HYDROGEN, FUEL CELL & ENERGY STORAGE

Studying the Waste Heat Recovery of a Gas Turbine Cycle from a Thermodynamic Perspective

Falah Hasan Mohammed Mohammed | Ata Chitsaz* | Morteza Khalilian

Mechanical Engineering Department, Engineering Faculty, Urmia University, Urmia, Iran
* Corresponding author, Email: `m.khalilian@urmia.ac.ir`

Article Information

Article Type
Research Article

Article History
Received: *27 Nov 2024*
Revised: *11 Feb 2025*
Accepted: *01 Mar 2025*
Published Online: *04 Mar 2025*

Keywords

Gas turbine cycle
Waste heat recovery
Hydrogen
Freshwater

Abstract

An evaluation was conducted to assess the effectiveness of a proposed integrated cycle designed to recover waste heat from a gas turbine for the production of power, hot water, freshwater, and hydrogen. The system comprises a gas turbine, a steam Rankine cycle, an organic Rankine cycle, a PEM electrolyzer, a reverse osmosis (RO) unit, and a domestic water heater (DWH), working together to deliver the primary outputs of power, hydrogen, hot water, and freshwater. A comprehensive thermodynamic simulation was performed using EES software, accompanied by a parametric analysis to evaluate the cycle's performance under varying input parameters. The results revealed that the system achieves energy and exergy efficiencies of 24.92% and 15.01%, respectively. Furthermore, the combined power output from the system's three turbines and two thermoelectric generators (TEGs) totals 320,412.8 kW. Moreover, the system produces 0.556 kg/s of hydrogen and 18.31 kg/s of freshwater. An exergy loss analysis identified the gas turbine and the steam Rankine cycle as the components with the highest exergy destruction rates. It was observed that increasing the evaporator temperature of the steam Rankine cycle enhances power output from TEG 2 and freshwater production, while simultaneously reducing power output from TEG 1 and lowering the total exergy destruction cost. Furthermore, raising the figure of merit of the TEG improves the system's energy and exergy efficiencies, boosts power generation from the TEG, and enhances freshwater production rates. Finally, it was demonstrated that improving the efficiency of the electrolyzer significantly increases the hydrogen output of the system.

Cite this article: Mohammed, F. H. M., Chitsaz, A., Khalilian, M. (2025). Studying the Waste Heat Recovery of a Gas Turbine Cycle from a Thermodynamic Perspective. DOI: 10.22104/hfe.2024.7166.1322

Publisher: Iranian Research Organization for Science and Technology (IROST)
DOI: 10.22104/hfe.2024.7166.1322

1 Introduction

Energy is essential for economic growth, social well-being, improved living standards, and the safety of a community. Global research consistently demonstrates a direct correlation between a country's development and its energy consumption. Consequently, accessing new energy sources is vital for developing nations to advance and enhance their economic position. In recent years, growing awareness has emerged regarding the sharp increase in energy consumption and the finite nature of fossil fuel resources. This awareness has spurred extensive global research aimed at reducing energy consumption and production costs without compromising a nation's development. Consequently, energy management initiatives and strategies have gained prominence. In large gas cycles powered by fossil or nuclear fuels, high-temperature exhaust gases can be utilized through a bottoming cycle to recover waste heat. The Rankine steam cycle is one of the most commonly employed methods for this purpose in such systems [1, 2]. By managing the energy from the exhaust gases produced by power plants, these gases can also be repurposed for multigeneration applications. Multigeneration systems, which optimize energy use effectively, typically achieve higher efficiency while significantly reducing environmental pollutant emissions. Numerous studies have explored waste heat recovery and its integration into multigeneration systems, highlighting its potential for sustainable energy utilization.

