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Energy, Exergy, Exergoeconomic and Exergoenvironmental Modeling of a Proposed Multigeneration Power Plant

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ABSTRACT

There is rising energy demand; yet, nonconventional fuels are yet to meet these demands. It has been established that fossil fuels contribute to global warming and climate change. How, then, do we use of fossils to power our lives and industries without endangering our environment and humanity? Here, comes integrated multigenerational power plant. A Multigeneration power plant system is an advanced and integrated approach that goes beyond cogeneration (Combined Heat and Power - CHP) by simultaneously producing multiple forms of energy from a single or double fuel source. In addition to generating electricity and useful heat, a multigeneration power plant can also produce cooling, desalination, or other valuable products or services. This innovative system maximizes the energy efficiency of the overall plant, utilizing the waste heat and by-products to provide additional functionalities. The present work is a proposed multigenerational power plant that comprises of a gas turbine, HRSG, steam turbine, a biomass gasification plant, solar PVT system, a PEM Electrcolyzer, VARS and a Kalina Cycle. The fuel input-output model is 2 X 5: natural gas and syngas from biomass gasification process, while outputting multiple sources of energy – electricity, heating, cooling, hydrogen production and drying. The whole integrated multigenerational power plant was modeled in Engineering Equation Solver (EES). The Net power is 51.404MW; Thermal efficiency 40.1%; exergy efficiency 62.02%; sustainability 1.39. Exergoeconomic assessment provided useful information to enhance the cost-effectiveness of the integrated multigenerational power plant system by evaluating each component separately. NO emission rates 0.04393 kg/s, CO emission 0.00934 kg/s, CO_2 specific emission is 0.3364 kgCO2/MWh; all environmental indicators confirmed it is the most environmentally friendly option.

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Introduction

Energy plays a critical role in driving almost all practical processes and is essential to sustain life. Energy exists in several forms, e.g., light, heat, electricity [1]. The environmental pollution resulting from the production of energy from fossil fuels has been augmented by an increase in global energy consumption, which has directed the researches to find alternative to produce clean energy [2]. Concerns exist regarding limitations on easily accessible supplies of energy resources and the contribution of energy processes to global warming as well as such other environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and radioactive emissions. Reducing the usage of carbon-based fuels and sources will contribute to decrease level of global warming. Hence, renewable energy based multigeneration systems emerge as an alternative solution [3]. Overall, the proposed multigeneration system offers a very promising application and a number of benefits such as a generating multiple useful product with no adverse effect on the thermodynamic efficiency of the triple power cycle [4]. Multigeneration systems are becoming increasingly appealing as effective methods to generate different useful products concurrently [4]. There are several studies in the literature conducted to develop, design, and evaluate different types of multigeneration systems based on energy recovery from power cycles. Recovering the waste or available heat from a source or process is one of the main objectives for developing multigeneration systems [5]. In any multigeneration system, the available heat can be used by different cycles and processes to generate electricity, cooling, heating, freshwater, hot water, hydrogen [2,6,7]. Renewable energy based multigeneration systems are a dynamic area of research, with many studies proposing various options for alternatives to current fossil fuel based systems [8].

Review of Previous Work

Reviews of peered reviewed journals are presented in this subsection. The objectives of this subsection is review literatures, who have designed, modeled, optimized and analysed monogeneration, cogeneration, trigeneration and multigeneration/or polygenerations. These systems efficiently manages and utilizes energy resources to achieve the best possible energy output sources, such that these power plants, when they are designed, modeled, optimized and analysed, are capable of achieving higher energy efficiency, higher exergy efficiency, cost-effectiveness, and are environmentally sustainable. It also involves using smart systems to optimize energy production. The goal of energy resource optimization is to minimize energy waste, reduce energy consumption, and maximize the utilization of renewable energy sources. Again, this review is to establish knowledge gab for the aforementioned goal of energy resource optimization.

Single Energy Source, Two Energy Ouput Power Plant

Figure 1 shows Single Energy Source, Two Energy Output model of power plant. in this model of power plant, A cogeneration power plant system, also known as a Combined Heat and Power (CHP) system, is an energy-efficient approach that simultaneously produces both electricity and useful heat from a single fuel source. In a cogeneration plant, the waste heat generated during electricity production is captured and utilized for heating or other industrial processes, increasing overall energy efficiency.

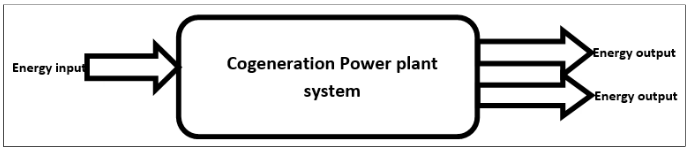

Figure 1: Single Energy Source, Two Energy Output model of power plant

presented a wide and deep analysis of the techno-energy and economic performance of a Solid Oxide Fuel Cell/Gas Turbine hybrid system fed by gas at different compositions of H_2, CO, H_2O, CO_2, CH_4, and N_2 [9]. The configuration of the proposed plant accounts for pressurizing of entering fluids, heat up to the set Solid Oxide Fuel Cell inlet conditions, Solid Oxide Fuel Cell thermo-electrochemical processing, Solid Oxide Fuel Cell-exhaust fluids combustion, turboexpansion after heat up, and final recovery unit for cogeneration purposes. An ad hoc numerical modeling was developed and then run in a Matlab calculation environment. The influence on the system was evaluated by investigating the change of the fuel composition, and by managing the main operating parameters such as pressure and the fuel utilization factor. The analysis reports on the specific mass flowrates necessary to the purpose required, by assessing the SOFC outlet molar compositions, specific energies (work) at main system elements, specific thermal energies at main system elements, energy and technical performance for Solid Oxide Fuel Cell energy unit; the performance such as electric and thermal efficiency, temperatures at main system elements. A final sensitivity analysis on the performance, Levelized Cost of Energy and Primary Energy Saving, is made for completion. The overall Solid Oxide Fuel Cell/Gas Turbine system showed a very promising electric efficiency, ranging from 53 to 63%, a thermal efficiency of about 37%, an LCOE ranging from 0.09 to 0.14 $\$$kWh^{-1}, and a Primary Energy Saving in the range of 33–52%, which resulted to be highly affected by the H_2/CO ratio. Also, real syngases at high H_2/CO ratio are noticed as the highest quality, revealing electric efficiency higher than 60%. Syngases with methane presence also revealed good performance, according to the fuel processing of methane itself to hydrogen. Low-quality syngases revealed electric efficiencies of about 51%. Levelized Cost of Energy varied from 0.09 (for high-quality gas) to 0.19 (for low-quality gas) $\$$kWh^{-1}, while Primary Energy Saving ranged from 44 to 52%. Their work is as presented in figure 2.

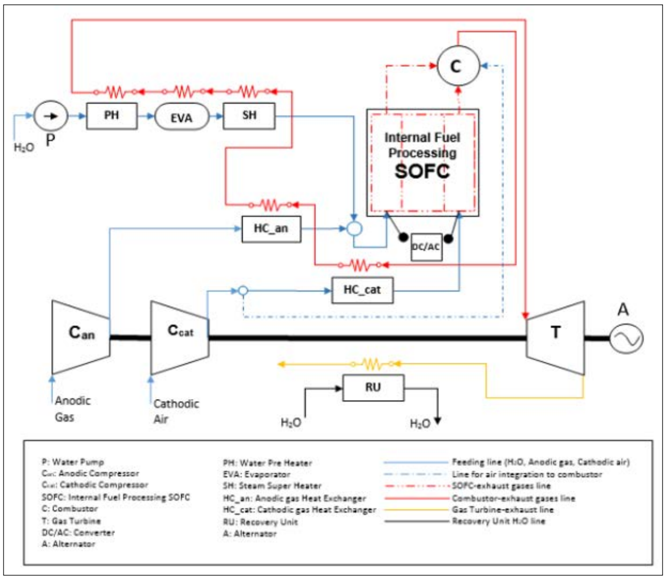

Figure 2: SOFC/GT plant layout [9].

Single Energy Input, Five Energy Output Power Plant

Figure 3 shows model of a single energy input, five energy output of multigeneration power plant; it simultaneously produces mulstiple forms of eenrgy from a single fuel source. In this system, it was designed to produce heating, cooling, drying, hydrogen and power generation with a single energy input. It is an innovative system which maximizes the energy efficiency of the integrated multigenerational power plant, utilizing the waste heat and other by-products to produce additional sources of energy.

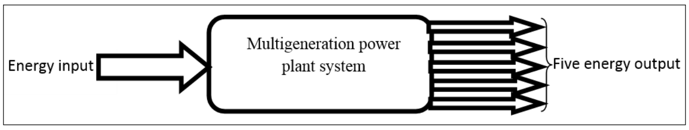

Figure 3: simplified model of a Single Energy Input, Five Energy Output multigenerational power plant.

In figure 4, designed and thermodynamically analyzed a new solar power assisted multigeneration system. In this system, it was designed to perform heating, cooling, drying, hydrogen and power generation with a single energy input [6]. The proposed study consists of seven sub-parts which are namely parabolic dish solar collector, Rankine cycle, organic Rankine cycle, PEM-electrolyzer, double effect absorption cooling, dryer and heat pump. The effects of varying reference temperature, solar irradiation, input and output pressure of high pressure turbine and pinch point temperature heat recovery steam generator are investigated on the energetic and exergetic performance of integration system. Thermodynamic analysis result outputs show that the energy and exergy performance of overall study are computed as 48.19% and 43.57%, respectively. Moreover, the highest rate of irreversibility has the parabolic dish collector with 24,750 kW, while the lowest rate of irreversibility is calculated as 5745 kW in dryer. In addition, the main contribution of this study is that the solar-assisted multi-generation systems have good potential in terms of energy and exergy efficiency.

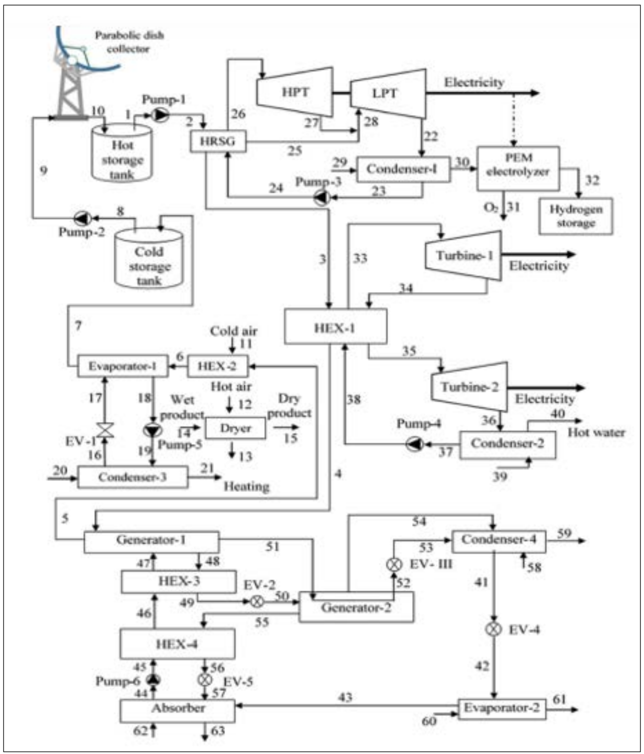

Figure 4: Schematic diagram integrated system with hydrogen production [6],

Two Energy Input, Four Energy Output power plant

Figure 5 shows Multigeneration Power plant system with a dual fuel input and a tetra energy output of hydrogen, power, heating-cooling and hot water generation.

