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Research article

Thermoeconomic study of a new combined power, heat and cooling system combined with an electrolyzer for producing hydrogen

Ali Eyvazi[1*], Hadi Ghaebi [2]

[1]*Phd, Department of Mechanical Engineering, Faculty of Engineering, Vali-e-Asr University of Rafsanjan, Rafsanjan, Iran*

[2] *Professor, Department of Mechanical Engineering, Faculty of Engineering, University of Mohaghegh Ardabili, Ardabi, Iran*

[*] alieyvazi1996@gmail.com

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Abstract

This evaluation presents an integrated and renewable multi-generation system. The system has a steam cycle, a double-effect absorption refrigeration cycle, a proton exchange membrane electrolysis, and a steam heat exchanger generator. This study investigates a multi-generation system that uses waste heat recovery from a steam turbine to provide the energy required for hydrogen production and cooling capacity in an absorption refrigeration unit. The performance of the proposed system is evaluated based on energy, exergy, and economic factors. A case study analyzed the behavior of the system under specific conditions. In addition, a sensitivity analysis was conducted to understand how different operating conditions affect the system performance. The results of the thermodynamic evaluation show that the energy efficiency of the proposed system is 37% while the exergy efficiency is 38%. The results show that the hydrogen production rate in the proposed system is 11.03 kg/h and the resulting power output is 4399 kW. The analysis shows that the total exergy destruction in the studied system is 31317 kW. The economic analysis shows the total system cost at 2.084$/GJ, which emphasizes its high economic justification. In addition, the electricity production cost is calculated at 1.138 cents /kWh and the hydrogen production cost is calculated at 3.529$/kg, which indicates the strong thermodynamic performance and better economic feasibility of the system.

Keywords: Thermoeconomic evaluation, Cogeneration, Electrolyzer, hydrogen, Double-effect absorption cooling

