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Energy, Exergy, and Economic Analysis and Optimization of Novel Multi-generation System with Combination of Heat Recovery Exchanger and Absorption Transformer

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Abstract
This evaluation presents a new multi-generation system that incorporates a gas turbine, an appropriate transformer, a cogeneration system, and a heat exchanger for generating electricity along with heating and cooling capabilities. A comprehensive analysis of the system's thermodynamic and economic performance has been conducted. The waste heat from the gas turbine is captured and utilized to generate additional electricity within the turbine, while cooling capacity is achieved by recovering heat from the absorption transformer. Among the assessment techniques used, the application of cutting-edge technology enhances cost efficiency, resulting in improved economic effectiveness across various production systems. A sensitivity analysis was also performed to assess how the system responds to different conditions. Additionally, a two-objective genetic optimization algorithm was employed to identify the optimal solutions. The thermodynamic assessment indicates that the proposed system achieves an energy efficiency of 21.29% and an exergy efficiency of 20.68%. The analysis reveals that the system's cooling capacity is 2,746 kW, while the total exergy destruction within the system is 2,409 kW. The system is expected to produce a heating load of 2,921 kW and an output power of 3,874 kW. The economic analysis shows that with a total cost of 93.56 $/s and a combined investment and maintenance cost of 1,732 $/s, the proposed system is highly cost-effective.

Keywords: *Absorption Cooling, Co-production, Economic evaluation, Exergy evaluation, Gas turbine.*

1. Introduction
As the demand for electricity and energy production rises, there is an increasing reliance on natural resources and fossil fuels to meet this need. The depletion of fossil fuels and the pollution they generate have prompted energy policy-makers and political leaders worldwide to prioritize renewable resources and enhance the efficiency of fossil fuel-powered equipment and facilities [1]. Adopting clean energy, reducing pollution, and exploring additional renewable energy options are effective strategies to address the growing reliance on fossil fuels and miti-gate environmental pollution [2]. A critical requirement for meeting international energy standards is the advancement of electrical equipment, which plays a vital role in initiatives aimed at reducing greenhouse gas emissions from fossil fuels [3]. In the recent years, nuclear energy has made significant strides in regions with moderate to high temperatures, owing to its eco-friendly, cost-effective, and reliable nature. The development of fourth-generation nuclear reactors particularly underscores the potential of nuclear energy for future electricity production [4]. The concurrent generation of electricity, heating, and air conditioning is currently the most efficient energy technology available. In addition to producing electricity, the energy that is typically wasted can be repurposed to meet the heating and cooling needs of residential and commercial clients, helping to conserve energy while providing economic and social benefits. The development of renewable energy sources and the enhancement of energy efficiency are recognized as viable solutions. Recently, decentralized energy systems (DES) have gained attention for their potential advantages, including increased efficiency, cost savings, and lower carbon emissions. A notable type of DES is Combined Cooling, Heating, and Power (CCHP) systems, which have become significant subjects of research due to their ability to improve energy