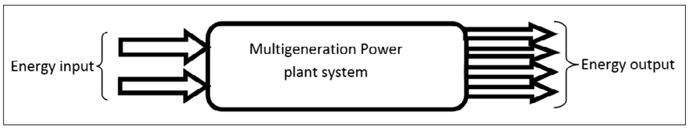

Figure 5: simplified model of a two energy input, four energy output multigeneration power plant

proposed a new combined gasification process using various waste materials for multigenerational operation, containing the hydrogen, power, heating-cooling and hot water generation [10]. In the present multigenerational plant, a waste material gasifier component is combined with the Brayton cycle, Stirling engine cycle, single effect absorption cooling cycle and proton exchange membrane electrolyzer for multiple outputs generation. To analyze and evaluate this integrated system, a comprehensive thermodynamic analysis and assessment for the multigeneration plant components is introduced, the second-law efficiency, associated with the overall system and its sub-systems are described, and the impacts of some arrangements and working statuses on the plant efficiency are investigated. The study results show that, this integrated plant has an overall energetic efficiency of 61.57% and an overall exergetic efficiency of 58.15%, when the produced net power is 94 MW, and also hydrogen generation rate is 0.077 kg/s, respectively.

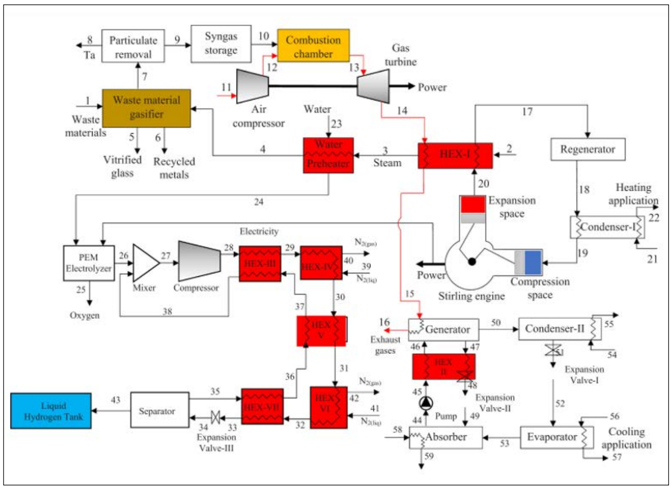

Figure 6A: The schematic diagram of the waste material gasification based integrated system [11].

In their study, (4) a novel multigeneration is proposed that uses the waste heat of a thermodynamically efficient triple power cycle with a 100 MWe capacity. The proposed system, which can generate power, freshwater, cooling, and domestic hot water concurrently, is evaluated using detailed thermodynamic and economic analyses. The triple cycle includes a simple Brayton cycle coupled with a supercritical carbon dioxide recompression cycle and a high-temperature organic Rankine cycle. The waste energy of the recompression and organic Rankine cycles is recovered by a half effect absorption chiller, a multi-effect distillation unit, and two heat exchangers. The results show that for an optimized triple cycle, up to 1,804 kW cooling and 8,472 m3/day of hot water can be generated from the hot supercritical carbon dioxide stream with a levelized cost of cooling and hot water of 0.0362/ton-hr and $0.6823/MWth, respectively. The integration of a multi-effect distillation unit with 7 effects can generate 4,167 m^3/day freshwater with a levelized cost of water of $1.142/$m^3$. The schematic developed and analyzed by (4).

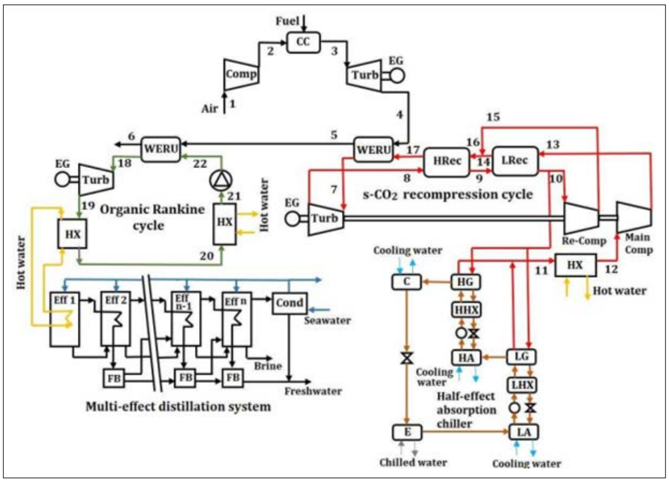

Figure 6B: Schematic of the proposed multigeneration system [4].

One energy source, three energy output system

The trigeneration power plant shown in figure 7, uses a single fuel source to produce multiple energy needs.

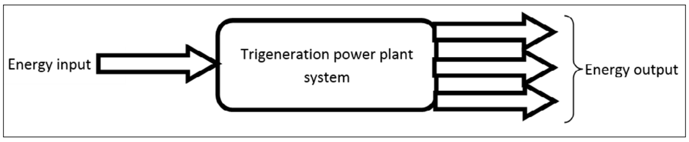

Figure 7: Model of a one energy source, three energy output trigeneration power plant system

proposed novel multi-generation energy system consisting of a solar gas turbine system, multi-effect seawater desalination, LNG cold energy recovery unit, and a double effect absorption chiller [12]. In addition, different working fluids of the ORC system are examined to select the suitable working fluid in terms of global warming potential and exergy efficiency of the system. Subsequently, energy, exergy, and economic (3E) analyses are performed to comprehensively evaluate the energy system. Besides, a parametric study is conducted to assess the effect of the most influential decision variables on the proposed system. Afterward, the novel multi-objective spiral optimization (MOSPO) algorithm is introduced to minimize total cost rate of the system while maximizing the exergy efficiency as the conflicting objective functions. The proposed algorithm is developed to optimize the decision variables effectively. To ascertain the final optimum solution point, three conventional methods i.e. TOPSIS, LINMAP and Shannon's entropy are implemented. The results revealed that exergy efficiency and total cost rate of the system at the baseline are 60.05%, and 36.75 $/h, respectively. Furthermore, the net power output of the system would be 106.5 kW in addition to 0.7703 kW heating load, 56.01 kW cooling capacity, and 35.74 kg/h fresh water production capacity. The eco-environmental assessment revealed the fact that the proposed renewable-based energy system is capable of avoiding 485 tons CO_2 emissions annually, and product cost rate reduction up to 6 $/hr in comparison to coal and natural gas-based energy systems. Figure 8 shows schematic of the solar gas turbine-based multi-generation energy system [12].

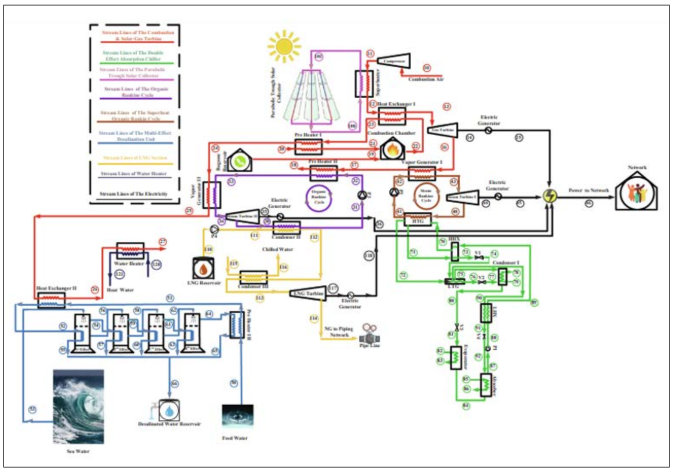

Figure 8: The schematic of the solar gas turbine-based multi-generation energy system [12].

A new gasification system is developed for the three useful outputs of electricity, heat and hydrogen and reported for practical energy applications [13]. The study also investigates the composition of syngas leaving biomass gasifier. The composition of syngas is represented by the fractions of hydrogen, carbon dioxide, carbon monoxide and water. The integrated energy system comprises of an entrained flow gasifier, a Cryogenic Air Separation (CAS) unit, a double-stage Rankine cycle, Water Gas Shift Reactor (WGSR), a combined gas–steam power cycle and a Proton Exchange Membrane (PEM) electrolyzer. The whole integrated system is modeled in the Aspen plus 9.0 excluding the PEM electrolyzer which is modeled in Engineering Equation Solver (EES). A comprehensive parametric investigation is conducted by varying numerous parameters like biomass flow rate, steam flow rate, air input flow rate, combustion reactor temperature, and power supplied to the electrolyzer. The system is designed in a way to supply the power produced by the steam Rankine cycle to the PEM electrolyzer for hydrogen production. The overall energy efficiency is obtained to be 53.7% where the exergy efficiency is found to be 45.5%. Furthermore, the effect of the biomass flow rate is investigated on the various system operational parameters. Figure is a representation of schematic flowsheet of the proposed energy system based on biomass gasification [13].

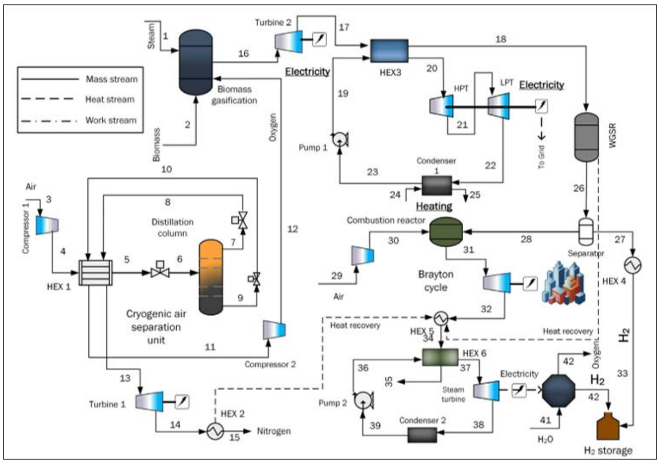

Figure 9: Schematic flowsheet of the proposed energy system based on biomass gasification [13]

A comprehensive thermodynamic study of a multigeneration system, based on a heat recovery unit, an organic Rankine cycle (ORC), an ejector refrigeration cycle, a domestic water heater and a proton exchange membrane (PEM) electrolyzer, for residential applications is undertaken to produce multiple commodities, in terms of power, heating, cooling, hot water, electricity and hydrogen [1]. The present study covers both energy and exergy analyses and multi-objective optimization. To determine the irreversibilities in each component and assess the system performance, a parametric study is performed to investigate the effects of varying design parameters and operating conditions on the system energy and exergy efficiencies. A multi-objective optimization with an evolutionary algorithm is applied to determine the best design parameters for the present system. The two objective functions utilized in the optimization are the total cost rate of the system (known as the cost associated with component purchasing and environmental impact) and the system exergy efficiency. The total cost rate of the system is minimized while the cycle exergy efficiency is maximized by using an evolutionary algorithm. To provide a better understanding, the Pareto frontier is shown for multi-objective optimization. In addition, a closed form relationship between exergy efficiency and total cost rate is derived. Figure 10 is a Schematic of a multigeneration system based on an ejector refrigeration cycle and PEM electrolysis for buildings [1].