1- Introduction

The energy problem that emerged in the early 1970s was caused by the rapid growth of energy consumption and the limited availability of traditional resources. The problem is that the main energy sources are oil-based and are available in limited areas of the world. In recent years, efforts to find national solutions to the energy problem have intensified. Some industrialized countries, faced with a sharp decline in economic growth due to rising oil prices, have started to economize on fuel consumption, hoping to reduce their dependence on this unreliable energy supply system. Other countries, especially in the Third World, have turned their attention to expanding exploration operations in untouched areas in order to exploit resources that have been technically and economically inaccessible until now. This is especially true for fossil fuels, hydropower, solar energy and wind energy, in order to meet part of their energy needs [1]. History shows that it takes decades to replace one energy source with another. It took more than half a century to replace wood with coal, and then oil and gas with coal. Oil-producing countries, knowing that their reserves are finite, have reduced production. In some other countries, energy production facilities have decreased, and coal production has not increased significantly despite the rise in oil and gas prices. Finally, many developing countries are facing an energy crisis, with large areas of these countries facing severe fuel shortages [2]. Environmental movements, concerned about global warming caused by the use of fossil fuels and the potential dangers of nuclear power, are calling for the use of renewable energy sources [3]. The heat stored deep in the earth remains almost untouched, this energy can be obtained in any conditions. The technologies that mankind has today have made it possible to use this energy practically everywhere. Among renewable energies, geothermal energy is at a global level. Due to the high amount of geothermal energy available, this energy power plants are distinguished from other renewable energy power plants. In general, the production of this energy is higher compared to wind, solar and tidal energies [4]. The heat inside the earth has been exploited for centuries. Currently, geothermal energy is used widely in many parts of the world and in various forms. Researchers have also developed new methods of energy supply while applying old energy supply technologies. In the future, efforts to develop it are considered essential, both in the field of discovering energy sources and in the field of technology transfer. The exploitation of geothermal energy as a potential energy source deep in the earth is independent of atmospheric conditions and has the ability to meet the current and future needs of humanity [5]. The limitation of fossil fuels and the negative impact of their consumption on the environment, the increase in the price of fossil fuels are among the reasons that have directed politicians towards the use of other energies. Hydrogen has received special attention as an energy carrier. Hydrogen is one of the abundant elements on the planet that can be produced in various ways. Hydrogen produces a large amount of energy when burned with oxygen, and the result of this chemical reaction is the production of water vapor, which is dispersed in the air and helps to soften the environment. Unlike the use of fossil fuels, which pollute the environment and have created a major problem for the inhabitants of the planet. Hydrogen is used after being stored and transported to the place of consumption. However, many believe that humanity will enter the hydrogen age in the not-too-distant future and that the future fuel of the world will be hydrogen. A fuel cell is a device in which ordinary fuel such as natural gas or hydrogen reacts with oxygen electrochemically and produces electrical energy in the form of direct current as long as fuel and oxygen are added to it. The efficiency of a fuel cell in optimal conditions is almost twice that of internal combustion engines, which can justify the world's attention to fuel cells. Hydrogen cells have shown their performance well in space engines, and while they do not pollute the environment, they are quickly finding their wide place. The main application of these cells is for use in vehicles instead of gasoline and diesel and in general to replace fossil fuels. The use of hydrogen cells is desirable in terms of not polluting the environment, because to start working they only need oxygen and hydrogen, which are cheap and easily accessible fuels. The result of burning these two elements and giving energy to the outside is water vapor, which causes the environment to be mild. All these processes have excellent and reliable efficiency, which has been achieved in space engines in the past decades [6, 7]. Hai et al. [8] proposed a multi-generation system that integrates gas turbine, organic Rankine cycle and absorption chiller to meet the heating, cooling and power needs of a city. They optimized the system using multi-objective genetic algorithm and selected the optimal design solution through a simple decision-making process. Their results showed that the optimized system achieved an exergy efficiency of 17.56%, a total cost rate of $49.74/h and a sustainability index of 1.21. Mashrvati et al. [9] used a multi-objective genetic algorithm to optimize a gas turbine-intercooler cooling system with exergy destruction rate, electricity cost, and energy efficiency as objectives. In their analysis, they also used the TOPSIS decision maker to select the final optimal option, which resulted in energy efficiency, total exergy destruction rate, and electricity cost rate of 53.91%, 2392.01 kWh, and 52.29 USD/h, respectively. Laouid et al. [10] used a multi-objective genetic algorithm to compare the performance of three different modified Rankine cycle configurations under optimal conditions. They identified the optimal operating conditions for each configuration using the TOPSIS decision maker. Their findings showed that the modified Rankine cycle configuration with an internal heat exchanger outperformed both the regenerator-equipped Rankine cycle and the original Rankine cycle in overall performance under optimal operating conditions. Sanaye et al. [11] used multi-objective genetic algorithm to optimize a multi-generation system using exergy efficiency and system cost rate as objective functions. They used TOPSIS and linear programming technique for multi-dimensional analysis LINAMP to select the final optimal solution after obtaining the Pareto front. They found that both decision makers selected the same Pareto front member for the final optimal option. Huang et al. [12] proposed a gas turbine-based multi-generation system. Their study used a two-objective genetic algorithm to perform multi-objective optimization, focusing on increasing exergy efficiency, minimizing system cost rate, and reducing normalized carbon dioxide emissions as key objectives. They identified the best optimal solution from the Pareto front using the TOPSIS method with equal weighting criteria. The results showed significant improvements after optimization, such that the exergy efficiency, system cost rate, and normalized carbon dioxide emissions increased by 6.45, 3.43, and 8.84 percent, respectively. In a study, Liu et al. [13] optimized a gas turbine-based hybrid multiple generation system using a multi-objective genetic algorithm, with total energy output, exergy efficiency, and unit exergy cost as objective functions. Using TOPSIS with equal weight criteria facilitated the selection of the best optimal solution. Their findings showed that after optimization, the total energy output and exergy efficiency increased by 35.58 kW and 0.2%, respectively, while the unit exergy cost experienced a slight increase of 0.21 USD/GJ. A solar tower power plant with a Brayton-SO2 cycle has been proposed by Wang et al. [14]. The results showed that at the optimum pressure close to the critical point, the system is thermally efficient. In addition, increasing the turbine inlet temperature and pressure ratio is beneficial to the thermal performance of the system. An experimental study and dynamic simulation of a solar tower collector system for Brayton-SO2 cycle power generation was conducted by Chen et al. [15]. The results show that the receiver outlet temperature can reach up to 882 °C with a pressure drop of 1.7 kPa and a thermal power of 132 kW during the experiment. An innovative solar-nuclear complementary energy system based on the combined Brayton cycle was proposed by Wang et al. [16]. The results show that with the increase of solar radiation, the net electric power and the electric power ratio increase. Siddiqui et al. [17] investigated the potential of carbon dioxide-based binary mixtures for operating a Rankine cycle with low-grade heat sources in hot regions. The results show that using a carbon dioxide-based binary mixture for a supercritical Rankine cycle not only improves the overall thermodynamic performance but also reduces the operating pressures of the cycle, which may lead to cheaper materials required for various plant components. This research focuses on developing renewable energy using efficient and readily available technologies and is ideal for small to medium-sized communities where large-scale projects are impractical. The flexibility and scalability of the system allow it to meet unique energy needs and provide a reliable and environmentally friendly energy source. This approach makes it an attractive option for communities transitioning to renewable energy without significant financial challenges. With an emphasis on practicality and efficiency, this system offers significant environmental and economic benefits and supports sustainable development. The integration of heat recovery sections significantly increases the performance of the multiple generation power plant. By combining advanced technologies such as the Rankine cycle, the double-effect absorption refrigeration cycle, and the proton exchange membrane electrolyzer unit, these power plants achieve higher energy conversion rates and better resource utilization. In the present study, the multiple generation system based on the Rankine cycle is evaluated and we see less pollution compared to the Brayton cycle. The performance of the proposed system is investigated under the operating conditions of the Rankine cycle with three different working fluids. The innovation of the present study is based on the fact that part of the waste heat of the Rankine cycle is recovered and provided by the double-effect absorption refrigeration cycle to provide the required cooling capacity, and at the same time, another part of the waste power is used to supply the energy required by the proton exchange membrane electrolyzer and produce hydrogen.

2- System description

Fig. 1 shows the schematic of the proposed cogeneration system. This system is a combination of a steam cycle, an absorption cooling system, and an electrolyzer. The Rankine cycle starts with saturated liquid water, which is pressurized by a pump. The water then enters the boiler at high pressure and absorbs heat and turns into superheated steam. This steam expands through a turbine and produces work. After expansion, the fluid exits the turbine and enters the heat exchanger to provide heat. This study includes a double-effect absorption cooling system consisting of components such as two high-temperature and low-temperature generators, two high-temperature and low-temperature heat exchangers, a condenser, an expansion valve, an evaporator, an absorber, a condenser heat exchanger, and a pump. This system increases the overall efficiency by recovering the waste heat from the steam Rankine cycle. It uses this heat to power a cooling process through the evaporator and a heating process through the condenser. A mixture of water and lithium bromide is used as the working fluid, and water acts as the refrigerant. Water and lithium bromide mixtures are chosen for absorption refrigeration because of their special properties. This dual absorption system operates by effectively utilizing waste heat from the Rankine cycle to provide both cooling and heating. This integrated approach to energy management optimizes the use of available heat sources and minimizes waste. The choice of water as the refrigerant further supports this strategy due to its favorable thermodynamic properties and its efficiency in absorption refrigeration cycles. In the proton exchange membrane electrolyzer system, water passes through a heat exchanger to be heated to the electrolyzer temperature. The input electrical energy causes the hot water to decompose into oxygen and hydrogen. The oxygen and hydrogen streams produced are then stored in the respective storage tanks.

