HYDROGEN, FUEL CELL & ENERGY STORAGE

Thermoeconomic Analysis of a Solar-Gas Turbine System for Power, Cooling, Hydrogen and Freshwater Production

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Abstract

This study evaluates the thermoeconomic performance of an innovative solar-gas turbine energy system, which simultaneously produces electricity, cooling, hydrogen, and freshwater. This power system utilizes a 10,302-kW thermal power solar tower receiver which presents concentrated solar energy to substitute standard combustion process in gas chambers. The system combines a Rankine steam cycle with a lithium bromide-water absorption chiller, and reverse osmosis desalination, and PEM electrolyzers. Total energy and exergetic efficiencies yielded a result of 20.52% and 17.87%, respectively. The solar tower stands as the primary source of exergetic point responsible for 51.11% of the total exergy destruction since the steam turbine generates 18.33%. The combined gas turbine and Rankine cycles produce 5,704 kW and 4,406 kW respectively that generate 1,523 kW of cooling output at a COP of 0.959, as well as 8.49 kg/s of freshwater and 0.0281 kg/s of hydrogen. By increasing the compressor pressure ratio to 10, the system achieves 20.63% thermal efficiency and 18.1% exergy efficiency, however, total system cost rises to 98.15 \$/s. The system's power output reduces to 6,983 kW while the absorption chiller COP reaches 1.11. Although the system shows great potential for efficient multi-energy production, optimizing the pressure ratio is essential to enhance efficiency without compromising cost-effectiveness. The system exhibits 10,098 kW exergy destruction at this point which necessitates further improvement.

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1 Introduction

As global energy demand continues to rise, scientists must create several energy output systems that produce electricity with minimal environmental impact. The hybrid solar-gas turbine system integrates the dispatchability of a conventional gas turbine with the renewable energy from solar collectors into a united power system. The systems develop configuration strategies aimed at maximizing both exergy efficiency and economic performance in cogeneration and trigeneration operations. Modern multigeneration systems have enabled power plants to simultaneously produce electricity, cooling, hydrogen, and freshwater resolving essential needs for sustainable energy and water supplies for arid regions. Solar thermal systems integrated with gas turbines produces more efficient results by reducingfuel and emissions while providing thermal energy for hydrogen production via thermochemical methods and sea water desalination. The integration of thermodynamic performance evaluations with economic assessments under thermoeconomic analysis represents an important method to study and enhance complex systems. The holistic system design process enables design improvements, optimized resource utilization, and reduction in economic and energetic costs. A complete thermoeconomic investigation supports this research to evaluate the hybrid solar-gas turbine multigeneration system, which generates electricity, cooling, and hydrogen to create freshwater. The proposed system receives assessments for its energy and exergy efficiency, and cost-effectiveness, and environmental impact.

Many researchers have recently focused on how single energy systems can produce multiple utility outputs. Research on multigeneration systems (also known as polygeneration systems) shows how they optimize fuel usage as well as lower emission levels [1, 2]. Research on solar-assisted gas turbine cycles for power generation extensively examines the integration of solar inputs through parabolic trough collectors and central receiver systems. Thermoeconomic analysis proves to be the crucial method for optimizing systems that involve multiple integrated components. Users of the thermoeconomic models developed by Dincer and Rosen [3] have concluded that combining economic analysis with exergy analysis leads to optimal criteria of practical optimization.

Sharifishourabi et al. [4] proposed a solar-powered multigeneration system utilizing Organic Rankine Cycle (ORC) technology to simultaneously generate electricity, heating, cooling, and hydrogen. Their study quantitatively assessed the system's performance, revealing an energy efficiency of 70% and an exergy efficiency of 53%. The results highlight the significant improvements in overall system performance when ORC technology is integrated with solar energy, demonstrating its potential for enhancing energy generation while fulfilling multiple demands in a sustainable manner.