Anvari et al. [3] assessed a multigeneration cycle incorporating a gas turbine, analyzing it from energy, exergy, environmental, and exergy-economic perspectives. The cycle achieved an energetic efficiency of 70.53% and an exergetic efficiency of 70.53%, with carbon dioxide emissions measured at 0.163 g/s. In this multigeneration system, the highest exergy loss occurred during the simultaneous production phase. Ahmadi et al. [4] performed an investigation on a combined cycle power plant, focusing on energy, exergy, and economic exergy analysis. Their investigation aimed to assess the impact of auxiliary heating from natural gas combustion on the performance of the lower Rankine steam cycle and explore whether it could contribute to reducing carbon dioxide emissions. Their thermodynamic analysis revealed that the combustion chamber is the primary location of exergy destruction. In their study, Tchanche et al. [5] provided an overview of various single and two-component Rankine cycles, including those that use an ammonia-water mixture. They also examined various heat sources and their potential to initiate the Rankine cycle. Their findings showed that the temperature of the heat sources in different scenarios significantly influences the performance of the Rankine cycle. Lastly, they concluded that the highest power generation efficiency currently achieved by Rankine cycle systems available on the market is 25%. In their study, Quoilin et al. [6] focused on optimizing the organic Rankine cycle for both energy and economic efficiency. They examined six different operating fluids for this purpose. Their findings revealed that the total efficiency of the cycle is 47.5% from an economic optimization perspective, while it is 5.22% from a thermodynamic optimization perspective. In their research, Yang J and Sobhani [7] created an integrated system that generates both electricity and heat through biomass gasification. They evaluated the system from both thermodynamic and thermoeconomic perspective. The proposed system utilized heat generated from biomass combustion in a supercritical carbon dioxide cycle, which was subsequently followed by the Kalina cycle. The study found that the exergy efficiency, cost of product production, and net present value were 40.97%, 15.5 $/GJ, and 5,730,444 $, respectively. Additionally, the investment return period was estimated to be 6.9 years. Hai and colleagues [8] presented a system capable of generating five different products by utilizing the waste heat from a gas turbine cycle fueled by biomass. The incorporation of subsystems into the gas turbine cycle led to a 7.8% progress in the system's exergetic efficiency. This advanced system is capable of producing approximately 8,126 kW of electricity, 2,023 kW of heating, and 1,305 kW of cooling. Additionally, it can generate 14.28 kg/h of hydrogen and 45.81 kg/s of freshwater. To evaluate its environmental impact, the system's sustainability index was determined to be 2.365, while its exergoenvironmental index was calculated at 0.6354.

2 System Description

The schematic design of the multigeneration system is shown in Figure 1. It consists of a gas turbine cycle, a steam Rankine cycle, an organic Rankine cycle, a domestic water heater, a PEM electrolyzer, and an RO desalination unit. The main outputs of the multigeneration system are power, hot water, hydrogen, and freshwater.

The compressor receives air at point 1 and increases its pressure. Once compressed, the air flows to the burner at point 2, where its temperature is raised. The hot compressed air then passes through the turbine and exits at point 4. The gas turbine generates the power required for the PEM electrolyzer, which produces hydrogen in this system. The hot waste gases from the gas turbine first enter the vapor Rankine cycle evaporator and then the organic Rankine cycle evaporator at point 5, after their temperature is reduced. The remaining heat is utilized by a domestic water heater before the waste gases are released into the air. In the steam Rankine cycle, water is pumped in at point 10, where its pressure is increased. At point 11, the water enters evaporator 1, absorbs energy from the hot waste gases, and transforms into steam before entering the turbine. After generating power, the steam is directed to the TEG unit at point 9. In this system, a TEG is used instead of a condenser to generate additional power. The same process occurs in the ORC cycle. The primary distinction between the SRC and ORC cycles lies in the working fluid used. Water serves as the working fluid in the SRC cycle, while an organic working fluid is used in the ORC cycle. Additionally, the working temperature of the SRC cycle is higher than that of the ORC cycle. For the purpose of freshwater production, the SRC and ORC turbines, along with the two TEG units, provide the energy required for the RO desalination unit.