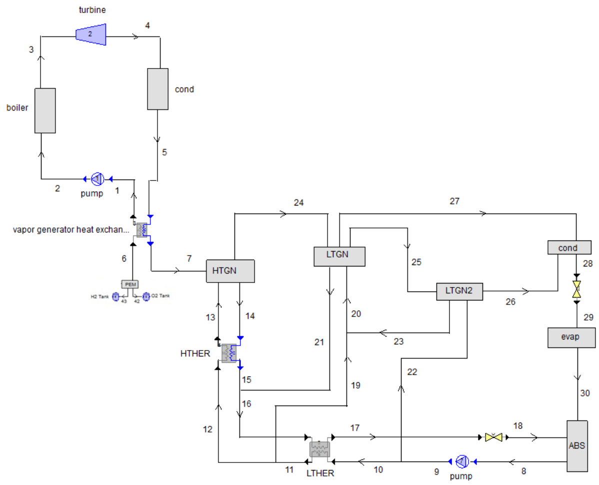

Fig. 1 Schematic of the proposed system

3- Methodology

A novel multi-generation system is studied in the present study. The proposed system is examined from different perspectives and the system performance is quantified through output parameters. In addition, a parametric study is carried out to evaluate the system performance by varying the performance parameters under specific operating conditions. In this study, a new arrangement of cogeneration system for hydrogen production is proposed. A multi-dimensional analysis is carried out to evaluate the performance of the proposed system from energy, exergy and economic perspectives. The purpose of the energy analysis of the system in a case study is to discuss the values of net output power, hydrogen production rate, system cooling load and energy efficiency. The mentioned parameters are essential factors for evaluating the energy performance of the proposed configuration. In addition, the performance quality of the proposed system is evaluated through an exergy study. Exergy analysis attempts to maximize the work output from a cycle. This analysis involves two key steps: First, it identifies and investigates inefficient thermodynamic processes by quantifying the exergy losses through exergy balance.

Second, it determines possible improvements based on avoidable and unavoidable exergy losses. Unavoidable exergy losses represent the minimum exergy degradation that is constrained by current technology and economic factors. Therefore, avoidable losses highlight the potential for process optimization. Therefore, exergy analysis quickly identifies inefficiencies and potential improvements in a system. An economic analysis is also performed to determine the profitability of the proposed system. An understanding of thermoeconomics, applied to thermodynamic systems, including renewable energy systems, is essential to achieve optimal system performance, balancing thermodynamic and economic considerations. By applying economic principles to the technical design of energy systems, conditions for equipment operation that minimize overall production costs are acknowledged.

The thermodynamic analysis of the system under study includes the following assumptions [18]:

• The conditions remain constant throughout the process.

• The steam turbine and pump operate with isentropic efficiency.

• Pressure drop and heat transfer in the system are negligible.

• The effect of kinetic and potential energy in the system has been neglected.

• The evaporator and condenser outputs are saturated vapor and saturated liquid, respectively.

• The enthalpy before and after the expansion valve remains constant.

4-Thermodynamic analysis of the system

Comprehensive energy analysis of a system involves quantifying energy inputs and outputs to determine efficiency and identify energy losses. This process uses thermodynamic principles to evaluate the performance of energy conversion methods. The insights gained are essential for optimizing system design and operation, ultimately promoting sustainable and efficient energy use. Mass and energy balance equations based on the first law of thermodynamics are used for each component. Equations (1) and (2) use h to represent the enthalpy of flow, with the subscripts “i” and “e” representing the inlet and outlet conditions, respectively [19]:

$$\sum m_i = \sum m_e \quad (1)$$

$$Q - W = \sum m_e h_e - \sum m_i h_i \quad (2)$$

The proposed multiple generation system is modeled using mass, energy and exergy balance equations. The data required for simulation are presented in Table 1.

Table 1: Initial thermodynamic data used for modeling [20]

Parameter	Value
Cooling cycle pump inlet pressure (kg/s)	9.127
Steam cycle pump outlet pressure (kPa)	8000
Cooling cycle pump inlet temperature (c)	1
Steam cycle turbine outlet temperature (c)	30
Steam cycle turbine outlet pressure (kPa)	1167
Turbine Isentropic Efficiency (%)	85
Isentropic pump efficiency (%)	80
Electrolyzer inlet temperature (c)	80
Electrolysis inlet pressure (kPa)	100

Specific exergy includes physical, chemical, kinetic and potential exergy. In practice, kinetic and potential exergy are often neglected. As a result, specific exergy is often approximated using physical and chemical exergy alone. Specific physical exergy is defined as follows. The specific exergy of a system is calculated by the following equation [21]:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \quad (3)$$

Chemical exergy is calculated according to the following equation:

$$ex_{ch}= \sum y_i ex_i^{ch,0} + RT_0 \sum y_i \ln(y_i) \quad (4)$$

The coefficient of performance of the absorption cooling cycle is calculated by the following equation:

$$COP=\frac{Q_{absorber}}{Q_{generator}+Q_{evaprator}} \quad (5)$$

The mathematical relationships for ejector modeling developed in previous research and summarized in Table 2 were used in this study. The coefficients a, b, and c are 3.382, 0.97, and 5.928, respectively.

