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Research Article

Design and Performance Evaluation of Multi-Generation System based on Transcritical CO_2 Rankine Cycle and Helium Gas Turbine with Hydrogen Production

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ABSTRACT

The advancement in nuclear energy embodied by the gas-cooled modular reactor (GCMR), incorporating the transcritical CO_2 Rankine cycle (tRC) and a helium turbine (He tur.) for hydrogen (H_2) production, signifies a substantial leap forward in this domain. This research endeavor aimed to amalgamate various technologies to enhance energy conversion efficiency and generate clean hydrogen, a versatile energy carrier. Helium, selected as the GCMR coolant, boasts advantageous properties such as superior heat transfer capabilities, chemical inertness, and the capacity to operate at elevated temperatures. These attributes facilitate effective heat extraction from the reactor core, mitigating corrosion risks while boosting both power output and energy efficiency. A pivotal aspect of this design lies in integrating the tRC with the helium turbine, maximizing energy conversion efficiency and resource utilization by harnessing waste heat from the He turbine to generate additional power through the CO_2 Rankine cycle. Furthermore, the system incorporates a hydrogen production module, enabling the clean generation of hydrogen as a byproduct of the nuclear power generation process. According to analysis results, the net power obtained from the Helium turbine was calculated as 241679 kW, and the net power produced from the tRC was calculated as 9902 kW. Additionally, with this developed system, 23.11 kg/h H_2 and 183.4 kg/h O_2 can be produced. The energetic and exergetic performance of the overall system is computed as 41.8% and 54.28%, while the total amount of exergy destruction is determined as 212199 kW. Moreover, analytical findings reveal that the reactor core exhibits the highest exergy destruction among system components at 91282 kW, whereas the heat exchanger (HEx) registers the lowest exergy destruction at 3.56 kW. In addition, in this study, parametric analyses are also performed to determine the effect of helium outlet temperature analysis and pressure ratio on system performance.

Keywords: *Gas-Cooled Modular Reactor, Helium Gas Turbine, transcritical CO_2 Rankine Cycle, Hydrogen Production, Energy, Exergy*

Hidrojen Üretimli Transkritik CO_2 Rankine Çevrimi ve Helyum Gaz Türbini Tabanlı Çok Üretimli Sistemin Tasarımı ve Performans Değerlendirmesi

ÖZ

Transkritik CO_2 Rankine çevrimini (tRC) ve hidrojen (H_2) üretimi için bir helyum türbinini (He tur.) birleştiren gaz soğutmalı modüler reaktör (GCMR) ile ilgili nükleer enerjideki çalışmalar, bu alanda önemli bir ilerleme anlamına gelmektedir. Bu araştırma çabası, enerji dönüşüm verimliliğini artırmak

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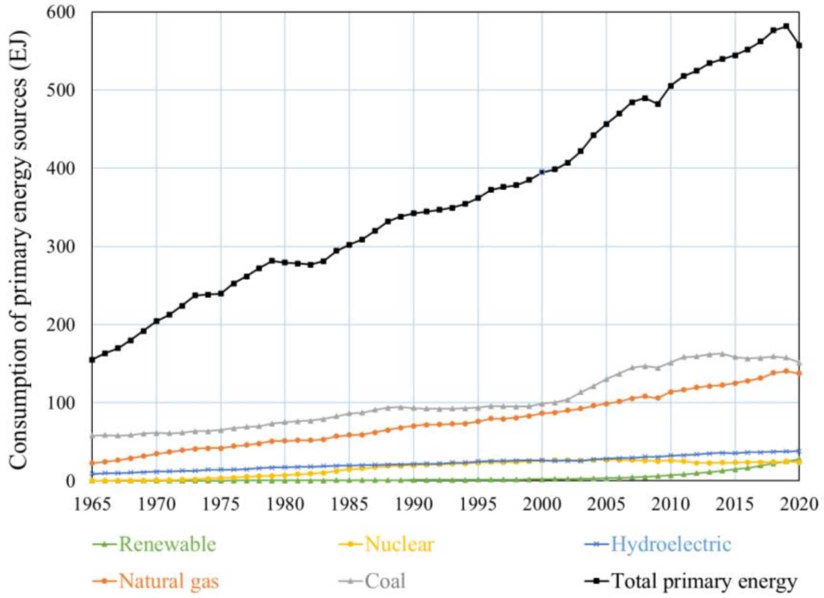
ve çok yönlü bir enerji taşıyıcısı olan temiz hidrojen üretmek için çeşitli teknolojileri birleştirmeyi amaçladı. GCMR soğutucusu olarak seçilen helyum, üstün ısı transfer kapasitesi, kimyasal eylemsizlik ve yüksek sıcaklıklarda çalışabilme kapasitesi gibi avantajlı özelliklere sahiptir. Bu özellikler, reaktör çekirdeğinden etkili ısı tahliyesini kolaylaştırır ve hem güç çıkışını hem de enerji verimliliğini artırırken korozyon risklerini azaltır. Bu tasarımın önemli yönü, tRC'nin helyum türbiniyle entegre edilmesi, CO_2 Rankine döngüsü yoluyla ek güç üretmek için He türbininden gelen atık ısıdan yararlanılarak enerji dönüşüm verimliliğinin ve kaynak kullanımının maksimuma çıkarılmasında yatmaktadır. Analiz sonuçlarına göre Helyum türbininden elde edilen net güç 241679 kW, tRC'den üretilen net güç ise 9902 kW olarak hesaplanmıştır. Ayrıca geliştirilen bu sistem ile 23.11 kg/h H_2 ve 183.4 kg/h O_2 üretilebilmektedir. Sistemin genel enerjetik ve ekserjetik performansı sırasıyla %41.8 ve %54.28 olarak hesaplanırken, toplam ekserji yıkım miktarı 212199 kW olarak belirlenmiştir. Ayrıca analitik bulgular, sistem bileşenleri arasında reaktör çekirdeğinin 91282 kW ile en yüksek ekserji yıkımını, ısı değiştiricinin (HEx) ise 3.56 kW ile en düşük ekserji yıkımını kaydettiğini ortaya koymaktadır. Ayrıca bu çalışmada, helyum çıkış sıcaklık analizi ve basınç oranının sistem performansına etkisini belirlemek amacıyla parametrik analizler de yapılmıştır.

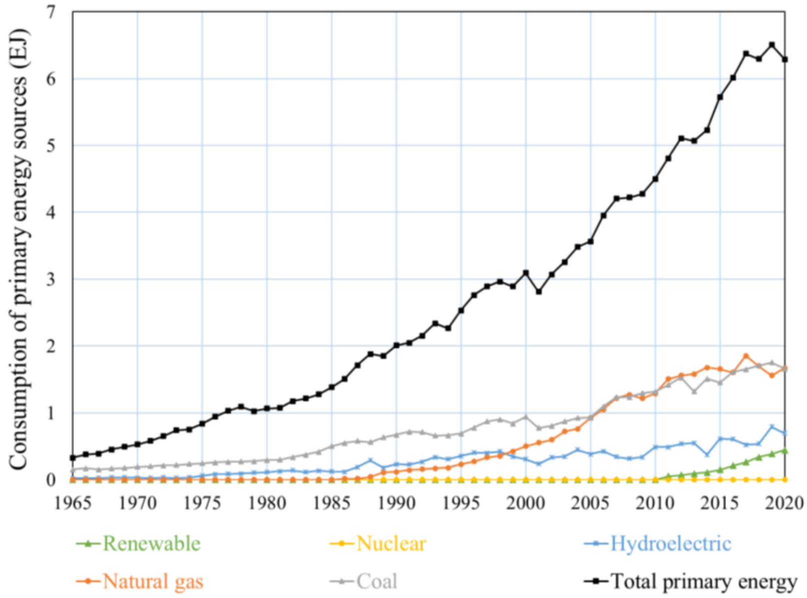
Anahtar Kelimeler: *Gaz Soğutmalı Modüler Reaktör, Helyum Gazı Türbini, Transkritik CO_2 Rankine Çevrimi, Hidrojen Üretimi, Enerji, Ekserji*