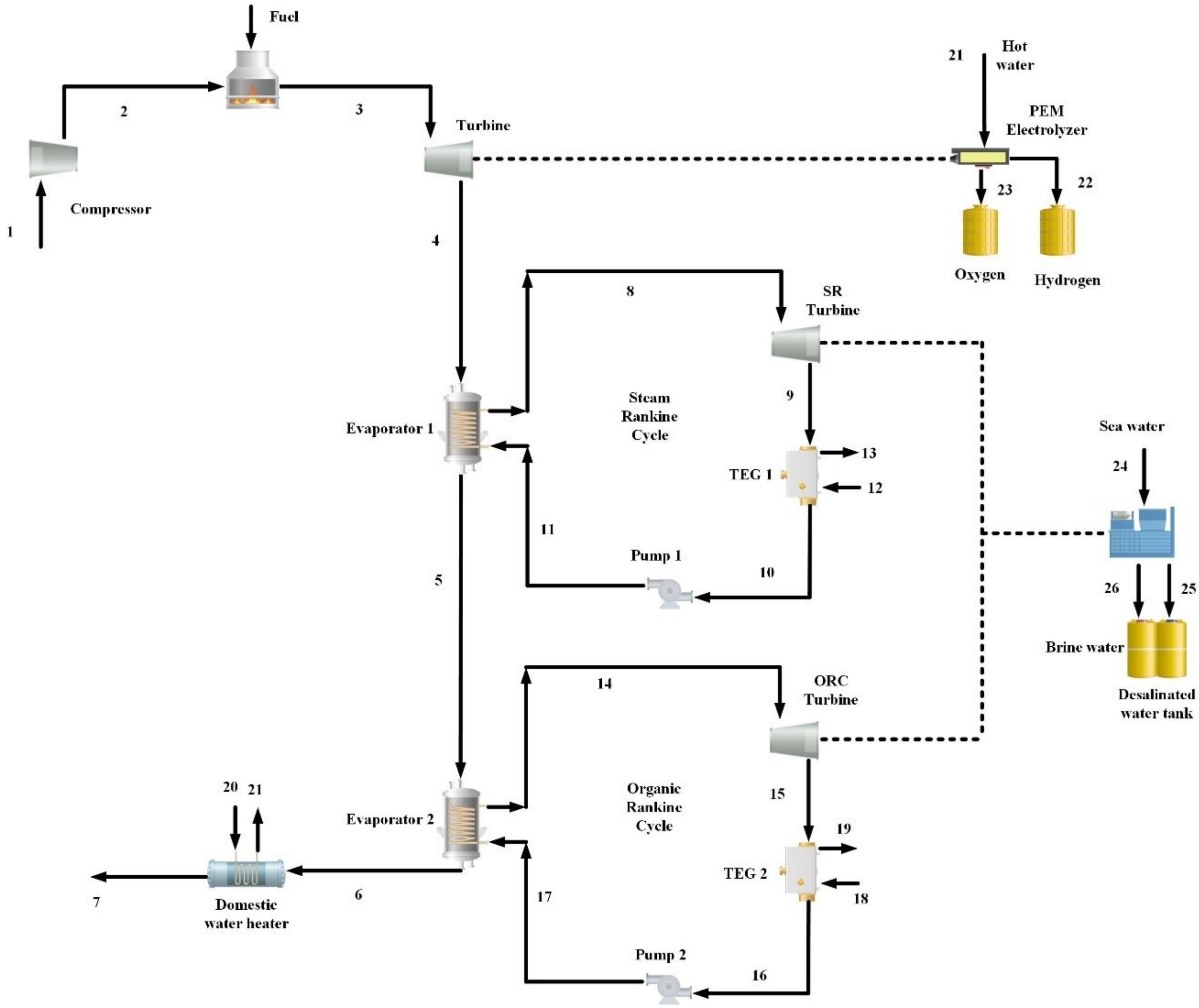

Fig. 1. The schematic of the proposed multigeneration system.

A thorough investigation of thermodynamic analysis includes the equations for mass balance, energy balance, energy and exergy efficiency, exergy destruction, as well as the economic analysis of the system. The simulation of the combined cycle takes into account the following assumptions:

- The system works in a uniform mode.
- Changes in kinetic and potential energy in different components are disregarded.
- Pressure drops in the heat exchangers and pipes connecting the components are considered negligible.

- The output fluid of the evaporator consists of superheated steam and organic matter, with a constant degree of superheating.
- The fluid serves as the outlet of the condenser and the inlet of the saturated liquid pump.
- Pumps and turbines exhibit specific isentropic efficiency.
- Pumps and turbines operate adiabatically.
- The reference temperature and pressure for exergy analysis are taken as the ambient temperature and pressure.

The energy and exergy balance equations for the proposed multigeneration system can be used to determine the amount of heat and power transferred, as well as the exergy destruction rate for each component, as shown in Table 1.

Table 1. Equations of energy balance and exergy destruction rate for each component of the proposed system.