Yilmaz and Jamil [5] designed a solar-powered integrated system combining solar tower technology with a Supercritical Brayton cycle, a topping steam Rankine cycle, and a bottoming Organic Rankine cycle. The system also uses a reverse osmosis unit for freshwater production. Their model achieves 25.12% energy efficiency, 17.64% exergy efficiency, and produces 3751 kW of electricity, 871.1 kW of heating, and 33.52 m^3 of freshwater daily.

Javadi et al. [6] developed a system the combines a concentrated solar power tower, steam-methane reforming cycle, hydrogen-gas turbine, and reverse osmosis desalination to generate hydrogen, freshwater, and electricity. The system produces 12.9 MW of electricity, 96.18 kg/s of freshwater, and 5.2 kg/s of hydrogen. The 4E analysis shows energy and exergy efficiencies of 50.18% and 51.91%, respectively. The total exergy destruction is reported 324,351 kJ/s, with the majority occurring in the methane reforming cycle and the reformer unit.

Ran et al. [7] developed a waste heat recovery system integrating an SOFC, MGT, S-CO_2 Brayton cycle, and lithium bromide absorption chiller. The system recovers waste heat from the SOFC-MGT to generate additional power via the S-CO_2 Brayton cycle. It produces 696.9 kW of electricity, 24.98 kW of heating, and 88.81 kW of cooling, with a round-trip efficiency of 70.49% and an electrical efficiency of 60.59%. Efficiency is mainly influenced by current density, while SOFC voltage is most affected by the reformer intake fuel flow rate. Shakouri et al. developed a multigeneration system capable of water purification, hydrogen production, and providing heating and cooling services [8]. The system produces 47.30 MW of electricity, 8.29 MW of heating, and 11.22 MW of cooling power, along with 2.49 kg/s of freshwater and 18.06 kg of hydrogen per hour. Yearly energy consumption and CO_2 emissions decrease by 26.47% with the integration of solar power, reducing annual emissions to 18,230 tons. The Pathfinder System operates at a cost of USD 9,299 per hour, with an operational cost of USD 34.5 per GJ, and achieves a break-even point in 2 years and 11 months. Over a 20-year operation period, the system is projected to generate a net revenue of USD 200 million. Sabbaghi et al. [9] designed a five-cycle multigeneration system powered by solar and biomass energy, integrating a modified gas turbine, steam Rankine cycle, transcritical CO_2 (TCO_2)

cycle, biomass boiler, and solar collector. Due to high heat losses, gas turbine thermal efficiency remains low. The system achieves energy and exergy efficiencies of 20.2% and 15.2%, respectively. The investment cost rate is \$0.007554/s, with an environmental impact of 0.0008611 pt/s. Exergoeconomic analysis reveals that environmental impacts outweigh economic value across system components, primarily due to lifecycle costs.

A research team led by Ghorbani [10] investigated four integrated power systems that simultaneously produce electricity and hot water, utilizing Kalina cycle, Organic Rankine Cycle (ORC), gas turbine, and steam Rankine cycle configurations. The proposed cycle achieves a power generation output of 148.5 MW along with hot water production at a rate of 46.02 kg/s. Hosseini et al. conducted an analysis of two cogeneration triple-hybrid systems, each comprising a gas turbine, solid oxide fuel cell (SOFC), and absorption chillers, evaluated under two distinct operational scenarios [11]. It examines their changes regarding the compressor pressure ratio and the air-to-fuel ratio on system performance. Experimental results indicated that increases in the pressure ratio inversely affect all analyzed efficiency parameters. Additionally, implementing a double-effect absorption chiller reduces exergy destruction by 5.4% and increases electricity production by 28%. The research by Pirkandi et al. [12] models and compares the performance of two hybrid systems: one combining a gas turbine (GT), steam turbine (ST), and solid oxide fuel cell (SOFC), and another with GT, organic Rankine cycle (ORC), and SOFC. Results show that while the steam cycle generates higher output, it doesn't necessarily indicate better performance. Among the ORC fluids analyzed, toluene provides the highest power output at a condenser temperature of 319 K. The study by Zoghi et al. [13] analyzes a hybrid system recovering waste heat from a regenerative gas turbine cycle (GTC) powered by solar power tower (SPT) and biomass gasification. The multi-generation system produces electricity, heating, cooling, and hydrogen. Waste heat is recovered using a steam Rankine cycle (SRC), thermoelectric generator (TEG), and absorption refrigeration system (ARS). The system achieves 43.11% exergy efficiency, producing 98.2 MW of electricity and 13 MW of heating.