Table 2: Relationships used for electrolyzer modeling [22,23]

parameter	Value
PEM electrolyzer work	$W_{PEM} = 0.25 \times W_{Total}$
Amount of hydrogen produced	$M_{H2_{out}} = a_{H2} \times W_{PEM}^{bH2} + c_{H2}$
Hydrogen production rate per hour	$N_{H2_{out}} = 3600 \times M_{H2_{out}}$
Theoretical energy for hydrogen production	$\Delta G = \Delta H + T \Delta S$
Electrical energy required	$E_{elec} = JV$
Electrolytic voltage	$V=V_0 + V_{ohm} + V_{act,a} + V_{act,c}$
Nernst voltage	$V_0= 1.229 - 8.5 \times 10^{-4} (T_{PEM} - 298)$
Anode and cathode overpotential	$V_{act,i} = \frac{RT}{F} \sinh^{-1}(\frac{J}{2J_0})$
Exchange current density	$J_0 = J^{ref} \exp(-\frac{E_{act,i}}{RT})$
Ohmic voltage	$V_{ohm} = J R_{PEM}$
Total ohmic resistance	$R_{PEM}= \int_0^L \frac{dx}{\sigma\lambda(x)}$
Local ionic conductivity	$\sigma\lambda(x)=[0.5139 \lambda(x) - 0.326] \exp [1268(\frac{1}{303} - \frac{1}{T})]$

The energy and exergy efficiency of the system can be calculated using the following relationships:

$$\eta_{energy}=\frac{Q_e+W_{net}+Q_c}{m_f LHV_f} \quad (6)$$

$$\eta_{exergy}=\frac{E_e+W_{net}+E_c}{m_f \varepsilon_f} \quad (7)$$

5-Economic analysis

Economic evaluation of energy systems assesses their financial feasibility and operational effectiveness by considering initial investments, ongoing costs, and potential revenue. A key aspect of this analysis is the calculation of an annual cost rate that reflects the total financial burden, including system startup, operation, and maintenance. Thermoeconomic analysis, commonly used in energy systems, simultaneously evaluates economic and thermodynamic performance. It evaluates costs to identify inefficiencies and determine the economic viability of system components. Such assessments help identify areas for improvement, optimize designs, and ensure efficient use of resources [24]. While increased investment can increase the efficiency of energy conversion systems, finding the right balance between cost and efficiency gains is critical [25]. A previous study analyzed energy and exergy values at specific points in the system. In addition, the development of separate cost equations is essential to ensure proper allocation of costs among different system components. The following relationship provides a method for calculating investment rates and capital maintenance requirements [26]:

$$Z_k = CRF \times \frac{\varphi_r}{(N \times 3600)} \times PEC_k \quad (8)$$

The variables φ, N and PEC represent the maintenance factor, operating time over one year and investment cost of the component, respectively. In addition, the parameter CRF represents the capital recovery factor, the value of which is obtained from the following equation.

$$CRF=\frac{i(1+i)^n}{(1+i)^n-1} \quad (9)$$

Thermoeconomic evaluation of thermodynamic systems uses various functions [27]. The following relationship shows the correlation between the levelized cost of energy (LCOE) and the levelized cost of hydrogen (LCOH) for the system considered in this study [28]:

$$LCOE=\frac{AOC}{(W_{total}+Q_{cooling}+Q_{heating})\times\tau} \quad (10)$$

$$LCOH=\frac{AOC}{((LHV_{H_2}N_{H_2}\dot{m}_{H_2})+Q_{cooling}+Q_{heating})\times\tau} \quad (11)$$

The variable τ represents the annual operating hours of the system, which is usually estimated to be 8000 hours per year. The annual operating cost (AOC) is subsequently calculated using the following method [29]:

$$AOC=(TOC\times\varphi\times CRF) \quad (12)$$

In this context, total operating costs (TOC) include all operating costs, while φ represents the maintenance factor, which is set to 1.06 [30]. The total system cost per hour is calculated by dividing the annual costs by the estimated 7446 operating hours in a year [31].

$$Z_{Toatal}=(TOC\times\varphi\times CRF)/t \quad (13)$$

Economic analysis helps business owners understand the current economic environment and its impact on the potential for success of their company. Table 3 provides a method for calculating the purchase cost of each component of the system shown in Fig. 1. Given the expected operational life of each component, the cost rate measured in dollars per gigajoule serves as a valuable metric for analysis [32].