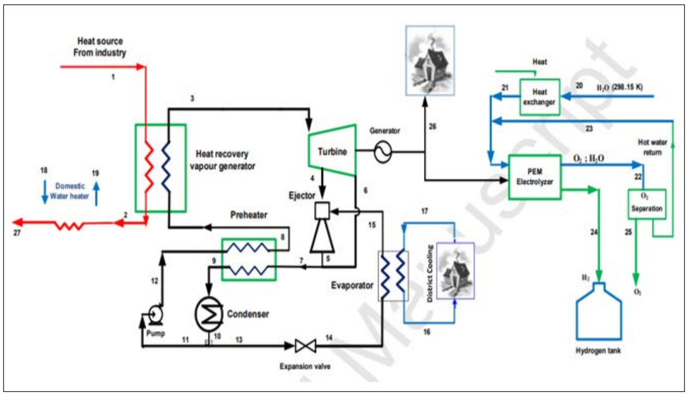

Figure 10: Schematic of a multigeneration system based on an ejector refrigeration cycle and PEM electrolysis for buildings [1].

One energy source, four energy source power plant

Figure 11 shows a schematic of one energy source, four energy source multigeneration power plant. The adoption of multigeneration power plant systems contributes to a more resilient and environmentally friendly energy infrastructure, addressing the increasing demand for diverse energy services in a world facing energy and environmental challenges.

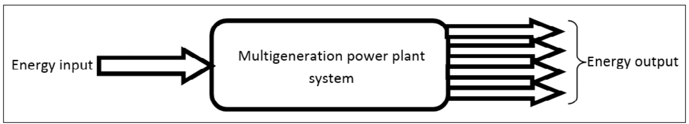

Figure 11: schematic of one energy source, four energy source multigeneration power plant

An energy-exergy methodology was applied to achieve more precise conditions for hot water, cooling, power and hydrogen production via a proposed multi-generation system comprised of a geothermal based organic Rankine cycle, domestic water heater, absorption refrigeration cycle and proton exchange membrane electrolyzer. The proposed novel multi-generation energy system in order to produce heating, cooling, electrical power and hydrogen. Furthermore, for evaluation of the proposed system performance, the effects of such key variables as brine temperature, turbine inlet temperature, generator temperature, brine mass flow rate and electrolyzer current density on the related efficiencies of energy and exergy for the whole system were investigated. For specified conditions, the results show that energy and exergy efficiencies of the entire system are calculated around 33.92% and 43.59%, respectively. Moreover, estimation of the exergy destruction rate in each system component indicated that the highest rate of exergy destruction occurred in the heat recovery steam generator (HRSG) with 16.65% of the total amount of exergy input to the system. And finally, net electrical power output, mass flow rate of hot water, cooling capacity and mass flow rate of hydrogen production are as follows: 816.7 kW, 7.06 kg/s, 1896 kW and 0.05g/s. Figure 12 shows schematic of the proposed multi-generation system [2].

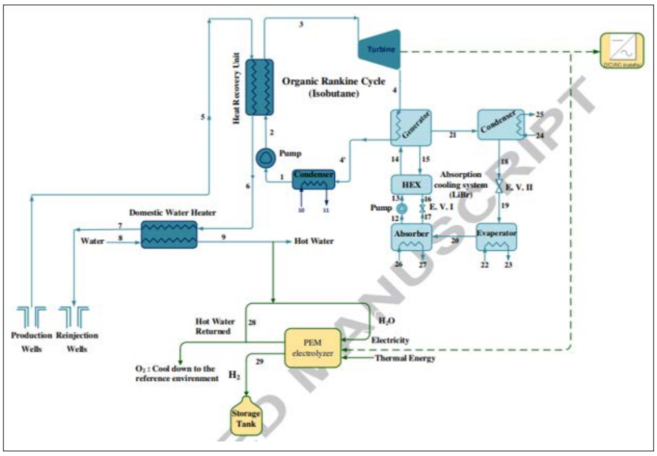

Figure 12: Schematic of the proposed multi-generation system [2].

Two energy input sources, three energy output power plant

Figure 13 is a representation of a two energy input sources, three energy output trigeneration power plant system. The system uses two fuel input to achieve, as product, three energy sources.

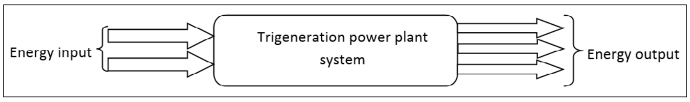

Figure 13: schematic of two energy input sources, three energy output power plant

Proposed a new renewable energy based multigeneration system, which integrates a solar PV/ T system and a geothermal energy system to produce electricity and heat for power, heating, cooling, hot water and drying air, and investigates the design, analysis and assessment of this integrated system [3]. The psychometric processes are utilized for obtaining required dry agent from the ambient air, and an air circulation system is used to benefit from the heat transferred from the PV modules to the air, which ultimately increases the PV/T efficiency and hence the overall efficiency. We also assess the performance of the system, through energy and exergy analysis methods, for a selected common case and obtain overall energy and exergy efficiencies of 11% and 28%, respectively. The selected parametric studies investigate the effects of various environmental and operating conditions on the energy and exergy efficiencies of the overall system and subsystems.

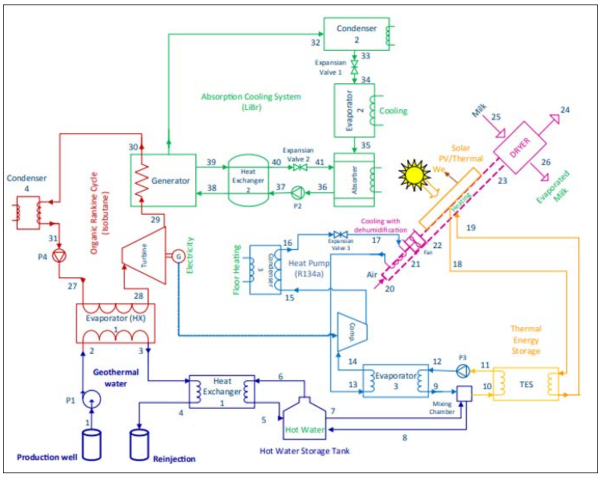

Figure 14: Schematic of designed multigeneration system [3].

However, the present work is to propose a multigeneration power plant that would produce heating (space, water, process heating), power, cooling (A/C, water, process cooling), synthetic fuel (hydrogen), using as energy input, natural gas and municipal solid waste. This multigeneration power plants was designed in such a way that it is beneficial to industries where multiple energy needs coexist, such as industrial complexes, data centers, and large-scale urban developments. It is to offer a sustainable and efficient solution by optimizing resource utilization and minimizing energy waste.

Systems description

s/no	Process		Component	Description of process
	State point			
	From	To		
1	1	2	air cooler	It absorbs heat from the air and reducing its temperature.
2	2	3	air compressor	It works by drawing in ambient air and compressing it to a higher pressure
3	3	4	combustion chamber	Fuel is mixed with compressed air, and the combustion process generates high-temperature and high-pressure gases that expand through the turbine, producing mechanical power or generating electricity.
4	4	5	Fuel input	Fuel to charge the combustion is inputed
5	6	4	Combustion chamber	Fuel is mixed with compressed air, and the combustion process generates high-temperature and high-pressure gases that expand through the turbine, producing mechanical power or generating electricity.
6	8	7	Biomass gasification	organic waste are thermochemically converted into a gas called "syngas" or "producer gas," by the process of partial combustion of biomass in a controlled oxygen-limited environment, producing a mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and other gases. It can be utilized in gas engines to generate electricity, in gas turbines for power generation, as a fuel for heating and cooking, or as a feedstock for the production of biofuels and chemicals.
7	7	6	biomass gasification product clean up	The syngas produced contains impurities such as tar (complex hydrocarbon that can cause blockages and damage downstream equipment), particulate matter (solid particles suspended in the syngas, which can cause wear on engine components and reduced combustion efficiency) , alkali metals (can cause catalyst poisoning and corrosion), sulphur compounds (high sulphur content can lead to corrosion and environmental pollution. desulphurization processes like absorption, adsorption, or catalytic conversion are used to reduce sulphur content) and other contaminants are removed before the gas is used as a fuel or feedstock into the combustion chamber
9	10	12	Supplementary firing	Supplementary firing allows for higher steam temperatures and pressures, leading to increased power generation. By injecting additional fuel into the combustion chamber or downstream sections, the temperature of the flue gases is raised, which in turn increases the heat transfer to the boiler's steam cycle. It boosts the power output during peak demand periods, by introducing additional fuel into the combustion chamber downstream of the gas turbine's primary combustion zone, the temperature and pressure of the exhaust gases are increased, leading to more power generation.
10	11		Fuel oil input	The fuel oil input is a critical parameter in energy systems, as it directly impacts the energy output and efficiency of the system. In power plants, the fuel oil input determines the power generation capacity and affects the overall cost of electricity production. In boilers and furnaces, the amount of fuel oil input influences the heat output and temperature levels, impacting the process efficiency and productivity.
11	12	13	HRSG	It recovered waste heat from gas turbines and convert it into steam. The HRSG captures the hot exhaust gases from the gas turbine and uses them to generate steam, which was then be used to drive the steam turbine for additional power generation. It maximizes the efficiency of power plants by utilizing the heat that would otherwise be wasted. It improves the overall energy conversion process and increases the power plant's efficiency, making it a cost-effective and environmentally friendly solution for electricity generation.
12	13	16	Heat exchanger	It allows the heat to transfer from one fluid to the other without the two fluids mixing. As the hot fluid passes through one side of the heat exchanger, it gives up its heat to the colder fluid on the other side, resulting in temperature exchange.
13	15	14	PVT system	It is a innovative hybrid solar energy systems that combine photovoltaic and solar thermal technologies with the use of nanofluids. It simultaneously generate electricity and harvest thermal energy from sunlight, maximizing the overall energy conversion efficiency. The PV component converts sunlight directly into electricity, while the thermal component absorbs excess heat from the PV module, preventing overheating and improving its electrical performance. The nanofluid-based collector enhances thermal energy absorption by using nanoscale particles suspended in a heat transfer fluid, which increases the fluid's heat-carrying capacity. By integrating these technologies, PV/T nanofluid-based collector systems provide multiple benefits, including increased electrical output, enhanced thermal efficiency, and reduced overall system costs. These innovative systems offer a promising solution for more efficient and sustainable solar energy utilization, contributing to the transition towards cleaner and renewable energy sources.