Component	Energy balance equations	Exergy destruction rate equations
Compressor	$\dot{W}_{\text{comp}} = \dot{m}_1(h_2 - h_1)$	$\dot{\text{E}}\text{x}_{D,\text{comp}} = \dot{W}_{\text{comp}} + \dot{\text{E}}\text{x}_1 - \dot{\text{E}}\text{x}_2$
Gas Turbine	$\dot{W}_{\text{GT}} = \dot{m}_3(h_3 - h_4)$	$\dot{\text{E}}\text{x}_{D,\text{GT}} = \dot{\text{E}}\text{x}_3 - \dot{W}_{\text{GT}} - \dot{\text{E}}\text{x}_4$
DWH	$\dot{Q}_{\text{dwh}} = \dot{m}_6(h_6 - h_7) = \dot{m}_2 0(h_{21} - h_{20})$	$\dot{\text{E}}\text{x}_{D,\text{dwh}} = \dot{\text{E}}\text{x}_6 + \dot{\text{E}}\text{x}_{20} - \dot{\text{E}}\text{x}_7 - \dot{\text{E}}\text{x}_{21}$
SRC evaporator	$\dot{Q}_{\text{eva,SRC}} = \dot{m}_4(h_4 - h_5) = \dot{m}_8(h_8 - h_{11})$	$\dot{\text{E}}\text{x}_{D,\text{eva,SRC}} = \dot{\text{E}}\text{x}_{11} + \dot{\text{E}}\text{x}_4 - \dot{\text{E}}\text{x}_8 - \dot{\text{E}}\text{x}_5$
ORC evaporator	$\dot{Q}_{\text{eva,ORC}} = \dot{m}_5(h_5 - h_6) = \dot{m}_{14}(h_{14} - h_{17})$	$\dot{\text{E}}\text{x}_{D,\text{eva,ORC}} = \dot{\text{E}}\text{x}_5 + \dot{\text{E}}\text{x}_{17} - \dot{\text{E}}\text{x}_6 - \dot{\text{E}}\text{x}_{14}$
SRC turbine	$\dot{W}_{t,\text{SRC}} = \dot{m}_8(h_8 - h_9)$	$\dot{\text{E}}\text{x}_{D,t,\text{SRC}} = \dot{\text{E}}\text{x}_8 - \dot{W}_{t,\text{SRC}} - \dot{\text{E}}\text{x}_9$
ORC turbine	$\dot{W}_{t,\text{ORC}} = \dot{m}_{14}(h_{14} - h_{15})$	$\dot{\text{E}}\text{x}_{D,t,\text{ORC}} = \dot{\text{E}}\text{x}_{14} - \dot{W}_{t,\text{ORC}} - \dot{\text{E}}\text{x}_{15}$
SRC TEG	$\dot{Q}_{\text{TEG,SRC}} = \dot{m}_9(h_9 - h_{10}) = \dot{m}_{12}(h_{13} - h_{12})$	$\dot{\text{E}}\text{x}_{D,\text{TEG,SRC}} = \dot{\text{E}}\text{x}_9 + \dot{\text{E}}\text{x}_{12} - \dot{\text{E}}\text{x}_{10} - \dot{\text{E}}\text{x}_{13}$
ORC TEG	$\dot{Q}_{\text{TEG,ORC}} = \dot{m}_{15}(h_{15} - h_{16}) = \dot{m}_{18}(h_{19} - h_{18})$	$\dot{\text{E}}\text{x}_{D,\text{TEG,ORC}} = \dot{\text{E}}\text{x}_{18} + \dot{\text{E}}\text{x}_{15} - \dot{\text{E}}\text{x}_{16} - \dot{\text{E}}\text{x}_{19}$
SRC Pump	$\dot{W}_{P,\text{SRC}} = \dot{m}_{10}(h_{11} - h_{10})$	$\dot{\text{E}}\text{x}_{D,P,\text{SRC}} = \dot{W}_{P,\text{SRC}} - \dot{\text{E}}\text{x}_{10} + \dot{\text{E}}\text{x}_{11}$
ORC Pump	$\dot{W}_{P,\text{ORC}} = \dot{m}_{16}(h_{17} - h_{16})$	$\dot{\text{E}}\text{x}_{D,P,\text{ORC}} = \dot{W}_{P,\text{ORC}} - \dot{\text{E}}\text{x}_{16} + \dot{\text{E}}\text{x}_{17}$
PEM	$\dot{W}_{\text{PEM}} = (\dot{m}_{21}h_{21} - \dot{m}_{22}h_{22} - \dot{m}_{23}h_{23})$	$\dot{\text{E}}\text{x}_{D,\text{PEM}} = \dot{\text{E}}\text{x}_{21} + \dot{W}_{\text{PEM}} - \dot{\text{E}}\text{x}_{22} - \dot{\text{E}}\text{x}_{23}$
RO	$\dot{W}_{\text{RO}} = (\dot{m}_{24}h_{24} - \dot{m}_{25}h_{25} - \dot{m}_{26}h_{26})$	$\dot{\text{E}}\text{x}_{D,\text{RO}} = \dot{\text{E}}\text{x}_{24} - \dot{\text{E}}\text{x}_{25} - \dot{\text{E}}\text{x}_{26}$

3 Results and Discussions

The simulation of the multigeneration system requires selecting specific parameters for input data. The input parameters for system modeling are listed in Table 2. It is essential to set these parameters before proceeding with further calculations.