I. INTRODUCTION

The rise in global population and the escalating energy requirements accompanying industrialization contribute to a rapid increase in the demand for fossil fuels. The change in consumption of energy resources in the world and Turkey according to fuel type is shown in Figure 1. Since 1965, fossil-based energy has been meeting the ever-increasing energy demand. As depicted in the figure, although the share of sustainable sources in energy generation has increased considerably, especially since the end of the 2000s, this increase cannot meet the increasing energy demand, and fossil-based energy generation is also increasing. Renewable energy sources meet 4.96% of the global energy demand, whereas in Turkey, they account for 6.33% [1].



a) World



b) Turkey

Figure 1. *Change in consumption of primary energy resources over the years* [1]

The exploration of advanced nuclear energy technologies presents a significant opportunity to tackle worldwide energy issues while reducing CO_2 emissions and environmental consequences. A promising area of investigation involves combining GCMRs with inventive power conversion systems, including helium gas turbines and tRCs, all while simultaneously producing H_2. This integrated strategy seeks to improve the general efficiency of the plant, boost power generation capacities, and facilitate the creation of clean H_2 as a versatile energy carrier [2]. GCMRs employ helium as the cooling agent, offering advantages over conventional water-cooled reactors. These advantages encompass enhanced energy efficiency, superior safety characteristics, and decreased water usage. The utilization of helium facilitates effective heat removal from the nuclear reactor core, enabling the transfer of heat to the power conversion systems [3]. In advanced nuclear power technology, a noteworthy advancement is the incorporation of a helium turbine coupled with a bottoming tRC within the GCMR system. The helium gas turbine plays a pivotal role as the primary power conversion system, utilizing the energy derived from the hot helium to propel turbine blades and produce electricity. The utilization of helium, with its exceptional heat transfer properties, enables higher operating temperatures, thereby enhancing the overall thermodynamic efficiency of the plant. To further optimize energy extraction, a bottoming tRC is integrated into the system. This secondary power conversion cycle captures waste heat from the helium turbine and utilizes CO_2 as the working fluid. The tRC operates at high pressures and temperatures, facilitating efficient power generation by effectively utilizing the available heat energy.

Several environmentally friendly techniques for producing low-carbon hydrogen are widely discussed in the literature [4,5]. Electrolysis stands out as one of the most prevalent and environmentally clean methods for hydrogen generation. Proton Exchange Membrane (PEM) electrolyzers are used for the electrolysis of water, which is a clean, easy, and efficient way to obtain hydrogen. PEM electrolyzers can function at a wider range of current densities compared to alkaline electrolyzers, making them easier to integrate with renewable energy sources that have fluctuating energy production levels. Additionally, the PEM electrolysis method offers several benefits over traditional hydrogen production techniques, including high efficiency, production of high-purity and high-pressure hydrogen, and environmentally friendly reaction products. In response to the increasing need for environmentally friendly energy sources, incorporating H_2 production into the hybrid system plays a crucial role. By leveraging excess heat from the nuclear reactor and the tRC, H_2 can be generated through thermochemical processes, contributing to the advancement of sustainable fuel technologies. This addresses the need for clean energy carriers and establishes a versatile energy system capable of meeting various demands across power generation and fuel production [6]. In the field of investigation of integrated systems containing GCMR-based helium turbine, Dardoura et al. [7] outlined the next stages leading to the progress of mathematical and physical models that facilitate the estimate of desalination process costs for the GCMR and the pebble bed modular reactor, both of which provide free thermal energy. El-Genk and Tournier [8] researched the characteristics and constraints of inert gases and two-component mixtures as potential working substances for gas-cooled nuclear power cycles employing Brayton cycles (BC). They performed a comparative examination of pressure losses and heat transfer coefficients, concentrating on different inert gases and helium. The study took into account standard working conditions in commercial power centrals, maintaining the same geometry and molecular flow rate for comprehensive analysis. Tournier and El-Genk [9] carried out comprehensive research on the specifications of inert gases such as helium, krypton, and argon, as well as their binary mixtures. This included a wide range of pressures and temperatures. They gathered a comprehensive dataset of experimental measurements and formulated property correlations. Zhao and Peterson [10] projected the efficiency of helium BCs incorporating multiple reheat and intercooling stages for sodium-cooled fast reactors. The investigation specifically considered reactor outlet temperatures spanning from 510 to 650 °C. The energy efficiencies obtained, varying between 39% and 47%, proved to be similar to those observed in recompression sCO_2 (supercritical CO_2) cycles. The findings of the study indicated that, for sodium-cooled fast reactors, the multiple reheat helium cycle is more favorable than the sCO_2 cycle. Temiz and Dincer [11] examined a hybrid system composed of a solar energy system and a nuclear power plant to produce electric power, fresh water, and H_2. They calculated energetic and exergetic efficiencies to determine the performance of the plant. They also performed numerous time-dependent dynamic analyses to examine the effects of some variable inputs, like solar irradiation intensity. According to the analysis, they determined the energetic efficiency of the system to be between 21.8% and 24.2% and the general exergetic efficiency of the system to be between 18.6% and 21.1%. Temiz and Dincer [12] proposed combining nuclear and renewable systems with a molten salt energy storage system. The suggested nuclear and sustainable integrated energy system produces heat, H_2, fresh water, power, and cooling effects to meet the needs of communities in a sustainable manner. The suggested system's exergetic and energetic efficiencies are calculated to be 57.96% and 63.54%, respectively. The maximum energetic efficiency was determined as 84.4%, and the maximum exergetic efficiency was calculated as 81.28%. In addition, with the designed system, 53.285.15 tons of H_2 were generated annually, in addition to the needs of the existing society. Hercog et al. [13] analyzed hydrogen production technologies based on the use of heat obtained from a nuclear cogeneration plant and thermochemical water splitting. Khan et al. [14] studied a new integrated power plant for solar tower systems composed of helium BC and tCO_2 (transcritical carbon dioxide). They examined the performance of the suggested cycle with respect to exergoeconomic and thermodynamics and compared it with different cycles. According to the analysis, they concluded that the solar subsystem has the highest exergy destruction rate and cost rate of around 72.37% and 56.8%, respectively, in the suggested general facility. Temiz and Dincer [15] have designed an integrated system to produce electricity, domestic hot water, H_2 fuel, district heating, and fresh water. The designed system consists of nuclear reactors, H_2 generation cycle, photovoltaic panels, gas and steam turbines and a multi-effect water desalination unit. They calculated the general energetic efficiency of the proposed integrated system as 62.64% and the general exergetic efficiency as 68.91%.

In the examination of existing literature, it is clear that although GCMRs are mature in technology, their applications are limited due to the high operating temperature, and they are efficient only when operated at higher temperatures due to the large back-work ratio.