14	16	17	Hydrogen production and storage	Proton Exchange Membrane (PEM) electrolyzer is an electrochemical device that uses electricity to split water into hydrogen and oxygen gases. It consists of an electrolyte membrane that conducts protons, separating the anode and cathode compartments. When an electric current is applied to the PEM electrolyzer, water molecules at the anode release protons (H+ ions) and oxygen gas (O2), while electrons flow through an external circuit to the cathode. At the cathode, protons and electrons recombine to produce hydrogen gas (H2). PEM electrolyzers are known for their fast response time, high efficiency, and ability to operate at low temperatures. They are widely used for hydrogen production, energy storage, and as a key component in renewable energy systems for converting excess electricity into storable hydrogen fuel.
15	16	18	Oxygen storage	Oxygen storage refers to the practice of storing oxygen gas in various forms for various applications. Oxygen is a critical element in supporting life and is used extensively in medical, industrial, and aerospace fields. In the medical sector, oxygen is stored in high-pressure cylinders or liquid oxygen tanks to provide supplemental oxygen to patients with respiratory conditions or during medical procedures. In industrial applications, oxygen storage is essential for various processes, such as metal cutting and welding, steel production, and wastewater treatment. In aerospace, oxygen storage is critical for providing breathable air to astronauts during space missions or high-altitude flights.
16	19`	20	Steam turbine	It is a vital component in power plants and other industrial applications for generating electricity or driving mechanical equipment. The steam turbine works on the principle of the Rankine cycle, where high-pressure steam is directed into the turbine's blades, causing them to rotate. As the steam expands and loses energy, it transfers its kinetic energy to the turbine rotor, creating rotational motion. The rotating turbine shaft is connected to a generator, where the mechanical energy is converted into electrical energy.
17	20	23	GEN of VARS	It provides the energy required to drive the refrigeration cycle. In a VARS, the generator uses heat input, typically from a heat source like a burner or waste heat recovery, to separate the refrigerant (usually ammonia or lithium bromide) from the absorbent (usually water or lithium bromide). During this process, the heat causes the refrigerant to vaporize and rise to a higher pressure level, while the absorbent remains in a liquid state. The high-pressure vaporized refrigerant then moves to the condenser, where it releases heat and condenses back into a liquid, transferring heat from the refrigerated space. The generator is a critical element in the VARS as it enables the continuous cycle of absorption and desorption, allowing the system to provide cooling or refrigeration. By utilizing heat as the driving force instead of mechanical power, Vapor Absorption Refrigeration Systems are more energy-efficient and suitable for certain applications, especially when waste heat or renewable heat sources are available.
18	23	37	COND. Of VARS	Its primary function is to release heat from the high-pressure, high-temperature vaporized refrigerant coming from the generator. In the condenser, the vaporized refrigerant undergoes a phase change from a gas to a liquid as it releases heat to the surrounding environment or a cooling medium, such as air or water. This heat removal process causes the refrigerant to condense into a high-pressure liquid. The condensed liquid refrigerant then moves to the expansion valve or throttling device, where its pressure is reduced, leading to a drop in temperature. This low-temperature, high-pressure liquid then enters the evaporator, where it absorbs heat from the refrigerated space, producing the cooling effect. The condenser's efficient operation is crucial for maintaining the VARS's performance and overall refrigeration cycle.
19	36	35	Valve of VARS	Regulate the flow and pressure of the high-pressure liquid refrigerant from the condenser to the evaporator. As the high-pressure liquid passes through the expansion valve, it undergoes a rapid pressure drop, causing it to expand and convert into a low-pressure, low-temperature mixture. This expansion results in a cooling effect in the evaporator, where the refrigerant absorbs heat from the surrounding space, providing the cooling or refrigeration.
20	35	32	EVAP of VARS	The low-pressure, low-temperature liquid refrigerant enters the evaporator from the expansion valve. As it flows through the evaporator, it absorbs heat from the surrounding environment, causing it to evaporate and change into a low-pressure vapor.
21	35	33	Cooling for office/ housing complex	Cooling of office/housing complex
22	32	30	ABS of VARS	The high-pressure vaporized refrigerant from the generator enters the absorber. At the same time, a solution of absorbent is circulated in the absorber. As the vaporized refrigerant comes into contact with the absorbent, it dissolves and forms a strong solution of the refrigerant and the absorbent. This absorption process leads to the removal of heat from the refrigerant, and it converts back to a liquid state. The refrigerant-absorbent solution then leaves the absorber and returns to the generator, where the refrigerant is separated from the absorbent through the application of heat in the heat source.

23	24	26	SHX of VARS	In the VARS, the solution heat exchanger plays a key role in improving the system's overall efficiency by preheating the weak solution (low concentration of refrigerant) before it enters the absorber. At the same time, it cools down the strong solution (high concentration of refrigerant) as it leaves the generator. The heat exchange between the two solutions in the SHX helps in reducing the energy consumption of the system, as it allows the weak solution to absorb refrigerant more effectively in the absorber, and the strong solution gives up more heat in the generator. This helps in maintaining the concentration gradient needed for the continuous cycle of the VARS.
24	26	28	Valve 2 of VARS	Used to control the flow and pressure of the refrigerant and absorbent within the system.
25	29	27	Pump of VARS	It operates by creating a flow and increasing the pressure of the fluid, allowing it to be transported through pipes or channels.
26	22	44	EVAP	The high-pressure vaporized refrigerant from the generator enters the absorber. At the same time, a solution of absorbent is circulated in the absorber. As the vaporized refrigerant comes into contact with the absorbent, it dissolves and forms a strong solution of the refrigerant and the absorbent. This absorption process leads to the removal of heat from the refrigerant, and it converts back to a liquid state. The refrigerant-absorbent solution then leaves the absorber and returns to the generator, where the refrigerant is separated from the absorbent through the application of heat in the heat source.
27	44	47	Preheater	It works by transferring heat from a high-temperature source, such as exhaust gases or waste heat, to the fluid or gas, thus increasing its thermal energy.
28	47	49	Hot water	Heated water
29	39	40	Separator	Its main function is to separate the ammonia-water mixture into two streams based on their varying concentrations. The lower concentration ammonia-water mixture is directed back to the evaporator, while the higher concentration mixture is sent to the generator for further heating. This separation process ensures that the working fluid maintains the desired concentration levels required for efficient power generation in the Kalina Cycle. The separator plays a critical role in maximizing the cycle's performance and increasing the system's overall energy conversion efficiency.
30	40	41	Turbine	In the Kalina Cycle, the high-pressure, high-temperature working fluid mixture enters the turbine. As it flows through the turbine, the mixture expands and undergoes an adiabatic process, converting its thermal energy into kinetic energy, causing the turbine blades to rotate. The rotating turbine shaft is connected to a generator, where the mechanical energy is converted into electrical power.
31	41	53	Mixer	Its primary purpose is to blend the higher concentration working fluid stream coming from the generator with the lower concentration stream from the evaporator. By mixing the two streams, the working fluid attains the desired concentration level for efficient power generation in the Kalina Cycle. The mixer plays a critical role in maintaining the working fluid's proper composition, optimizing the cycle's performance, and enhancing the system's overall energy conversion efficiency.
32	53	50	Condenser	In the Kalina Cycle, the vaporized working fluid mixture enters the condenser after the turbine. As the mixture comes into contact with a cooling medium, such as air or water, it releases heat, causing it to condense and transform back into a liquid. The condenser's function is vital for the efficient operation of the Kalina Cycle, as it facilitates the heat rejection process and ensures the working fluid's proper phase change. This high-pressure liquid is then directed to the mixer to blend with the lower concentration working fluid stream from the evaporator, enabling continuous power generation.
33	50	46	Feedpump	The feed pump in the Kalina Cycle ensures a continuous flow of the working fluid mixture to the generator, maintaining the desired pressure level required for the generation process. It plays a critical role in the efficient operation of the Kalina Cycle, as it helps in maintaining the working fluid's proper flow and pressure throughout the cycle.

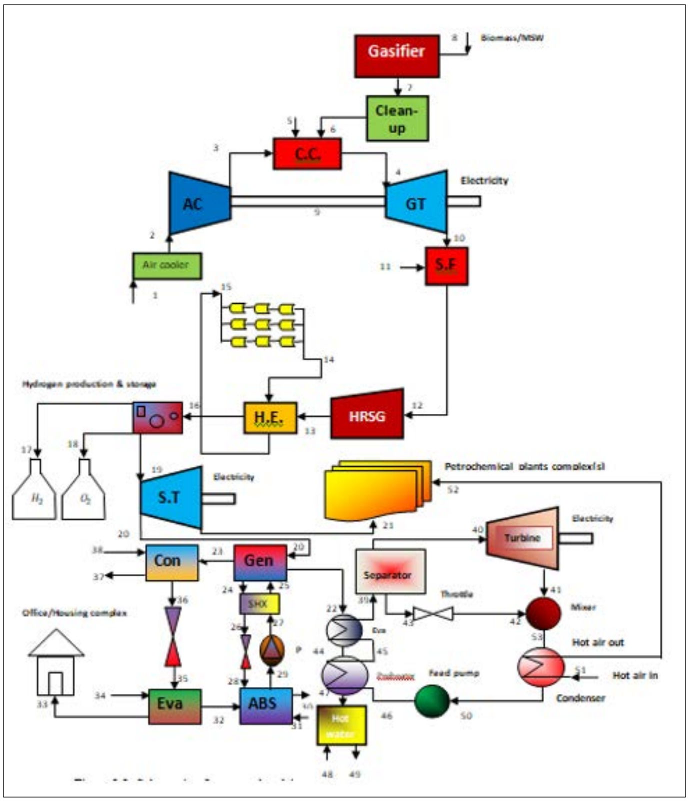

Figure 15: proposed multigeneration power plant

Thermodynamic Modeling of the System

Power Plant Component Energetic and Exergetic Analyses

The energetic and exergetic efficiencies of the entire unit that makes up the selected multigeneration plant was evaluated; they are both tools of the first and second laws of thermodynamics, respectively. For the purpose of investigating the effect of interaction of the plant's units on the energetic and exergetic efficiencies, the thermal power plant units were then grouped into subsystem and overall system. The energy and exergy balances on inlet and exit streams of each process unit were used in the estimation of their energetic and exergetic efficiencies. This study, it is aimed to determine which component of the system should be revised first to raise the efficiency and decrease the loss of exergy. Second law analysis of thermodynamics is applied to each component due to consider the effects of environmental conditions and take the quality.

