Doi: 10.61435/jbes.2025.19970

Journal of Bioresources and Environmental Sciences, 4, (2), 132-146

Research Article

Energy and Exergy Analysis in Combined Cycle Power Plant and Open Cycle Operating Conditions Effect on the Environment

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Received: 16th June 2025
Accepted: 22nd June 2025
Published: 19th August 2025

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Abstract. Efforts are required to save energy and utilize energy efficiently because of fossil fuel depletion. Purpose of this study to determine performance of Tutong CCPP through a study of energy and exergy efficiency, also exergy losses analysis by determining four scenarios. Energy and exergy analysis using Cycle Tempo program obtained energy efficiency in scenario 1, which is 49.26%, almost the same as energy efficiency in scenario 2, which is 49.1% where CCPP operates with same GTs and ST loads but in scenario 2 ST ASV experiences actuator damage. Scenario 3 obtained CCPP efficiency of 47.6% and scenario 4 obtained open cycle efficiency of 28.2%. The largest exergy loss occurred in Condenser, which is 81.9% in scenarios 1 and 2 and 83.4% in scenario 3. From these results, it shown the greatest exergy loss occurred in scenario 3 where two ACC fans were malfunction, resulting in greater losses due to suboptimal vacuum. A significant exergy loss also occurs in combustion chamber, which are 15.1%, 15.05%, 15.6% in scenarios 1, 2, 3 and also 16.7% in scenario 4. A large exergy loss in scenario 4 also occurs in chimney, that is 16.7%.

Keywords: Exergy, Cycle Tempo, Efficiency, Combined Cycle Power Plant (CCPP)

1. Introduction

In recent decades, increasing world population and higher energy demand caused an increase in fossil fuel consumption, leading to global warming, ozone layer depletion, and environmental pollution. Therefore, renewable energy utilization and the employment of more efficient technologies that provide lower environmental impacts are flourishing (Shamoushaki et al., 2021).

Excessive fossil fuels consumption nowadays has caused fossil fuels resources become increasingly depleted so efforts to save and utilized energy efficiently is required. Fossil fuels combustion also releases gases such as CO_2, NO_x, methane and hydrocarbons into the atmosphere resulting air pollution. Increase in carbon gas emissions causes carbon gas to be trapped in the atmosphere which affect the increasing of earth's temperature also and earth become hotter which affecting on climate change and it is prone to natural disasters (Raja et al., 2006). To overcome problems of global warming and reduce its negative impacts, it is necessary to comply with Paris Agreement which aims to sustainably reduce carbon gas emissions in an effort to limit global temperature increment to only 1.5°C. The agreement includes commitments from all countries producing carbon emissions to reduce pollution and carbon emissions which may affect climate every day and strengthen this commitment from time to time, such as reducing using of private vehicles, preventing of forest burning for industrial purposes, using energy resources from renewable energy and other environmentally friendly efforts (IAE, 2021).

Increasing fossil fuel prices, global warming, and growing energy demand are three long-term drivers of sustainable power generation, which are becoming gradually competitive. Alternative solution to overcome energy shortage which is by including viable energy sources such as innovative combined cycle power plants (CCPP) with higher performance (Khan, 2020).

As major users of fossil fuels, CCPP have become more popular due to their advantages such as high overall efficiency, low fuel consumption, low emissions and lower operating costs (Chahartaghi et al., 2021). Achieving optimum

energy conversion in thermodynamic systems, such as in thermal power plants is a complex task due to involvement of several factors. Effective ways of determining quantity and quality of energy systems are via energy and exergy analysis (Khaleel et al., 2022). Combined cycle power plant has lower CO_2 emissions per KWH generation if it compared with usual power generation (Zahedi et al., 2021).

First law of thermodynamics gives equations based on energy conservation. However, they do not describe information about quality and quantity of losses and do not locate elements responsible for them, so these limitations require to utilize exergy analysis (Fakhari et al., 2021). Exergy analysis is a powerful tool to evaluate energy conversion systems. Exergy is composed of four main components, including physical exergy, chemical exergy, kinetic exergy, and potential exergy (He et al., 2021).

With depleting fossil fuel resources and increasing energy consumption, as well as environmental issues and global warming, it is important to find a method that utilizes energy as much as possible with high efficiency and has a low environmental impact (Ebrahimi et al., 2021).

The first step to save and use energy efficiently is by conducting process study so CCPP performance can be identified through energy and exergy efficiency, energy and exergy distribution and losses in the system. Based on this information along with energy audit, recommendations can be made and implemented so that various problems which may affect power plant performance such as steam leaks in the Heat Recovery Steam Generation (HRSG), equipment malfunction, ineffective insulation and various other problems can be identified then corrective actions can be taken.

These energy saving are certainly in line with global efforts to realize initiatives that promote energy efficiency, energy savings and develop projects using clean energy.

At Tutong Combined Cycle Power Plant, an analysis and study of energy and exergy will be carried out where four scenarios are determined as follows:

1. Combined cycle operations (2-2-1 operational mode).
2. Derating due to ASV Steam Turbine actuator damage.
3. ACC A and E fans damage, which affect Condenser vacuum pressure.
4. Open Cycle Operations, conditions where only two Gas Turbines operate with exhaust gas discharged into the atmosphere through the stack.

In this study, energy and exergy analysis is conducted to determine performance, energy and exergy distribution and losses in the CCPP as well as the environmental impact in scenario 4.

Energy and exergy have same units where exergy transfer accompanies energy transfer, but energy and exergy fundamentally have different concepts. Exergy provides sharper picture of performance compared to energy because in addition to include energy transfers in general, it also clearly takes into account the effects of irreversibility through concept of exergy destruction (Moran et al., 2018). First law of thermodynamics defines the conservation of energy. However, first law of thermodynamics does not provide information about direction in which process will occur spontaneously, namely reversibility aspect of thermodynamic process. First law of thermodynamics does not provide information about inability of any thermodynamic process to convert heat completely into mechanical work. Principles to explain these phenomena and to characterize availability of energy are needed in this case. These principles are found in the second law of thermodynamics (Dincer and Rosen, 2013). Exergy is useful quantity in analyzing energy and processes. Exergy is considered as an indicator of maximum work that can be done by a system when system is reversibly moved to its standard point. Exergy is a measure that coordinates quality with quantity of energy. The irreversibility in a process can be accounted for a detailed exergy analysis, which uses first and second laws of thermodynamics simultaneously (Zhao et al., 2021). Energy analysis calculates efficiency of energy utilization in the system but cannot measure thermodynamic losses which occur within the system. Thus, exergy analysis was performed to determine the causes, locations, and magnitudes of process inefficiencies (Khosravi et al., 2021).

Main components of combined cycle power plant with high exergy destruction rate have higher exergy efficiency as well. Components such as Turbines, Compressors, and Pumps which are related to electricity generation have low exergy destruction (Saharkhiz et al., 2021). Exergy has characteristic that is conserved only when processes occurring in system and environment are reversible. Exergy is destroyed (consumed) when an irreversible process occurs. Irreversible always generates entropy and anything that generates entropy always destroys exergy (Cengel et al., 2019). Losses are related to difference between input and output of a system (Maruf et al, 2021). The analysis of losses in a power generation system can be studied from exergy analysis. In CCPP, several processes occur in Gas Turbine which are consists of Brayton cycle (topping cycle) and Rankine cycle in steam-water section (bottoming cycle). Energy and exergy analysis are used as an effective method to determine quantity and quality of energy sources (Ibrahim et al., 2018).