He offers various advantages surpassing those of alternative working fluids. The elevated heat capacity of helium at high temperatures leads to a decrease in the helium mass flow rate, consequently diminishing the sizes and costs of components. This is mainly responsible for the improved economic performance of helium as a working fluid. Conventionally, organic Rankine cycle (ORC) is commonly favored for lower-temperature applications because of the advantageous operational characteristics exhibited by various organic fluids in such conditions. The tCO_2 cycle presents a superior alternative for harnessing heat from a high-temperature heat resource when compared to conventional ORC cycles. This is attributed to its more effective temperature-compatible shifting in the evaporator than traditional organic liquids. Utilizing organic fluids in applications gives rise to challenges associated with pinch point temperatures within the evaporator. When considering the thermodynamic average heat rejection temperature, tCO_2 demonstrated superior performance compared to ORC. The literature study does not supply proof of comprehensive analysis of GSMR-based integrated systems containing helium turbine, especially in recent years. Therefore, in this study, a new system composed of a GCMR-based helium turbine and tCO_2 cycle was examined from a thermodynamic perspective. In this study, the performance of the cycle was significantly improved by using helium liquid. Additionally, the tCO_2 cycle was used to recover waste heat. This innovative approach combines multiple technologies to enhance the system's overall efficiency while enabling the production of H_2, a clean and versatile energy carrier. The originality of this concept lies in the integration of these various technologies into a single system. The development of a GCMR based on a helium turbine with a bottoming tRC and H_2 production represents a crucial step towards the realization of advanced nuclear energy systems. In summary, the convergence of nuclear energy with advanced thermodynamic cycles and sustainable hydrogen production represents a transformative leap in energy technology. The originality of the proposed system lies in its unique integration of a gas-cooled modular reactor (GCMR) with a helium gas turbine, a transcritical CO2 Rankine cycle, and green hydrogen generation. Each component, while individually well-established, combines in this context to create a synergetic, high-efficiency system that addresses multiple energy challenges simultaneously.

II. SYSTEM OVERVIEW

Figure 2 exhibits the schematic representation of the integrated system consisting of a GCMR, a helium tur., a tRC, and an H_2 generation system. The GCMR serves as the core component of the system. It utilizes helium as the coolant, providing advantages like higher energy efficiency, improved safety features, and reduced water consumption. The GCMR produces high-temperature helium gas because nuclear fission is used as a heat source for subsequent power conversion processes. The helium turbine is the primary power conversion system in the integrated setup. It utilizes the high-temperature helium gas from the GCMR to drive the turbine blades and generate electricity. The He turbine operates based on the principles of thermodynamics, extracting energy from the hot helium and converting it into mechanical energy, which is then transformed into electrical energy through a generator. To further optimize the system's energy extraction, a bottoming tRC is incorporated. This secondary power conversion cycle captures waste heat from the helium turbine. The tRC operates at high pressures and temperatures, making efficient use of the waste heat by utilizing CO_2 as the working fluid. The CO_2 expands through a turbine, driving a generator to produce additional electricity. Concurrent with power generation, the system facilitates hydrogen production. Excess heat from the GCMR, which is not utilized by the gas turbine or the bottoming transcritical CO_2 Rankine cycle, is diverted to a thermochemical water-splitting process. This process utilizes the excess heat to separate water molecules into hydrogen and oxygen, generating clean H_2 as a valuable byproduct. The hydrogen can be captured, stored, and utilized for various applications, like fuel cells, transportation, and industrial processes. Overall, the integrated system operates in a closed-loop manner, with heat being extracted from the GCMR using helium as the coolant. With a higher temperature, Helium is used to drive the He turbine, producing electricity. Waste heat from the Helium turbine is further harnessed through the bottoming transcritical CO_2 Rankine cycle, maximizing the energy extraction from the system. Concurrently, excess heat is utilized in a thermochemical process for H_2 generation, enhancing the general efficiency and sustainability of the plant. The default initial parameters of the integrated system are arranged in Table 1.

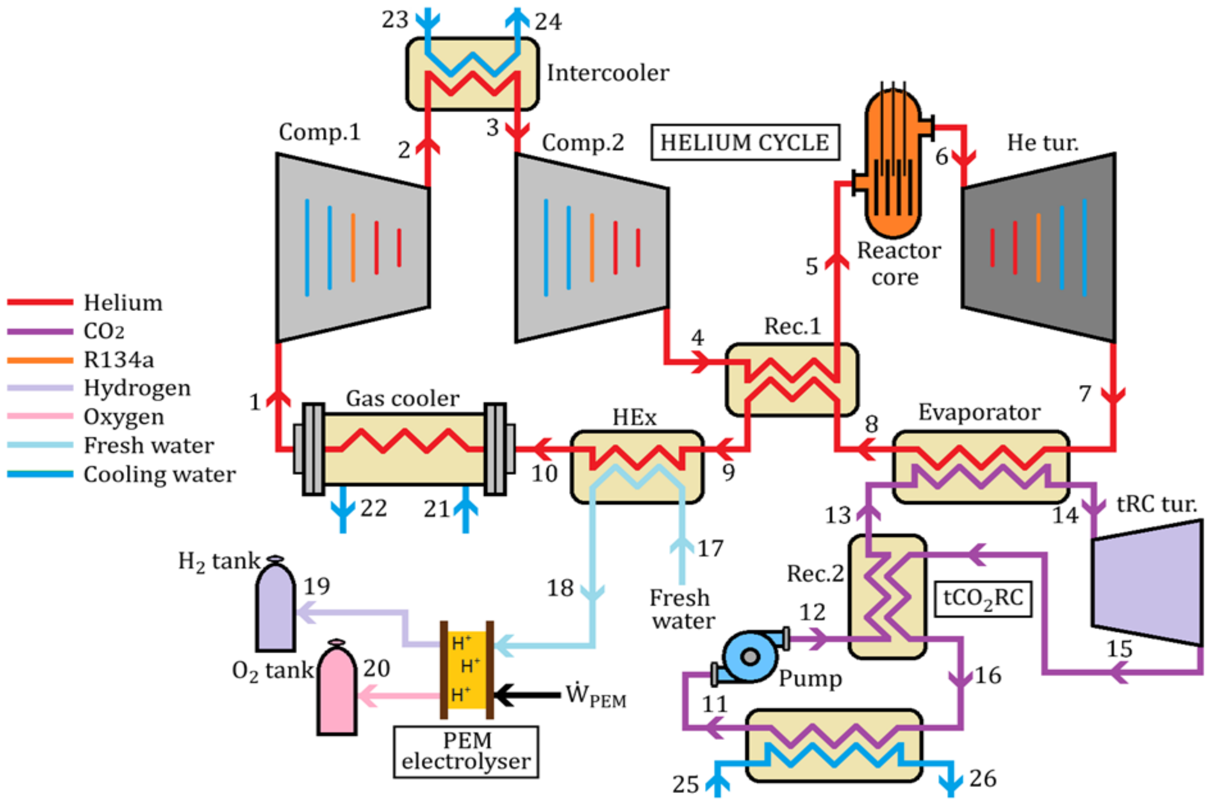


Figure 2. *Schematic drawing of a GCMR integrated with the tRC cycle and H_2 production.*