Table 3: Cost rate of system

system components	Cost rate
Steam cycle turbine	$z = 4750 \times (W_{Turb})^{0.75}$
Steam cycle pump	$z = 200 \times (W_{pump})^{0.65}$
Absorption cooling cycle generator	$z = 17500 \times \left(\frac{A_{Gen}}{100}\right)^{0.6}$
Steam cycle condenser	$z = 516 \times (A_{condeser})^{0.6}$
Steam heat exchanger	$z = 2143 \times (A_{heat\ exchanger})^{0.5}$
Absorption cooling cycle condenser	$z = 8000 \times \left(\frac{A_{Cond}}{100}\right)^{0.6}$
Absorption cooling cycle absorber	$z = 16000 \times \left(\frac{A_{Absorb}}{100}\right)^{0.6}$
Absorption cooling cycle evaporator	$z = 16000 \times \left(\frac{A_{Evap}}{100}\right)^{0.6}$
Absorption cooling cycle heat exchanger	$z = 12000 \times \left(\frac{A_{SHE}}{100}\right)^{0.6}$
PEM electrolysis	$Z = 1000 \times (W_{elec})$

6-Validation

The proposed system in this study introduces a new arrangement of the simultaneous generation system. In order to validate this study, the study conducted by Emadi et al. [33] was used and the results of this study were compared with the results of the aforementioned work in Table 4. The method of validating this study with the aforementioned study is that using initial conditions and assumptions such as a static temperature of 25 ° C and a static pressure of 101 kPa in the present study, the proposed system in this study was modeled and the results were compared with each other. The results of the comparison show a slight difference, which indicates the high accuracy of the validation.

7-Results and Discussion

This section presents a comprehensive analysis of the economic and engineering results obtained from the system modeling. It includes an in-depth parametric study that investigates the effects of various parameters on the system performance.

Table 4: System validation with the work of Emadi et al. [33]

parameter	Results of the present study	Reference results
Steam cycle turbine inlet pressure (kPa)	8050	8000
Steam cycle condenser temperature (c)	30.1	30
Steam cycle pump outlet pressure (kw)	8035	8000
Steam cycle condenser pressure (kw)	1130	1167

In addition, it presents the results of optimization efforts aimed at identifying the optimal operating parameters for the system. The thermodynamic modeling of the proposed system was performed using EES software. The energy and exergy analysis, detailed in Table 5, shows an energy efficiency of 37% and an exergy efficiency of 38%, indicating a high system performance.

Table 5: Results of Thermodynamic evaluation

Parameter	Value
System energy efficiency (%)	37
System exergy efficiency (%)	38
Steam cycle turbine power (kw)	4404
Steam cycle pump power (kw)	4.172

Thermodynamic inefficiency in multiple generation systems arises from exergy degradation and loss. Exergy analysis identifies the system components and processes that exhibit the highest thermodynamic inefficiency. In general, reducing inefficiency in a component is beneficial unless it results in an increase in overall capital or fuel costs in other areas. Energy conservation efforts should focus on components with the highest potential for improvement. The exergy degradation of various components within the system is evaluated by simulating the thermodynamic properties at different points using EES software. According to the findings presented in Table 6, the total exergy degradation for the proposed system is 31,317 kW. The PEM electrolyzer experiences the highest exergy degradation, while the absorption cycle condenser exhibits the lowest exergy loss among all the system components.

Table 6: Exergy destruction of system components

Parameter	Value(kw)
Electrolyzer (kw)	4547
Steam cycle pump (kw)	155.5
Steam cycle condenser (kw)	1035
Steam cycle boiler (kw)	5650
Refrigeration cycle evaporator (kw)	532.1
Steam cycle turbine (kw)	9309
Refrigeration cycle absorber (kw)	263.3
Cooling cycle valve (kw)	4039
Cooling cycle high temperature generator (kw)	33525
High temperature cooling cycle heat exchanger (kw)	446.3
low temperature generator 1 of cooling cycle (kw)	24.81
Steam heat exchanger generator (kw)	1602
low temperature generator 2 of the cooling cycle (kw)	2.15
cooling cycle heat exchanger (kw)	4891
Refrigeration cycle condenser (kw)	

The proposed system is analyzed from an economic perspective and revised cost functions are created for its various components to ensure high economic efficiency in various applications. Table 7 presents the results of the economic analysis including the costs associated with the various components of the system. Among the evaluated components, the electrolysis represents the largest portion of the total system cost, while the steam cycle pump is the least costly component.

Table 7: Cost of system components

Parameter	Value($/GJ)
Steam cycle boiler ($/GJ)	553
Steam cycle pump ($/GJ)	506
Steam cycle condenser ($/GJ)	31230
low temperature generator 2 cooling cycle ($/GJ)	524
Steam Heat Exchanger Generator ($/GJ)	55816
Steam cycle turbine ($/GJ)	256878
Refrigeration cycle evaporator ($/GJ)	19737
Low temperature heat exchanger cooling cycle ($/GJ)	3807
Electrolyzer ($/GJ)	5127675
High temperature generator cooling cycle ($/GJ)	31467
High temperature heat exchanger cooling cycle ($/GJ)	29945
Steam cycle condenser ($/GJ)	824
Low temperature generator cooling cycle ($/GJ)	4634

The key parameters in the economic evaluation of the system have been calculated and according to the results in Table 8, the total system cost is $2.084/GJ. The levelized cost of electricity (LCOE) and the cost of hydrogen (LCOH) are two important parameters of the economic analysis in the system under study, which are obtained as 1.138 cents per kWh and $3.529 per kilogram, respectively.

Table 8: Economic evaluation results

Parameter	Value
Cost of electricity production (cent/kwh)	1.138
Cost of hydrogen production ($/kg)	3.529
Payback period	18
Total system cost ($/GJ)	2.084

7-1 Parametric Analysis

Parametric analysis is an effective method for evaluating the performance of a system under different conditions, which provides a comprehensive understanding of the system under consideration. To optimize the design and operational strategies, it is essential to conduct a thorough analysis of the variables with the aim of identifying the key factors that significantly affect the energy efficiency and long-term sustainability of the system. This study investigates the impact of these critical factors on the technical and economic performance of the system. In the proposed system, the effects of changes in key design parameters including turbine isentropic efficiency, pump isentropic efficiency, steam cycle turbine inlet pressure, and steam cycle pump outlet temperature on the system performance are investigated.