The thermodynamic analysis (energetic and exergetic) was developed based on the following basic assumptions:

- The cogeneration system are considered as steady state [14,15].
- The principle of ideal-gas mixture was applied for the air and combustion products [14].
- The fuel injected to the combustion chamber (CC) was assumed to be natural gas [14]
- Heat loss from the combustion chamber (CC) was considered to be 2% of the fuel lower heating value (LHV). Heat transfer across the boundaries of other components was assumed negligible, i.e. the heat transfer was considered adiabatic [14].
- The dead/reference state condition is P0 =1.013 bar and T0=298.15 K [14]
- In the combustion chamber (CC), 2% pressure drop was assumed [14].
- Working fluid was assumed to behave as an ideal gas with variable specific heat [14].
- The isentropic efficiency of compressor and turbine are assumed to be constant and equal to 0.85 and 0.87 respectively [14].
- Combustion efficiency and mechanical efficiency were assumed to be constant and equal to 0.98 and 0.99 respectively [14].
- Complete combustion of fuel occurs in combustion chamber [14].
- The exergy value of air entering the compressor was assumed zero chamber [14].
- Kinetic and potential components of energy and exergy were neglected [14].
- The temperature and mass flow rate of the exhaust gases from gas turbine was constant for the HRSG [16].
- The turbine in the system is considered adiabatic [15].
- Physical exergy of natural gas is not used in the analysis since it can be neglected when compared to chemical exergy [15].
- The PVT system is considered as control volume and is assumed to be in semi-steady state condition [17].

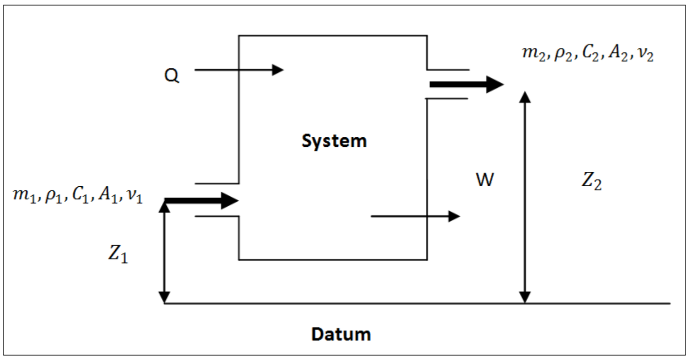

Figure 16: schematic of control volume used modeling of each component

Mass Balance

Mass balance is a fundamental principle in engineering and environmental sciences that involves accounting for the mass of materials entering and leaving a system. It ensures that the total mass of substances in a closed volume (figure 11) remains constant, following the law of conservation of mass [18].

$$\sum_n \dot{m}_i - \sum_n \dot{m}_e = \frac{dm_{cv}}{dt} \qquad (1)$$

Where $\dot{m}$ is the mass flow rate, and cv denotes the volume fraction; the subscripts i and e denotes inlet and outlet of the control volume (figure 11).

Energy Balance

Energy balance is a fundamental principle in thermodynamics that involves accounting for the energy entering and leaving a system. It ensures that the total energy within a closed system remains constant, adhering to the law of conservation of energy.

$$\Delta E = \dot{Q} - \dot{W} + \sum \dot{m}_i h_i - \sum \dot{m}_e h_e \qquad (2)$$

where ΔE is zero for steady state, $\dot{Q}$ and W represent the heat transfer and work energy crossing the component boundaries and m and h represent the mass flow rate and the specific enthalpy of the streams of the system working fluid.

Exergy Balance

Exergy balance is a crucial concept in thermodynamics, particularly in the field of exergy analysis. It involves accounting for the exergy (useful energy) entering and leaving a system. Unlike energy balance, which accounts for total energy, exergy balance focuses on the useful energy potential available within a system. Exergy balance calculations help identify irreversibilities and inefficiencies within processes, allowing engineers to optimize systems for maximum energy utilization and minimal exergy destruction. By understanding the exergy flow rates and transformations, researchers can assess the sustainability and effectiveness of energy conversion systems, leading to improved designs and resource management. Exergy balance is a powerful tool for analyzing the true efficiency and potential of energy systems. The exergy balance for our control volume as shown him figure 11, was modeled using (2):

$$\dot{E}x_q + \sum_i m_i ex_i = \sum_i m_e ex_e + \dot{E}x_W + \dot{E}x_D \qquad (3)$$

In which, subscript i and e are related to the input and output flows. The first term on the left side of the equation is related to the exergy rate associated with Q and the second and third terms in the right of the equation represent the performed work exergy rate the and the exergy destruction rate, respectively. The relations of the energy balance and exergy destruction rate for each

Entropy Balance

Entropy balance is a fundamental concept in thermodynamics that involves accounting for the entropy (measure of disorder) entering and leaving a system. It ensures that the total entropy within a closed system remains constant or increases, following the second law of thermodynamics. For a steady state system, as modeled in figure 11, the entropy balance is defined as

$$\dot{S}_{gen} = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i - \sum_k \frac{\dot{Q}}{T_k} + \frac{dS_{cv}}{dt} \qquad (4)$$

Exergy Destruction

Exergy destruction refers to the irreversibilities and inefficiencies that occur within a thermodynamic system during energy transformations. It represents the amount of exergy (useful energy) lost or wasted during a process. Exergy destruction is a crucial parameter in exergy analysis, as it helps identify sources of inefficiency and potential areas for improvement. Minimizing exergy destruction is essential for enhancing the efficiency and sustainability of energy conversion processes, allowing for better resource utilization and reduced environmental impacts. For a steady state system which was used to modeled the control volume of figure 11, exergy destruction is defined as thus [19].

$$\dot{E}x_i + \dot{E}x_Q = \dot{E}x_e + \dot{E}x_w + \dot{E}x_D \qquad (5)$$

Where $\dot{E}x_i$ and $\dot{E}x_e$ are the outlet and inlet exergy flow rates, respectively. Besides, $\dot{E}x_Q$ is the exergy rate related to the heat transfer (positive for inlet heat), $\dot{E}x_w$ is the work transfer rate (positive for work done by the system), and $\dot{E}x_D$ is the exergy destruction. The exergy destruction modeled in equation (5) for the present work, has as the following defined for each of its term (table 1).

Table 1: Mathematical expressions of terms and or definition of equation (5)

inlet exergy flow rates	outlet exergy flow rates	Exergy heat transfer rate	Exergy work transfer rate	Exergy destruction rate
$\dot{E}x_i = \dot{m}_i ex_i$	$\dot{E}x_e = \dot{m}_e ex_e$	$\dot{E}x_Q = \left(1 - \frac{T_0}{T_i}\right) Q_i$	$\dot{E}x_W = \dot{W}$	$\dot{E}x_D = T_0 \dot{S}_{gen}$

Exergoeconomic Analysis

Exergy Pricing

Exergy pricing is an economic approach that assigns a monetary value to exergy (useful energy) in various energy systems. Unlike traditional energy pricing, which focuses on quantity alone, exergy pricing considers the quality and usefulness of energy. By valuing exergy based on its ability to perform useful work, exergy pricing provides a more accurate assessment of the true costs and benefits of energy resources and processes. This approach helps optimize energy use, prioritize efficient technologies, and incentivize sustainable energy practices, contributing to a more effective and environmentally friendly energy system. The exergy pricing was modeled using [19].

$$\dot{C}_i = c_i \dot{E}x_i \qquad (6)$$

Where $\dot{E}x_i$ is the flow energy rate and c_i is the corresponding cost per exergy unit. Also, the cost is attributed to the exergy flow corresponding to work and heat transfer [19].

$$\dot{C}_q = c_q \dot{E}x_q = c_q Q_k \left(1 - \frac{T_0}{T_i}\right) \qquad (7)$$

$$\dot{C}_w = c_w \dot{W} \qquad (8)$$

Cost Balance

A cost balance which is used for kt^h component of the system determines that the output flows' total cost expresses as the sum of total input flows, investment costs, and repair & maintenance costs.

$$\sum \left(c_e \dot{E}x_e\right)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}x_{q,k} + \sum \left(c_i \dot{E}x_i\right)_k + \dot{Z}_k \qquad (9)$$

where $\dot{Z}_k$ is the cost rate for component, kt^h which is defined as follows

$$\dot{Z}_k = \frac{Z_k . CRF . \varphi}{N} \quad (10)$$

where Z_k is the component's initial buy cost, φ is the coefficient related to the component's repair and maintenance cost, N is the component's annual performance hours, and CRF is the capital recovery factor defined

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (11)$$

where i and n represent the capital profit rate and the system's year of performance, respectively.

Exergoeconomic Variables

Exergoeconomic variables are key parameters used in the field of exergoeconomics, which combines exergy analysis and economic considerations to evaluate energy systems. They play a crucial role in assessing the economic feasibility and efficiency of energy systems, helping engineers and researchers make informed decisions for cost-effective and sustainable energy utilization. The average fuel unit cost for the k^{th} component of the system indicates the average cost under which the fuel exergy unit provides for the component:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}x_{F,k}} \quad (12)$$

Similarly, the average product unit cost defines as the average cost at which every exergy unit is supplied for the component's product

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}x_{P,k}} \quad (13)$$

Exergy Loss and Destruction Cost

The exergy loss and destruction cost is calculated by using concepts of fuel exergy cost, $\dot{C}_{F,k}$, product exergy cost, $\dot{C}_{P,k}$. And the loss cost in a component, $\dot{C}L,k$

$$\dot{C}_{P,k} = \dot{C}_{F,k} - \dot{C}_{L,k} + \dot{Z}_k \quad (14)$$

Exergoeconomic Factor

A component's cost term consists of two different types: exergy depended cost (exergy loss and destruction cost) and the cost independent of the exergy (such as the initial and maintenance and repair costs). The exergoeconomic factor provides the ratio of independent expenditure to an total cost for a component in the system [19].

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \quad (15)$$

In any system, the low amount of exergoeconomic factor shows the high exergy loss and destruction cost, which is usually associated with increased initial investment costs. On the other hand, the high exergoeconomic factor corresponded to a reduced cost of initial investment of that component.

Exergoenvironmental Analyses

To evaluate the system from the environmental point of view and the relation with exergy destruction rate (EDR), exergoenvironmental assessment is noticed. Exergoenvironmental analysis is an extension of exergy analysis that considers the environmental impact of energy systems [20]. It evaluates the exergy destruction and associated environmental consequences, such as greenhouse gas emissions and other pollutants, during energy conversions. This approach helps identify areas of high exergoenvironmental impact and enables the optimization of energy systems for reduced environmental footprint. By integrating environmental considerations with exergy analysis, exergoenvironmental analysis contributes to sustainable energy planning and decision-making, promoting more eco-friendly and efficient energy practices. The exergoenvironmental impact balance for the kth component was modeled by [21- 24].

$$\varepsilon_{ei} = \frac{\dot{E}_D}{\sum \dot{E}_i} \quad (16)$$

Where i represent inlet and D represent destruction.