Recent developments have focused on free-piston [14] and thermoacoustic Stirling engines [15] due to their ability to convert solar thermal losses into additional electricity. These engines possess effective heat recovery from medium- and low-grade thermal sources due to their high-performance reliability, low maintenance requirements, and versatility in heat sources. The combination of these technologies used with solar thermal systems achieves better energy transformation rates while providing lasting sustainable operations. While present study emphasizes the integration of solar towers with gas turbine-based multigeneration systems, future developments should explore the incorporation of Stirling engines as a means to reduce energy losses and further optimize the efficiency of solar-powered multigeneration plants. The present study presents a new multigeneration system which uses a solar tower receiver to fully replace the combustion chamber of a gas turbine for complete renewable operation as shown in Table 1.

Table 1. Comparative taxonomy of key features in recent solar-driven multigeneration systems, highlighting the unique integration and innovation of the present study relative to the existing literature

Feature/Study	This Study	Sharifishourabi et al.	Yilmaz & Jamil	Javadi et al.	Ran et al.	Shakouri et al.
Solar Collector Type	Solar tower receiver	Parabolic trough	Solar tower	Solar tower	None	Solar + others
Main Power Cycle	Gas turbine + Rankine	ORC	Brayton + Rankine	Steam-methane + GT	SOFC + MGT + $S-CO_2$	Gas turbine + others
Combustion Chamber	Replaced by solar receiver	Standard	Standard	Standard	Standard	Standard
Cooling Tech	$LiBr-H_2O$ absorption chiller	Absorption chiller	Not specified	Not specified	LiBr absorption	Cooling included
Desalination	Reverse osmosis	Not included	Reverse osmosis	Reverse osmosis	Not included	Included
Hydrogen Production	PEM electrolyzer	Included	Not specified	Steam-methane	Not included	Included
Thermoeconomic Analysis	Yes (detailed)	Partial	Partial	Partial	Partial	Yes
Optimization	Compressor pressure ratio	No	No	No	No	No

A single plant integrates a gas turbine cycle a Rankine steam cycle, a lithium bromide–water absorption chiller, reverse osmosis desalination, and a PEM electrolyzer in a unique configuration to simultaneously produce electricity, cooling, hydrogen, and freshwater. This study combines state-of-the-art power generation technologies and thermodynamic cycles into a single system, along with an exergoeconomic evaluation that uniquely incorporates compressor pressure ratio optimization – an aspect not yet investigated in existing literature. The combined method extends existing knowledge on solar-driven multigeneration systems by delivering crucial findings about operational effectiveness, economical efficiency, and sustainable resource management.

2 System Description and Analysis

The integrated power system utilizes a modified gas turbine cycle in which conventional combustion chambers are replaced with solar tower receivers, aligning with a sustainable energy strategy. A central receiver on a tower receives solar radiation that comes from solar power concentrators which comprise the heliostat field. The heat transfer fluid absorbs solar power at the receiver which subsequently raises the temperature of compressed air in the heat exchanger to a level suitable for turbine expansion. A complete diagram of the multigeneration system appears in Figure 1.