The EES software was used to simulate the system based on the initial data. Upon reviewing the overall results of the simulated system, it is evident that the system achieves an energy efficiency of 24.92% and an exergy efficiency of 15.01%. Additionally, the cycle generates 320,412.8 kW of power. The substitution of the condensers with a TEG unit has the potential to generate an additional 5,046.08 kW of power. Based on the fundamental assumptions, this multigeneration system has the capacity to generate 0.556 kg/s of hydrogen and 18.31 kg/s of freshwater.

To improve system efficiency, minimizing exergy destruction is crucial. This section examines the exergy destruction within the cycle components. The exergy destruction rates for the primary components are illustrated in Figure 2. The data from the graph indicate that the GT cycle and SRC cycle exhibit the highest rates of exergy loss. This suggests that, during system design, particular attention should be given to these cycles. Efforts to reduce exergy destruction in these components will contribute significantly to improving overall system efficiency.

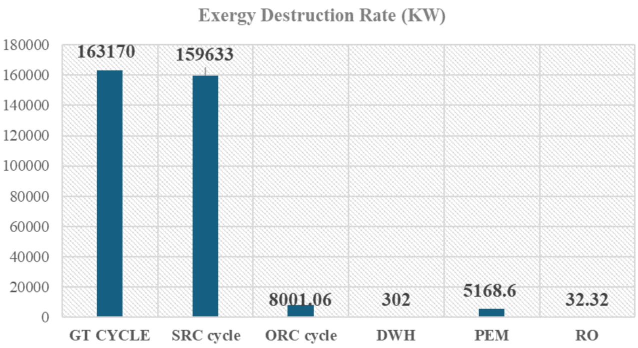

Fig. 2. The rate of exergy loss in the equipment employed in the cycle.

Table 2. Initial considered parameters for cycle analysis.

Parameters	Unit	Value
SRC turbine inlet temperature	°C	450
ORC turbine inlet temperature	°C	120
Air inlet mass flow rate	kg/s	500
isentropic efficiency of the GT Compressor	%	85
Isentropic efficiency of the GT Turbine	%	85
PEM		
P_{H_2}, P_{O_2}	atm	1
T_{PEM}	°C	80
$E_{\text{act},a}$	kJ/mol	76
$E_{\text{act},c}$	kJ/mol	18
λ_a	-	14
λ_c	-	10
D	mm	50
J_a^{ref}	A/m^2	1.7×10^5
J_c^{ref}	A/m^2	4.6×10^3
RO		
Recovery ratio, RR	-	0.3
Number of elements, n_e	-	7
Number of pressure vessels, n_v	-	42
Seawater salinity, X_f	g/kg	43

Figure 3 depicts the variations in power generated by TEG 1 and TEG 2 as the temperature of the steam Rankine cycle evaporator rises. The graphs indicate that as the SRC evaporator temperature increases from 720 K to 820 K, the power output of TEG 1 decreases, while TEG 2 shows an increase in power output. The power produced by TEG 1 is directly influenced by the SRC evaporator temperature. An increase in the evaporator inlet temperature causes a rise in the mass flow rate of the SRC cycle, leading to a reduction in the power output of TEG 1. The power generated by TEG 1 decreases from 2192 kW to 866.4 kW, while the power generated by TEG 2 increases from 1173 kW to 1609 kW.

Figure 4 illustrates the effect of changes in the steam Rankine cycle (SRC) evaporator temperature on hydrogen and freshwater production rates. The results show that as the evaporator temperature increases, the system's freshwater production rises, while hydrogen production remains constant. Specifically, when the SRC evaporator temperature increases from 720 K to 820 K, the freshwater production grows from 20.49 kg/s to 21.56 kg/s, whereas the hydrogen generation rate remains steady at 0.5567 kg/s. The rate of hydrogen production is determined by the power output of the GT turbine, which remains constant despite increases in evaporator temperature. Conversely, freshwater production is influenced by the power generated by the SRC and ORC turbines, as well as the TEGs. Therefore, an increase in evaporator temperature enhances the power output from the SRC and ORC cycles, leading to higher rates of freshwater production.