The environmental damage effectiveness index is modeled thus [22- 24].

$$\varepsilon_{ed} = \frac{\varepsilon_{el}}{\eta_{ex}} \quad (17)$$

The exergy stability factor is calculated by [22-24].

$$\varepsilon_{es} = \frac{\dot{E}_D}{\dot{E}_{out} + \dot{E}_D + 1} \quad (18)$$

Component	Energy Balance	Exergy Balance	Energetic efficiency	Exergetic efficiency
Heat Exchanger (HEX)	$\sum(\dot{m}h)_{in} = \sum(\dot{m}h)_{out} + Q_{HEX}$	$\sum Ex_{in} = \sum Ex_{out} + Ex_Q + Ex_D$	$\eta_{HEX} = \frac{\dot{E}_{15} + \dot{E}_{16}}{\dot{E}_{13} + \dot{E}_{14}}$	$\eta_{ex,HEX} = \frac{Ex_{in,C} - Ex_{Out,C}}{Ex_{Out,H} - Ex_{in,H}}$
Pump (PUMP),	$\dot{m}_{in}h_{in} + W_p = \dot{m}_{out}h_{out}$	$Ex_{in} + W_P = Ex_{out} + Ex_D$	$\eta_{PUMP} = \frac{\dot{E}_{13} - \dot{E}_{14}}{W_P}$	$\psi_{PUMP} = \frac{Ex_{out} - Ex_{in}}{W_{in}}$
Compressor (COMP)	$\dot{m}_{in}h_{in} + W_{COMP} = \dot{m}_{out}h_{out}$	$Ex_{in} + W_{COMP} = Ex_{out} + Ex_D$	$\eta_{COMP} = \frac{\dot{E}_{14} - \dot{E}_{13}}{W_P}$	$\psi_{COMP} = \frac{Ex_{out} - Ex_{in}}{W_{in}}$
Steam Turbine (STB-1)	$\dot{m}_{in}h_{in} = W_{STB-1} + \dot{m}_{out}h_{out}$	$Ex_{in} = Ex_{out} + W_{STB-1} + Ex_D$	$\eta_{STB} = \frac{W_{STB}}{\dot{E}_{13} - \dot{E}_{14}}$	$\psi_{STB} = \frac{W_{STB}}{Ex_{in} - Ex_{out}}$
Condenser (COND)	$\dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + Q_{COND}$	$Ex_{in} - Ex_Q = Ex_{out} + Ex_D$	$\eta_{COND} = \frac{\dot{E}_{14}}{\dot{E}_{13}}$	$\psi_{COND} = \frac{Ex_S - Ex_W}{Ex_{Prod} - Ex_{fg}}$
Evaporator (EVAP)	$\dot{m}_{in}h_{in} + Q_{EVAP} = \dot{m}_{out}h_{out}$	$Ex_{in} + Ex_Q = Ex_{out} + Ex_D$	$\eta_{EVAP} = \frac{\dot{E}_{13}}{\dot{E}_{14}}$	$\psi_{EVAP} = \frac{Ex_{Prod}}{Ex_{FUEL}}$
Boiler Exch. (HRSG)	$\sum(\dot{m}h)_{in} = \sum(\dot{m}h)_{out} + Q_{HSRG}$	$\sum Ex_{in} = \sum Ex_{out} + Ex_Q + Ex_D$	$\eta_{HRSG} = \frac{\dot{E}_4 - \dot{E}_3}{\dot{E}_2 - \dot{E}_1}$	$\psi_{HRSG} = \frac{Ex_{out,C} - Ex_{in,C}}{Ex_{in,H} - Ex_{out,H}}$
Valve (VALV)	$\dot{m}_{in}h_{in} = \dot{m}_{out}h_{out}$	$Ex_D = \dot{m}_1 T_o(s_2 - s_1)$		
Gas Turbine (GTM)	$\dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + W_{GTB}$	$Ex_{in} = Ex_{out} + W_{GTB} + Ex_D$	$\eta_{GT} = \frac{W_{GT}}{\dot{E}_1 - \dot{E}_2}$	$\psi_{GT} = \frac{W_{GT}}{Ex_1 - Ex_2}$
Combustor (COMB)	$\dot{m}h_{AIR} + \dot{m}LCV_{FUEL} = \dot{m}h_{COMBGAS}$	$Ex_{Air} + Ex_{Fuel} = Ex_{Prod} + Ex_D$	$\eta_{CC} = \frac{\dot{E}_{in} - \dot{E}_{out}}{\dot{m}_{FUEL}LHV}$	$\psi_{CC} = \frac{Ex_{Prod}}{Ex_{Fuel}}$
Absorber (ABSOBA)	$\dot{m}_1h_1 - \dot{m}_6h_6 - \dot{m}_7h_7 = \dot{m}_{6D}h_{6D} - \dot{m}_{5D}h_{5D}$	$Ex_1 - (Ex_6 + Ex_7) + (Ex_{6D} - Ex_{5D}) = Ex_D$	$\eta_{ABSOBA} = \frac{\dot{E}_1 + \dot{E}_3}{\dot{E}_3}$	$\psi_{ABSOBA} = \frac{Ex_{Prod}}{Ex_{FUEL}}$
Solution HEX (SHX)	$\dot{m}_2h_2 + \dot{m}_4h_4 = \dot{m}_3h_3 + \dot{m}_5h_5 + Q_{SHX}$	$Ex_D = (Ex_2 - Ex_3) + (Ex_4 + Ex_5)$		
Generator (GEN)	$\dot{m}_{out}h_{out} = \dot{m}_{in}h_{in} + Q_{GEN}$	$Ex_{in} + Ex_Q = Ex_{out} + Ex_D$	$\eta_{GEN} = \frac{\dot{E}_1}{\dot{E}_2 - \dot{E}_3}$	$\psi_{GEN} = \frac{Ex_{Prod}}{Ex_{FUEL}}$
PEM Eleectrolyzer	$\tau_G[\alpha_c I(t)\beta_c + (1 - \beta_c)\alpha_T I(t)]bdx$	$Q_{sun}\psi_P = Q_R\theta_r + W_{PV} \times 1 + D'_{total} = Q_R\theta_r + W_{PV} \times 1 + [[Q_R(\psi_P - \theta_r)] + Q'_L\psi_P + W_{PV}(\psi_P - 1)]$	$F_R(\tau\alpha)_{eff} - F_R U_L\left(\frac{T_i - T_a}{G}\right)$	$\epsilon_{total} \cong \frac{\dot{E}x_{therm.} + \dot{E}x_{elect.}}{\dot{E}x_{sun}} = \frac{\int_{t_2}^{t_1}(A_c\dot{E}x_{therm.} + A_{PV}}{A_c\int_{t_2}^{t_1}(\dot{E}x_{sun}} = \epsilon_{therm} + \tau\epsilon_{elect.}$
Evaporator (KC)	$Q_{Evap} = m_{22}(h_{39} - h_{22}) = m_{40}(h_{43} - h_{45})$	$\dot{E}x_i + \dot{E}x_Q = \dot{E}x_e + \dot{E}x_w + \dot{E}x_D$	$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	$\frac{E_{x39} - E_{x22}}{E_{x43} - E_{x45}}$
Superheater (KC)	$Q_{sup} = m_6(h_{38} - h_{42}) = m_{22}(h_{22} - h_{43})$	$\dot{E}_{37} + \dot{E}_{HS1} = \dot{E}_{38} + \dot{E}_{HS1} + \dot{E}_D^{Sup.}$	$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	$\frac{E_{x42} - E_{x38}}{E_{x40} - E_{x43}}$
Seperator (KC)	$m_{43}h_{43} + m_{38}h_{38} = m_{22}h_{39}$	$\dot{E}_{39} = \dot{E}_{43} + \dot{E}_{46} + \dot{E}_D^{Sep.}$	$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	
Condenser (KC)	$Q_{cond.} = m_{43}h_{51} - m_{22}h_{50}$	$\dot{E}_{53} = \dot{E}_{50} + \dot{E}_D^{cond.}$	$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	

Turbine (KC)	$W_T = m_{38}(h_{51} - h_{41,s})\eta_{s,T}$	$\dot{E}_{38} = \dot{E}_{41} + \dot{W}_T + \dot{E}_D^T$	$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	
Pump (KC)	$W_P = m_{22}(h_{50,s} - h_{41})/\eta_{s,p}$	$\dot{E}_{50} + \dot{W}_p = \dot{E}_{35} + \dot{E}_D^p$	$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	
Throttle valve (KC)	$h_{43} = h_{41}$		$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	
	$m_{43}h_{41} + m_{38}h_{42} = m_{22}h_{45}$		$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	
Kalina cycle			$1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	$\frac{W_{net\ KC}}{E_{x40} - E_{x45}}$

Results and Discussions

In the present study, energy, exergy, exergoeconomic and exergoenvironmental analyses of a proposed multigeneration power plant. The water-ammonia solution is used as the working fluid. The energy and mass conservation equations and the irreversibilities relations are solved in the first part. Then the equations related to the exergy and energy analyses for different system components are performed. To this end, the Engineering Equation Solver (EES) software is used.

Results for Gas Turbine

Effect of TIT on SFC and Thermal efficiency

As has been countlessly proven by researchers be they unigeneration, cogeneration or trigeneration or multigeneration, thermal power plants are largely dependent on the ambient temperature and or turbine inlet temperature [25-28]. As shown in figure 12, there is a direct proportionality between TIT and thermal efficiency; although, for the TIT and SFC, showed concave up, increasing.

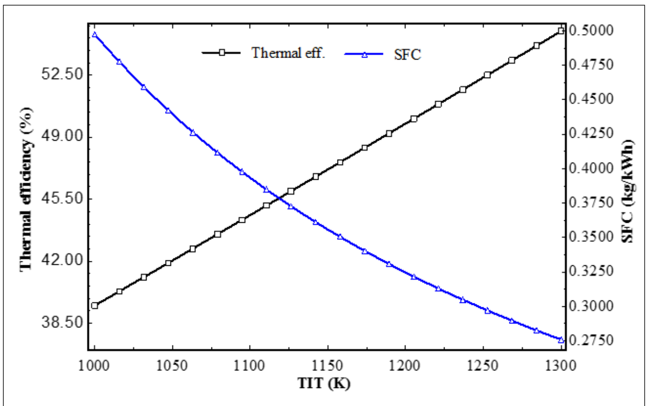

Figure 17: Effect of TIT on SFC and Thermal Efficiency

Effect of TIT on Work Ratio

Reported the same trend; however, reported an inverse relationship work ratio and TIT as compared to the present work as well as [29, 30]. The reason the author could infer for this obvious opposite trend was that the authors - (30) - worked on Combined Regenerative and Reheat Gas Turbine Cycle, unlike the aforementioned researchers who worked on a simple gas turbine.