Table 1. *The default initial parameters*

Parameter	***Value***
Reference temperature	25 °C
Reference pressure	100 kPa
Thermal power from the reactor	600 MW [16]
Gas cycle turbine inlet temperature	750°C [17]
Gas cycle turbine inlet pressure	8000 kPa [17]
Gas cycle compressor inlet temperature	30°C [8]
Gas cycle compressor inlet pressure	2500 kPa
Gas cycle recuperator efficiency	0.9
tRC pump inlet temperature	23.5°C
tRC pressure ratio	1.45
Isentropic efficiency of the tRC turbine	0.90
Isentropic efficiency of the tRC pump	0.85
tRC recuperator efficiency	0.85
Reactor core temperature	1300 K
Gas turbine pressure ratio	3.2
Pinch point temperature	8°C
Core thermal power (MW)	600
PEM Electrolyzer [18]	
T_{PEM} (°C)	79
P_{PEM} (kPa)	101.325
A_{PEM} (m^2)	1.3805
η_{PEM}	%80
$E^a{}_{act}$(kJ/mol)	76

__Table 1(cont).__ The default initial parameters

E^{c}_{act} (kJ/mol)	18
λ_a	14
λ_c	10
D(μm)	100
J^{a}_{ref} (A/m^2)	1.76×10^5
$J^{c}_{ref}$$A/m^2$)	4.60×10^3
F (C/mol)	96487
LHV of H_2 (kJ/kg)	120040

III. TERMODYNAMIC ANALYSIS

In this section, a comprehensive description of the thermodynamic methodology used in this paper is presented. The system's performance is evaluated through energetic and exergetic analyses conducted using the Engineering Equation Software (EES) [19]. The thermodynamic analysis in this study is based on the following assumptions:

- Whole system components are selected to operate under steady-flow and steady-state conditions.
- The alterations in potential and kinetic energies are disregarded when considering energy changes.
- Heat losses from pumps and turbines are not taken into consideration.
- Pressure drops across pipelines and heat exchangers are omitted from consideration.
- The properties at the reference state are defined at a temperature of 25°C and a pressure of 101.325 kPa.

The mass balance for the designed system can be defined as follows [20]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where, $\dot{m}$ represents the mass flow rate, with the subscript *in* indicating the inlet and *out* indicating the outlet. The energy balance is determined as [20]:

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \tag{2}$$

In this equation, $\dot{Q}$ signifies the rate of heat transfer, $\dot{W}$ represents work, and *h* denotes specific enthalpy. In the context of exergy analysis, the balance equation is outlined as [21]:

$$\dot{Ex}_Q - \dot{Ex}_W = \sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} + T_0 \dot{S}_{gen} \tag{3}$$

In the given expression, the initial and subsequent terms pertain to the exergy of heat and work, respectively. $\dot{Ex}$ shows the flow exergy rate, T_0 is the temperature of the reference state, and the final term signifies entropy generation. Each term in the equation is defined as follows:

$$\dot{Ex}_{dest} = T_0 \dot{S}_{gen} \tag{4}$$

$$\dot{Ex}_Q = \dot{Q}\left(\frac{T - T_0}{T}\right) \tag{5}$$

$$\dot{E}x_W = \dot{W} \tag{6}$$
$$\dot{E}x = \dot{m}\, ex \tag{7}$$

In Equation (7), *ex* denotes the specific flow exergy and can be computed using the following equation:

$$ex = (h - h_0) - T_0(s - s_0) \tag{8}$$

Furthermore, the general equilibrium equations of thermodynamics given above are applied to all components of the hybrid system and are tabulated in Table 2.

In explain energy and exergy efficiency within power generation or utilization systems, it is common to employ non-dimensional ratios of quantities. The equation representing energetic efficiency can be recognized as:

$$\eta_{energy} = \frac{\dot{W}_{net,He\ tur.} + \dot{W}_{net,tRC} + \dot{m}_{19} LHV_{H2}}{\dot{Q}_{core} + \dot{W}_{PEM}} \tag{9}$$

The exergy efficiency equation can be defined as:

$$\eta_{exergy} = \frac{\dot{W}_{net,He\ tur.} + \dot{W}_{net,tRC} - \dot{E}x_{19}}{\dot{E}x_{core} + \dot{W}_{PEM}} \tag{10}$$

Table 2. *Formulations of thermodynamic equilibrium equations of integrated system elements*

Component	Energy balance	Exergy balance	Entropy balance
Comp-1	$\dot{m}_1 h_1 + \dot{W}_{Comp-1} = \dot{m}_2 h_2$	$\dot{E}x_1 + \dot{W}_{Comp-1} = \dot{E}x_2 + \dot{E}x_{dest,Comp-1}$	$\dot{S}_1 + \dot{S}_{gen,Comp-1} = \dot{S}_2$
Intercooler	$\dot{m}_2 h_2 + \dot{m}_{23} h_{23} = \dot{m}_3 h_3 + \dot{m}_{24} h_{24}$	$\dot{E}x_2 + \dot{E}x_{23} = \dot{E}x_3 + \dot{E}x_{24} + \dot{E}x_{dest,intercooler}$	$\dot{S}_2 + \dot{S}_{23} + \dot{S}_{gen,intercooler} = \dot{S}_3 + \dot{S}_{24}$
Comp-2	$\dot{m}_3 h_3 + \dot{m}_5 h_5 + \dot{W}_{Comp-2} = \dot{m}_1 h_1 + \dot{m}_6 h_6$	$\dot{E}x_3 + \dot{E}x_5 + \dot{W}_{Comp-2} = \dot{E}x_1 + \dot{E}x_6 + \dot{E}x_{dest,Comp-2}$	$\dot{S}_3 + \dot{S}_5 + \dot{S}_{gen,Comp-1} = \dot{S}_1 + \dot{S}_6$
Rec.-1	$\dot{m}_4 h_4 + \dot{m}_8 h_8 = \dot{m}_5 h_5 + \dot{m}_9 h_9$	$\dot{E}x_4 + \dot{E}x_8 = \dot{E}x_5 + \dot{E}x_9 + \dot{E}x_{dest,Rec.-1}$	$\dot{S}_4 + \dot{S}_8 + \dot{S}_{gen,Rec.-1} = \dot{S}_5 + \dot{S}_9$
HEx	$\dot{m}_9 h_9 + \dot{m}_{17} h_{17} = \dot{m}_{10} h_{10} + \dot{m}_{18} h_{18}$	$\dot{E}x_9 + \dot{E}x_{17} = \dot{E}x_{10} + \dot{E}x_{18} + \dot{E}x_{dest,HEx}$	$\dot{S}_9 + \dot{S}_{17} + \dot{S}_{gen,HEx} = \dot{S}_{10} + \dot{S}_{18}$
Reactor core	$\dot{Q}_{Core} + \dot{m}_5 h_5 = \dot{m}_6 h_6$	$\dot{E}x_{core} + \dot{E}x_5 = \dot{E}x_6 + \dot{E}x_{dest,Reactor,core}$	$\dot{Q}_{Core}/T_{core} + \dot{S}_5 + \dot{S}_{gen,Reactor\ core} = \dot{S}_6$
Helium tur.	$\dot{m}_6 h_6 = \dot{m}_7 h_7 + \dot{W}_{He\ tur.}$	$\dot{E}x_6 = \dot{E}x_7 + \dot{W}_{He\ tur.} + \dot{E}x_{dest,He\ tur.}$	$\dot{S}_6 + \dot{S}_{gen,He\ tur.} = \dot{S}_7$
Evaporator	$\dot{m}_7 h_7 + \dot{m}_{13} h_{13} = \dot{m}_8 h_8 + \dot{m}_{14} h_{14}$	$\dot{E}x_7 + \dot{E}x_{13} = \dot{E}x_8 + \dot{E}x_{14} + \dot{E}x_{dest,Evaporator}$	$\dot{S}_7 + \dot{S}_{13} + \dot{S}_{gen,Evaporator} = \dot{S}_8 + \dot{S}_{14}$
Pump	$\dot{m}_{11} h_{11} + \dot{W}_{Pump} = \dot{m}_{12} h_{12}$	$\dot{E}x_{11} + \dot{W}_{Pump} = \dot{E}x_{12} + \dot{E}x_{Pump}$	$\dot{S}_{11} + \dot{S}_{gen,Pump} = \dot{S}_{12}$
Rec.-2	$\dot{m}_{15} h_{15} + \dot{m}_{12} h_{12} = \dot{m}_{13} h_{13} + \dot{m}_{16} h_{16}$	$\dot{E}x_{15} + \dot{E}x_{12} = \dot{E}x_{13} + \dot{E}x_{16} + \dot{E}x_{dest,Rec.-2.}$	$\dot{S}_{15} + \dot{S}_{12} + \dot{S}_{gen,Rec.-2} = \dot{S}_{13} + \dot{S}_{16}$
tRC tur.	$\dot{m}_{14} h_{14} = \dot{m}_{15} h_{15} + \dot{W}_{tRC\ tur.}$	$\dot{E}x_{14} = \dot{E}x_{15} + \dot{W}_{tRC\ tur.} + \dot{E}x_{dest,tRC\ tur.}$	$\dot{S}_{14} + \dot{S}_{gen,tRC\ tur} = \dot{S}_{15}$
Gas cooler	$\dot{m}_{10} h_{10} + \dot{m}_{21} h_{21} = \dot{m}_1 h_1 + \dot{m}_{22} h_{22}$	$\dot{E}x_{10} + \dot{E}x_{21} = \dot{E}x_1 + \dot{E}x_{22} + \dot{E}x_{dest,Gas\ cooler}$	$\dot{S}_{10} + \dot{S}_{21} + \dot{S}_{gen,Gas\ cooler} = \dot{S}_1 + \dot{S}_{22}$
PEM-El	$\dot{m}_{18} h_{18} + \dot{W}_{PEM-El} = \dot{m}_{19} h_{19} + \dot{m}_{20} h_{20}$	$\dot{E}x_{18} + \dot{W}_{PEM-El} = \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{des,PEM-El}$	$\dot{S}_{18} + \dot{S}_{gen,PEM-El} = \dot{S}_{19} + \dot{S}_{20}$
Condenser	$\dot{m}_{16} h_{16} + \dot{m}_{25} h_{25} = \dot{m}_{11} h_{11} + \dot{m}_{26} h_{26}$	$\dot{E}x_{16} + \dot{E}x_{25} = \dot{E}x_{11} + \dot{E}x_{26} + \dot{E}x_{dest,Condenser}$	$\dot{S}_{16} + \dot{S}_{25} + \dot{S}_{gen,Condenser} = \dot{S}_{11} + \dot{S}_{26}$