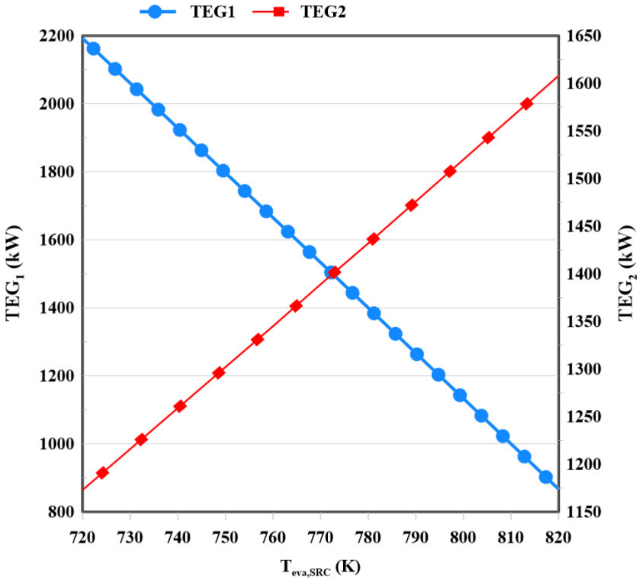

Fig. 3. The impact of steam Rankine cycle evaporator temperature changes on the power generated by TEG 1 and TEG 2.

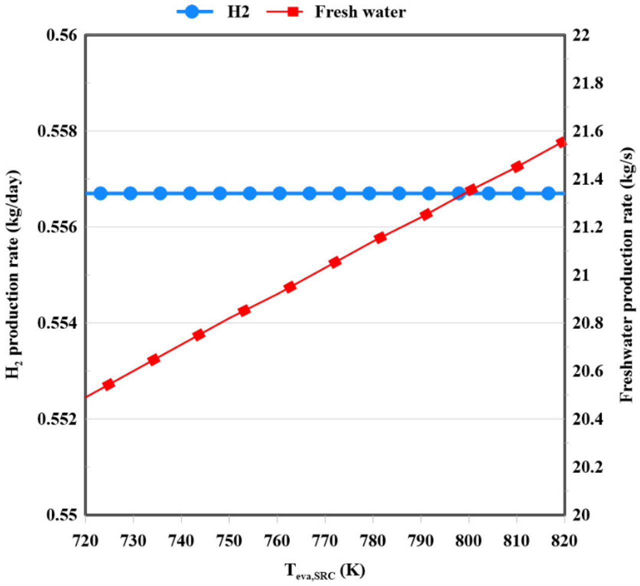

Fig. 4. The impact of steam Rankine cycle evaporator temperature changes on the amount of hydrogen and freshwater production rates.

The performance of the thermoelectric unit is directly impacted by the figure of merit, known as ZT. As depicted in Figure 5, an increase in the ZT value leads to a proportional rise in both the energy and exergy efficiencies of the system. A higher ZT improves the power generation capabilities of the two TEG units, thereby increasing the overall power output of the system. This enhancement in power generation translates to improved system efficiency. Increasing the figure of merit (ZT) from 0.4 to 1 results in the energy efficiency rising from 24.87% to 24.92% and the exergy efficiency increasing from 14.98% to 15.01%. Analyzing these incremental changes reveals that the improvements in efficiencies are relatively modest. This is attributed to the fact that the power output from TEG 1 and TEG 2 is significantly smaller compared to the power generated by the GT turbine, thereby limiting their impact on the overall system efficiency.

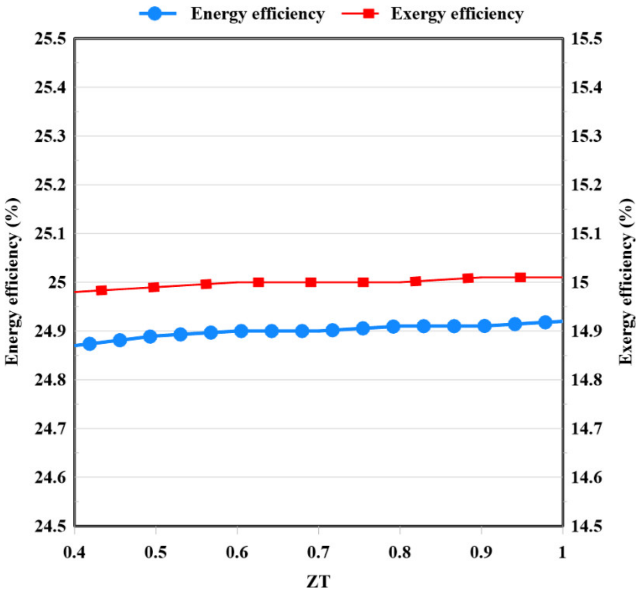

Fig. 5. The effect of the ZT on the energetic and exergetic efficiency of the system.