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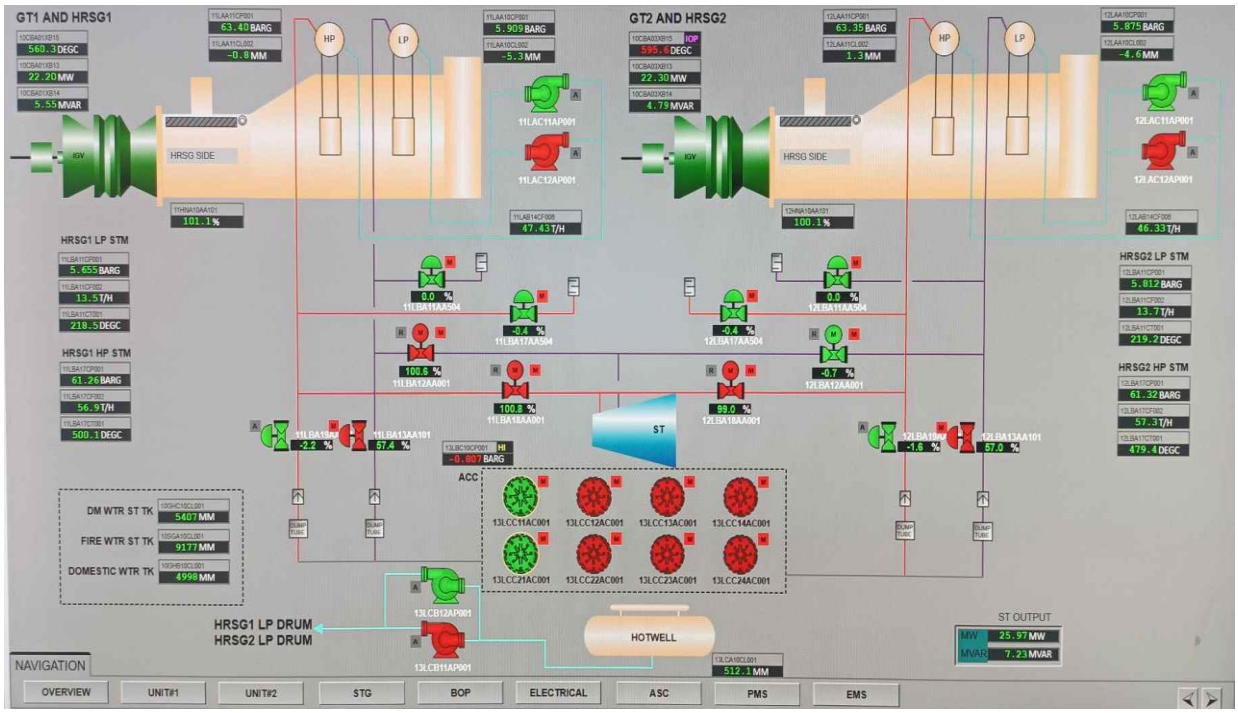


Figure 1. Overview of Tutong Combined Cycle Power Plant

CCPP has a high potential for providing high thermal efficiency. This combined cycle consists of two parts. The gas turbine cycle is primary section of the system and HRSG with steam turbine cycle is the second part of the cycle (Ghorbani et al., 2020). CCPP have thermal efficiency, power output and less emission as compared to individual gas turbine (Brayton) or steam turbine (Rankine) cycles (Aliyu et al, 2020). According to Zare and Hasanzadeh (2016), in a Brayton cycle, turbine and compressor efficiencies are important factors affecting the overall system performance.

CCPP is a preferred technology for power generation because it has high efficiency with less emissions (Kaviri et al., 2012). This CCPP consists of two GE Frame 6B Gas Turbines, one GE Steam Turbine, two Heat Recovery Steam Generators each consisting of Low Pressure (LP) and High Pressure (HP) Drums, Condensers with air-cooled types, Air Cooled Condenser (ACC) consisting of eight air fans, two Condensate pumps, Condensate Extraction Pump (CEP), two boiler feed pumps on each HRSG, Boiler Feed Pump (BFP) and there are also LP and HP bypass valves on each HRSG.

2. Method

This research categorized as quantitative research with energy and exergy analysis using Cycle Tempo program. Cycle Tempo is a thermodynamic modeling program for systems that produce electricity. These systems consist of subsystems which are interrelated.

There are two types of data taken, which are primary data and secondary data.

- Primary Data Collection: data taken directly from DCS based on process and operational variables.
- Secondary Data Collection: which comes from literature studies in form of supporting data and references related to the research.

Flow diagram in research process can be described as follows:

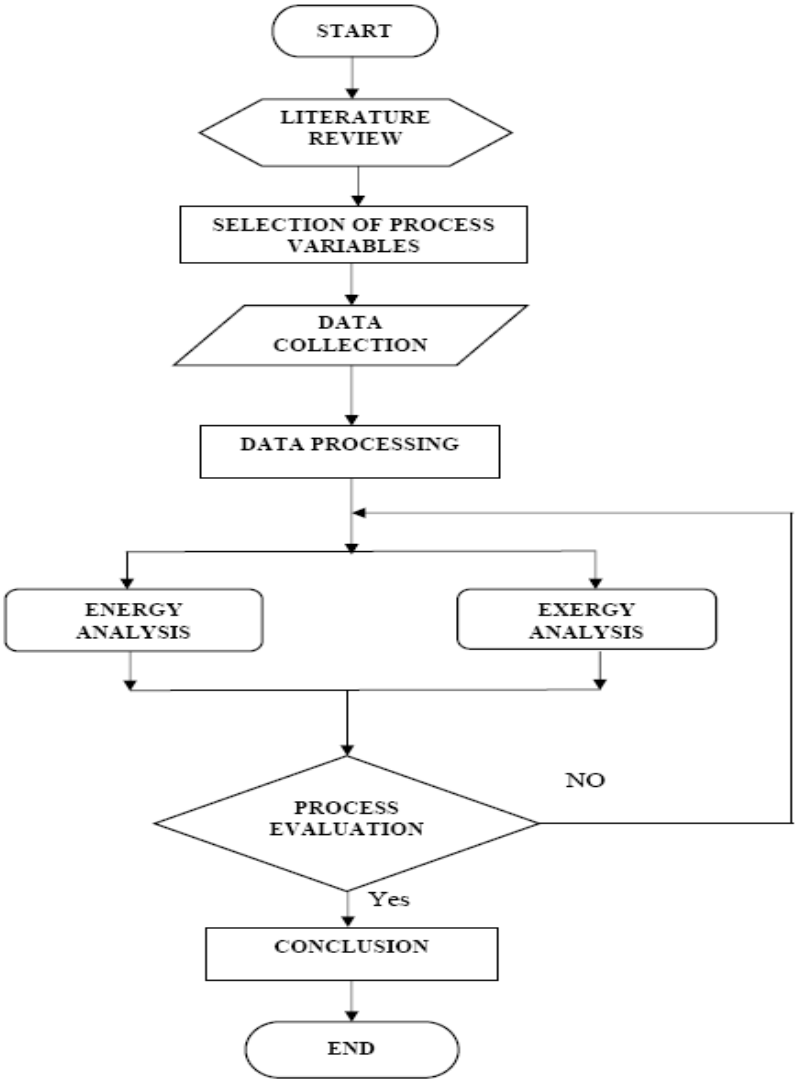


Figure 2. Research flowchart

3. Result and Discussion

3.1. Scenario 1 Combined Cycle Power Plant

Scenario with power plant on 2-2-1 configuration by Cycle Tempo analysis result as follows:

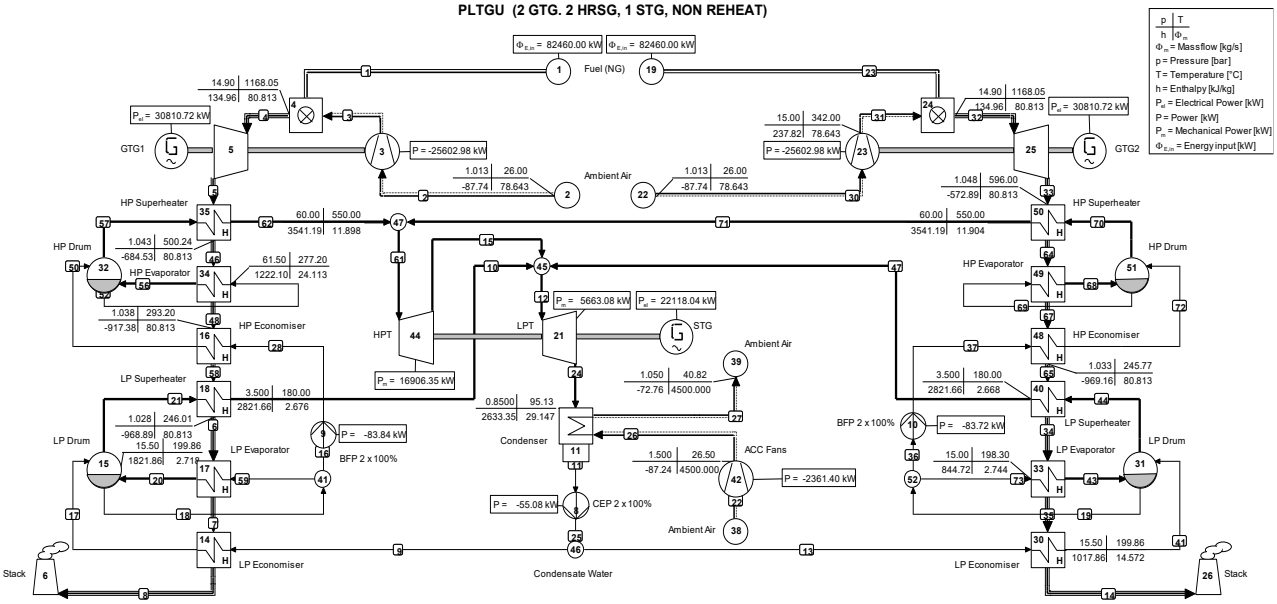


Figure 3. Scenario 1 process diagram

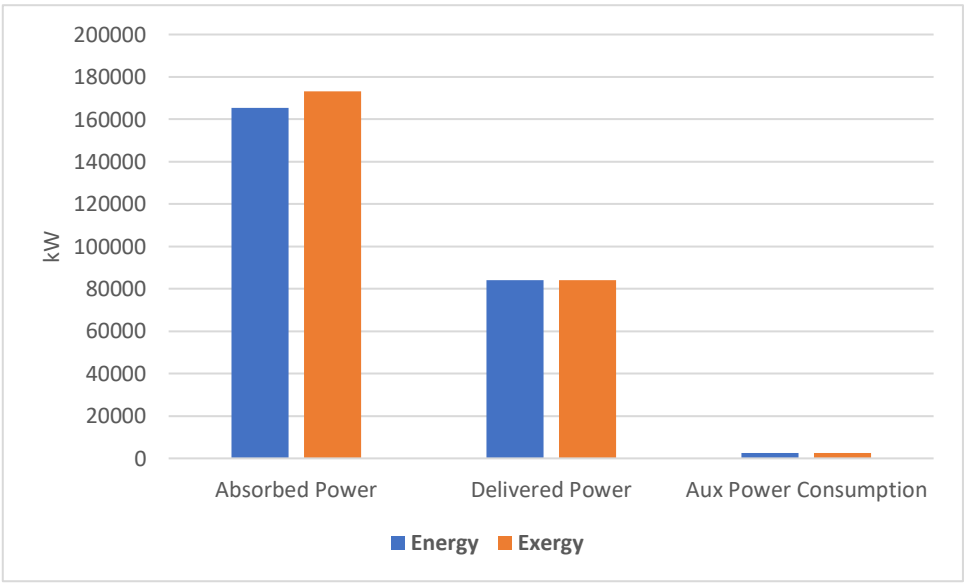


Figure 4. Power generated in scenario 1

Total load of scenario 1 is 84 MW and load used for CCPP self-consumption is 2.58 MW so net load produced is 81.4 MW. Energy absorption from natural gas is 165.3 MW. Exergy absorption from natural gas is 173.1 MW. Total exergy produced is 84 MW and self-consumption exergy is 2.58 MW so net exergy produced is 81.4 MW (Figure 4). From Cycle Tempo analysis, energy efficiency result of scenario 1 is 49.26% with net exergy 47.04%.

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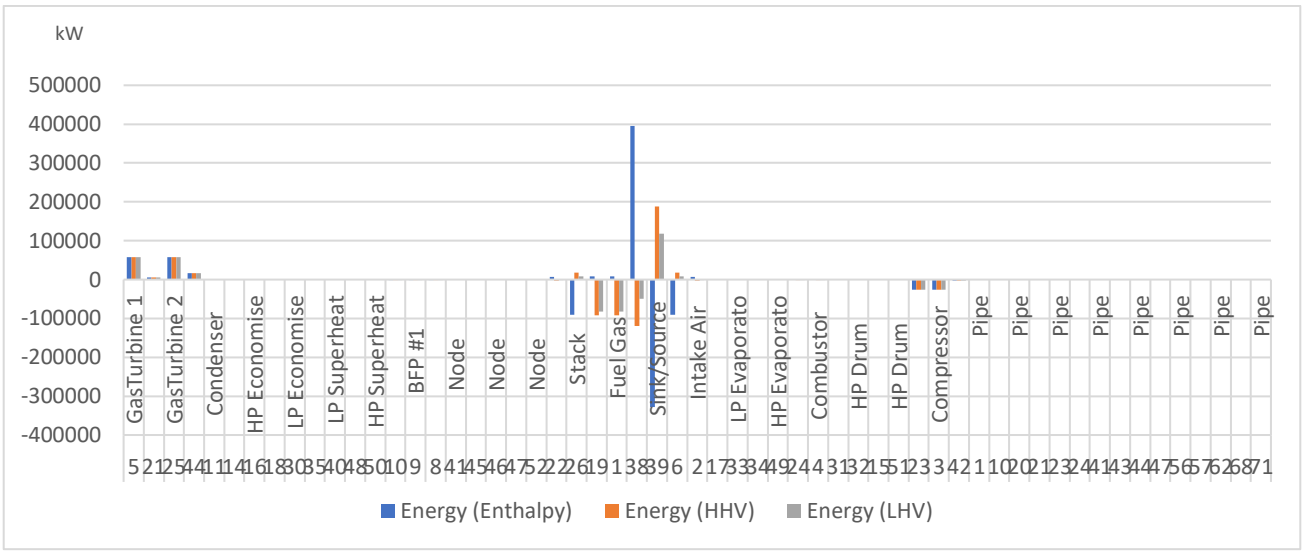


Figure 5. Energy distribution in scenario 1

Figure 5. is a graph of energy balance in form of enthalpy distributed in various parts: natural gas 1 and 2 both are 7.8 MW, Gas Turbine 1 and 2 both are 57.2 MW, Steam Turbine HPT: 16.9 MW, LPT: 5.7 MW, intake air: 6.9 MW, Sink Source 38 (intake air as a steam condensation medium): 394.8 MW. Equipment which absorbs energy are compressors 1 and 2 both are 25.6 MW, ACC Fan: 2.27 MW, stack: 90.1 MW, sink source 39 (intake air absorbs energy in the condenser then released into environment): 327.4 MW.