A. PEM ELECTROLYZER

This research employs PEM electrolysis for hydrogen production, a versatile technology that breaks down water into hydrogen and oxygen atoms through electrochemical reactions. Table 3 showcases the PEM equations, while Table 1 outlines its limitations.

Table 3. *Mathematical equations for PEM electrolysis unit modeling* [18]

H_2 generation	$H_2O + \Delta H \rightarrow H_2 + (0.5)O_2$
Total energy	$\Delta H = \Delta G + T\Delta S$
Molar hydrogen generation	$\dot{N}_{H_2} = \frac{J_{elect.}}{2F}$
Electrical power	$\dot{W}_{elect.} = J_{elect.}V$
Cell overall potential	$V = V_0 + V_{act,a} + V_{act,c} + V_{ohm}$
Reversible potential	$V_0 = 1.229 - 8.5x10^{-4}(T_{PEM} - 298)$
$\sigma_{PEM}[\lambda(x))] = [0.5139\lambda(x) - 0.326]\ \exp\left[1268\left(\frac{1}{303} - \frac{1}{T_{PEM}}\right)\right]$	
$\lambda(x) = \frac{\lambda_a - \lambda_c}{D}x + \lambda_c$	
Ohmic overpotential	$V_{ohm} = J_{elect.}R_{PEM}$
Overall ohmic resistance	$R_{PEM} = \int_0^L \frac{dx}{\sigma_{PEM}[\lambda(x))]}$
$V_{act,i} = \frac{RT_{PEM}}{F}\sinh^{-1}\left(\frac{J}{2J_0^i}\right), i = a, c$	
$J_{0,i} = J_{ref}^i \exp\left(-\frac{E_{act}^i}{RT_{PEM}}\right), i = a, c$	

B. VALIDATION of PEM ELECTROLYZER

To ensure the accuracy of the H_2 production process, the PEM Electrolyzer model was validated using both empirical data from Ioroi et al. [22] and theoretical data from Ahmadi et al. [23]. Figure 5 compares the three models, showing the relationship between cell potential and current density. The figure indicates that the discrepancy between the current model and Ioroi et al.'s experimental results [22] is within an acceptable range, with an average error of 3.72%. Additionally, the results closely align with the findings of Ahmadi et al. [23].

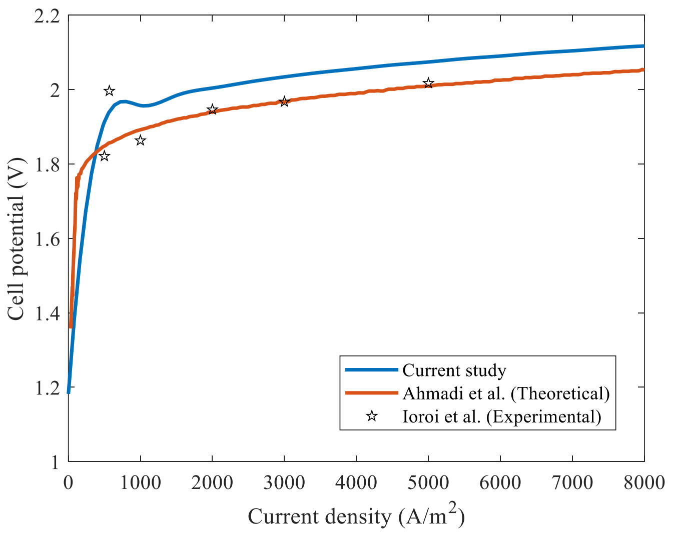


Figure 5. *Validation of the PEM Electrolyzer model with two separate research (Modified from Ref* [19]*)*

IV. RESULTS AND DISCUSSION

The current research aims to integrate a helium turbine with a bottom tRC and evaluate the performance of the H_2-producing GCMR-based plant. At the same time, parametric studies were carried out to explore the effects of helium temperature and pressure ratio at the reactor outlet on the cycle performance. Using the balance equations and under the assumptions given above, the analyses are performed by EES software. The results of the current study were calculated, taking into account the data shown in Table 1. According to these results, the net power obtained from the He turbine was calculated as 241679 kW, and the net power produced from the tRC was calculated as 9902 kW. Additionally, with this developed system, 23.11 kg/h H_2 and 183.4 kg/h O_2 can be produced. The energetic and exergetic performance of the overall system is computed as 41.8% and 54.28%, while the total amount of exergy destruction is determined as 212199 kW. Utilizing these input data, Table 4 presents the thermal properties and corresponding mass flow rates per case.