The graph in Figure 6 illustrates the relationship between the figure of merit (ZT) and the power output of the two TEG units. The power generated by the TEGs is directly influenced by the ZT value. As ZT increases, the power output from both TEGs also rises. Specifically, when ZT varies from 0.4 to 1, the power output of TEG1 increases from 4,349 kW to 4,696 kW. Similarly, TEG2's power output grows from 341.1 kW to 350.8 kW as ZT escalates. This demonstrates the positive impact of a higher ZT on the performance of the thermoelectric units.

The impact of the figure of merit (ZT) on the system's freshwater production. As ZT increases from 0.4 to 1, the freshwater generation rises from 18.15 kg/s to 18.31 kg/s. This growth is attributed to the higher power output from the TEG units as ZT improves, which in turn supports increased rates of freshwater production. This correlation highlights the role of enhanced thermoelectric performance in boosting the system's desalination capacity.

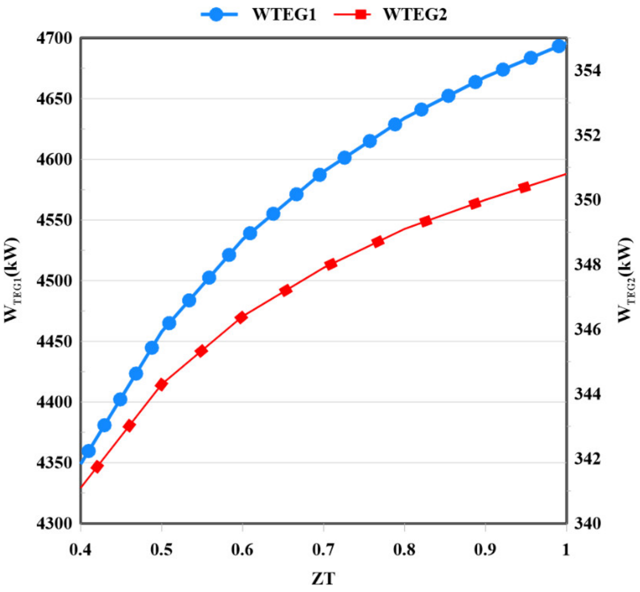

Fig. 6. The impact of the ZT on the quantity of power generated by the TEGs.

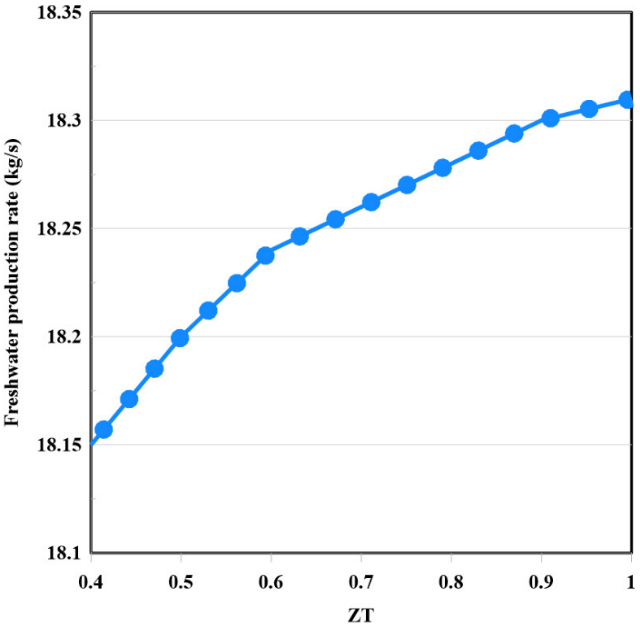

Fig. 7. The impact of the ZT on the quantity of freshwater generated by the TEGs.

Figure 8 illustrates the relationship between the efficiency of the electrolyzer and the hydrogen production rate of the PEM electrolyzer. As the electrolyzer's efficiency improves, the amount of hydrogen generated increases significantly. Specifically, when the efficiency rises from 0.5 to 0.9, the hydrogen production rate grows from 0.3976 kg/s to 0.7157 kg/s. This trend underscores the importance of optimizing electrolyzer efficiency to maximize hydrogen output in the system.