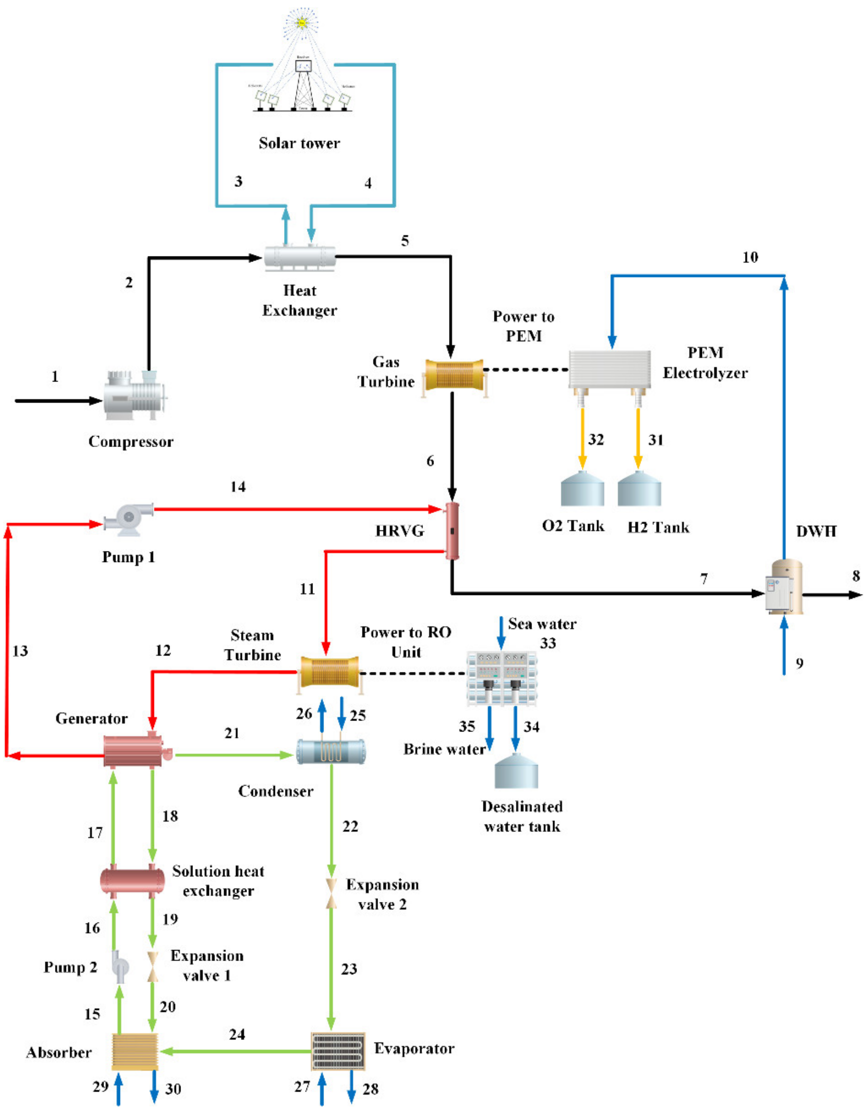

Fig. 1. The schematic of the proposed multigeneration system

The proposed system reaches peak efficiency by using a gas turbine cycle and Rankine steam cycle operating in combined configuration. After the compression process, ambient air receives heat from the HTF before the solar heat exchanger increases its temperature for gas turbine expansion. The exhaust gases from the turbine propagate into the Heat Recovery Vapor Generator (HRVG), extracting residual heat to drive the Rankine cycle. The exhaust gas moves to a domestic water heater (DWH) for useful thermal heating purposes before being released into the atmospheric. The Rankine cycle incorporates two operations: a pump raises the fluid pressure, and the Heat Recovery Vapor Generator (HRVG) heats the fluid by recovering heat from the gas turbine exhaust. A steam turbine generates power by applying heated fluid through expansion procedures. This technology enables a single-effect lithium bromide-water absorption cooling process by utilizing the condensation heat released from the vapor in combination with low-temperature thermal sources. Standard absorption system devices consist of generators, absorbers, evaporators, condensers, solution heat exchangers, solution pumps, and expansion valves.