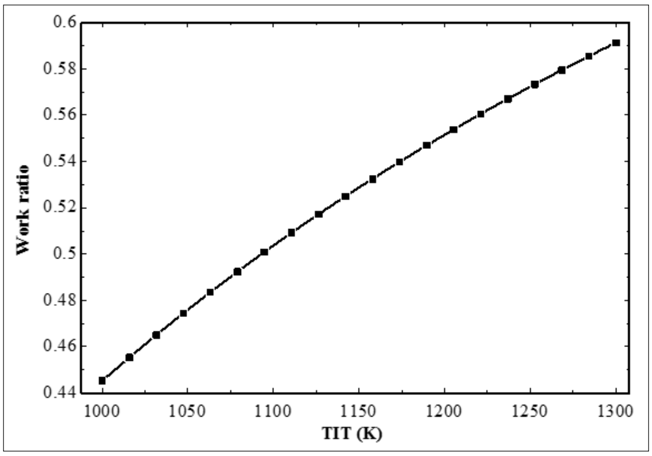

Figure 18: Effect of TIT on Work Ratio

Effect of TIT on SI_{GT} and W_{GTNet}

In a gas turbine, the turbine inlet temperature (TIT) has a significant impact on its performance, specifically on its thermal efficiency and work output. The turbine inlet temperature refers to the temperature of the combustion gases entering the turbine section of the gas turbine [12]. As shown in Figure 13, the turbine inlet temperature is directly related to the S.I. of the gas turbine. Higher turbine inlet temperatures lead to increased S.I.. This is because the efficiency of a gas turbine is determined by the temperature difference between the hot gases entering the turbine and the cooler gases exiting the turbine. When the turbine inlet temperature is higher, the temperature difference becomes larger, resulting in improved thermal efficiency. For the work output of the gas turbine (figure 13), he work output of a gas turbine is closely linked to the turbine inlet temperature. Higher turbine inlet temperatures generally lead to increased work output. This is because the work output of a gas turbine is directly proportional to the enthalpy drop across the turbine. Enthalpy is a measure of energy in the gas flow, and it is related to temperature. With higher turbine inlet temperatures, the enthalpy drop across the turbine is greater, resulting in higher work output. However, there are practical limits to the turbine inlet temperature due to material constraints. The turbine blades and vanes must withstand the high temperatures, and as the temperature increases, the materials used in the turbine must be capable of handling the thermal stress. Advanced materials and cooling techniques are employed to push the limits of turbine inlet temperatures and enhance the gas turbine's performance.

Effect of Compression Ratio on Thermal Efficiency

The compression ratio is defined as the ratio between the volume of the cylinder with the piston in the bottom pressure position Vbottom and in the top position, Vtop. The compression ratio is one variable available to design engineers to modify as they seek higher efficiency [31,32]. Thermal impact of operating conditions on the performance of a combined cycle gas turbine. It can be seen that as the compression ratio increases so does the efficiency of the gas turbine; however, the efficiency of the gas turbine steadies between 8.25 and 9.0 compression ratios. The maximum compression ratio occurred at about 8.625, corresponding to the highest thermal efficiency of about 50.25 %. Aina et. al., 2012 estimated their maximum compression ratio to be 9.0. the present results and that of are relatively close to each other; the small difference could be in the type of engine, or the pressure at the relevant state points. A research work on HPCR diesel has shown that lower compression ratios allow for engine downsizing, which tends to operate at higher specific engine loads in other to achieve lower fuel consumption. As can be seen from the diagram, the greater will be the power output from the given engine, and thus, its efficiency.

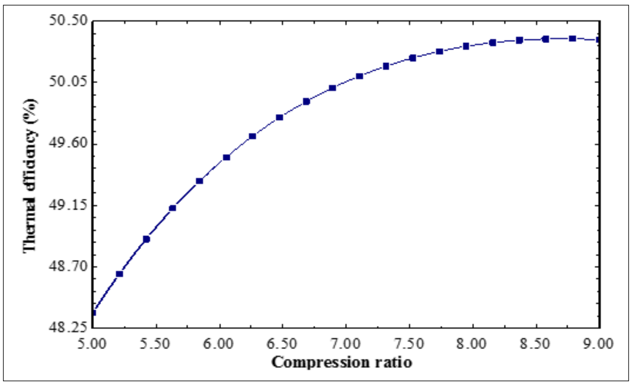

Figure 19: Effect of Compression Ratio on Thermal Efficiency

Results for Multigeneration Power Plant

Effect of TIT on gas turbine and multigeneration output

The effect of TIT and compression ratio on power output of gas cycle and multigeneration power plant is depicted in Figure 15. Power output of gas cycle and multigeeneration power plant increases with increase in TIT. An increase in the TIT leads to an increase in the GT exergy efficiency due to the fact that the GT turbine work output increases. As the load increases thus leads to reduction in exergy destruction. Therefore, it can be concluded that TIT is the most important parameter in designing the gas turbine cycle due to the decrease in exergy destruction and increase in cycle exergy efficiency. These results are in agreement with the work of.

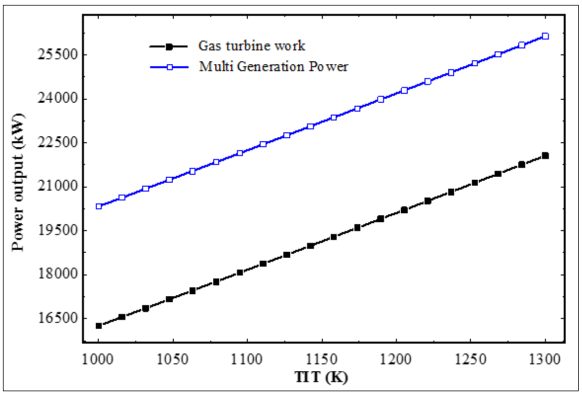

Figure 20: Effect of gas turbine and multigeneration power output versus Turbine inlet temperature

Effect of Compression Ratio on Work Ratio and SFC

Figure 16 shows variation of compression ratio with specific fuel consumption and work rario. At lower compression ratios, the specific fuel consumption decreases linearly with increasing compression ratio. The effect of variation of SFC is more significant at higher ambient temperature. This implies that the thermal losses have been reduced in compressor and turbine, which leads to increased power output. The rate of increase in power is more significant at higher TIT and higher isotropic compressor and turbine efficiencies. The trend of the indicators is analogous to other sustainability indicators of the work of researchers. A marked reduction in fuel consumption follows the use of a heat exchanger over a wide range of output. This accounts for the reason a heat exchanger was incorporated into the multigeneration power plant. furthermore, it can deduced that there is a direct relationship between TIT and efficiency, that is increasing the TIT leads to increased efficiency. However, pursuing an unchecked increase in the TIT, could result design and material selections of materials that can withstand such high temperature.

Also, in gas turbine power plants, air is the working fluid; in steam power plant, water is the working fluid. From our basic chemistry, specific volume of air is much higher than the specific volume of water; so the work done for the compression in gas turbine is much higher than the work done for compression steam power plant. Therefore, back work ratio in gas turbine power plant is very high. The present results are in agreement with these theoretical concepts, as the work produced by the gas turbine is much more than that of the steam turbine. Therefore, higher specific volume of the working fluid in the gas turbine results in the higher back work ratio in gas turbine power plant. Since, the temperature rise does not occur at the peak of compression, the fuel is not burnt completely or efficiently as in the engine combustion chamber and a higher specific fuel consumption must result.

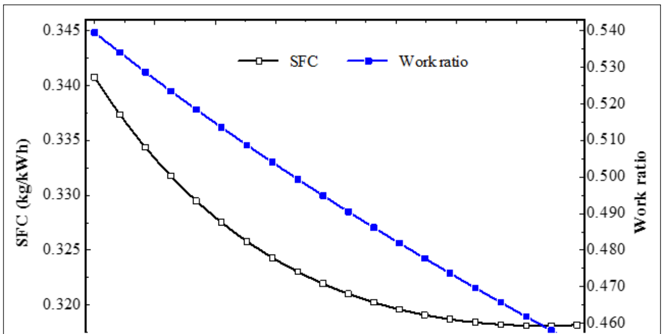

Figure 16: Effect of compression ratio on work ratio and SFC

Effect of Compression Ratio on Gas Turbine and Multigeneration Output

Figure 17 shows the Effect of compression ratio on gas turbine and multigeneration output. It would be observed that the relationship between the compression ratio and the power output, approximately, follows a straight line; that is as the compression ratio increases so does the power output (kW).

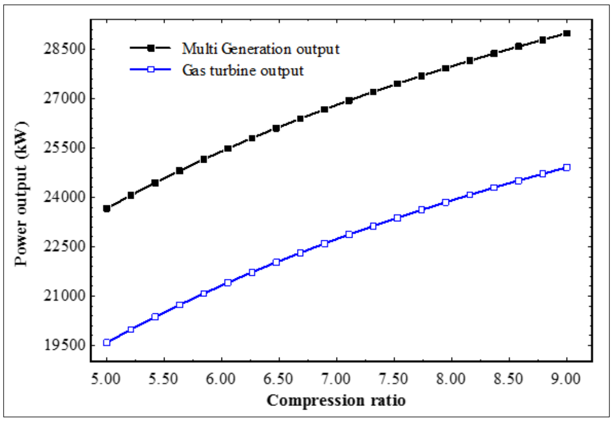

Figure 21: Effect of compression ratio on gas turbine and multigeneration output

Results for Exergoeconomic Analysis

The exergoeconomic performance of the gas turbine and the multigeneration power plant is carried out using measured properties, such as temperature, pressure and mass flowrate. The exergoeconomic parameters for each components of the proposed plant in this study are presented in figures

In analytical terms, the components with the highest value of Żk + ĊDk are considered the most significant components from an exergoeconomic perspective (figure 18 to figure 22). This provides a means of determining the level of priority a component should be given with respect to the improving of the system. For all the plants considered, the gasifier has the highest value of 96%, the other components share the 4% of the value of the sum Żk + ĊDk and are, therefore, the most important components from the exergoeconomic (thermoeconomic) viewpoint. The low value of exergoeconomic factor, f, associated with the combustion chamber suggests that the cost rate of exergy destruction is the dominant factor influencing the component. Hence, it is implied that the component efficiency is improved by increasing the capital investment. This can be achieved by increasing gassifier inlet temperature and the Gas turbine inlet temperature (GTIT). itemized the factors to improve the performance of a gasifier. A method for improving the efficiency of electricity production by a gasifier and generator combination, comprising:

I. utilizing the waste heat produced by the generator to produce low quality steam;
II. exchanging heat from the gasifier outlet stream to increase the temperature and quality of the steam;
III. introducing the steam along with some air into a suitable gasifier device; and,
IV. superheating the steam through oxidation of biomass to the point where at least partial reaction between the steam and biomass occurs.

Considering gas turbine which has the second highest value of the sum Żk + ĊDk, the relatively large value of the factor *f* suggests that the capital investment and O & M costs dominate. According to equation of the cost model, the capital investment costs of the gas turbine depend on pressure ratio (P2/P1) and compressor isentropic efficiency. To reduce the Ż value associated with the air compressor may be achieved by reducing the pressure ratio (P2/P1) and /or the isentropic efficiency [19]. This implies that the systems performance may be improved by increasing the investment cost of this component.