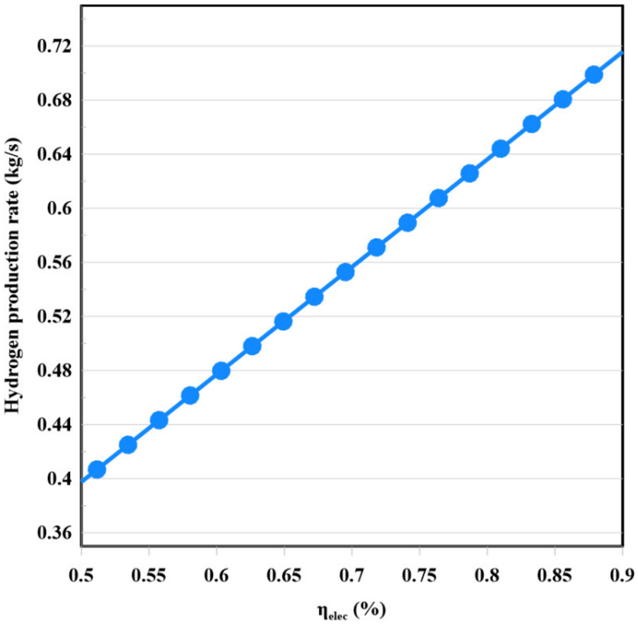

Fig. 8. The impact of the electrolyzer efficiency on the quantity of hydrogen generated by the PEM electrolyzer.

4 Conclusions

An assessment has been conducted on the efficiency of a proposed cycle designed to generate power, hot water, freshwater, and hydrogen by utilizing the waste heat from a gas turbine. This cycle incorporates a gas turbine, steam Rankine cycle, organic Rankine cycle, PEM electrolyzer, RO unit, and domestic water heater (DWH). The system's primary outputs include power, hydrogen, hot water, and freshwater. The study employed both thermodynamic and thermoeconomic analyses to effectively assess the cycle's overall performance.A comprehensive thermodynamic simulation was conducted using EES software, and a parametric study was performed to evaluate the operability of the proposed cycle under various input parameters. The key findings obtained from this study are as follows.

- The system attains energy and exergy efficiencies of 24.92% and 15.01%, respectively and the total amount of power generated by the system is 320412.8 kW.
- A total of 0.556 kg/s of hydrogen and 18.31 kg/s of freshwater is produced by this system.
- The GT and SRC cycles exhibit the highest exergy destruction rates.
- Increases in the SRC evaporator temperature lead to a rise in the power produced by TEG 2 and the freshwater production rate, while decreasing the power output of TEG 1 and the overall exergy destruction cost.
- The rise in the figure of merit of the TEG leads to enhanced energy and exergy efficiency in the system, as well as higher power production rates for TEGs and an enhanced freshwater production rate.
- An increase in the electrolyzer efficiency results in a higher amount of hydrogen produced by the system.

References

[1] Ahmadi P, Dincer I. Thermodynamic analysis and thermoeconomic optimization of a dual pressure combined cycle power plant with a supplementary firing unit. Energy Conversion and Management. 2011;52(5):2296–2308.

[2] Ahmadi P, Dincer I, Rosen MA. Thermodynamic modeling and multi-objective evolutionary-based optimization of a new multigeneration energy system. Energy Conversion and Management. 2013;76:282–300.

[3] Anvari S, Mahian O, Taghavifar H, Wongwises S, Desideri U. 4E analysis of a modified multigeneration system designed for power, heating/cooling, and water desalination. Applied Energy. 2020;270:115107.

[4] Ahmadi P, Dincer I, Rosen MA. Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants. Energy. 2011;36(10):5886–5898.

[5] Tchanche BF, Pétrissans M, Papadakis G. Heat resources and organic Rankine cycle machines. Renewable and Sustainable Energy Reviews. 2014;39:1185–1199.

[6] Quoilin S, Declaye S, Tchanche BF, Lemort V. Thermo-economic optimization of waste heat recovery Organic Rankine Cycles. Applied thermal engineering. 2011;31(14-15):2885–2893.

[7] Ji-chao Y, Sobhani B. Integration of biomass gasification with a supercritical CO2 and Kalina cycles in a combined heating and power system: a thermodynamic and exergoeconomic analysis. Energy. 2021;222:119980.

[8] Hai T, Ali MA, Alizadeh Aa, Almojil SF, Almohana AI, Chauhan BS, et al. Optimization next to environmental analysis of harvesting waste heat from a biomass-driven externally-fired gas turbine cycle for sub-zero cooling and production of hydrogen, freshwater, and hot water. Applied Thermal Engineering. 2023;223:119884.