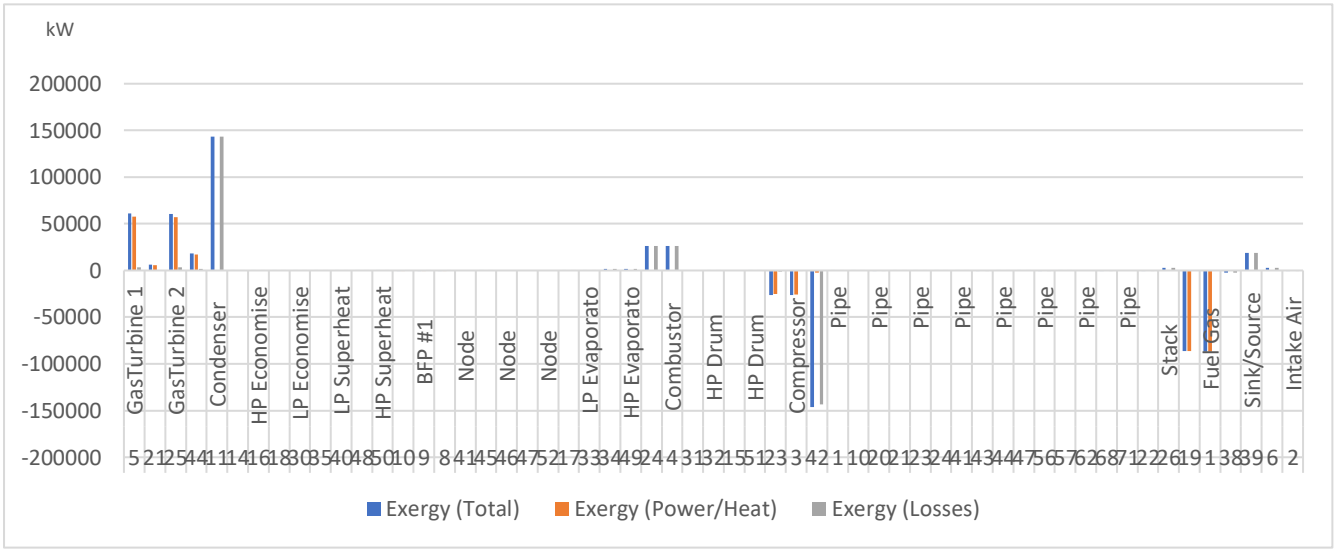


Figure 6. System Exergy in scenario 1

Figure 6. shown exergy distribution graph and exergy losses in each part of CCPP. The largest exergy loss is in condenser of 143.5 MW (81.9%). Exergy losses that also large are in combustion chamber of Combustor 1: 26.5 MW (15.1%), Combustor 2: 26.4 MW (15.06%), sink source 39 (steam condensation process with air): 18.9 MW (10.8%), GT1: 3.6 MW (2.1%), GT2: 3.56 MW (2%), stack 1: 2.66 MW (1.52%), stack 2: 2.65 MW (1.5%) and HPT Steam Turbine: 1.4 MW (0.8%). Large exergy losses are found in ACC Fans: 143.7 MW (81.95%), sink source 38 (energy losses to atmosphere): 2.15 MW (1.23%).

3.2. Scenario 2 Steam Turbine De-rating

Scenario 2 with 2-2-1 configuration but experiences slight decrease in electrical power due to LP Turbine ASV actuator damage.

Cycle Tempo analysis obtained following results:

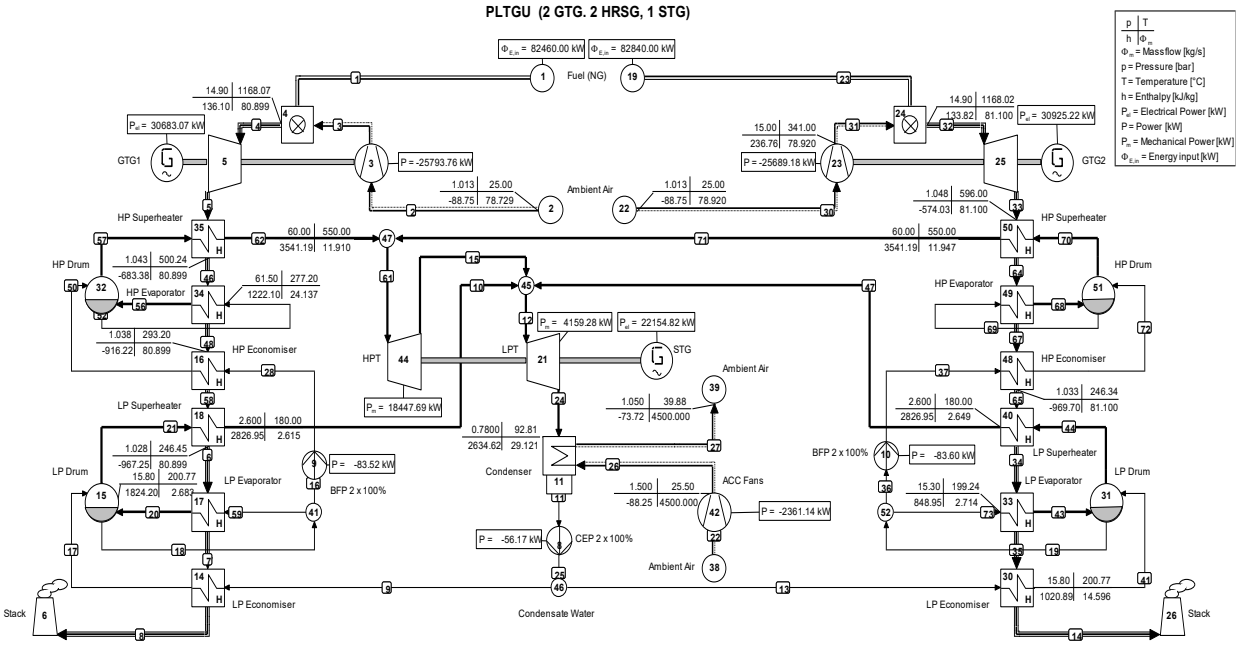


Figure 7. Scenario 2 process diagram

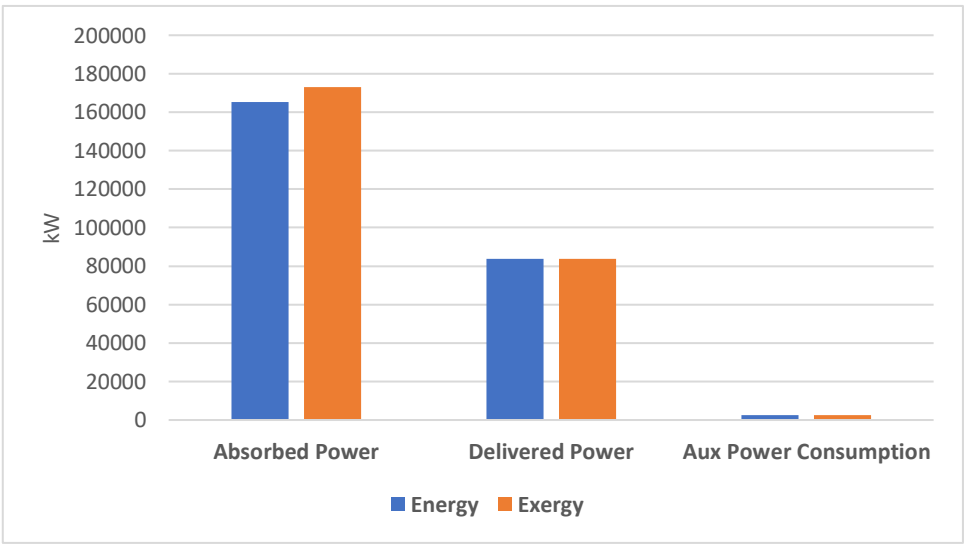


Figure 8. Power generated in scenario 2

Total load of scenario 2 is 83.8 MW and load used for CCPP self-consumption is 2.58 MW so net load produced is 81.2 MW. Energy absorbed from natural gas fuel is 165.3 MW. Exergy absorbed from natural gas is 173.1 MW. Total exergy produced is 83.8 MW and self-consumption exergy is 2.58 MW so net exergy produced is 81.2 MW (Figure 8). Based on Cycle Tempo analysis, energy efficiency result on scenario 2 is 49.1% with net exergy 46.9%.