efficiency and reduce harmful emissions. The Gas Turbine Cycle (GTC) is especially favored for its dvantages such as quick start-up, high fuel efficiency, short operational times, and low emissions, making it a common choice in distributed power generation. However, stand-alone GTC units without a waste heat recovery system (WHRS) typically exhibit lower fuel consumption and higher heat output. Therefore, it is essential to incorporate WHRS design alongside GTC technology. By integrating cooling equipment with the electricity produced through cogeneration, it is possible to create a contract that encompasses electricity, heating, and cooling. Cooling capacity is achieved using coolants such as hot water, hot water coolers, and water vapor, in conjunction with heat, and power. The heat required for the chiller is generated through the combination of heat and energy, depending on the chiller type, which may be a water heater or boiler system. During the summer, a heat recovery system captures waste heat to meet the cooling requirements of the building. Some of this heat is directed to the vacuum cooler for cooling, while some of the heat lost in winter is utilized for heating the building. If the combined heat and power (CHP) system malfunctions due to unforeseen circumstances, an auxiliary boiler can provide heating and cooling, ensuring continuous service. The limited and non-renewable nature of fossil fuels, along with the high costs associated with refining them, has prompted society to seek solutions and explore new methods for generating clean electricity. The steep costs of conventional electricity generation, coupled with the economic challenges faced by many countries, have led to significant supply issues. As a result, researchers are increasingly focused on developing innovative approaches to enhance the efficiency of power plants and lower the expenses of electricity supply systems. The ability to generate three types of energy from a single source, reduce the cost of electricity transmission from the grid to consumers, and recover waste heat from a gas turbine for cooling purposes highlights the critical importance of research in this field to achieve these benefits. Abdus et al. are studying polygeneration systems that provide air conditioning, heating, electricity, and drinking water. Their research indicates that the unit cost decreases by 21% when the turbine inlet temperature rises by 67 degrees [6]. Jagtap et al. have developed and implemented an advanced, generalized coordinated condition monitoring strategy aimed at enhancing early fault detection and diagnosis for essential equipment. This method integrates various condition monitoring techniques, including vibration analysis, noise measurement, wear debris analysis, and ultrasonic monitoring, which has improved the accuracy of fault diagnosis. They conducted a case study on the failure analysis of Induced Draft (ID) fan 2A from a 250 × 2 MW thermal power plant in western India. The vibration trend for the acceleration parameter of the hydraulic coupling input bearing was notably high, reaching 4.2 g. A sound level meter recorded a noise level of 99.8 dB, while an ultrasonic meter detected a high-frequency sound at 18 dB in the ultrasound range. The vibration data provides critical insights into early failures, while noise, wear, and ultrasound levels are used to monitor fault location, severity, and their impact on other process parameters. Additionally, this approach has effectively prevented secondary damage to the motor and fan. The integration of these techniques not only detects early faults but also aids in diagnosis before any major failures occur. The results of this study have enabled the plant's maintenance engineer to proactively plan maintenance activities [7]. Yan et al. integrated photovoltaic and wind turbine technologies with a Combined Cooling, Hating, and power (CCHP) system, developing a dual-level multi-objective optimization model. This model aimed to enhance the CCHP system's capacity by incorporating new prime movers and to effectively evaluate the economic feasibility of the resulting hybrid system [8]. Jagtap et al. conducted a simulation modeling study based on availability to examine the boiler-furnace system of a 500 MW thermal power plant. They employed a Markov-based simulation model for performance analysis, which included differential equations derived from a transition diagram depicting the system's states: full capacity, reduced capacity, and failure. These differential equations were solved using a normalization condition. Their analysis revealed that failures in the boiler drum had the most significant impact on system availability, while failures in the reheater had the least effect. The findings indicated a peak system availability of 99.9845%. The optimized failure and repair rate parameters for each subsystem were used to develop a maintenance strategy specifically designed for the plant's boiler-furnace system. This information supports decision-making for planning maintenance activities and allocating resources based on the importance of subsystems [9]. Li et al. enhanced the traditional Combined Cooling, Heating, and Power (CCHP) system by integrating storage for electricity, thermal energy, and cooling energy, resulting in a CCHP-MES system. They subsequently developed a multi-objective, two-stage stochastic robust optimization approach. Using a tracking-economic extreme scenario trade-off model, they examined how uncertain extreme weather conditions affect the optimal configuration of equipment capacity [10]. Jagtap et al. investigated the turbo-generator subsystem of a thermal power plant, employing particle swarm optimization to evaluate its performance. Their research focused on the turbine governing and lubrication systems, as well as the generator's oil, gas, and excitation systems. They found that the turbine lubrication and generator excitation subsystems had the greatest impact on system availability, achieving a maximum availability of 98.9394% with a particle size of 30, after which the availability remained constant. The optimized availability parameters were then utilized to determine the best maintenance strategy for the turbo-generator system of the plant [11]. Dai et al. developed an innovative system that integrates hybrid storage with combined cooling, heating, and power (CCHP) systems. Their study addressed various energy needs and employed a dual-layer optimization approach, merging Particle Swarm Optimization (PSO) with Genetic Algorithm (GA) to determine the optimal capacity for all system components. Additionally, they examined how the use of internal combustion engines as primary movers impacts the system's economic performance and energy efficiency [12]. Jagtap et al. established a framework to analyze reliability, availability, and maintainability (RAM) to assess the performance of a coal-fired power plant's (CFPP) water circulation system (WCS). The WCS comprises five interconnected subsystems: the condensate extraction pump (CEP), low-pressure feedwater heater (LPH), deaerator (DR), boiler feed pump (BFP), and High-Pressure feedwater Heater (HPH), arranged in a series-parallel configuration. To assess the performance of the WCS, a Reliability Block Diagram (RBD) and Fault Tree Analysis (FTA) were employed. The study found that the boiler feed pump has a significant impact on system availability, while failures in the deaerator have minimal effects. To improve system availability, particle swarm optimization was utilized. This optimization led to the proposal of a new maintenance strategy that includes optimized time between failures (TBF) and time to repair (TTR). Additionally, the optimized failure and repair rates for the subsystems contributed to an effective maintenance strategy for the thermal power plant's water circulation system [13]. Zhang et al. developed a solar-powered combined cooling, heating, and power (CCHP) system that incorporates thermochemical energy storage. They evaluated its performance through sensitivity analysis and a 4E (Energy, Exergy, Economics, and Environment) analysis. Their findings indicated that CCHP systems with hybrid storage exhibit better energy efficiency and lower carbon emissions during the processes of energy storage, power generation, heating, and cooling [14]. Gadhave et al. examined the charging process and solidification characteristics of stearic acid ($C_{18}H_{36}O_2$) in a finned triplex pipe heat exchanger with holes on the fin surfaces. This study investigates how different flow rates of the heat transfer fluid (HTF) affect the solidification and melting behavior of a Phase Change Material (PCM). The findings compare the average effectiveness of a finned triplex tube heat exchanger with cylindrical holes on the fin surface to one without, specifically at flow rates of 0.33 and 0.43 kg/s. The results indicated a notable difference in average effectiveness between the perforated and standard finned triplex tubes. During the charging phase, the perforated finned tube demonstrated a 4-5% enhancement, depending on the flow rates of 0.33 kg/s and 0.43 kg/s. This benefit was even more significant during the discharging phase, with improvements of 14% and 11% observed at the same flow rates [15]. Ye et al. introduced a Combined Cooling, Heating, and Power (CCHP) system that incorporates electric-hydrogen storage and accounts for the heat generated by batteries during operation. They utilized this battery-generated heat as an additional heat source and optimized the system by focusing on economic factors, energy usage, and carbon emissions, demonstrating the practicality of their design [16]. Jagtap et al. conducted a study aimed at identifying faults in the cooling water pump of a condenser system in a thermal power plant, employing a coordinated condition monitoring strategy. This approach combined various monitoring techniques including vibration, noise, and ultrasound analyses. The study presents a case that illustrates the enhanced reliability of the condenser achieved through this integrated monitoring method, successfully identifying a fault in the cooling water pump by pinpointing a damaged bearing. After replacing the bearing during maintenance, subsequent analysis confirmed that the pump had returned to its normal operational condition. The results indicate that coordinated condition monitoring enhances the precision of fault detection and diagnosis [17]. Dezhdar et al. improved the design of an integrated Combined Cooling, Heating, and Power (CCHP) system for multiple residential buildings. Their model incorporated key components such as fuel cells, hydrogen storage tanks, and electrolyzers. By analyzing energy usage, economic costs, and equipment efficiency across various cities, they identified the location that offered the best overall performance [18]. The study by Balaso et al. examines power generation through steam turbines in a sugar factory setting, focusing on failure modes and evaluating maintenance strategies to optimize turbine availability in thermal power plants. This research enhances our understanding of steam turbines, emphasizing their significance and the factors that contribute to failures in both the turbines and their components. The reviewed literature highlights the role of artificial intelligence and machine learning, providing valuable insights into maintenance models and repair scheduling for steam turbines. This information is essential for ensuring reliable operations and maximizing the uptime of steam turbines in thermal power plants [19]. Li et al. presented operational strategies for Interactive combined cooling, heating, and power (ICCHP) systems. These strategies encompass approaches that respond to electrical load, thermal load, or a combination of both, and were implemented in systems serving multiple users. Their research demonstrated that leveraging the complementary characteristics of various loads and energy sources through interactive operation significantly enhances the performance of ICCHP systems [20]. Jagtap et al. employed a Markov birth-death probabilistic model to simulate the coal supply subsystem for a 500 MW thermal power plant (unit 1) located in western India. Their availability analysis focused on equipment such as coal mills, stacker reclaimers, and wagon tipplers. The research identified the stacker reclaimer as the most critical component of the coal supply system, requiring the most maintenance attention, followed by the coal mill and wagon tippler. The study demonstrates that availability simulation modeling, utilizing a Markov birth-death probabilistic approach, is an effective method for identifying critical equipment in thermal power plants. Additionally, a particle swarm optimization technique is employed to establish optimal availability parameters, aiding in the selection of appropriate maintenance strategies [21]. Fu et al. developed a novel coupling technique for capacity design factors and dual-source regulation by integrating power-to-electricity (PPE), power-to-thermal (PPT), flexible electricity load (FEL), and flexible thermal load (FTL). They tested their method on a traditional combined cooling, heating, and power (CCHP) system in a hotel, and the results underscored the limitations of relying on a single operational strategy. Their proposed approach, which effectively integrated PPE and FEL with PPT and FEL, resulted in a notable 7.45% increase in the energy saving ratio (ESR), marking a significant advancement compared to using a single strategy [22]. Jagtap and colleagues conducted a review of existing literature to assess the application of condition monitoring techniques in thermal power plants for detecting, identifying, and classifying machinery faults. Their findings underscored the need for enhanced reliability analysis of essential equipment in thermal power plants. This study outlines the challenges and strategies associated with condition monitoring for diagnosing faults in systems used within thermal power plants [23]. Azhar and colleagues studied how factors such as battery operating temperature and pressure influence system performance, using a solid oxide fuel cell as the primary power source and examining various operational strategies [24]. Kumar et al. explored both conventional and unconventional optimization methods to enhance reliability in process industries. Conventional techniques gradually refine an initial solution to reach an optimal result, but their effectiveness can be significantly affected by the starting point, and they often encounter challenges with discontinuous objective functions. As a result, unconventional methods, frequently inspired by natural phenomena, have gained increasing importance. This chapter presents various optimization techniques and compares traditional and non-traditional methods [25]. Song and colleagues introduced a solar-powered combined cooling, heating, and power (CCHP) system that incorporated solar collectors. They utilized the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to enhance the system's efficiency, focusing on achieving a balance between cost reduction and lower fuel usage [26]. In a related study, Jagtap et al. provided valuable insights into recent developments in wind energy technology research and development. These insights can improve the efficiency and effectiveness of wind energy generation, thereby fostering sustainable energy production for future generations. The study specifically examines various control methods for Doubly-Fed Induction Generators (DFIGs), which are commonly used in variable-speed wind turbines. The control options explored include proportional-integral (PI) control, pitch control, vector control, voltage control mode, bandwidth-based repetitive control, super-twisting sliding mode control, and DFIG coordination control strategies. Each method features distinct key components, simulation outcomes, and control objectives. The assessment of these strategies highlights their ability to optimize energy capture, improve resilience to grid frequency variations, produce optimal aerodynamic torque, maintain stable stator output voltage and frequency, ensure continuous operation of the DFIG during fault isolation and power restoration, and sustain DFIG operational capability during such incidents. Consequently, these control strategies can enhance the performance, efficiency, and stability of DFIG-based wind turbines, with their effectiveness validated by both real-world applications and simulation models [27]. Zhang and colleagues conducted an extensive investigation into various absorption power cycles that harness waste heat from the sCO2 cycle. The benefits of the sCO2/APC system were further validated through measurements of temperature and humidity [28]. Ma and colleagues assessed a multi-generation system that integrates biomass and solar energy, employing a direct heat pump system to distribute the generated energy. They utilized multi-objective optimization to enhance operational efficiency. Their findings indicate that, compared to other systems, annual costs were reduced by 40.37%, and carbon dioxide emissions decreased by 88.93%. Additionally, operating costs were lowered by 557.11 yuan [29]. Yuan et al. introduced a combined cooling and power (CCP) system that exclusively uses CO2 as its working fluid. They evaluated the performance of this innovative CCP system against two separate CCP systems, and found that their design is better suited for lower turbine inlet pressures than the independent systems. Additionally, the absorption refrigeration cycle (ARC) demonstrates efficiency in using low-temperature air for cooling purposes [30]. Yao and colleagues utilized compressed air energy storage along with syngas fuel in a multi-generation system, assessing energy, exergy, economic, and environmental factors to enhance the supply capacity and stability of the distribution network. They applied a multi-objective optimization approach to enhance the system's thermodynamic efficiency while reducing costs [31]. Liu and colleagues employed a comprehensive method to optimize the multi-production system, analyzing the energy, exergy, and economic aspects of their study. They implemented an optimization technique to improve the proposed system and compared the outcomes with four other optimization methods. Their results indicated that comparing different approaches led to an 11.73% increase in connection speed [32]. Noorani et al. conducted an analysis of the energy, exergy, and exergeoeconomics of a cogeneration system using Internal Combustion Engines (ICE). They examined two different scenarios to identify the most effective energy source for optimizing the performance of various production machines. In the first scenario, water was used, while in the second, a cold water pump served as the coolant in the Rankine cycle condenser. The results indicated a significant improvement in energy efficiency, performance, and cooling of the production process in the second scenario compared to the first. However, the costs for fuel and the production of goods associated with these systems increased [33]. Ghorbani and colleagues developed a comprehensive system for the simultaneous production of Liquefied Natural Gas (LNG) and Liquefied Carbon Dioxide (LCO2) by utilizing biogas treatment units in conjunction with a mixed fluid cascade process. Their findings revealed that the specific energy consumption was 0.4761 kWh/kg of bioLNG, while the total energy and exergy efficiency were 0.7311 and 0.7258, respectively [34]. Hai and colleagues developed a multi-generation system that includes a gas turbine, an organic Rankine cycle, and an absorption cooling system. After optimizing the system, they achieved an exergy efficiency of 17.56%, a total cost of $74.49 per hour, and a sustainability index of 1.21 [35]. Ebrahimi et al. created an innovative integrated system for producing biomethane (bioCH4) and Liquid Carbon dioxide (CO2) by utilizing raw biogas and emissions from power plants. Their financial assessment revealed a payback period of 4.45 years and a production cost of $0.8189 per cubic meter of biomethane. Additionally, sensitivity analysis indicated that increasing the methane concentration in the raw biogas from 55 mol% to 75 mol% resulted in an overall thermal efficiency increase to 72.50%, while the air ground temperature decreased to 7808 kW [36]. Huang and colleagues integrated a gas turbine multi-generation system with a Solid Oxide Fuel Cell (SOFC). They employed multi-objective optimization algorithms to enhance exergy efficiency and reduce the system's cost ratio. The optimal solution was identified using a Pareto chart through the TOPSIS method. The findings indicated that as exergy efficiency increased, the system's costs and CO_2 emissions rose by 6.45%, 3.43%, and 8.84%, respectively [37]. Liu and colleagues improved a hybrid multi-generation system powered by a gas turbine by focusing on output energy, exergy efficiency, and exergy cost as their primary objectives. They employed the TOPSIS decision-making method to identify the best solution. The results indicated that total energy consumption and physical activity increased by 35.58 kW and 0.20%, respectively, while the exergy value rose by 0.21 USD/GJ [38]. Liu and colleagues proposed the implementation of a multi-generation system in a gas supply company. The optimization process considered various factors, including environmental impact, economic feasibility, energy consumption, and energy efficiency. The capacity of the primary driving mechanism was optimized and determined to be 78,146 kW. Additionally, an analysis of the key parameters influencing the system was conducted [39]. Lucarelli and colleagues introduced a novel multi-objective optimization method that integrates three objectives—economic, environmental, and technical—for different production systems. Their study involved various electronic devices, including internal generators, absorption and compression heat pumps, as well as two types of proton exchange membranes and oxides. They found that a heat pump with a capacity of 39 x 10^4 W is utilized for generating cooling power, while a gas compression heat pump with a capacity of 16 x 10^5 W is employed to produce thermal power [40]. Khanmohammadi and colleagues developed a cogeneration system that harnesses geothermal energy. Their proposed system included the Kalina cycle, a refrigeration unit, a heating system, and a power generation system. They discovered that the 449 kW reverse osmosis unit caused the most significant damage output in the system [41]. Safavi and colleagues evaluated a multi-production system designed for commercial use in temperate regions. Their findings indicated that the system produces carbon dioxide emissions ranging from 230 to 260 grams per kilowatt-hour [42]. Wang and colleagues developed a double-pressure evaporation method in a multi-production system that utilizes a shared condenser. Their results demonstrate that the boiler and condenser experience the most significant damage; however, the optimized mode achieves a 32% reduction in exergy loss [43]. Chen et al. introduced a new approach that integrates a compressed air energy storage system with a multi-generation system. They conducted an optimization focused on two main objectives: minimizing costs and enhancing the system's thermal performance. Their findings indicated that during winter, the costs, usage, and labor expenses were $3,330, 22%, and 16.9%, respectively. In comparison, the summer figures were $3,507, 14.7%, and 60%, respectively [44]. In a separate research project, Roshanas et al. introduced a cogeneration system that features a compressed air energy storage cycle, generating both heat and electricity simultaneously. The design was assessed using energy and exergy analysis, and the researchers measured the carbon dioxide emissions released into the atmosphere, finding intensity levels of 58% and 78%, respectively [45]. This project aims to develop a small-scale renewable energy system that utilizes efficient and readily available technologies, making it well-suited for small to medium-sized communities where larger projects are impractical. The system's flexibility and potential for expansion allow it to meet specific energy needs, ensuring a reliable and eco-friendly power source. This approach offers an appealing solution for communities transitioning to renewable energy while facing limited financial or logistical challenges. By prioritizing practicality and efficiency, the system delivers significant environmental and economic benefits, promoting sustainable development. Furthermore, the integration of heat recovery elements significantly enhances the effectiveness of the multigeneration system. This study provides a comprehensive thermodynamic and economic assessment of the system. The study includes calculations of exergy destruction to identify the primary sources of irreversibility and improve the system's design. Additionally, it evaluates the economic viability of the system using revised cost functions. A sensitivity analysis is performed to assess how changes in key parameters affect the system's efficiency. By incorporating advanced technologies such as gas turbines, absorption refrigeration cycles, and heat recovery systems, these plants enhance energy conversion efficiency and optimize resource utilization. This research aims to address existing gaps by exploring the combined use of various technologies to improve energy efficiency, minimize heat loss, and effectively generate power, heating, and cooling. The study emphasizes the evaluation of the advantages and drawbacks of integrating these advanced technologies into a cohesive system. Utilizing HRVG to provide heat for the ammonia turbine and produce the cooling load for an absorption transformer represents an innovative approach to optimizing energy use. The originality of this study lies in its unique method of integrating these cycles and evaluating their performance within a multigeneration system, a topic that has not been thoroughly explored in current literature. This methodology offers fresh perspectives on optimizing renewable energy systems and enhancing multigeneration technologies. The collaborative integration improves overall efficiency, reduces costs, and promotes sustainable resource management. This paper introduces and assesses a new Combined Cooling, Heating, and Power (CCHP) system that effectively harnesses high-temperature waste heat from a gas turbine's outlet. The system comprises a gas turbine, an ammonia-water turbine, a LiBr-H2O absorption chiller, and a hot water heat exchanger. The benefits of thermodynamic performance are illustrated through a thorough comparison with a reference system. An exergy and energy analysis is conducted under specific design conditions to uncover the mechanisms behind energy savings. Many previous studies have focused on energy, exergy, or thermoeconomic analyses separately when investigating Combined Cooling, Heating, and Power (CCHP) systems. While energy analysis, based on the first law of thermodynamics, can yield optimal operational solutions for a cycle, it does not account for irreversibility in different parts of the system. Moreover, neither exergetic analysis nor thermoeconomic analysis effectively evaluates energy systems on their own. This paper provides an in-depth analysis of a CCHP system using energy analysis, exergy, and thermoeconomic principles. It emphasizes the recovery of waste heat from the Brayton cycle and the cost-effective use of single-effect absorption cooling. The research investigates how various operational parameters influence fuel consumption, heat and cold output, net power output, first and second law efficiencies, exergy loss in each system component, and overall operational and capital costs. A key strategy to improve system performance is to raise the average temperature of heat extraction in the boiler. Findings indicate that most exergy destruction occurs in the boiler, and increasing the inlet temperature can enhance the system's work output. The originality of this study lies in the direct use of waste heat from the gas turbine via a heat exchanger, which enables waste heat recovery to satisfy the cooling demand of the absorption chiller. Thus, this paper delivers a comprehensive analysis of the CCHP system based on Brayton cycle waste heat recovery and a commercial single-effect absorption refrigeration system, integrating energy analysis, energy efficiency, and thermal economics. This research is significant due to its thorough assessment of thermodynamic and economic aspects, ensuring that the system is both efficient and cost-effective. The detailed parametric analysis backing this study explores the effects of different operational variables, aiming to enhance system efficiency.