Table 4. *Thermodynamic specifications of every point in the hybrid system*

State	Working fluid	T (°C)	P (kPa)	$\dot{m}$ (kg/s)	h (kJ/kg)	s (kJ/kgK)	e (kJ/kg)	$\dot{E}x$ (kW)	$\dot{S}$ (kW/K)
1	Helium	30	2500	261.7	1588	21.41	2001	523703	5603
2	Helium	118.8	4472	261.7	2055	21.53	2430	636070	5636
3	Helium	30	4472	261.7	1594	20.2	2367	619500	5287
4	Helium	118.8	8000	261.7	2066	20.33	2801	733057	5321
5	Helium	308.2	8000	261.7	3050	22.38	3174	830682	5857
6	Helium	750	8000	261.7	5342	25.31	4592	1.202E+06	6624
7	Helium	394.3	2500	261.7	3479	25.5	2670	698954	6676
8	Helium	329.3	2500	261.7	3141	24.97	2492	652142	6536
9	Helium	139.9	2500	261.7	2158	23.01	2093	547716	6023
10	Helium	139.9	2500	261.7	2158	23.01	2093	547711	6023
11	CO_2	23.5	6216	425.5	-238.2	-1.51	213.1	90694	-642.6
12	CO_2	29.13	9013	425.5	-233.7	-1.508	216.9	92294	-641.7
13	CO_2	61.35	9013	425.5	-61.07	-0.961	226.5	96376	-408.9
14	CO_2	215	9013	425.5	146.5	-0.4412	279.1	118749	-187.7
15	CO_2	181.4	6216	425.5	118.8	-0.4344	249.4	106108	-184.9
16	CO_2	42.63	6216	425.5	-53.86	-0.8935	213.6	90878	-380.2
17	Freshwater	25	100	0.0792	104.9	0.3672	0	0	0.02908
18	Freshwater	80	100	0.0792	335.1	1.076	18.94	1.5	0.08518
19	H_2	80	100	0.00642	791.4	67.25	118364	759.8	0.4317
20	O_2	80	100	0.05095	50.68	6.567	128.2	6.534	0.3346
21	Cooling water	22.85	100	8504	95.94	0.337	0.03246	276	2866
22	Cooling water	27.05	100	8504	113.5	0.3959	0.02944	250.4	3367
23	Cooling water	22.85	100	7397	95.94	0.337	0.03246	240.1	2493
24	Cooling water	26.75	100	7397	112.3	0.3917	0.02148	158.9	2898
25	Cooling water	22.85	100	4936	95.94	0.337	0.03246	160.2	1663
26	Cooling water	26.65	100	4936	111.8	0.3903	0.01911	94.3	1926

Figure 6 demonstrates the exergy destruction rate of the components that make up the hybrid system. The orange color on the right side of the graph shows the exergy destruction rate in the reactor core, and the blue color on the left shows the exergy destruction rate on the other components of the system. As seen in the figure, the highest exergy destruction is in the reactor core with 91282 kW. The reactor core is followed by the evaporator, gas cooler, intercooler, and He turbine, respectively. The component with the least exergy destruction in the system is the HEx, which has a value of 3.56 kW.

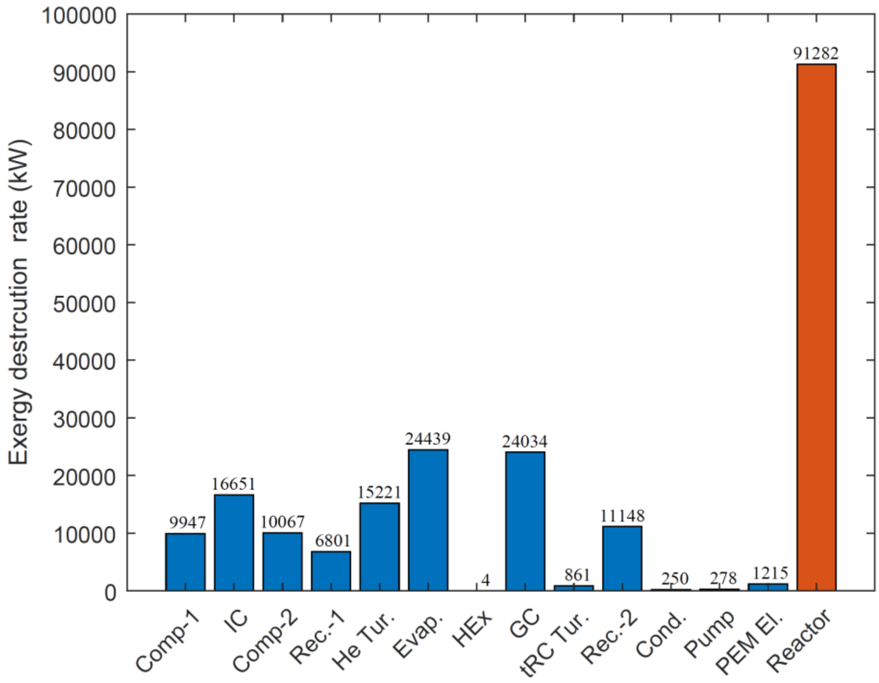


Figure 6. *Exergy destruction rates across the various components of the plant*

Parametric studies have been carried out to determine the impacts of He temperature at the reactor exit on the plant performance. Figure 7 depicts how the He temperature at the reactor outlet influences both total power production and energy efficiency. As depicted in the figure, when the He temperature at the reactor outlet is increased from 700°C to 900°C, the total power generation and overall energy efficiency increase. The effect of He temperature at the reactor outlet on total power generation and overall energy efficiency depends on the specific characteristics of the system and reactor design. Generally, the temperature of the working fluid, in this case, helium, can significantly influence the performance of a nuclear reactor and its overall energetic efficiency. The temperature of the fluid at the reactor outlet influences the power conversion efficiency. Higher temperatures typically lead to higher energy efficiencies in power conversion processes. The efficiency of a power cycle, such as a BC used with helium as the working fluid, often improves with higher outlet temperatures. Higher helium outlet temperatures contribute to increased power production. This is because the temperature variance between the reactor core and the heat sink (usually the environment or a heat exchanger) plays a crucial role in determining the potential power output.

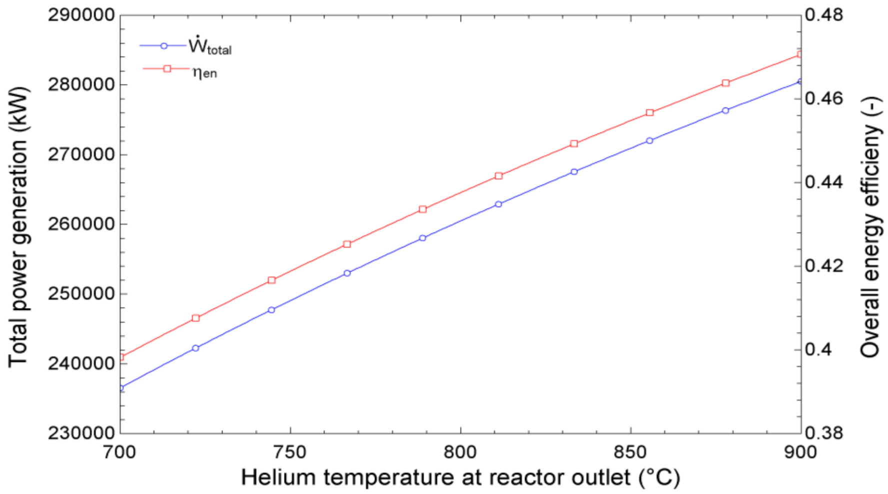


Figure 7. *Impact of helium temperature at the reactor outlet on total power production and overall energy efficiency*

