.27	0.531	581.20	1.72	8.69
19	Water	87.58	426.56	0.571	646.91	1.88	9.68
20	Steam	8.97	426.52	0.521	2749.92	6.81	7.12
21	Steam	8.97	584.85	0.491	3088.99	7.51	8.34
22	Steam	8.97	582.00	0.485	3083.24	7.51	8.30
23	Steam	17.95	583.39	0.485	3086.11	7.51	16.63
23’	Steam	17.95	583.28	0.475	3086.11	7.52	16.58
24	Water	11.43	426.56	0.571	646.91	1.88	1.27
25	Water	76.14	426.56	0.571	646.91	1.88	8.41
26	Water	11.43	426.89	2.938	649.79	1.88	1.30
27	Water	11.11	426.89	2.938	649.79	1.88	1.26
28	Water	0.32	426.89	2.938	649.79	1.88	0.04
29	Water	11.11	499.14	2.898	971.52	2.57	2.61
29’	Water	11.11	499.13	2.888	971.52	2.57	2.61
30	Steam	11.11	504.71	2.878	2803.15	6.20	10.94
31	Steam	10.71	588.15	2.788	3037.76	6.65	12.08
31’	Steam	10.71	588.13	2.787	3037.76	6.65	12.08

Table 3 continuation

Point	Substance	Mass [kg/s]	Temp. [K]	Pressure [MPa]	Enthalpy [kJ/kg]	Entropy [kJ/kgK]	Exergy [MW]
32	Water	76.14	428.69	15.880	665.50	1.88	9.73
32’	Water	76.14	429.07	13.280	665.50	1.89	9.59
33	Water	75.36	429.07	13.280	665.50	1.89	9.49
34	Water	75.36	506.41	13.275	1007.56	2.62	19.39
35	Water	75.36	576.32	13.235	1357.35	3.27	33.39
36	Steam	75.36	604.01	13.230	1530.50	3.56	38.41
37	Steam	74.65	605.09	13.180	2658.59	5.42	82.20
38	Steam	74.65	684.93	12.880	3072.24	6.08	100.18
39	Water	0.78	429.07	13.280	665.50	1.89	0.10
40	Steam	74.65	675.33	12.870	3038.73	6.03	97.05
41	Steam	74.65	841.65	12.570	3523.73	6.69	119.60
42	Water	75.00	838.00	12.200	3517.91	6.69	119.60
43	Water	8.68	294.00	0.103	87.57	0.31	0.02
44	Water	3175.36	288.00	0.150	62.50	0.22	7.83
45	Water	3175.36	320.00	0.149	196.29	0.66	29.95
46	Water	96.50	411.17	1.226	581.20	1.72	8.74
47	Water	96.55	412.35	1.226	587.56	1.73	9.06
48	Water	96.50	322.33	1.226	207.81	0.69	1.21

Table 4: Exergetic data for topping cycle in Sabiya CCPP.

Point	Substance	Mass [kg/s]	Temp. [K]	Pressure [MPa]	Enthalpy [kJ/kg]	Entropy [kJ/kgK]	Exergy [MW]
A	Air	577.22	288.00	0.101	15.01	6.85	0.00
B	Air	577.22	684.64	1.702	426.47	6.93	223.91
C	Fuel	13.84	368.00	1.891	142.27	–	653.40
D	Exhaust gases	591.06	1550.00	1.652	1531.22	8.21	716.29
E	Exhaust gases	591.06	896.84	0.100	700.39	8.35	239.90
F	Exhaust gases	591.06	845.69	0.100	639.13	8.28	224.63
G	Exhaust gases	591.06	825.00	0.100	614.56	8.25	202.50
H	Exhaust gases	591.06	777.80	0.100	558.92	8.18	178.16