2. System description

The system consists of a gas turbine, a combined cooling and power subsystem, and a heat exchanger, as illustrated in figure 1. At point 1, the compressor raises both the pressure and temperature of the air. The compressed air then moves to the combustion chamber at point 2, where combustion occurs. At point 3, the resulting mixture enters the turbine to generate electricity. In the water-ammonia Rankine cycle, the water-ammonia solution at point 10 is initially pumped from pump 1 at point 7, and then flows through the pipeline. A generator at point 8 converts the solution into superheated ammonia vapor, while removing waste heat from the generator. At point 8, the superheated ammonia vapor is expanded in axial turbine 2 to produce electricity. The elevated temperature of the ammonia vapor at point 9, along with the vapor and liquid temperatures at point 10, provides the necessary heat for the lithium bromide-water absorption refrigeration subsystem. Points 7, 8, 9, and 10 illustrate the transformations within the ammonia Rankine cycle. The single-effect water-lithium bromide absorption refrigeration cycle comprises a condenser, generator, evaporator, absorber, heat exchanger, pump, and two expansion valves. A dilute lithium bromide solution accumulates at the bottom of the absorber, from where the pump sends it to the shell-and-tube converter for preheating. After exiting the converter, the dilute solution is moved to the top of the cooler, where it is contained in a copper tube that allows air or hot water to flow around it. Heat is transferred to the dilute solution from hot water, steam, or hot air, causing it to boil and release water vapor. This vapor then enters the condenser at the top of the generator to condense. The concentrated solution is subsequently sent to the heat exchanger to cool down, while the solution being pumped back to the generator is heated. The cooling vapor generated in the generator is directed to the condenser through a copper pipe, which also carries the cooling tower water, known as condensate, collected in the condenser unit. The refrigerant moves from the condenser to the evaporator, varying by refrigerator model and manufacturer. It is typically sprayed onto the copper tubes of the evaporator, influenced by the vacuum level, while maintaining the hot water temperature at 3.9 °C. This causes the water to boil, resulting in heat transfer from the air inside the copper tubes to the refrigerant, which then vaporizes, creating water vapor in the evaporator. The evaporator and absorber are connected, allowing the water vapor from the evaporator to flow into the absorber. A concentrated lithium solution is then transferred from the generator to the heat exchanger and subsequently to the absorber, aided by the absorbent properties of lithium. The vapor produced in the evaporator absorbs lithium bromide, diluting the solution. It is important to note that when lithium bromide absorbs water, it generates heat, which is released by the cold water circulating through the lithium bromide solution in the copper tubes. This process cools the bottom of the system and continues in a cycle.