7-1-1 Effect of changes in turbine isentropic efficiency on system performance

The effect of changes in turbine isentropic efficiency on system output power, total exergy destruction, cost rate, and energy and exergy efficiency of the system is shown in Fig. 2. As the isentropic efficiency of the turbine rises from 82% to 88%, both the energy and exergy efficiency of the system improve. Exergy is the useful work produced in the system. Exergy efficiency is directly related to output power, and as a result, more output power is obtained from the system by increasing the turbine isentropic efficiency. The reason for the increase in power is due to the favorable effect of the turbine isentropic efficiency on the output work. The turbine is crucial in the generation of electricity, and the electricity generated by the turbine serves as the main energy source needed by the electrolyzer. The performance of the electrolyzer improves with increasing output power, and as a result, more hydrogen is produced. Increasing turbine efficiency increases the cost rate of the system. The reason for this increase can be found in the need for more complete and expensive equipment to achieve higher output power. Other factors such as the increase in the total cost of output production, energy cost and system shutdown cost contribute to the growth of the system cost rate. When we use a turbine with high isentropic efficiency, we see an improvement in the system output power and the system shows a desirable performance in a way that the exergy losses in the system are reduced and its energy and exergy efficiency are increased. The results show that among the three different working fluids, ammonia provides the highest efficiency for the system. The system cost rate is reduced by using benzene as the working fluid.

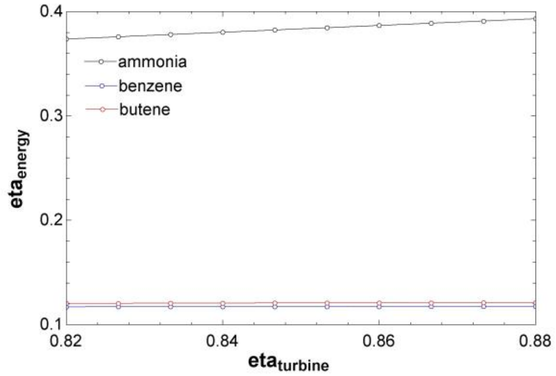

Fig. 2 The effect of changes in turbine isentropic efficiency on energy efficiency

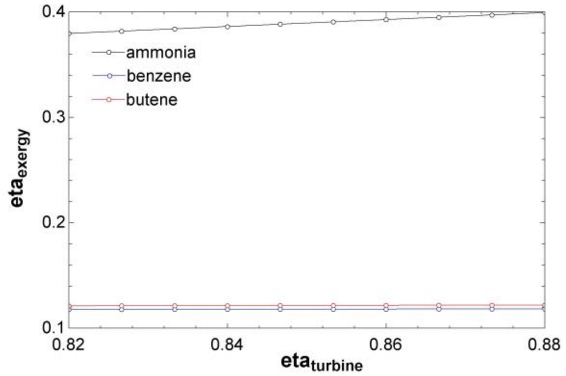

Fig. 3 The effect of changes in turbine isentropic efficiency on exergy efficiency

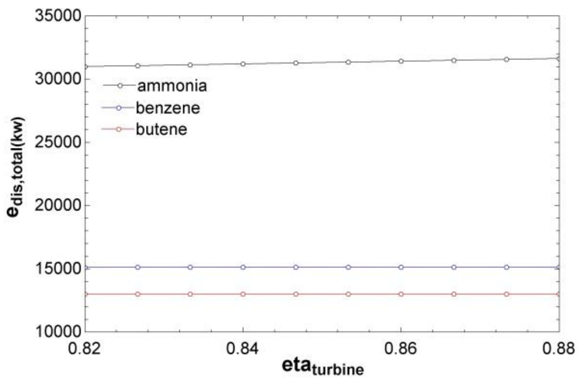

Fig. 4 The effect of changes in turbine isentropic efficiency on total exergy destruction

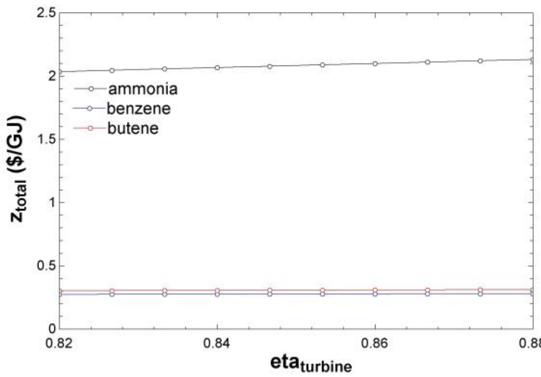

Fig. 5 The effect of changes in turbine isentropic efficiency on total cost rate

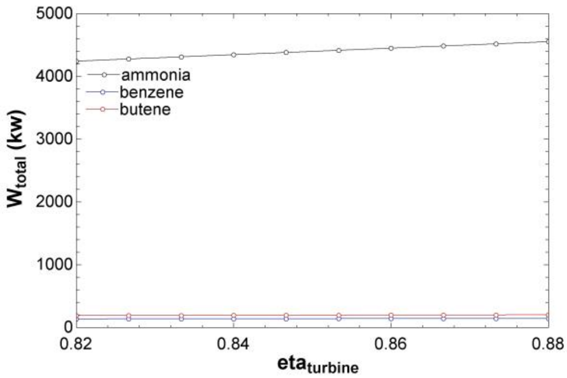

Fig. 6 The effect of changes in turbine isentropic efficiency on total work

7-1-2 The effect of changes in the isentropic efficiency of the pump on system performance