The system functions to perform freshwater generation tasks in combination with producing hydrogen. The RO technology for water desalination takes power from the steam turbine to convert seawater into drinkable freshwater. The PEM electrolyzer utilizes water produced from freshwater generation to perform electrolysis, using electricity from gas turbines to produce hydrogen and oxygen as energy carriers. The process simultaneously generates power, provides heating and cooling services, and produces water and hydrogen, thereby maximizing overall resource utilization. A detailed thermodynamic examination of system performance happens through an exergoeconomic analysis method. The model adopts realistic operational parameters together with component efficiency limitations and local solar conditions in all its presumed assumptions. The subsystem models present thermodynamic frameworks in addition to economic analyses to evaluate all operational aspects of the integrated system through energy and exergy flow assessments, as well as cost evaluation techniques.

The proposed multigeneration system is evaluated through comprehensive energy and exergy analyses, which provide detailed numerical insights into thermal and electrical energy exchanges, as well as the exergy destruction rates caused by irreversibilities in each system component. These analytical methods are essential for assessing the system's thermodynamic performance under varying operational conditions. By applying the principles of energy and exergy balance, the study systematically tracks both the quantity and quality of energy flows throughout the system. This dual-level analysis facilitates the identification of inefficiencies and highlights opportunities for performance improvement. Table 2 summarizes the results of heat and power transfer calculations alongside the corresponding exergy destruction values for individual components, providing a clear foundation for evaluating system behavior and optimization potential. Thermoeconomics facilitates the integration of thermodynamics and economics to design energy systems that are both efficient and cost-effective. This evaluation method yields results that go beyond traditional thermodynamic and economic assessments. Often referred to as exergoeconomics, the term is derived from the exergy principles of thermodynamics. By balancing system performance with financial expenditure, thermoeconomic analysis enables more informed decision-making. This approach applies economic calculations to thermodynamic parameters, offering a comprehensive understanding of both energy efficiency and cost. The overall system cost balance equation is presented below [19]:

$$\dot{C}_{p,\mathrm{tot}} = \dot{C}_{F,\mathrm{tot}} + \dot{Z}_{\mathrm{tot}}^{\mathrm{CI}} + \dot{Z}_{\mathrm{tot}}^{\mathrm{O\&M}} \tag{1}$$

This equation relates the cost rates associated with fuel and products to the input and output material flow rates, as well as the power and heat transfer within the system.

$$\dot{C}_i = c_i \dot{\mathrm{E}}\mathrm{x}_i \tag{2}$$

$$\dot{C}_e = c_e \dot{\mathrm{E}}\mathrm{x}_e \tag{3}$$

$$\dot{C}_W = c_W \dot{W} \tag{4}$$

$$\dot{C}_q = c_q \dot{\mathrm{E}}\mathrm{x}_q \tag{5}$$

The system cost rate can be determined by:

$$\dot{Z}_k = \frac{Z_k \times \phi \times \mathrm{CRF}}{\tau} \tag{6}$$

The definition of capital recovery factor appears in [20] as follows:

$$\mathrm{CRF} = \frac{i_r(1+i_r)^n}{(1+i_r)^n - 1} \tag{7}$$

The equation relates the interest rate i with the system lifetime n to determine the equipment value using specific values of 0.1 and 20.

The theoretical model analyzes the multigeneration system through simulated parameters with basic assumptions. The model functions without depending on data from operating plants or particular solar irradiation conditions in specific locations. The model enables basic system performance evaluation while allowing researchers to determine optimization opportunities that support future optimal designs and experimental tests.

Table 2. Energy Balance and Exergy Destruction Equations for System Components [16–18]