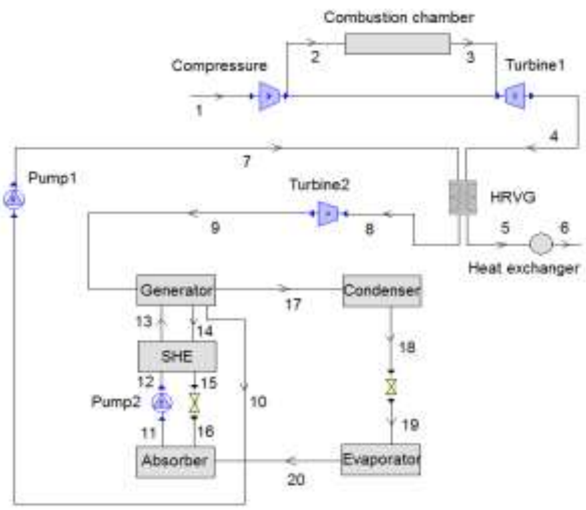

Figure 1. The schematic of the cogeneration system is investigated.

3. Methodology

This study presents a detailed thermodynamic and economic model of a multi-production system. The modeling was conducted using EES software, which has capabilities for calculating thermodynamic properties. The thermodynamic equations were solved simultaneously in a steady state. In the economic analysis, all prices and inflation rates were updated to provide a comprehensive justification for the plan. A parametric analysis was conducted to assess how variations in key parameters affect system performance. Additionally, a two-objective optimization was performed to enhance system performance. The optimization algorithm focused on two objective functions: exergy efficiency and cost rate, with optimization variables including the compression ratio and the isentropic efficiency of both the turbine and compressor.

4. Thermodynamic modeling of system

4.1 Gas turbine cycle energy analysis

A thorough energy assessment of a system involves measuring both energy inputs and outputs to evaluate efficiency and identify energy losses. This analysis applies thermodynamic principles to determine how effectively energy is converted. The findings are essential for improving system design and performance, resulting in more sustainable and efficient energy use. In the gas cycle, we explore the key relationships necessary for calculating the operation of compressors and turbines, the heat in combustion chambers, and other related components. The heat exchanged in the steam heat exchanger recovery vapor generator is determined using the following equation [46]:

$$\mathrm{Q_{HRVG}} = \mathrm{m_4(h_5 - h_4)} \tag{1}$$

The heat exchanged in the combustion chamber is obtained from the following equation [46]:

$$\mathrm{Q_{comb}} = \mathrm{m_{dot}(h_3 - h_2)} \tag{2}$$

The network exchanged in the gas cycle is calculated from the following equation [46]:

$$\mathrm{W_{net_{gas}}} = \mathrm{m_{dot}}\left(\mathrm{w_{a_{turb_1}}} - \mathrm{w_{a_{comp}}}\right) \tag{3}$$

The efficiency of the gas turbine cycle is calculated by this relation [46]:

$$\eta_{total_{gas}} = \frac{W_{net_{gas}}}{Q_{comb}} \tag{4}$$

The pressure ratio in the compressor is 6.7, and the isentropic efficiencies of the compressor and turbine are 0.84 and 0.87, respectively.

4.2. Gas turbine cycle exergy analysis

Examining exergy destruction in an energy system necessitates assessing the irreversibility of each component. A comprehensive energy analysis must account for factors such as temperature differences, pressure changes, and flow limitations. This detailed approach is essential for measuring exergy losses during energy conversions, helping to reveal inefficiencies within the system and inform optimization strategies. By pinpointing the sources of exergy loss, engineers can identify opportunities to improve system efficiency and minimize environmental impacts, enabling targeted enhancements. The exergy loss in gas cycle components is calculated using the following equations [46]:

$$E_{dist_{comp}} = m_{dot}(h_1 - T_0 \times s_1) - m_{dot}(h_2 - T_0 \times s_2) + m_{dot}\left(w_{a_{comp}}\right) \quad (5)$$

$$E_{dist\_comb} = m_{dot}(h_2 - T_0 \times s_2) - m_{dot}(h_3 - T_0 \times s_3) + Q_{comb}(1 - \frac{T_0}{T_H}) \quad (6)$$

$$E_{dist_{turb_1}} = m_{dot}(h_3 - T_0 \times s_3) - m_{dot}(h_4 - T_0 \times s_4) - m_{dot}\left(w_{a_{turb}}\right) \quad (7)$$

$$E_{dist_{hx}} = m_{dot}(h_5 - T_0 \times s_5) - m_{dot}(h_6 - T_0 \times s_6) \quad (8)$$

4.3. Water–ammonia cycle energy analysis

In the water-ammonia cycle, the operation of the turbine and the pump is calculated using the following equations [47]:

$$W_{p\_1} = (m_{10} \times v_{10}(p_7 - p_{10}))/\eta_{pump\_1} \quad (9)$$

$$W_{turb_{2_s}} = m_8\left(h_8 - h_{9_s}\right) \quad (10)$$

$$W_{turb_{2_a}} = m_8(h_8 - h_9) \quad (11)$$

The isotropic efficiency of the turbine is determined using the following equation [47]:

$$\eta_{turb_2} = \left(\frac{h_9 - h_8}{(h_{9_s} - h_8)}\right) \quad (12)$$

The network of the water-ammonia cycle is derived from the following relation [47]:

$$W_{net_{water-ammonia}} = m_{dot}\left(w_{a_{turb_2}} - w_{pump_1}\right) \quad (13)$$

4.4. Exergy analysis of water–ammonia cycle

The elimination of exergy in a water-ammonia turbine is derived from the following equation [47]:

$$E_{dist_{turb_2}} = m_{dot}(h_8 - T_0 \times s_8) - m_{dot}(h_9 - T_0 \times s_9) - m_{dot}\left(w_{a_{turb_2}}\right) \quad (14)$$

The isotropic efficiencies of Turbine Two and Pump One are 0.88 and 0.70, respectively.

4.5. Energy analysis of water-lithium absorption

The relationship between heat calculation and component work in the water-lithium bromide absorption refrigeration cycle is as follows [48]. The performance coefficient of the absorption refrigeration cycle is calculated using the following equation:

$$Cop=((Q_{evap}/(Q_{gen} + W_{pump_2})) \quad (15)$$

The work of the absorption refrigeration cycle is calculated using the following equation:

$$W_{net_{abs}} = W_{pump_2} \quad (16)$$

4.6. Exergy analysis of water-lithium absorption cycle

The exergy destruction of water-lithium bromide absorption refrigeration components is derived from the following equations [48]:

$$E_{dist_{abs}} = m_{20}(h_{20} - T_0 \times s_{20}) + m_{16}(h_{16} - T_0 \times s_{16}) - m_{11}(h_{11} - T_0 \times s_{11}) - Q_{abs}\left(1 - \frac{T_0}{T_{abs}}\right) \quad (17)$$

$$E_{dist_{gen}} = m_{13}(h_{13} - T_0 \times s_{13}) - m_{14}(h_{14} - T_0 \times s_{14}) - m_{17}(h_{17} - T_0 \times s_{17}) - Q_{gen}\left(1 - \frac{T_0}{T_{gen}}\right) \quad (18)$$

$$E_{DIST_{COND}} = M_{17}(H_{17} - T_0 \times S_{17}) - M_{18}(H_{18} - T_0 \times S_{18}) - Q_{COND}\left(1 - \frac{T_0}{T_{COND}}\right) \quad (19)$$

$$E_{DIST_{EVAP}} = M_{19}(H_{19} - T_0 \times S_{19}) - M_{20}(H_{20} - T_0 \times S_{20}) - Q_{EVAP}\left(1 - \frac{T_0}{T_{EVAP}}\right) \quad (20)$$

$$E_{DIST_{SHE}} = M_{12}(H_{12} - T_0 \times S_{12}) + M_{14}(H_{14} - T_0 \times S_{14}) - M_{13}(H_{13} - T_0 \times S_{13}) - M_{15}(H_{15} - T_0 \times S_{15}) \quad (21)$$

$$E_{DIST\_STV} = M_{15}T_{10}(S_{16} - S_{15}) \quad (22)$$

$$E_{DIST\_RTV} = M_{18}T_{10}(S_{19} - S_{18}) \quad (23)$$

4.7. Energy analysis of the whole system

The network of the system is calculated using the following equation [50]:

$$W_{net_{total}} = W_{net_{gas}} + W_{net_{water-ammonia}} + W_{net_{abs}} \quad (24)$$

The efficiency of the entire system is calculated using the following equation [50]:

$$\eta_{cchp} = \frac{Q_{heating} + Q_{cooling} + W_{net_{total}}}{m_{fuel} \times LHV_{fuel}} \quad (25)$$

4.8. Exergy analysis of the whole system

Exergy efficiency is calculated using the following equation [50]:

$$\eta ex = \frac{W_{net_{total}} + E_c + E_H}{m_{fuel} \cdot \varepsilon_{fuel}} \quad (26)$$

The cooling exergy output is obtained from the following equation [50]:

$$E_c = m_{ref}\left[\left(\left(h_{EVA,in} - h_{EVA,out}\right)\right) - T_0\left(S_{EVA,in} - S_{EVA,out}\right)\right] \quad (27)$$

The output of the heating exergy is obtained from the following equation [50]:

$$E_H = Q_H\left(1-\frac{T_0}{T_H}\right) \quad (28)$$

The chemical exergy of the fuel is obtained from the following equation [50]:

$$\varepsilon_{fuel} = LHV\,(1.033+0.0169\frac{b}{a}-\frac{0.0698}{a}) \quad (29)$$

Using electricity sourced from the grid, cooling generated by a compression chiller, and heating provided by a natural gas boiler, fuel consumption is represented by the following equation [50]:

$$F_{sp} = \frac{W}{\eta_g}+\frac{Q_c/cop_e}{\eta_g}+\frac{Q_H}{\eta_b} \quad (30)$$

In this context, the efficiency of the generator is 0.33, while the efficiency of the boiler is 0.80.