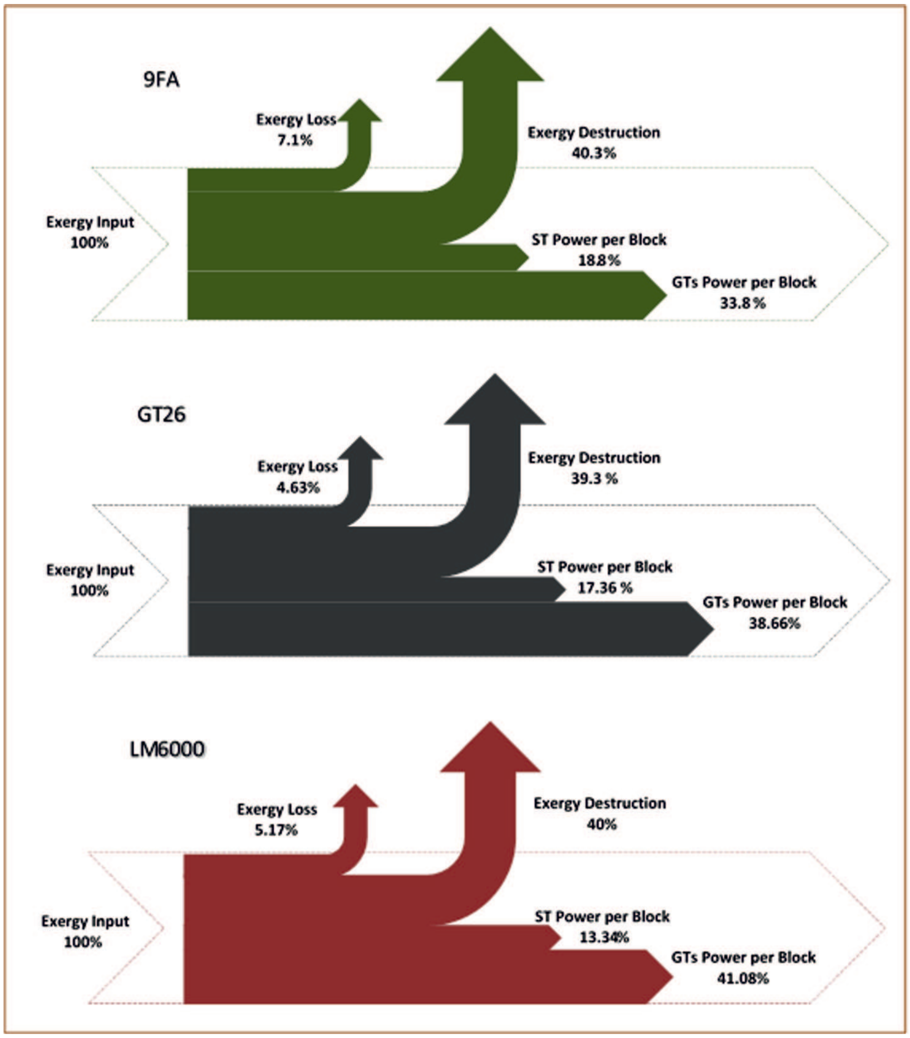

Figure 4: Predicted exergy flow as a percentage of input fuel exergy for different primary movers in the Al Subiya CCPP, using a Grossman diagram.

The GT26-reheat gas turbine engine is the best choice for primary mover due to low waste exergy, 43.93% compared to 47.4% for the 9FA and 45.17% for the LM6000. The use of the reheat GT engine GT26 with a high-pressure ratio, will achieve substantial improvement in the Al Subiya CCPP due to a reduction in fuel consumed, more power produced, and with the exhaust temperature maintained at a high level, which is compatible with the triple pressure reheat HRSG. The LM6000 is considered the second best choice but the CCPP would then consist of larger number of engines compared to the other prime movers, and that may increase capital and maintenance costs, and the auxiliary equipment required.

The energetic and exergetic efficiency of CCPP for different primary movers is shown in Fig. 5. The GT26 reheat industrial GT engine has the highest energetic and exergetic efficiency, 56.02% and 55.44%, respectively, which may be attributed to the high pressure ratio and reheat effect. The KUW6000 comes next due to high-pressure ratio and technical design. Despite the 9FA engine having the lowest energetic and exergetic efficiency, 53.12% and 52.65%, respectively, it is considered a heavy-duty machine for power generation applications as compared to the LM6000 aeroderivative engine. The CCPP can be improved by selecting an appropriate primary mover which, in the current case, is the GT26 (an industrial reheat GT). However, the pressure ratio plays a significant role in reducing fuel consumption and thus reducing exergy destruction as well. The reheat principle augments the power generation, increasing turbine efficiency and is considered more compatible with advanced HRSGs. There are slight differences between energetic and exergetic efficiency due to the irreversibilities effect.