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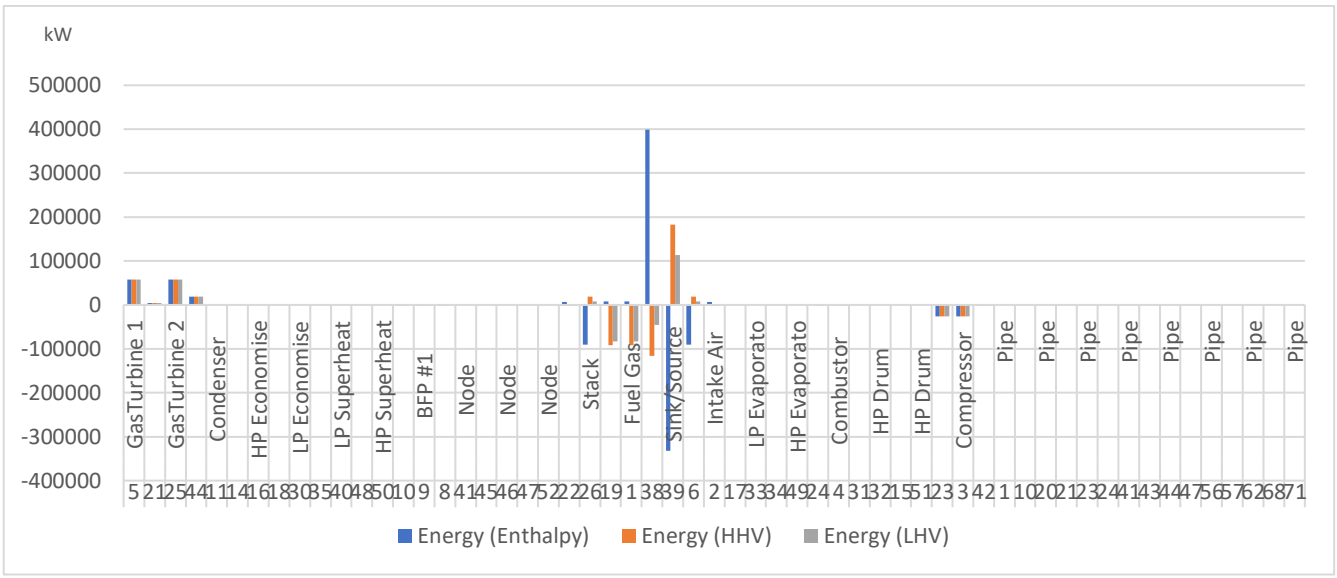


Figure 9. Energy distribution in scenario 2

Figure 9. is energy balance graph in form of enthalpy distribution in natural gas 1 and 2 both are 7.8 MW, GT1: 57.2 MW, GT2: 57.4 MW, HPT Steam Turbine: 18.4 MW, LPT: 4.2 MW, intake air: 7 MW, Sink Source 38 (air enters as a medium for steam condensation): 399.4 MW. Equipment which absorbs energy are compressors 1 and 2 both are 25.7 MW, ACC Fan: 2.27 MW, stacks 1 and 2 both are 90.1 MW, sink source 39 (air exits after absorbing heat in condenser then released into environment): 331.7 MW.

Steam is able pass through damaged ASV so steam can open ACV to produce 4.2 MW of LPT power (Figure 10).

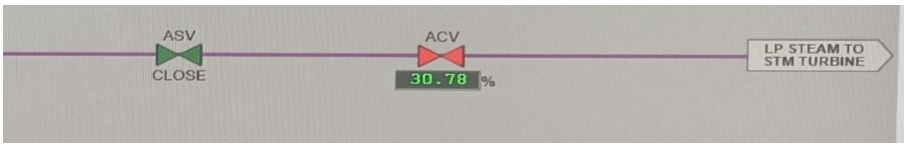


Figure 10. ASV and ACV position on LP Turbine

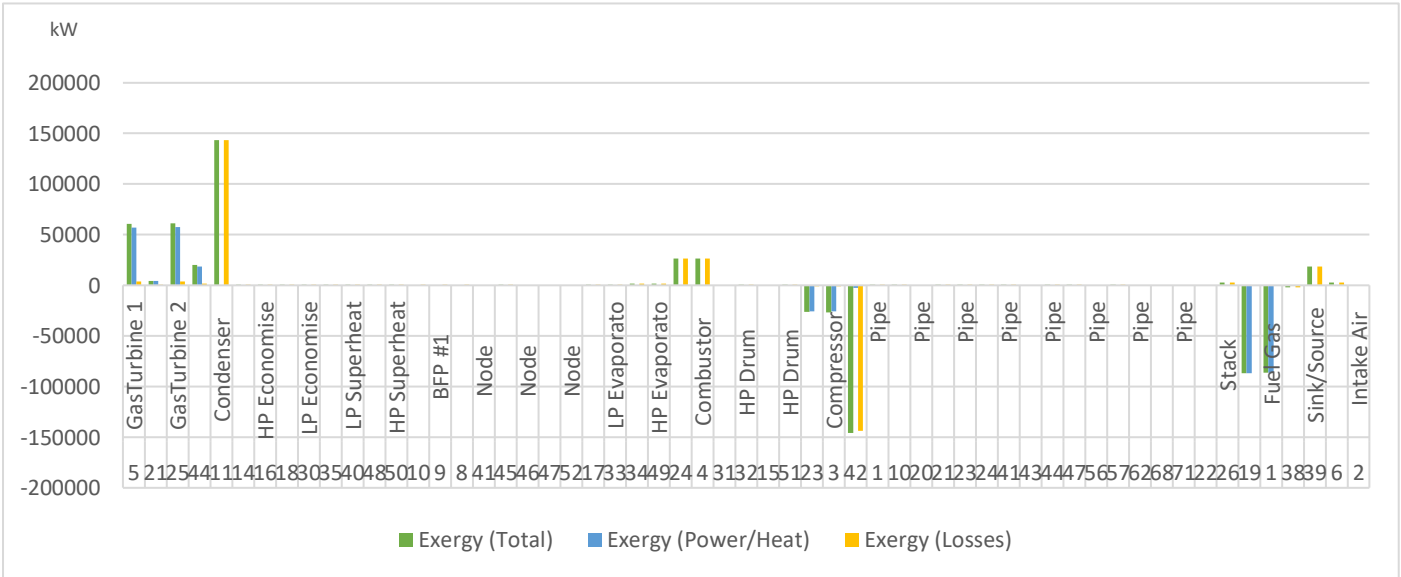


Figure 11. System Exergy in scenario 2

Figure 11. shown exergy distribution and exergy losses graph in each part of CCPP. The largest exergy loss is in condenser: 143.4 MW (81.9%). Large exergy losses are in combustion chamber of Combustor 1: 26.4 MW (15.05%) and Combustor 2: 26.5 MW (15.14%), sink source 39 (air used for steam condensation process): 18.5 MW (10.6%), GT1: 3.57 MW (2%) and GT2: 3.58 MW (2.1%), stack 1: 2.65 MW (1.5%) and stack 2: 2.64 MW (1.5%) with HPT Steam Turbine: 1.5 MW (0.9%) and LPT: 0.26 MW (0.15%). Exergy losses are found in ACC Fans: 143.7 MW (82%), sink source 38 (heat loss to atmosphere): 1.9 MW (1.14%).