5. Economic evaluation

The economic evaluation of energy systems examines their financial feasibility and operational effectiveness by considering initial investments, ongoing expenses, and potential revenue. A key component of this assessment is the calculation of the annual cost rate, which reflects the total financial commitment associated with system installation, operation, and maintenance. The total cost function is defined as the sum of the operating cost rate, related to fuel expenses, and the cost rate, which encompasses investment and maintenance costs. Consequently, the total cost function indicates the total cost rate in dollars per unit of time, as expressed by the following relation [51]:

$$C_T = C_{env}+C_{fuel}+\sum C_{CIM} \quad (31)$$

The initial factor is the expense associated with carbon dioxide; the second factor is the price of fuel, and the third factor pertains to the investment and maintenance rates. Here, c signifies the cost of fuel for each energy unit, and m indicates the fuel's mass flow rate. To convert capital investment into a cost rate and to calculate the investment rate and capital maintenance, the following equation is employed for various components of the system [51]:

$$C_{CIM} = CRF\times\frac{\varphi_r}{(N\times3600)}\times PEC_k \quad (32)$$

Where PEC is a function of purchase cost, expressed in terms of system thermodynamic parameters, and the maintenance coefficient, which has a value of 1.06. CRF is the economic parameter that depends on the interest rate and the estimated lifespan of the equipment, which is obtained using the following relation [51]:

$$PEC_{comp} = \left(\frac{39.5\times m_2}{0.9-eta_{comp}}\right)\left(\frac{P_2}{P_1}\right)\ln\left(\frac{P_2}{P_1}\right) \quad (34)$$

$$PEC_{comb} = \left(\frac{46.08\times m_2}{0.995-\frac{P_3}{P_2}}\right)(1+\exp(0.018\times T_3-26.4)) \quad (35)$$

$$PEC_{gas\ turbine} = \left(\frac{479.34\times m_3}{0.92-eta_{gas\ turbine}}\right)\ln\left(\frac{P_3}{P_4}\right)\ (1+\exp(0.036\times T_3-54.4)) \quad (36)$$

$$PEC_{HRVG} = \left(\frac{576.1}{397}\right)C_{0_{HRVG}}\left(B_{1,HRVG}+B_{2,HRVG}\times F_{M_{HRVG}}\times F_{P_{HRVG}}\right) \quad (37)$$

$$PEC_{pump\_2} = 1120\times W_{pump_2}{}^{0.8} \quad (38)$$

$$PEC_{evap} = 1397\times A_{evap}{}^{0.89} \quad (39)$$

$$PEC_{cond} = 1397\times A_{cond}{}^{0.89} \quad (40)$$

$$PEC_{she} = 383.5\times A_{she}{}^{0.65} \quad (41)$$

$$PEC_{abs} = 16500\times(0.01\times A_{abs})^{0.6} \quad (42)$$

$$F_{P_{HRVG}} = \exp(Y_{-1_{HRVG}}+Y_{-2_{HRVG}}\times4.11+Y_{-3_{HRVG}}\times(4.11)^2 \quad (43)$$

$$c_{0\_turb\_2} = \exp(k_{\_1\_turb\_2}+k_{\_2\_turb\_2}+k_{\_3\_turb\_2}) \quad (44)$$

$$c_{0\_HRVG} = \exp(k_{-1_{HRVG}}+k_{-2_{HRVH}}\times1.26+k_{\_3\_HRVG}\times(1.26)^2) \quad (45)$$

The cost functions for various components of the system have fixed values that are utilized in calculating the total cost, as shown in table 1.

Table 1. Fixed values of economic analysis [16].

parameter	value
$k_{\_1\_turb\_2}$	2.705
$k_{\_2\_turb\_2}$	1.44
$k_{\_3\_turb\_2}$	-0.1776
$k_{\_1\_HRVG}$	4.325
$k_{\_2\_HRVG}$	-0.303
$k_{\_3\_HRVG}$	0.1634
$B_{\_1\_pump}$	1.89
$B_{\_2\_pump}$	1.35
$B_{\_1\_HRVG}$	1.63
$B_{\_2\_HRVG}$	1.66
$Y_{\_1\_HRVG}$	0.03881
$Y_{\_2\_HRVG}$	0.11272
$Y_{\_3\_HRVG}$	0.08183
F_{M_pump}	2.2
C_{fuel}	8.58
F_{p_pump}	1.8
F_{M_HRVG}	1
$F_{\_BM\_turb}$	3.5

The proposed system is analyzed for energy, exergy, and economic aspects using primary data, which is sourced from table 2, for thermodynamic and economic modeling.

Table 2. Basic data in thermodynamic calculation.

parameter	value
First pump efficiency (%)	70
Combustion chamber efficiency (%)	99
First turbine efficiency (%)	87
compression ratio	6.7
Heat exchanger efficiency (%)	70
Compressor efficiency (%)	84
Second turbine efficiency (%)	88
Interest rate (%)	14
Performance period (year)	15
Annual operating hours (hour)	7300
Maintenance coefficient	1.06

As shown in figure 2, the temperature-entropy (TE) diagram for the proposed system is displayed. This diagram depicts the state transitions of the ammonia-water Rankine cycle, with pressure ranging from 7,600 to 13,000 kPa, while assuming an ambient pressure of 101 kPa.

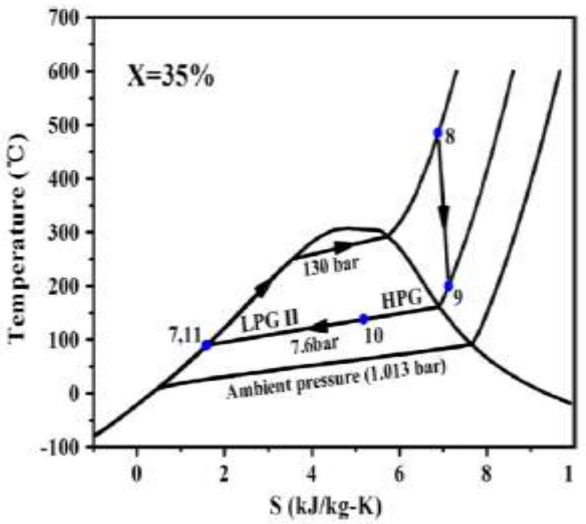

Figure 2. TS diagram of the proposed system.

6. Genetic algorithm optimization of system

The Genetic Algorithm (GA), inspired by genetic science, operates on the principle of survival of the fittest and is used to produce high-quality solutions for optimization challenges. One key research area in energy systems is optimizing multigeneration systems for peak performance. This study aims to either minimize or maximize exergy efficiency and total cost rate based on the specific conditions of the problem. The variables selected for system optimization include the compressor pressure ratio and the isentropic efficiencies of both the turbine and compressor. For optimization, we assume that the compression ratio ranges from 6 to 8, while the isentropic efficiency for both the turbine and compressor is estimated to be between 0.8 and 0.9. Improving energy systems is a complex task focused on enhancing their efficiency and performance. The genetic algorithm (GA), a robust technique based on natural selection principles, is employed to achieve this. The GA creates a population of potential solutions and gradually improves them through processes akin to genetic crossover and mutation. Genetic algorithms provide significant advantages for optimizing energy systems, as they can discover global optima in complex search environments and can be tailored to meet various goals and constraints. Their effectiveness is demonstrated by successful implementations in power systems that address challenges such as generation expansion planning, unit commitment, and economic load dispatch. In power system engineering, which often involves large and complex systems, genetic algorithms (GAs) offer a valuable heuristic method for optimization. By leveraging GAs, engineers can make significant strides in design, management, and operation, ultimately promoting sustainability and enhancing the efficiency of energy generation and distribution. The genetic algorithm, inspired by the principles of genetic science, is based on the concept of survival of the fittest and is employed to develop effective solutions for optimization problems. A key area of research in energy systems focuses on optimizing multigeneration systems to achieve optimal performance. This research employs a dual-objective optimization approach to identify the best and most efficient operating conditions for the system. The goal of the optimization is to establish the most effective and cost-efficient arrangement of the system's components under ideal circumstances. The two-objective genetic algorithm assesses the performance of all design variables to determine the optimal conditions for the system. This study aims to enhance system productivity by maximizing exergy efficiency while minimizing the total cost rate.