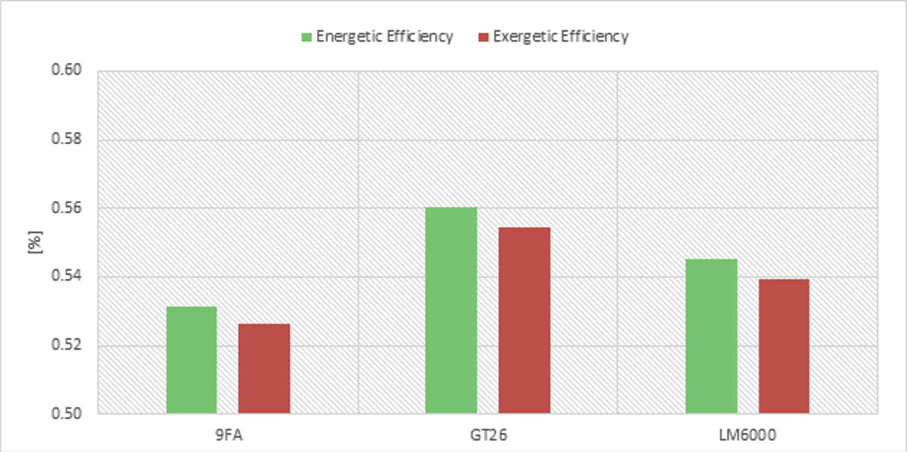

Figure 5: Energetic and exergetic efficiency of CCPP as a percentage for different primary movers at ISO condition.

Figure 6 shows waste exergy across all major components of the CCPP under ISO condition for different primary movers. The effect of pressure ratio clear in compressor increases as the exergy destruction increase, and the relation between them is directly proportional. The compressor of the 9FA engine has the lowest pressure ratio (16.8) and lowest exergy destruction as well. Although the GT26 compressor has a higher-pressure ratio than the LM6000, it has lower exergy destruction and that may be attributed to a higher number of engines in the LM6000 case, which creates greater irreversibility. The combustor in all cases was the major source of irreversibilities. In the 9FA engine, the combustor has high exergy destruction due to the low inlet temperature of the compressed air because of the low-pressure ratio. Although the GT26 has a higher-pressure ratio, it has higher level of irreversibilities compared to the LM6000, largely due to reheat combustor effects. The turbine of the GTs was the second source of irreversibilities in all cases with the highest level occurring in 9FA engine because it has a single turbine whereas the GT26 and LM6000 each consist of two turbines which reduced the amount of energy extracted from the exhaust gases stream. The effect of reheat in the GT26 noticeably improved turbine efficiency and reduced exergy destruction relative to the 9FA engine. The aeroderivative LM6000 GT engine has the lowest value of exergy destruction due to lowest fuel exergy. Generally, the HRSG exergy destruction was significantly affected by fuel exergy, which is associated with exhaust gas temperature and the relation between them is inversely proportional. The reverse occurs with the steam turbine and condenser because the exergy destruction increases with fuel exergy due to aerodynamic and heat transfer losses.

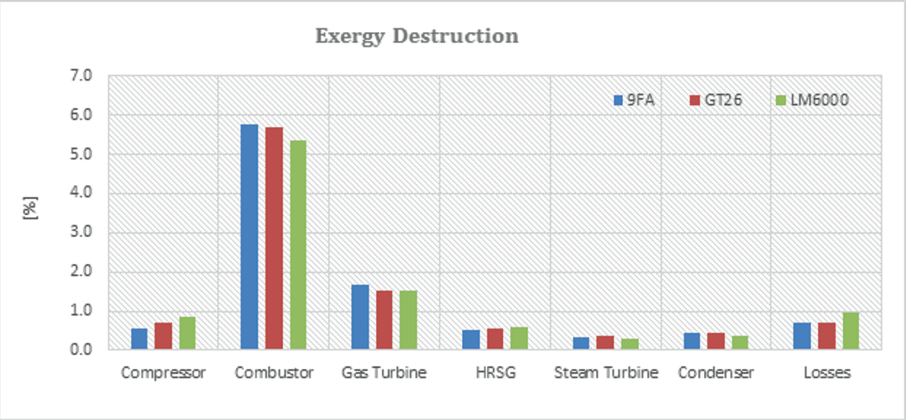

Figure 6: Waste exergy as a percentage for all components in CCPP at ISO condition for different primary movers.

5 Conclusions

This paper carries out exergetic analysis for combined cycle power plant using different primary movers. The main conclusions that can be extracted from this study are as follows:

1. The exergy analysis showed that the combustion chamber is the main source of irreversibility, with the high exergy destruction.

2. Inefficiency in the combustor can be reduced by improving the combustion process, adding an air preheater, and reducing the air–fuel ratio to be close from stoichiometric ratio.

3. The pressure ratio plays an important role in reducing fuel consumption as well as exhoust gases temperature, therefore optimization prorces is required in order to adjust the optimum value and achive high combined cycle power plant efficiency with high power output.

4. The combustor of 9FA engine has high exergy destruction due to the low inlet temperature of the compressed air due to low-pressure ratio.

5. The reheat gas turbine engine with high pressure ratio has shown a substantial improvement in the combined cycle power plant compared to the original Sabiya design.

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