As shown in Fig. 3, the changes in the isentropic efficiency of the pump on the output products of the system are expressed. The output power of the system increases with increasing the isentropic efficiency of the pump from 70% to 90%. The efficiency of the pump has a direct effect on pumping the cycle flow and accelerating the cycle. Therefore, considering that the performance of the electrolyzer depends on the electricity output from the turbine, as a result, with increasing the output power, we see an improvement in the performance of the electrolyzer and the production of hydrogen in the system increases. With increasing the output power, the exergy of the system also increases because these two are directly proportional to each other. The ability to do work in the system increases and as a result, we see less exergy destruction with increasing the isentropic efficiency of the pump. Higher output power increases the need for expensive equipment, so that the cost rate of the system increases. Among the three working fluids evaluated, ammonia provides greater energy and exergy efficiency with increasing the isentropic efficiency of the pump. Butane and benzene are in the next positions, respectively, with the highest efficiency achieved for the system.

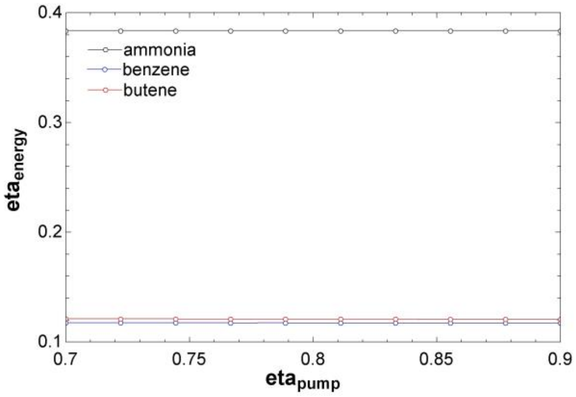

Fig. 7 The effect of changes in the isentropic efficiency of the pump on energy efficiency

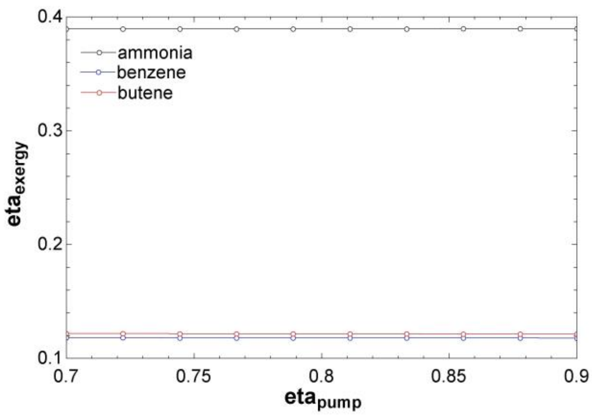

Fig. 8 The effect of changes in the isentropic efficiency of the pump on exergy efficiency

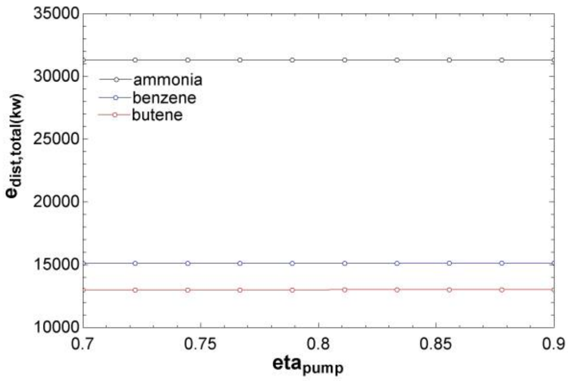

Fig. 9 The effect of changes in the isentropic efficiency of the pump on total exergy destruction

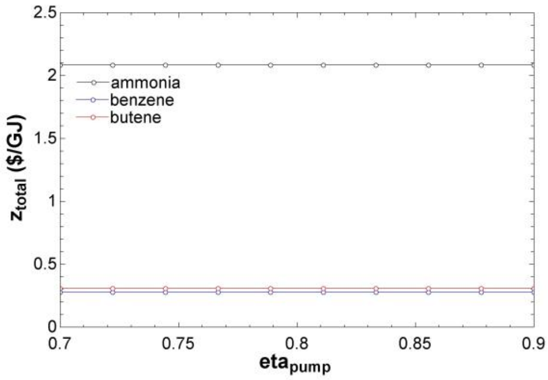

Fig. 10 The effect of changes in the isentropic efficiency of the pump on total cost rate

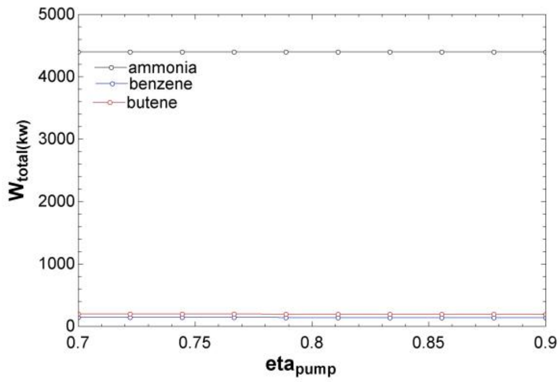

Fig. 11 The effect of changes in the isentropic efficiency of the pump on total net work

7-1-3 Effect of steam cycle turbine inlet pressure changes on system performance

The effect of the steam cycle turbine inlet pressure on the thermodynamic performance of the system is shown in Fig. 4. When the steam cycle turbine inlet pressure increases from 7500 kPa to 8500 kPa, the energy efficiency and exergy of the system increase by 3 and 2 percent, respectively. As the steam cycle turbine inlet pressure increases, the enthalpy of the fluid increases, increasing the turbine work and, consequently, the system output power. As the output work increases, the cost of the equipment required for the system increases. Increasing the steam turbine inlet pressure results in a greater enthalpy difference in the turbine, and exergy losses decrease, and the hydrogen produced in the system increases with the increase in output power. The output power, energy efficiency, and exergy of ammonia are higher compared to the other two working fluids. The thermodynamic performance of the system using butene and benzene as working fluids is more similar to each other.