7. Validation

This research work introduces a new approach to organizing a simultaneous production system. To evaluate the effectiveness of the proposed system, we assessed it against the findings of Arora et al. [48] and Kumar et al. [49], with comparisons made to the data presented in table 3. Both this study and the previous research will be analyzed by modeling the described processes. The models will be based on initial conditions and assumptions, including an ambient temperature of

25 °C and an ambient pressure of 101 kPa. The results will then be compared. The changes in pressure and heat due to movement through the system components are minimal. It is assumed that, under equilibrium conditions, the solutions exiting the absorber and generator are saturated according to their respective temperatures and concentrations. The refrigerant leaving the condenser is considered saturated, similar to the vapor exiting the evaporator, both at their respective saturation temperatures. The vapor refrigerant exiting the generator is in a superheated state, matching the generator's temperature. This analysis reflects real-world scenarios by considering non-equilibrium conditions at the inlets of both the generator and absorber, as well as the conditions at the outlets of the solution pump and solution heat exchanger. It is assumed that the temperatures of the heat source and generator are identical. The refrigerant flows at a rate of 1 kg/s, with the generator operating at a temperature of 87.8°C. The evaporator temperature is 7.2°C, while both the condenser and absorber function at 37.8°C. The comparison results reveal a slight difference, indicating a high level of accuracy in the validation process.

Table 3. Validation of the present work with references [48, 49].

Parameter	Present work	Ref.[48]	Ref.[49]
absorber heat (kW)	2943	2945.26	2922.38
condenser heat (kW)	2506	2505.91	2507.89
evaporator heat (kW)	2355	2355.4	2357.16
coefficient of performance	0.79	0.7609	0.767

8. Results

This section offers a comprehensive assessment of the economic and engineering results derived from system modeling. It includes a detailed parametric analysis that examines how various parameters affect system performance. Additionally, it presents the results of optimization efforts aimed at identifying the optimal operational parameters for the system. The proposed system is simulated using EES software based on the established design conditions. The thermodynamic data for all states illustrated in figure 1 encompassing temperature, pressure, mass flow, specific enthalpy, specific entropy, and specific exergy can be found in table 4.

Table 4. Thermodynamic properties of the multi-generation system in each state.

point	T(c)	P(kPa)	h(kj/kg)	S(kj/kgK)	e (kj/kg)	$\dot{m}$ (kg/s)
1	25	101.3	298.6	5.695	0.2538	7.832
2	280.4	678.7	558.8	5.778	235.8	7.832
3	1155	651.6	1549	6.85	906.2	8.7
4	637	97.25	944.6	6.872	295.4	8.7
5	170	101.3	445.1	6.096	27.49	8.7
6	90	101.3	364	5.894	6.464	8.7
7	93.19	13000	205.6	1.152	44.38	1.521
8	500	13000	3064	6.458	1320	1.521
9	206.3	970	2460	6.636	633.4	1.521
10	90	970	184.6	1.135	28.58	1.521
11	37.8	1.016	91.46	0.2287	1723	10.54
12	37.8	6.558	91.46	0.2287	1723	10.54
13	72.84	6.558	163.2	0.4472	1730	10.54
14	87.8	6.558	221.2	0.4791	1778	9.374
15	52.8	6.558	156.2	0.2895	1770	9.374
16	52.8	1.016	156.2	0.2895	1770	9.374
17	87.8	6.558	2664	8.58	110.8	1.166
18	37.8	6.558	158.3	0.5428	1.023	1.166
19	7.2	1.016	158.3	0.5661	5.913	1.166
20	7.2	1.016	2514	8.968	155.5	1.166

An exergy assessment has been conducted on the proposed system. To achieve the optimal operational condition, exergy losses in various components have been identified, as shown in table 5. The analysis indicates that the highest exergy loss occurs in the boiler, primarily due to the significant temperature differential and the combustion process taking place there. A practical recommendation for enhancing the system's efficiency is to increase the heat extraction temperature in the boiler. The total exergy loss for the system is estimated to be 2409 kW.

Table 5. Exergy destruction of components.

parameter	value
Condenser (kw)	7.701
Expansion valve (kw)	8.085
Combustion chamber (kw)	1628
Steam heat exchanger (kw)	10.32
Compressor (kw)	193.4
Evaporator (kw)	100.6
Generator (kw)	58.18
First Turbine (kw)	57.28
Absorbent (kw)	81.79
Heat exchanger (kw)	182.9
Second turbine (kw)	80.8

The results of assessments are the most crucial element of any scientific research, as they significantly influence the quality of the study. This section details the energetic, exergetic, exergoeconomic, and exergoenvironmental evaluations of the proposed multi-generation system, utilizing the input parameters presented in table 1, and applying the defined simplifying assumptions. The energetic analysis focuses on measuring and presenting the net output power, the rate of liquefied hydrogen production, the cooling load requirements of the system, and its overall energetic efficiency. An exergetic analysis is conducted to assess the performance quality of the proposed system. A comprehensive thermodynamic analysis has been performed on the multi-generation system. The findings from the energy and exergy evaluations, shown in table 6, indicate the optimal thermodynamic performance of the proposed system. The energy and exergy efficiencies for the studied system are 21.29% and 20.68%, respectively. The findings from the thermodynamic evaluation indicate that the output power of the studied system is 3,874 kW.

Table 6. Results of energy and exergy efficiency of system.

parameter	value
Energy efficiency (%)	21.29
Exergy efficiency (%)	20.68
Fuel consumption coefficient	25890
Absorption refrigeration system performance coefficient(%)	79.24

A key goal of this research work is to develop an efficient system that minimizes expenses for investors involved in commercialization and large-scale production. To achieve this, an economic assessment of the proposed system is conducted using current cost functions. Table 7 presents the cost figures for various components of the system, indicating that the steam heat exchanger generator incurs the highest cost compared to the other components.

Table 7. Cost functions of system components.

parameter	value
Absorber ($/s)	40816
Turbine One ($/s)	166482
Double turbine ($/s)	1311506
Condenser ($/s)	160830
Steam heat exchanger generator ($/s)	4174477
Combustion chamber ($/s)	10349
Pump one ($/s)	17851
Compressor ($/s)	65713
Double pump ($/s)	4470
Evaporator ($/s)	323004
Steam heat exchanger ($/s)	7696
Generator ($/s)	19484
Fuel ($/s)	85.88
Carbon Dioxide ($/s)	87

8.1. Conduction of sensitivity analysis

Sensitivity analysis is a vital method for evaluating a system's performance under varying conditions, providing a comprehensive understanding of the system in question. To enhance design and operational strategies, it is essential to analyze variables thoroughly to identify the key factors that significantly affect the system's energy efficiency and sustainability over time. This study examines how these critical factors influence the system's technical and economic performance. In the proposed system, the effects of key design parameters, such as the density ratio and gas turbine inlet mass flow rate, on the system's output products are assessed.

8.1.1. Effect of variation of density ratio on system performance

Fuel consumption decreases as the pressure ratio increases. This effect is due to the rise in air temperature entering the combustion chamber; specifically, a higher temperature reduces the amount of fuel needed to achieve thermal equilibrium. Furthermore, a higher pressure ratio enhances cold production. Power generation initially increases to a peak before beginning to decline. The work required by the compressor increases at a slower rate at lower pressure ratios compared to higher ones, resulting in net power production reaching a maximum before decreasing with further increases in pressure ratios. The reduction in steam flow rate through the HRVG leads to decreased heat production. As shown in figure 3, increasing the compression ratio in the compressor results in a decline in both energy and exergy efficiency. The effects of changes in the density ratio on overall cost and exergy destruction are illustrated in figures 4 and 5. An increase in the pressure ratio raises total cost, while total exergy destruction and the exergy destruction associated with the system cycles both decline. The significant reduction in exergy destruction within the combustion chamber, as the pressure ratio increases, can be attributed to a smaller exergy difference between the compressed air entering and the combustion products exiting. While a higher pressure ratio decreases exergy destruction in the heat recovery vapor generator (HRVG), it simultaneously increases the exergy of the combustion products and decreases the exergy of the turbine exhaust. Consequently, the turbine experiences a greater extent of exergy destruction. Furthermore, exergy destruction in the air compressor shows a positive correlation with the pressure ratio, which is related to increased heat generation within the compressor at elevated pressure ratios. Additionally, the higher pressure ratio leads to an increased steam flow rate to the absorption chiller, further amplifying exergy destruction within the chiller. The exergy destruction in the compressor also rises with an increase in the pressure ratio, as a greater pressure ratio generates additional heat within the compressor. As illustrated in figure 6, an increase in the compression ratio results in enhanced power generation. A higher pressure ratio significantly reduces exergy loss in the combustion chamber by creating a smaller exergy difference between the compressed air and the combustion products. Additionally, elevated pressure ratios enhance the combustion energy in the products while decreasing the volume of exhaust gas in the turbine, leading to increased power dissipation within the turbine. Ultimately, an increase in the pressure ratio raises the velocity of the steam flow entering the absorption chiller, which in turn amplifies exergy loss in the chiller. As the density ratio increases, cold production improves, while heat production and fuel consumption decrease. Initially, net power rises at lower density ratios but begins to decline at higher levels.