3.3. Air Cooled Condenser A and E malfunction in Scenario 3

Scenario 3 with 2-2-1 configuration but power plant load must be reduced to prevent generator from being tripped due to low condenser vacuum protection caused by damage of two ACC fans A and E. Result of Cycle Tempo analysis as follows:

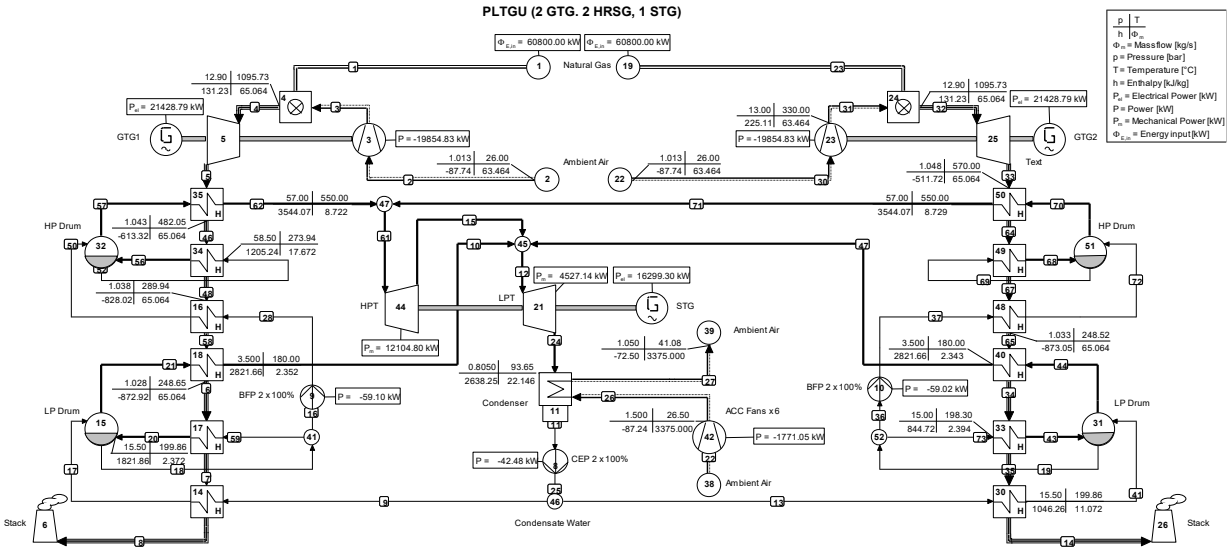


Figure 12. Scenario 3 process diagram

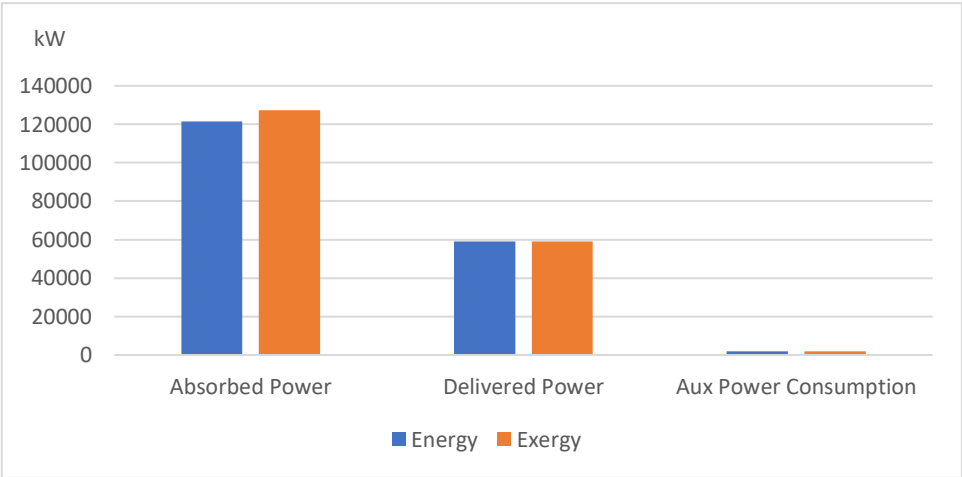


Figure 13. Power generated in scenario 3

Total load of CCPP with scenario 3 is 59.2 MW and load used for CCPP self-consumption is 1.93 MW so net load produced is 57.2 MW. Energy absortion from natural gas fuel is 121.6 MW. Exergy absorption from natural gas is 127.3 MW. Total exergy produced is 59.16 MW and exergy self-consumption is 1.93 MW so net exergy produced is 57.2 MW (Figure 13). Based on Cycle Tempo analysis, energy efficiency result from scenario 3 is 47.06% with net exergy 44.94%.

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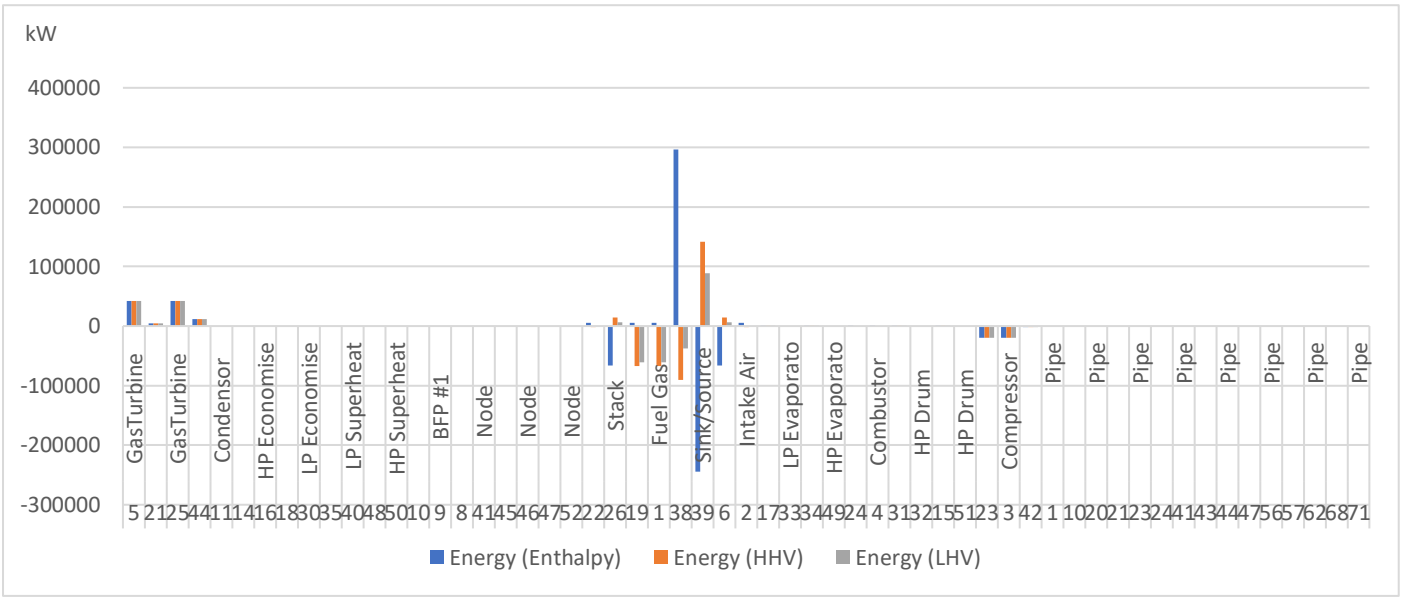


Figure 14. Energy distribution in scenario 3

Figure 14. is energy balance graph in form of enthalpy distribution in various parts, including natural gas 1 and 2 both are 5.7 MW, GT 1 and 2 both are 41.8 MW, Steam Turbine HPT: 12.1 MW, LPT: 4.56 MW, intake air 1 and 2 both are 5.56 MW, Sink Source 38 (air enters as a medium for steam condensation): 296.1 MW. Equipment which absorbs energy are compressors 1 and 2 both are 19.8 MW, ACC Fans: 1.7 MW, stacks 1 and 2 both are 66.4 MW, sink source 39 (air exit after absorbing heat in condenser then released into environment): 244.7 MW.