Component	Energy balance equations	Exergy destruction rate equations
Solar tower	$\dot{m}_3 + \dot{Q}_{\text{rec}} = \dot{m}_4 h_4$	$\dot{\text{E}}\text{x}_{D,\text{ST}} = \text{DNI} \times A_h \times \left(1 - \frac{T_0}{T_{\text{sun}}}\right) + \dot{\text{E}}\text{x}_3 - \dot{\text{E}}\text{x}_4$
Compressor	$\dot{m}_1 h_1 + \dot{W}_{\text{comp}} = \dot{m}_2 h_2$	$\dot{\text{E}}\text{x}_{d,\text{comp}} = \dot{\text{E}}\text{x}_1 - \dot{\text{E}}\text{x}_2 + \dot{W}_{\text{comp}}$
Gas turbine	$\dot{W}_{\text{gturb}} = \dot{m}_5 h_5 - \dot{m}_6 h_6$	$\dot{\text{E}}\text{x}_{D,\text{gturb}} = \dot{\text{E}}\text{x}_5 - \dot{W}_{\text{gturb}} - \dot{\text{E}}\text{x}_6$
Heat Exchanger	$\dot{Q}_{\text{HX}} = \dot{m}_2(h_5 - h_2) = \dot{m}_3(h_4 - h_3)$	$\dot{\text{E}}\text{x}_{D,\text{HX}} = \dot{\text{E}}\text{x}_2 + \dot{\text{E}}\text{x}_4 - \dot{\text{E}}\text{x}_3 - \dot{\text{E}}\text{x}_5$
HVRG	$\dot{Q}_{\text{HVRG}} = \dot{m}_6(h_6 - h_7) = \dot{m}_{11}(h_{11} - h_{14})$	$\dot{\text{E}}\text{x}_{D,\text{HVRG}} = \dot{\text{E}}\text{x}_6 + \dot{\text{E}}\text{x}_{14} - \dot{\text{E}}\text{x}_7 - \dot{\text{E}}\text{x}_{11}$
Steam turbine	$\dot{W}_{\text{sturb}} = \dot{m}_{11} h_{11} - \dot{m}_{12} h_{12}$	$\dot{\text{E}}\text{x}_{D,\text{sturb}} = \dot{\text{E}}\text{x}_{11} - \dot{W}_{\text{sturb}} - \dot{\text{E}}\text{x}_{12}$
Pump 1	$\dot{W}_{\text{pump1}} = \dot{m}_{13}(h_{14} - h_{13})$	$\dot{\text{E}}\text{x}_{D,\text{pump1}} = \dot{W}_{\text{pump1}} - \dot{\text{E}}\text{x}_{14} + \dot{\text{E}}\text{x}_{13}$
Generator	$\dot{Q}_{\text{gen}} = \dot{m}_{12}(h_{12} - h_{13})$	$\dot{\text{E}}\text{x}_{d,\text{gen}} = \dot{\text{E}}\text{x}_{12} + \dot{\text{E}}\text{x}_{17} - \dot{\text{E}}\text{x}_{13} - \dot{\text{E}}\text{x}_{18} - \dot{\text{E}}\text{x}_{21}$
Condenser	$\dot{Q}_{\text{cond}} = \dot{m}_{21}(h_{21} - h_{22})$	$\dot{\text{E}}\text{x}_{d,\text{cond}} = \dot{\text{E}}\text{x}_{21} + \dot{\text{E}}\text{x}_{25} - \dot{\text{E}}\text{x}_{22} - \dot{\text{E}}\text{x}_{26}$