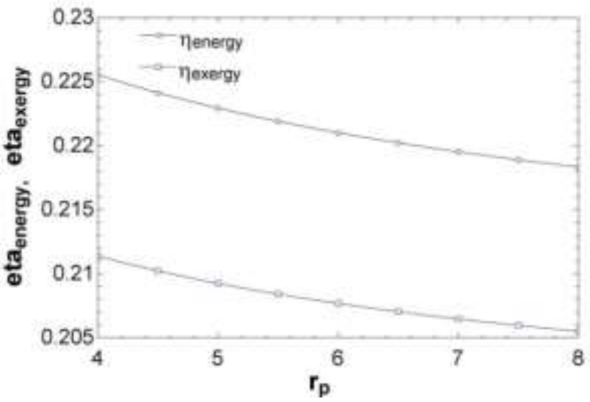

Figure 3. Effect of the variation of the density ratio on energy and exergy efficiency.

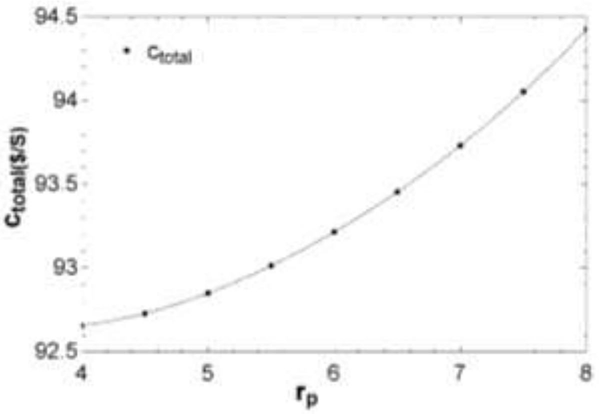

Figure 4. Effect of the variation of the density ratio on total cost.

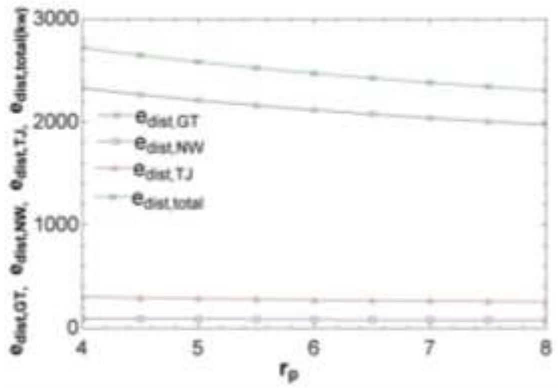

Figure 5. Effect of the variation of the density ratio on the exergy destruction of system cycles.

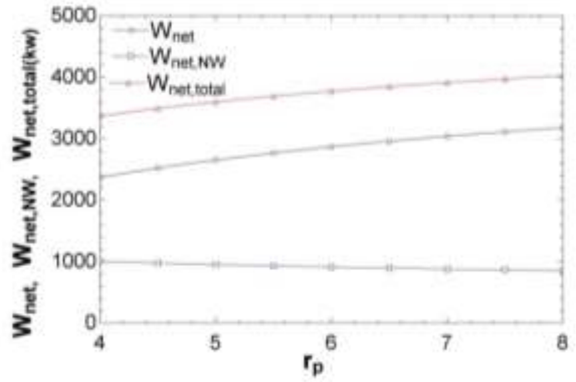

Figure 6. Effect of the variation of the density ratio on the work of system cycles.

8.1.2. Effect of the variation of the gas turbine inlet mass flow rate on system performance

The impact of fluctuations in the gas turbine inlet mass flow rate on both energy and exergy efficiency is illustrated in figure 7. To maintain thermal equilibrium within the combustion chamber, fuel consumption increases as the turbine inlet mass flow rate rises. This increase in mass flow rate also leads to greater heat generation, as evidenced by a higher exhaust temperature from the turbine. A reduction in steam flow to the heat recovery vapor generator (HRVG) results in decreased cold production. Consequently, net power output increases due to the enhanced power generated by the turbine. However, exergy destruction within the combustion chamber intensifies with a higher turbine inlet mass flow rate, as this leads to an elevated mean temperature during the heat addition process. Furthermore, the increased temperature differential between the flue gas and the water/steam in the HRVG leads to greater exergy destruction in that component. The rise in turbine output power corresponds to an increase in turbine exergy. A decrease in steam flow to the HRVG reduces exergy destruction in the absorption chiller, while exergy destruction in the air compressor remains constant. An elevated turbine inlet mass flow rate enhances energy efficiency. As expected, this increase also significantly boosts net power output, heat generation, and fuel consumption. However, the higher turbine inlet mass flow rate results in increased fuel consumption, which raises fuel costs. As the mass flow rate of the gas turbine increases, the system's capacity expands, allowing a greater volume of fluid at elevated temperatures to enter the operational framework. This results in improved efficiency of the gas cycle used for power generation. The correlation between exergy efficiency and variations in system output power indicates that heat transfer from the heat recovery steam generator increases, thereby enhancing the system's exergy efficiency as the mass flow rate into the generator fluctuates. Furthermore, both exergy efficiency and cost rate are directly linked to production capacity; thus, an increase in production capacity results in a rise in both exergy efficiency and cost rate. It is essential to recognize that as production capacity grows, the expenses related to system repairs and maintenance also escalate. The increase in the exergy rate illustrated in this diagram can be explained by the direct relationship between exergy efficiency and system output power; as the work output of the system increases, the exergy rate correspondingly rises. Additionally, the increase in cost rates can be attributed to the fact that system expenses will grow with the expansion of total system capacity, necessitating more extensive and larger equipment. Other factors contributing to the rising cost rates include increased output costs, energy expenditures, and expenses associated with non-production during system downtime. Additionally, it is important to note that costs were incurred for each sub-system within the main system. Consequently, the production capacity did not yield a cost-effective return on investment, resulting in an overall rise in system costs. Exergy is defined as the maximum amount of work that can be derived from a system, representing the useful work generated by the turbine. Fluctuations in total work lead to corresponding changes in exergy efficiency; as total work increases or decreases, so does exergy efficiency. Notably, an increase in the mass flow rate at the gas turbine inlet leads to a 3% enhancement in both energy and exergy efficiency, thereby improving the system's overall performance. The effects of changes in the gas turbine inlet mass flow rate on work output and exergy loss within the system cycles are illustrated in figures 8 and 9. An increase in the mass flow rate at the gas turbine inlet results in higher exergy loss and boosts the system's output power. Factors such as compression ratio, ambient temperature, air-to-fuel ratio, and isentropic efficiency significantly influence the thermal efficiency of a gas turbine power plant. Understanding how thermal efficiency varies with increased compression ratios, turbine inlet temperatures, and ambient temperatures is essential. Figure 10 illustrates how changes in the gas turbine inlet mass flow rate impact total costs. Specifically, an increase in gas turbine inlet temperature results in a higher overall system cost. As ambient temperature and air-to-fuel ratio rise, both thermal efficiency and power output decline linearly. Additionally, higher ambient temperatures and air-to-fuel ratios lead to a linear increase in fuel consumption and heat generation. Optimal efficiency, power output, and specific fuel consumption are achieved at higher compression ratios and lower ambient temperatures.

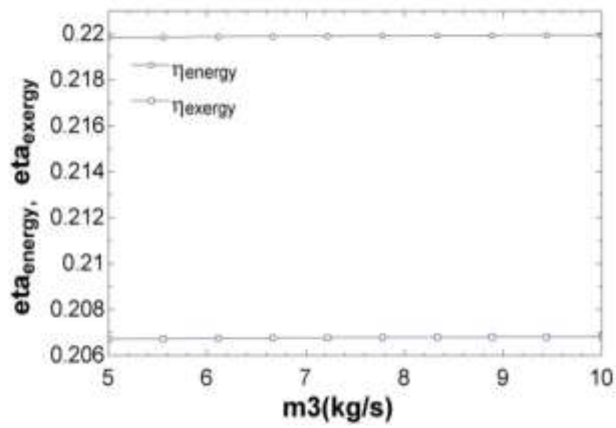

Figure 7. Effect of the variation of the gas turbine inlet mass flow rate on energy and exergy efficiency.

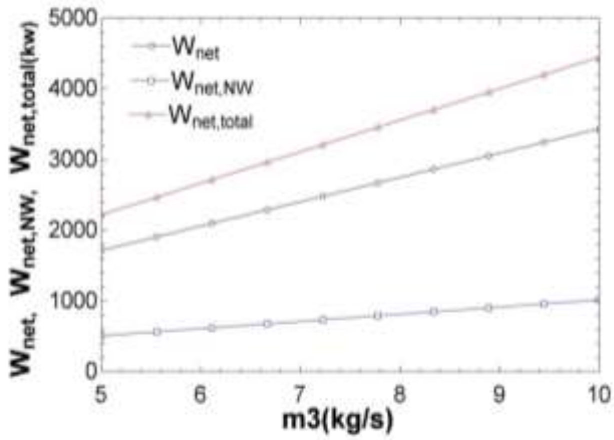

Figure 8. Effect of the variation of the gas turbine inlet mass flow rate on the work of the system cycles.