Figure 18 shows variation of investment and O &M costs rate Ż for each components of the proposed power plant. The gasification unit or biomass gassifier has the highest of the operation and maintenance cost this in tandem with other works. The reason has been adduced to be due to: (1) fuel quality and availability (2) complex equipment, which require very high temperatures and can easily lead to tear and wear (3) Tar and Ash removal, which contributes to this operation and maintenance cost (4) corrosion and erosion, resulting from high temperature and chemically aggressive operation environment of the gassifier (5) monitoring and control (6) safety measures and (7) skilled labor

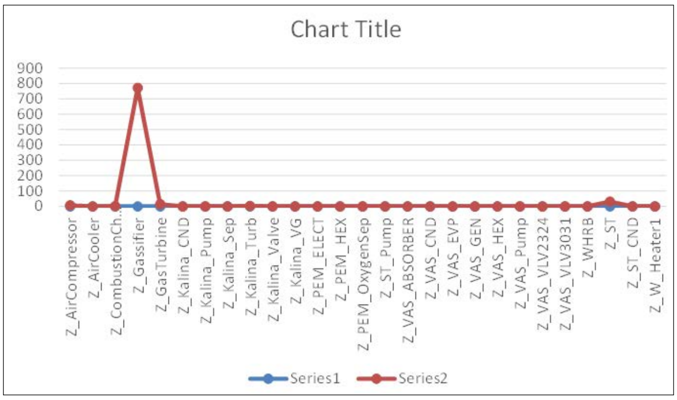

Figure 22: Variation of investment and O &M costs rate Ż for each components of the proposed power plant.

$Z_k + \dot{C}D_K$) values reports highest for kalina pump. The implication is that amongst the components – air compressor, combustion chamber, gas turbine, kalina pump, kalina turbine, kalina VG, PEM HEX, Steam turbine pump, VAS condenser, VAS GEN, VAS pump, VAS valve, steam turbine and heater - of the proposed multigeneration power plant, the kalina pump is most significant. Figure 19 shows value of the sum Żk + ĊDk for the various components of the proposed power plant. The Gas Turbine reports the highest of these values.

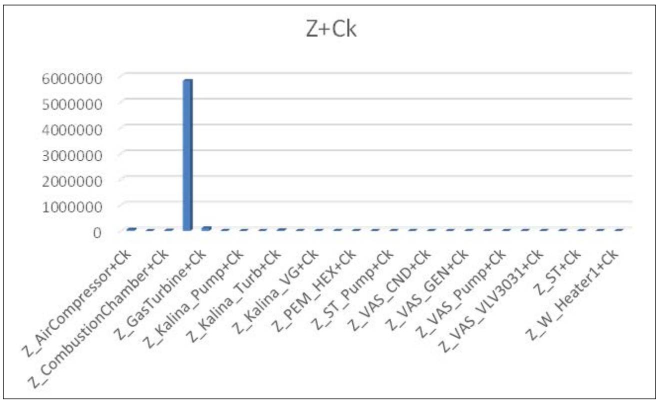

Figure 23: value of the sum Żk + ĊDk for the various components of the proposed power plant.

Figure 20 shows pie chart representation of value of the sum Żk + ĊDk for all the components of the proposed power plant. The biomass gassifier or gasification unit reported the highest value.

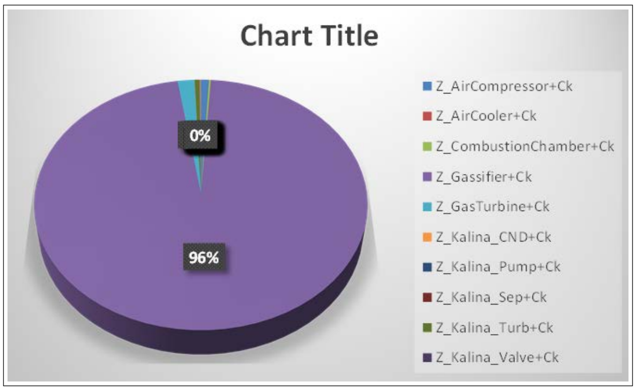

Figure 24: pie chart representation of value of the sum Żk + ĊDk for all the components of the proposed power plant

Figure 21 shows plot of purchase equipment cost, PEC for each component of the proposed power plant. The steam turbine reported the highest purchase equipment cost, followed by the Gas Turbine.

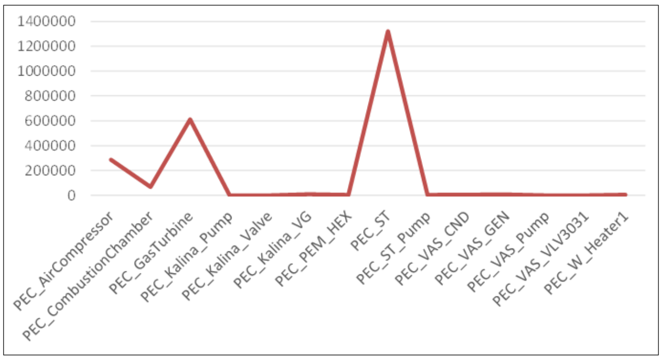

Figure 25: purchase equipment cost, PEC for each component of the proposed power plant

From figure 22, purchase equipment cost for the gassifier reported the highest value for the gassifier, while all other the least purchase equipment cost.

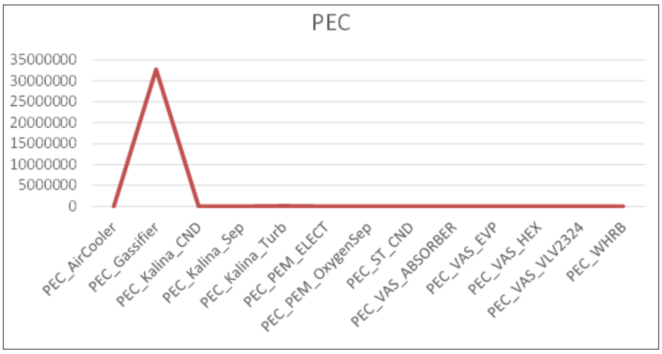

Figure 26: purchase equipment cost, PEC for other components of the proposed power plant

From figure 23, shows the cost rate of exergy destruction for each component of the proposed power plant with the combustion chamber having the highest cost rate of exergy destruction. The component with second highest cost rate of exergy is Steam turbine.

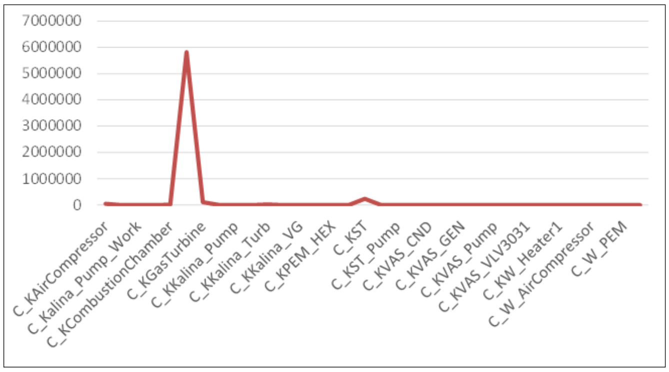

Figure 27: cost rate of exergy destruction for each components of the proposed power plant

Results from Exergoenvironmental Analyses

Table 4.23: Results Exergoenvironmental Analysis

PARAMETERS	SYMBOL	UNIT	VALUE
NO Emission Rates	mNO	kg/s	0.04393
CO Emission	mCO	kg/s	0.00934
CO_2 Specific Emission	$CO_{2,spe}$	kgCO2/MWh	0.3364
Fuel emission harmful factor	FEF		0.1028
Exergo utility Index	EUI		0.2917
Exothermal index	ETI		0.8454

Table 4.23 shows results exergoenvironmental analysis of the proposed multigeneration power plant. CO_2 emission had the highest emission at 0.3364 kgCO_2/MWh, while the lowest emission was recorded for CO emission.

Figure 24 shows results of environmental analysis and is the pictorial representation of table 4.23 of all the exergoenvironmental parameters, total cost rate of emission was highest, while the lowest was recorded for CO_2 emission.

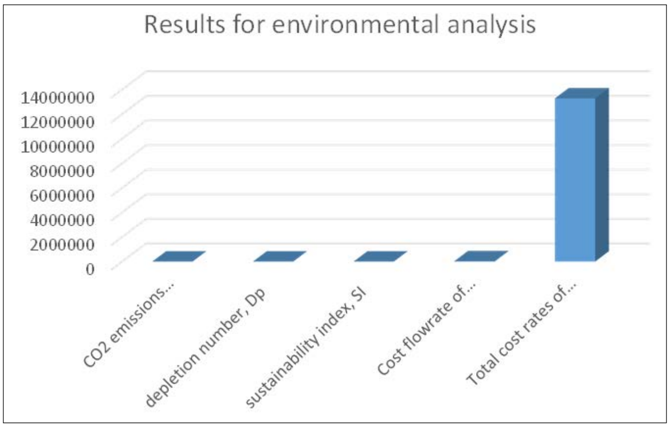

Figure 28: Results of Environmental Analysis

Conclusion

Multigeneration systems provide an opportunity to fulfil multiple useful commodities by incorporating several cycles, which require relatively lower temperatures [33]. Design of multigeneration systems require the application of multi-objective, multivariable optimization methods [34]. The Engineering goal of energy systems designers of such multigeneration energy systems is the maximization of critical performance indicators such as energy efficiencies, exergy efficiencies, and to minimize some critical performance indicators, including payback period, levelized electricity cost, total cost rate (exergy-economics) and specific emissions factor. [34]. The main object of the technology of integrated multigeneration power plants is to optimize-minimization of input energy source, maximization of useful output energy sources and, minimization of the resultant effects of the operations of the power plants.

Energy, exergy, economic, exergoeconomic and exergoenvironmental models were built for each subsystem of the multigeneration power plant. For the gas turbine, the energy, exergy, economic, exergoeconomic and exergoenvironmental models for each component, i.e. compressor, turbine, combustor and stack gas loss are formulated. The formulated models are used to evaluate the components thermal exergy, chemical exergy and mechanical exergy, exergy destruction rates, exergy efficiency for a wide range of operating parameters. To achieve this aim, a simulation code was developed in Engineering Equation Solver, EES software program [35-48].

The models developed and subsequently simulated showed that operating parameters-compression ratio, turbine inlet temperature and ambient temperature-had significant influence on the performance of the gas turbine power plant and the proposed multigeneration power plant. The thermodynamic simulation results are summarized as follows:

- The thermal efficiency and power output decrease linearly with increase of ambient temperature.
- The thermal efficiency and power output increase linearly at lower compression ratio with increase in turbine inlet temperature.
- Heat supplied increases with turbine inlet temperature but decreases with compression ratio.
- Specific fuel consumption increases with increase ambient temperature but decreases with increase compression ratio and turbine inlet temperature.
- Increasing the turbine inlet temperature increases the output power and thermal efficiency as a result of increasing the turbine work.

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