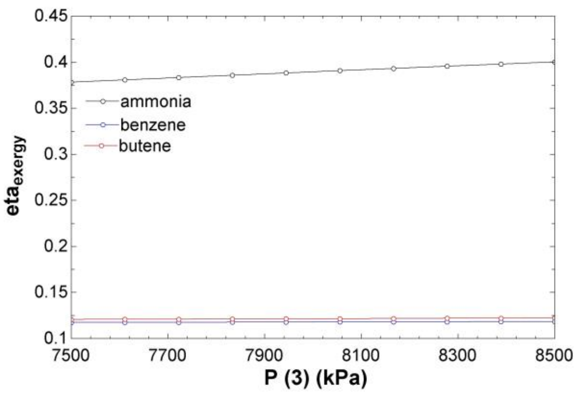

Fig. 12 The effect of steam cycle turbine inlet pressure changes on exergy efficiency

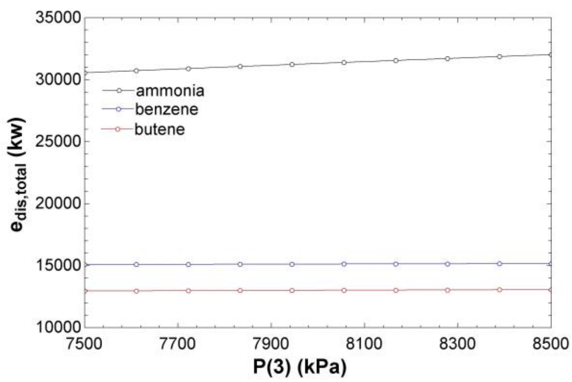

Fig. 13 The effect of steam cycle turbine inlet pressure changes on total exergy destruction

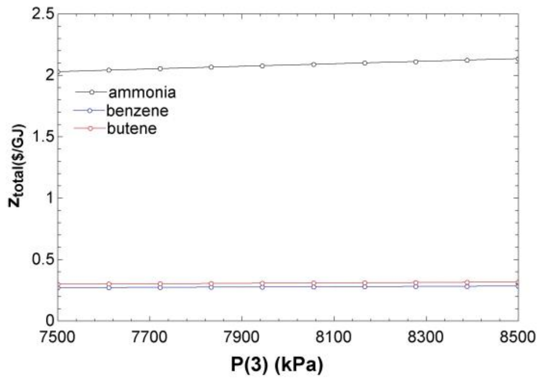

Fig. 14 The effect of steam cycle turbine inlet pressure changes on total cost rate

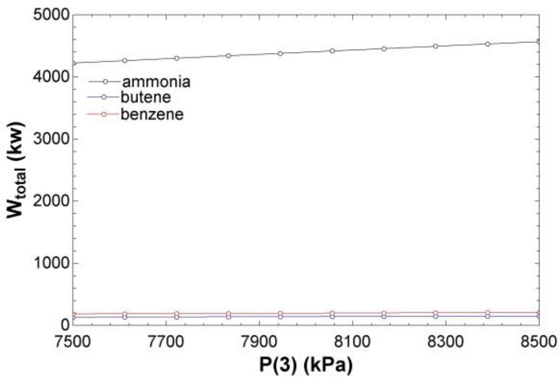

Fig. 15 The effect of steam cycle turbine inlet pressure changes on total work

8- Conclusions

This study presents a comprehensive thermodynamic development and analysis of a novel multi-generation system for the co-generation of electricity, hydrogen, and coolant. The system consists of a steam cycle, a steam heat exchanger generator, a double-effect absorption refrigeration cycle, and an electrolyzer unit. This research proposes and evaluates an innovative multi-generation system designed for this purpose. The feasibility of the system is evaluated using thermodynamic principles, and its performance, including its subsystems, is thoroughly analyzed under different conditions to identify key findings. The system performance evaluation showed an energy efficiency of 37% and an exergy efficiency of 38%. The output power in the studied system is calculated to be 4399 kW and the total exergy destruction of the system is 31317 kW. The results show that among the system components, the electrolyzer has the highest exergy destruction. The highest contribution to the cost rate among the system components belongs to the electrolyzer. The economic analysis estimated the total system cost at $2.084 per gigajoule. The research investigated the effects of changes in key system parameters, including turbine and pump isentropic efficiency, steam cycle turbine inlet pressure, and steam cycle pump outlet temperature, on the overall system performance using three different working fluids: ammonia, benzene, and butane. Future studies should also focus on the scalability of the system and its adaptability to different locations and resource conditions. System evaluation should include its performance in different environments and its integration with other renewable energy technologies. To increase operational efficiency and reliability, advanced control strategies should be implemented. Future research should prioritize the development and testing of these control mechanisms to achieve dynamic system optimization.

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