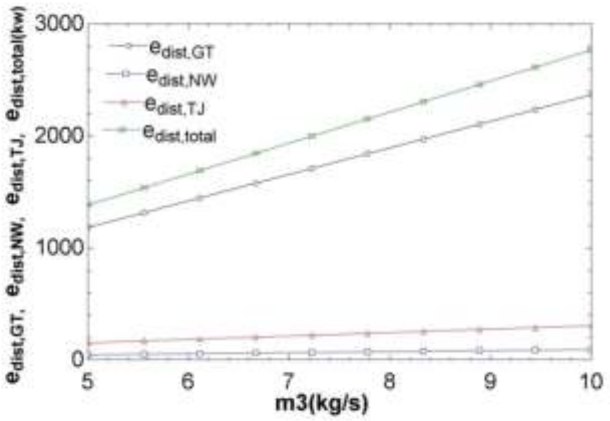

Figure 9. Effect of the variation of the gas turbine inlet mass flow rate on the exergy destruction of the system cycles.

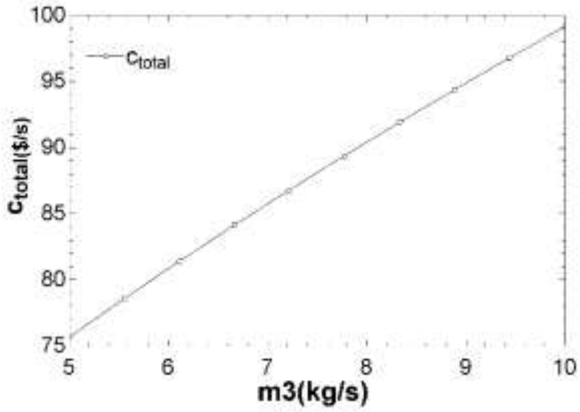

Figure 10. Effect of the variation of the gas turbine inlet mass flow rate on the total cost.

8.2. Two-objective genetic optimization results

Identifying the ideal values for target functions and design parameters presents a significant optimization challenge. This complexity stems from the nature of the target functions, the number of variables involved, and the linearity or non-linearity of the equations. To tackle this challenge, Genetic Algorithms (GAs) are employed to enhance system performance. GAs are renowned for their ability to mimic natural selection, enabling them to find near-optimal solutions for complex optimization and search problems. This research applies a two-objective genetic algorithm to identify the best values for the objective functions and optimization variables. The primary focus is on improving two specific objective functions: exergy efficiency and system cost, with the goal of determining their optimal values. This optimization endeavor aims to improve the thermodynamic performance metrics of the proposed system by enhancing exergy efficiency while simultaneously reducing system costs. The optimal values obtained from the two-objective genetic algorithm optimization are presented in table 8. The results indicate that, under ideal conditions, the system can achieve an energy efficiency of 22%, an exergy efficiency of 21%, and operate at a cost rate of $92.73 per second.

Table 8. Results of genetic algorithm optimization of system.

Decision variable	Optimum case
Total cost of system($/s)	92.73
Exergy efficiency of system(%)	21
Energy efficiency of system(%)	22
Total exergy destruction (kw)	2649

The primary aim of this geothermal system is to produce clean energy while minimizing environmental impact. To identify the optimal operating point for system efficiency, a criterion is needed to evaluate the available alternatives. In this research, we selected the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) as the decision-making approach. Establishing a link between cost and efficiency provides a foundation for understanding and predicting the relationship between these objectives. The objective functions of the optimization problem are defined by exergy efficiency and total cost rate. Solutions that lie on the Pareto front are considered non-dominant, and any of these solutions may be chosen as the optimal choice based on the designer's preferences. However, a solution that offers the most favorable trade-off among the various objective functions is typically of primary interest. In this context, the TOPSIS method was used to identify the optimal trade-off solution. As shown in figure 11, the set of optimal system points is represented by the Pareto frontier. The red point has been designated as the final optimal point for the system based on the TOPSIS decision-making criterion.

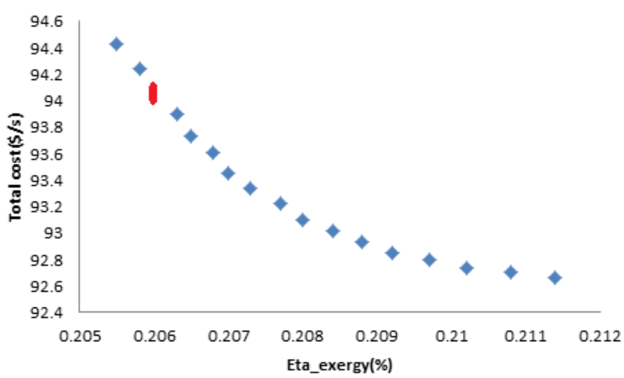

Figure 11. Pareto diagram considering exergy efficiency and total cost.

9. Conclusion

This research work explores the development of a compact and efficient renewable energy system tailored to meet the energy needs of small to medium-sized communities, providing a flexible and adaptable solution. The system offers significant environmental and economic benefits, due to its practicality and efficiency, thereby supporting sustainable development. This study represents a crucial step in optimizing energy use and reducing environmental pollution. A new multi-generation system, which includes a gas turbine, vacuum transformer, and generator, has been introduced and assessed. The waste heat produced by the gas turbine is captured by the transformer and repurposed for cooling applications. By implementing this method at the power generation site, costs associated with transmitting electricity from the source to the end-user can be reduced, leading to a decrease in primary power consumption. Additionally, the electricity generated by the ammonia turbine can also be used for cooling purposes. A thermodynamic model of the multi-generation system, which incorporates an efficient absorption chiller, has been developed. Exergy analysis reveals that the combustion chamber and heat recovery exchanger experience the highest exergy destruction compared to other system components. This is primarily due to the significant temperature differences that enhance heat transfer in these two components, along with the combustion reaction occurring in the combustion chamber. The efficiency of the system is affected by changes in the compressor pressure ratio, the inlet temperature of the gas turbine, and the isentropic efficiency of the high-temperature generator. An increase in the compressor pressure ratio generally results in a decrease in exergy efficiency, which in turn leads to higher carbon dioxide emissions. In contrast, an enhancement in the isentropic efficiency of the gas turbine is associated with improved overall system efficiency. Moreover, as the turbine inlet temperature rises, the operational power of the gas turbine also increases. A sensitivity analysis was also performed to better understand the system's performance under different conditions. The figure demonstrates that an increase in the pressure ratio and total cost leads to a reduction in both the fuel consumption coefficient and total exergy destruction. Additionally, as the turbine inlet mass ratio rises, there is a notable increase in the fuel consumption storage coefficient, total cost, total exergy removal, and both energy and exergy efficiencies. To optimize the proposed system, a two-objective genetic algorithm was combined with the TOPSIS decision-making method. Performance assessments revealed an energy efficiency of 21.29% and an exergy efficiency of 20.68%. The implementation of multi-generation systems for electricity, heating, and cooling proves to be an effective approach to boost energy production while simultaneously lowering energy consumption. Enhancing the combustion chamber by raising the inlet temperature, ensuring complete combustion, and reducing excess air can decrease maximum exergy, as well as lower carbon dioxide emissions and other environmental pollutants. The incorporation of genetic algorithms into the optimization process significantly improves the system's operational efficiency, achieving an exergy efficiency of 21% and a total cost rate of $92.73 per second. Future investigations should also explore the scalability of the system and its capacity to adjust to diverse locations and resource conditions. Evaluating the system should encompass its performance across various geothermal environments and its integration with other renewable energy technologies. To enhance operational efficiency and reliability, it is crucial to adopt sophisticated control strategies and real-time monitoring systems. Subsequent research should prioritize the development and testing of these control mechanisms to facilitate dynamic optimization of the system.

Nomenclature

CRF	Return on investment factor
C	Cost
E_c	Cooling exergy
Ex	Exergy
H	Enthalpy
S	Entropy
T	Temperature
P	Pressure
n	Economic life
E_H	heating exergy
I	Interest rate
ε_{fuel}	Fuel exergy
η_{cchp}	Energy efficiency
ηex	Exergy efficiency
F_{sp}	Fuel consumption
E_{dist}	Exergy destruction

Abbreviations

HRVG	heat exchanger recovery vapor generator
Comb	Combustion chamber
net	Net work
gas	Gas cycle
a	actual
Turb	Turbine
Comp	Compressure
E_{dist}	Exergy destruction
hx	Heat exchanger
T_H	Heat source temperature
P	Pump
$Evap$	Evaporator
Gen	Generator
abs	Absorber
$Cond$	Condenser
SHE	Steam heat exchanger
LHV	Low heating value
E_c	Cooling exergy
E_h	Heating exergy
F_{sp}	Fuel consumption
C_T	Total cost rate
C_{env}	cost of carbon dioxide
C_{fuel}	cost of fuel
C_{CIM}	Cost rate of investment and maintenance
φ_r	maintenance coefficient
PEC	Cost function

Declarations

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Availability of Data and Material
The data will be made available on request

Code Availability
The Code will be made available on request

Authors' Contributions
A. Eyvazi suggested the idea and stated the theory; A. Eyvazi performed optimization; A. Eyvazi wrote the manuscript; A. Eyvazi discussed the results and contributed to the final manuscript; A. Eyvazi read and approved the final manuscript.

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This article does not contain any studies with human participants or animals performed by any of the authors.

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