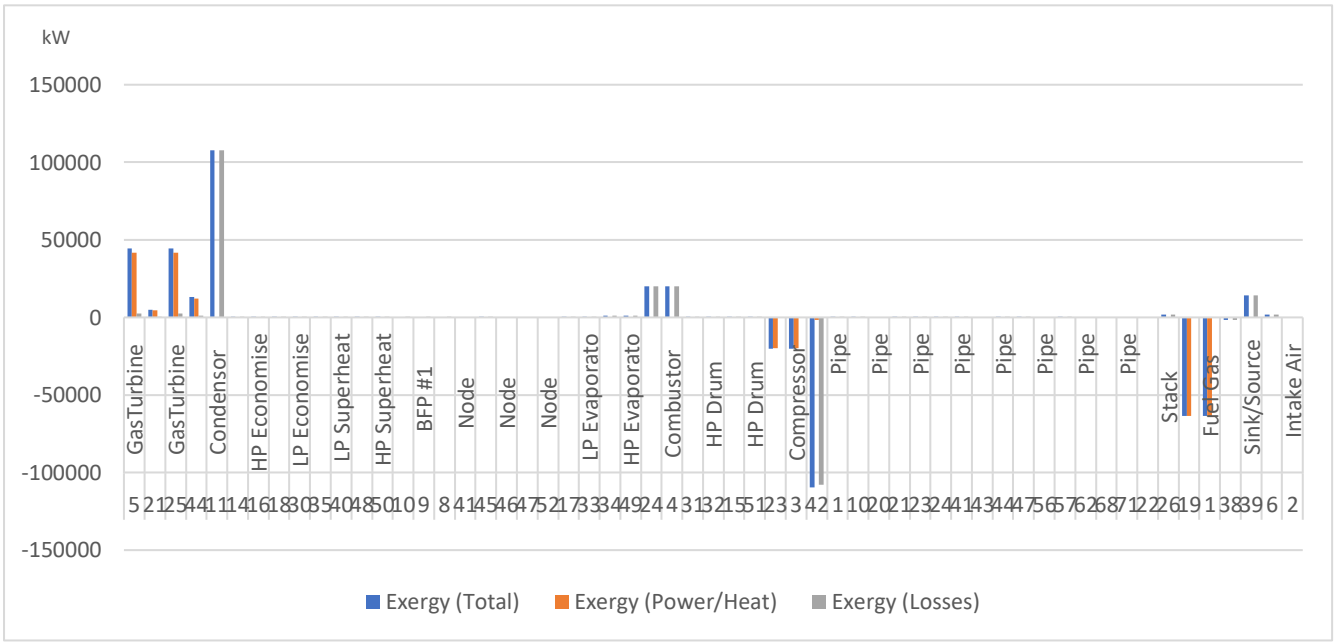


Figure 15. System Exergy on scenario 3

Figure 15 shown exergy distribution and exergy losses graph in each part of CCPP. The largest exergy loss is in condenser: 107.6 MW (83.41%). Large exergy losses are also found in combustion chambers of Combustor 1 and 2 both are 20.2 MW (15.6%), sink source 39 (steam condensation process with air):14.2 MW (11.02%), GT1 and GT2 both are 2.7 MW (2.1%), stack: 1.98 MW (1.54%) and HPT Steam Turbine: 1.1 MW (0.87%). Large exergy losses are found in ACC Fans: 10.8 MW (83.5%), sink source 38 (energy loss to atmosphere): 1.62 MW (1.25%).

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3.4. Open Cycle Operation in Scenario 4

In scenario 4 power plant operates with 2-0-0 configuration, where only two Gas Turbines are operating. Cycle Tempo analysis produces following results:

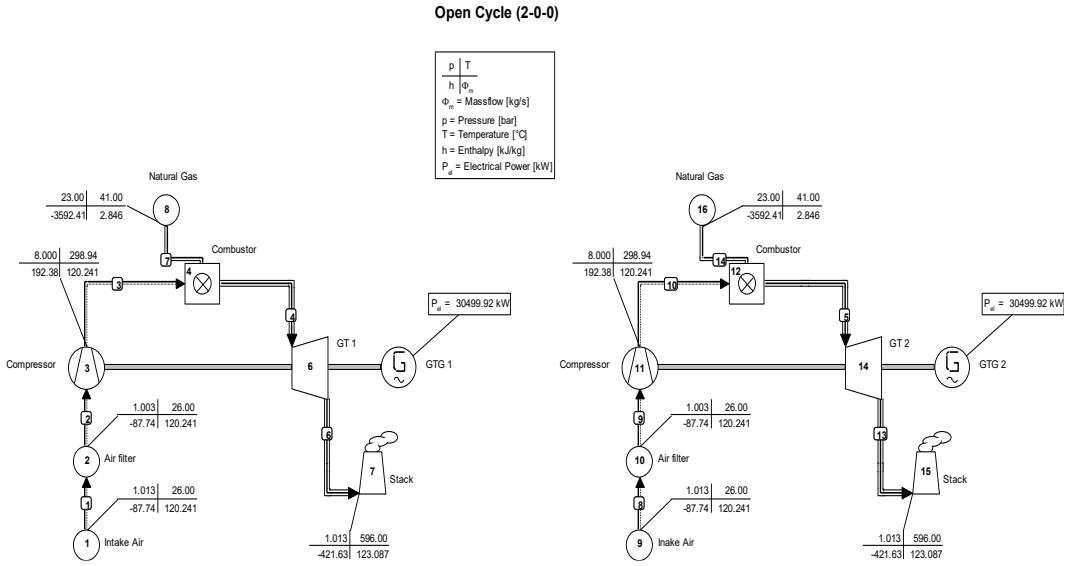


Figure 16. Scenario 4 process diagram

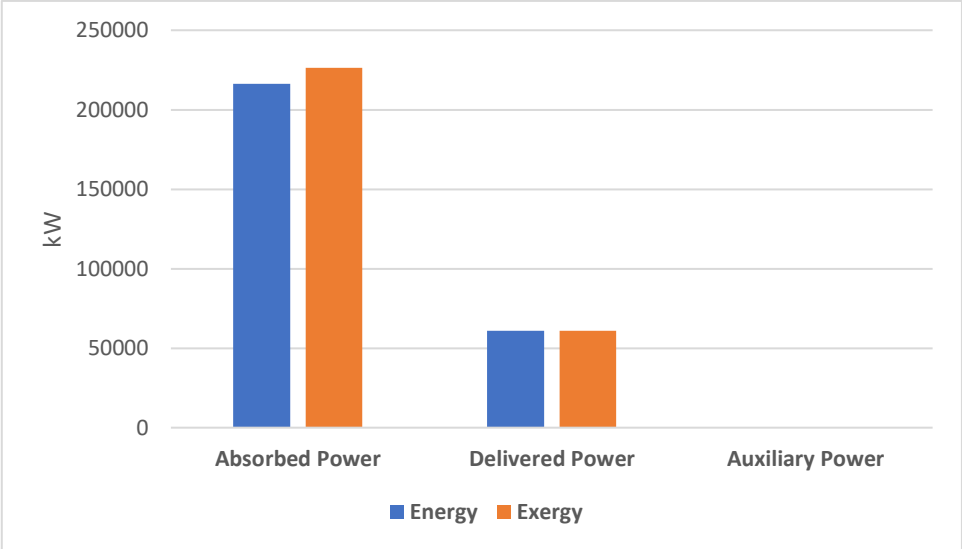


Figure 17. Power generated in scenario 4

From Figure 17, energy efficiency result for scenario 4 is 28.21% and exergy efficiency is 26.9%, with total load 61.0 MW and energy absorption from natural gas fuel is 226.45 MW.