The impact of He temperature at the reactor outlet on both the destruction of exergy and the overall efficiency of exergy is shown in Figure 8. The temperature of helium at the reactor outlet plays a crucial role in influencing the exergy destruction within the system. It is quite clear that as the helium temperature at the reactor exit increases, the exergy destruction rate decreases. Higher temperatures generally result in lower exergy destruction, as the temperature variance between the heat source (reactor) and the heat sink (environment or heat exchanger) influences the thermodynamic losses. As depicted in the figure, contrary to exergy destruction, exergy efficiency increases as helium temperature at the reactor outlet increases. Exergy efficiency increases as higher helium outlet temperatures allow a higher working fluid temperature in the power conversion cycle, potentially increasing thermodynamic efficiency.

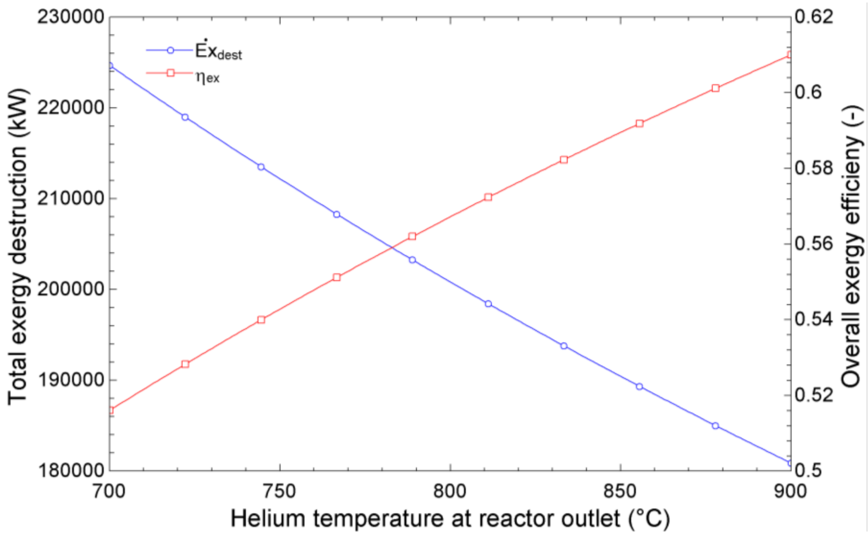


Figure 8. *Impact of helium temperature at the reactor outlet on total exergy destruction and overall exergy efficiency*

The influence of the helium temperature at the reactor outlet on both hydrogen production and net power generation in the transcritical carbon dioxide Rankine cycle (tRC) is shown in Figure 9. As evident from the figure, an elevation in helium temperature results in a decrease in the energy efficiency of the tRC. This is because the heat transferred to helium is less effective in generating electricity. At higher helium temperatures, heat dissipation to the environment becomes more pronounced. This is due to the widening of the temperature variance between helium and the environment. This heat loss reduces the amount of heat available for energy production, further reducing net power production and energy efficiency. In addition, hydrogen production in high-temperature GCMR is achieved by thermochemical processes. These processes involve a series of temperature-dependent chemical reactions. As the helium temperature increases, the reaction equilibrium of these processes shifts towards less favorable conditions for hydrogen production. In summary, the decrease in H_2 production and tRC net power production with increasing helium temperature is due to a combination of factors that influence the overall efficiency of the gas-cooled reactor system.

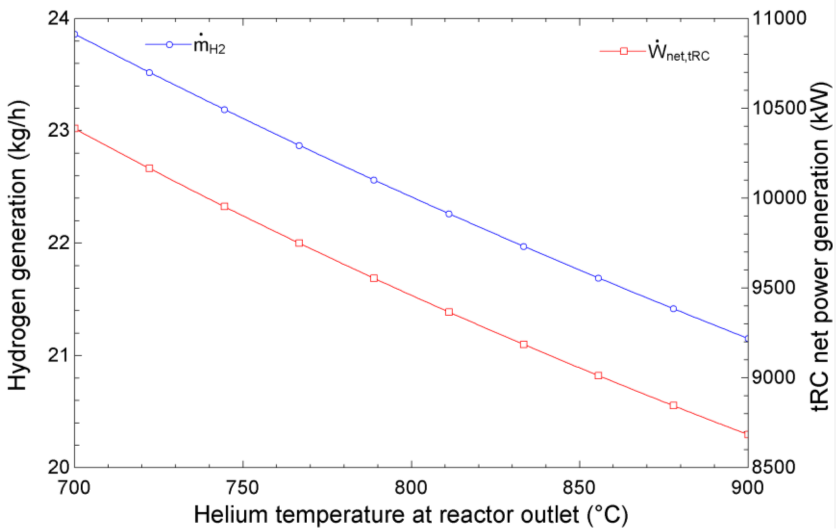


Figure 9. *Impact of helium temperature at the reactor outlet on H_2 production and tRC net power generation*

The effect of the pressure ratio on both total power generation and overall energetic efficiency is illustrated in Figure 10. As the pressure ratio rises, total power production and efficiency exhibit an increase, reaching their peak at a pressure ratio of 2.6. This maximum value shifts to higher pressure ratios when elevated turbine inlet temperatures are employed. The temperature escalation raises the average heat intake temperature in the cycle, subsequently enhancing Carnot efficiency and overall cycle efficiency. Furthermore, the heightened temperature contributes to an increased enthalpy variance across the turbine, enabling greater power generation and achieving heightened efficiencies for all cycles. Additionally, the temperature increase results in an elevated turbine inlet temperature and pressure in the transcritical carbon dioxide Rankine cycle (tRC), leading to an augmented power output in the tRC turbine. It is seen that when the pressure ratio is approximately 2.7 and above, the total power production and general energy efficiency decrease. Pressure changes affect the cycle's efficiency and performance, and further increases lead to reduced returns or negative effects. Therefore, it is necessary to determine an optimal pressure ratio in these systems. The observed reduction in power production and energy efficiency results from the combined effects of increased compressor work, reduced heat exchanger efficiency, higher flow losses, lower turbine efficiency, and unfavorable reaction equilibrium for hydrogen production.