Evaporator	$\dot{Q}_{\text{eva}} = \dot{m}_{23}(h_{24} - h_{23}) = \dot{m}_{27}(h_{28} - h_{27})$	$\dot{\text{E}}\text{x}_{d,\text{eva}} = \dot{\text{E}}\text{x}_{23} + \dot{\text{E}}\text{x}_{27} - \dot{\text{E}}\text{x}_{24} - \dot{\text{E}}\text{x}_{28}$
Absorber	$\dot{Q}_{\text{abs}} = \dot{m}_{24} h_{24} + \dot{m}_{15} h_{15} - \dot{m}_{20} h_{20} = \dot{m}_{29}(h_{30} - h_{29})$	$\dot{\text{E}}\text{x}_{d,\text{abs}} = \dot{\text{E}}\text{x}_{24} + \dot{\text{E}}\text{x}_{15} + \dot{\text{E}}\text{x}_{19} - \dot{\text{E}}\text{x}_{20} - \dot{\text{E}}\text{x}_{30}$
Pump 2	$\dot{W}_{\text{pump2}} = \dot{m}_{15}(h_{16} - h_{15})$	$\dot{\text{E}}\text{x}_{D,\text{pump2}} = \dot{W}_{\text{pump2}} - \dot{\text{E}}\text{x}_{16} + \dot{\text{E}}\text{x}_{15}$
Solution heat exchanger	$\dot{Q}_{\text{SHX}} = \dot{m}_{16}(h_{16} - h_{17}) = \dot{m}_{18}(h_{19} - h_{18})$	$\dot{\text{E}}\text{x}_{d,\text{SHX}} = \dot{\text{E}}\text{x}_{16} + \dot{\text{E}}\text{x}_{18} - \dot{\text{E}}\text{x}_{17} - \dot{\text{E}}\text{x}_{19}$
EXV1	$\dot{m}_{19} h_{19} = \dot{m}_{20} h_{20}$	$\dot{\text{E}}\text{x}_{D,\text{EXV1}} = \dot{\text{E}}\text{x}_{19} - \dot{\text{E}}\text{x}_{20}$
EXV2	$\dot{m}_{22} h_{22} = \dot{m}_{23} h_{23}$	$\dot{\text{E}}\text{x}_{D,\text{EXV1}} = \dot{\text{E}}\text{x}_{22} - \dot{\text{E}}\text{x}_{23}$
DWH	$\dot{Q}_{\text{DWH}} = \dot{m}_7(h_7 - h_8) = \dot{m}_9(h_{10} - h_9)$	$\dot{\text{E}}\text{x}_{\text{DWH}} = \dot{\text{E}}\text{x}_7 + \dot{\text{E}}\text{x}_9 - \dot{\text{E}}\text{x}_8 - \dot{\text{E}}\text{x}_{10}$
PEM	$\dot{W}_{\text{PEM}} = \dot{m}_{10} h_{10} - \dot{m}_{31} h_{31} - \dot{m}_{32} h_{32}$	$\dot{\text{E}}\text{x}_{D,\text{PEM}} = \dot{\text{E}}\text{x}_{10} + \dot{W}_{\text{PEM}} - \dot{\text{E}}\text{x}_{31} - \dot{\text{E}}\text{x}_{32}$
RO	$\dot{W}_{\text{RO}} = \dot{m}_{33} h_{33} - \dot{m}_{34} h_{34} - \dot{m}_{35} h_{35}$	$\dot{\text{E}}\text{x}_{D,\text{RO}} = \dot{\text{E}}\text{x}_{33} - \dot{\text{E}}\text{x}_{34} - \dot{\text{E}}\text{x}_{35}$
COP	$\text{COP} = \frac{\dot{Q}_{\text{eva}}}{\dot{Q}_{\text{gen}} + \dot{W}_{\text{net,ARC}}}$	