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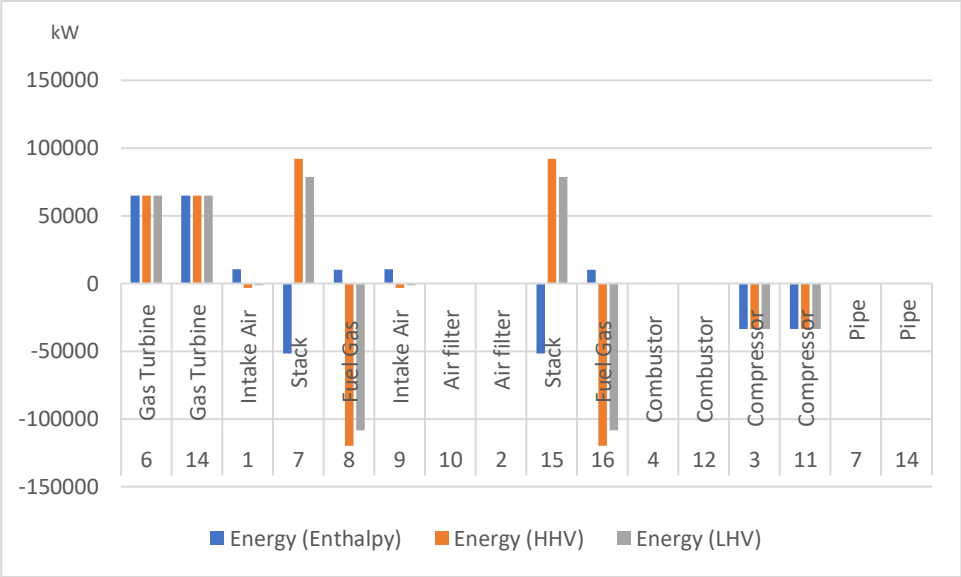


Figure 18. Energy distribution on scenario 4

Figure 18. is an energy balance graph in which energy distribution on GT 1 and 2 both are 64.8 MW, Intake Air 1 and 2 both are 10.5 MW and natural gas 1 and 2 both are 0.2 MW. Energy discharged through stack 1 and 2 both are 51.9 MW, and Compressors 1 and 2 both consumed 33.7 MW of energy.

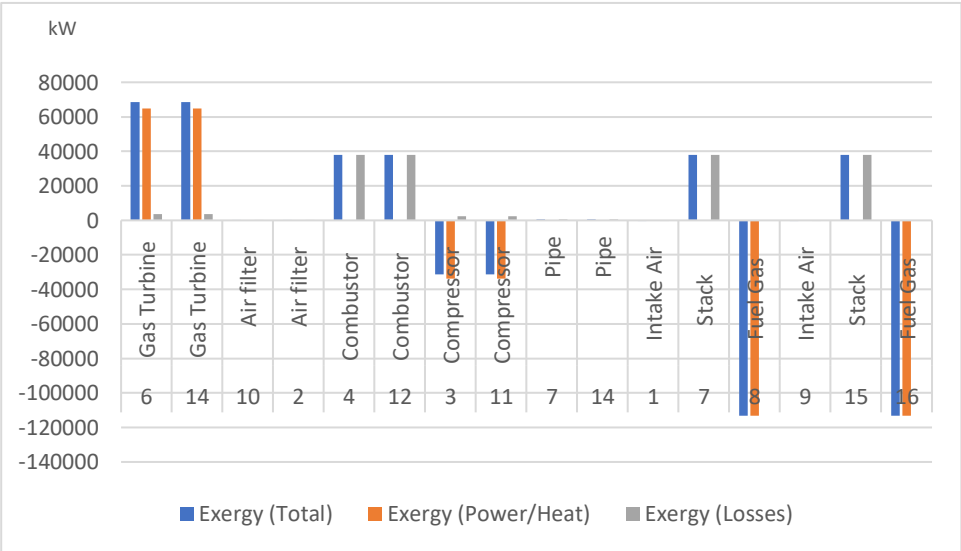


Figure 19. System Exergy on scenario 4

Figure 19 shown the largest exergy loss in combustion chamber of Combustor 1 and 2 both are 37.9 MW (16.7%), stack 1 and 2 both are 37.8 MW (16.7%), GT 1 and 2 both are 3.65 MW (1.61%) and Compressor 1 and 2 both are 2.3 MW (1%).

3.5. Effect of Open Cycle Operation on Environment

Power plant operation challenge nowadays is sustainable and "clean" generation of electric power without exacerbating the adverse impact of the climate change with relevant considerations such as Carbon dioxide emissions – primarily from the heat Heat Recovery Steam Generaton stack but also from the secondary sources such as the emergency diesel generator (black start), pollutant emissions (specifically NO_x and CO), wastewater treatment, water conservation and noise emissions (Gulen, 2020). In thermal process, CO_2, SO_2, and NO_x emissions are mainly important factors in assessing environmental performance and emissions (Javadia et al., 2021). In contrast to other fossil fuel types,

the environmental impact of natural gas consumption is significantly lower, with far lower carbon dioxide (CO2) emissions. For this reason, natural gas is expected to serve as an essential potential factor in shifting to the use of fuels, allowing energy production without generating CO_2. However, it would be important that natural gas be consumed using highly energy efficient technologies such as Combined Cycle Power Plant (Sukpancharoen. S and Prasartkaew. B, 2021)

Special attention to environment must be given during operational of scenario 4 with an open cycle, because exhaust gas from both Gas Turbines are not utilized and still in high temprature (596°C) which then discharged directly into surrounding environment and it can increase level of greenhouse gas emissions and air pollution. High exhaust gas temperatures indicate inefficient fuel combustion, which means more greenhouse gas emissions such as carbon dioxide (CO_2) are released into the atmosphere.

Open cycle power plants, raise environmental concerns due to their reliance on fossil fuels and associated emissions. These plants release significant amounts of pollutants into the air, including sulfur dioxide, nitrogen oxides, and carbon dioxide which contribute to climate and air quality issues. Additionally, they can impact water resources through water intake for cooling and discharge of heated water.

Several type of emissions from open cycle operations may create air pollution because of fossil fuels burning inside open cycle gas turbines combustion chamber which releases CO_2 as a major contributor to climate change, it can result in air quality degradation because of SO_2 and NO_x emissions which contribute to acid rain, smog and respiratory problems and it can also relesase particulate matter which can have adverse health effects.

Whilst open cycle gas turbines are a relatively inexpensive and quick way to generate electricity, their environmental impact necessitates careful consideration and mitigation efforts. Exploring more efficient technologies, renewable energy sources, and strategies to minimize emissions are crucial for a sustainable energy future.

On the other side Open cycle conditions are sometimes unavoidable when the CCPP experiences start up, shutdown, disruption or maintenance. Open cycle operation 2-0-0 on CCPP should be avoided as much as possible and carried out as briefly as possible. It is not recommended to carry out CCPP operations continuously.

4. Conclusion

Energy efficiency in scenario 1 which is 49.26%, is almost the same compared to energy efficiency in scenario 2, which is 49.1% where CCPP operates with the same GTs and ST loads but in scenario 2 ST ASV experiences actuator malfunction. Total load in scenario 1 is 84 MW and scenario 2 is 83.8 MW. Based on these two scenarios, it shown that LPT damage does not have a major impact on CCPP efficiency. Although ASV actuator is damaged, steam can still pass through an ASV so Control Valve is able to open by 30.8% to produce 4.2 MW power at LPT. Scenario 3 where load of both GT must be reduced to 21.4 MW to avoid low vacuum tripped protection where ST load is 16.3 MW with net CCPP efficiency is 47.6%. Total load in scenario 3 is 59.2 MW in which CCPP experiences load reduction of 23 MW in order for continue operation. In scenario 4, an open cycle efficiency of 28.2% was obtained with a total load of both GTs is 61 MW. When compared to scenario 3 where both scenarios operate with almost the same load but Combined Cycle efficiency is much greater (47.6%) compared to the open cycle efficiency of 28.2% which is caused by exhaust gas temperature that is not utilized but is discharged through stack to the atmosphere. The largest exergy loss occurs in the Condenser, which is 81.9% in each of scenarios 1 and 2 and 83.4% in scenario 3. Based on these results, greater exergy loss occurs in scenario 3 where 2 ACC fans are malfunction, resulting in greater losses due to suboptimal vacuum. Significant exergy losses also occur in combustion chamber: 15.1%, 15.05%, 15.6% in scenarios 1, 2 and 3 and 16.7% in scenario 4. Large exergy losses in scenario 4 also occur in the stack which is 16.7%.

Acknowledgement

We are grateful and thankful to the power plant colleagues and renewable energy team for the support and discussion required in this research.

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