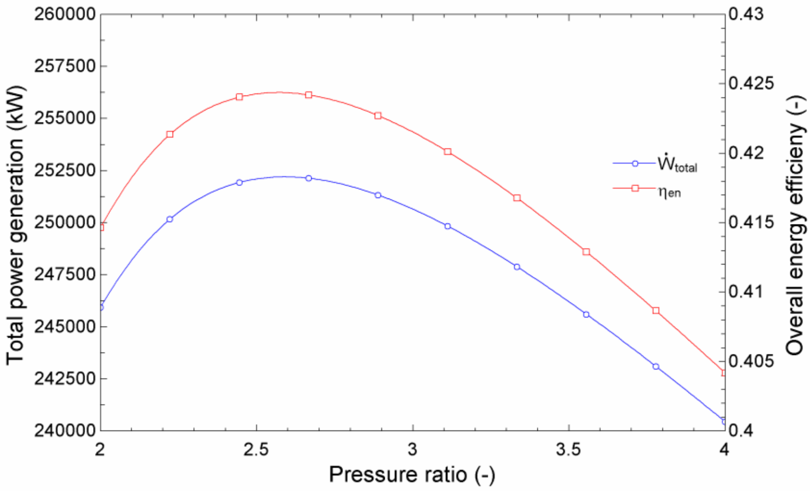


Figure 10. *Impact of pressure ratio on total power production and overall energy efficiency*

Figure 11 shows the influence of pressure ratio on total exergy destruction and general exergy efficiency. There is generally an optimal pressure ratio at which overall exergy efficiency is maximized, and exergy destruction is minimal. While exergy efficiency decreases at higher pressure ratios, exergy destruction tends to increase. The figure shows that exergy efficiency reaches its maximum value when the pressure ratio is approximately 2.6. After this value, it is seen that as the pressure ratio increases, exergy destruction and efficiency decrease. This is because as the pressure ratio increases, the exergy destruction in the compressor also increases. Additionally, the compressor must do more work to compress the helium to a higher pressure, resulting in increased irreversibility and exergy loss. Higher pressure ratios increase exergy destruction in heat exchangers due to larger temperature differences between fluid flows. This increased temperature difference results in higher entropy production and exergy loss. Higher pressure ratios also increase exergy destruction due to increased flow losses in components such as valves and pipes. These losses represent wasted exergy that reduces overall efficiency.

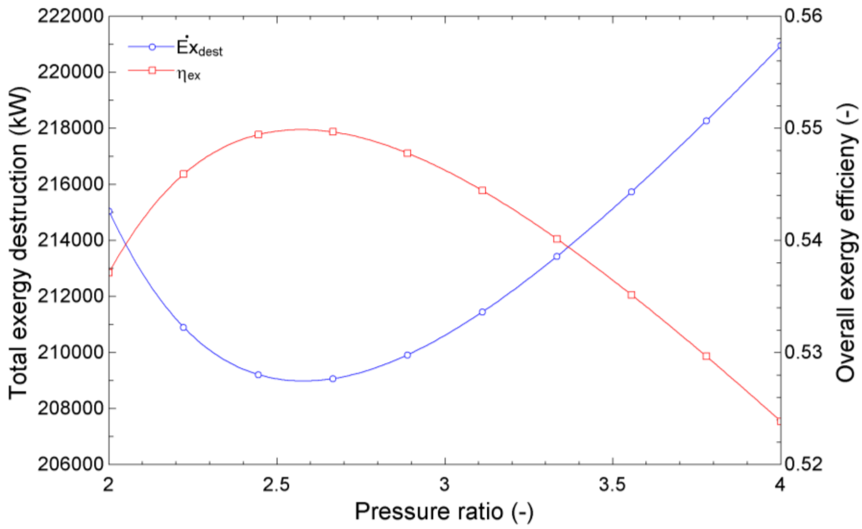


Figure 11. *Impact of pressure ratio on total exergy destruction and overall exergy efficiency*

Figure 12 displays the effect of pressure ratio on H_2 generation and tRC net power production. Increasing the pressure ratio generally leads to a decrease in H_2 production. This is primarily attributed to the shifting reaction equilibrium of thermochemical hydrogen production processes. At higher pressure ratios, the equilibrium shifts towards less favorable conditions for hydrogen formation, resulting in lower H_2 production rates. Also, higher pressure ratios can affect the efficiency of heat exchangers' efficiency in thermochemical hydrogen production. Heat transfer effectiveness may decrease as the pressure ratio increases due to increased fluid velocities and reduced residence time. This reduced heat transfer can further limit H_2 production. Moreover, higher pressure ratios demand more work from the compressor, which consumes more power. This increase in compressor power consumption can negate the initial gain in turbine power output, potentially leading to a decrease in tRC's net power generation. Also, while the turbine power output initially increases with the pressure ratio, the specific heat capacity of helium decreases. This results in a lower enthalpy drop across the turbine, reducing its power output and contributing to the overall efficiency decline.

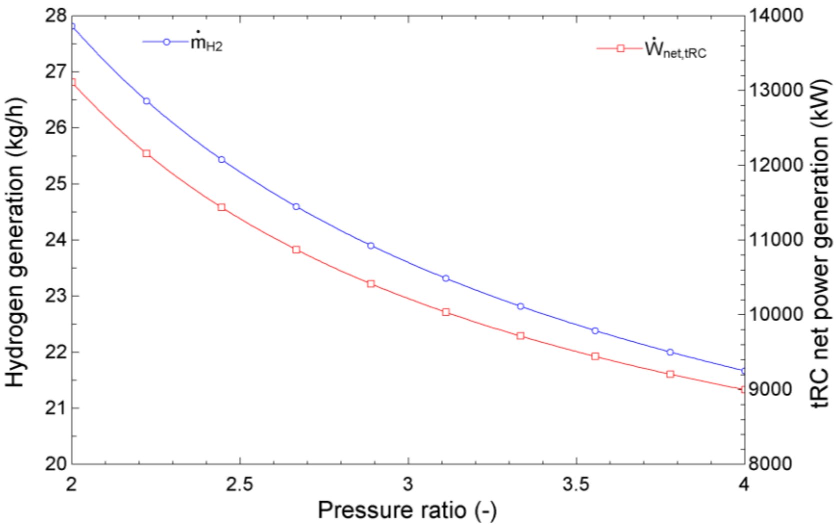


Figure 12. *Impact of pressure ratio on H_2 generation and tRC net power generation*

V. CONCLUSIONS

In this research, the performance of a GCMR-based system that facilitates hydrogen production while integrating a helium gas turbine with the bottoming out transcritical CO_2 Rankine cycle is investigated. At the same time, parametric studies were carried out to evaluate the effects of helium temperature and pressure ratio at the reactor outlet on the cycle performance. The key findings from this research are as follows:

- The net power gained from the He turbine is 241679 kW.
- The net power produced from the tRC is 9902 kW.
- The amount of H_2 produced is 23.11 kg/h, and the amount of O_2 is calculated as 183.4 kg/h.
- The overall rate of exergy destruction in the system amounts to 212199 kW.
- Analysis results show that the system has an energy efficiency of 41.8% and an overall exergetic efficiency of 54.28%.
- As per the outcomes of the parametric analysis, an increase in the helium temperature at the reactor outlet positively impacts both the total power generation and the general energetic efficiency of the integrated plant.
- As stated by the results of the parametric analysis, H_2 production decreases as the exit temperature of helium from the reactor increases.
- Finally, the pressure ratio has an important effect on system performance. According to the results of the parametric analysis, as the pressure ratio increases, H_2 production and net power production of the tRC cycle decrease.

In conclusion, the development of a GCMR based on a helium turbine with a bottoming tRC and H_2 production holds significant promise for advancing the field of nuclear energy. This innovative approach enhances the sustainability of the system by optimizing resource utilization. Developing a GCMR based on a helium turbine with a bottoming tRC and H_2 production is crucial to realizing advanced nuclear energy systems. This integrated approach offers a range of advantages, including high energy efficiency, reliable and safe operation, reduced environmental impact, and clean hydrogen production. However, further research, development, and demonstration efforts are required to optimize and validate this concept's technical and economic feasibility at a larger scale. With continued advancements in nuclear technology and a focus on sustainable energy solutions, the GCMR, with a bottoming tRC and H_2 production, holds immense potential for transforming the energy landscape and driving us toward a greener and more sustainable future.

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