3 Results and Discussions

A thorough evaluation of primary gas turbine cycle elements was conducted to ensure proper results from the thermodynamic model. The analysis referenced [9] for specified input parameters. Previous research findings match exactly with the evaluation results presented in Table 3 for the model. The proper modeling of the GTC is verified through system discrepancies that stay within predefined parameters.

The evaluation and operational specifications of the proposed multigeneration system are summarized in Table 4. The solar tower delivers a thermal power output of 10,302 kW, which starts both the GT cycle and the Rankine cycle. The GT cycle creates power output of 5,704 kW whereas the Rankine cycle generates 4,406 kW. During cooling operation, the system delivers 1,523 kW of cooling capacity with a coefficient of performance (COP) of 0.959, indicating high energy efficiency. The system produces 8.49 kg/s of freshwater and 0.0281 kg/s of hydrogen. It operates effectively as a multigeneration system, achieving an energy efficiency of 20.52% and an exergy efficiency of 17.87%. However, further improvements are required to reduce losses and enhance performance, as the total exergy destruction reaches 10,098 kW.

Table 3. Comparison of the present study results with the results obtained by Khaljani et al. [21] for GT cycle

Parameter	Exergy destruction rate (kW)	
	Current study	Ref. [21]
Gas turbine	3.02	3.03
Combustion Chamber	25.36	25.63
Compressor	2.14	2.2
Regenerator	2.71	2.83

A breakdown of exergy destruction occurs throughout the proposed solar-based multi-generation system as depicted in Figure 2. The Solar Tower stands out as the main source of exergy destruction accounting for 51.11% of the whole system because of thermal constraints alongside variable solar energy input. Additionally, high-temperature expansion losses in the Steam Turbine account for 18.33% of the total exergy destruction. The Heat Exchanger system together with the HVRG, Gas Turbine and Compressor form 22.09% of the total exergy destruction from mechanical and thermal inefficiencies. The PEM electrolyzers (2.19%), Generator (1.99%), DWH (1.27%), Absorber (1.03%), and Evaporator (0.97%) among others comprise the remaining exergy destructions in the system. Exergy destruction from the Condenser and the Solution Heat Exchanger together with the RO Unit and EXV1 and Pump 1 and EXV2 reaches only 0.57%.

Table 4. Operational characteristics of the proposed multigeneration system

Parameter	Unit	Value
Heat transferred by Solar tower	kW	10302
GT Cycle Power Output	kW	5704
Steam Rankine Cycle Power Output	kW	4406
Cooling Output	kW	1523
COP	-	0.959
Freshwater Production Rate	kg/s	8.49
Hydrogen Production Rate	kg/s	0.0281
Energy Efficiency	%	20.52
Exergy Efficiency	%	17.87
Total Exergy Destruction	kW	10098

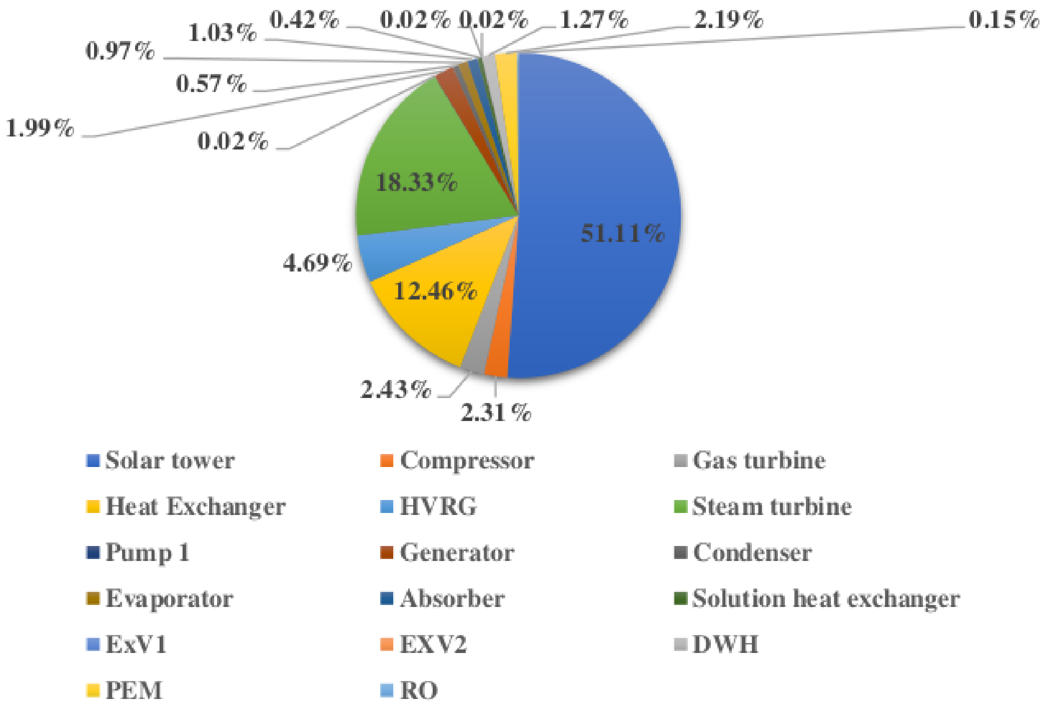

Fig. 2. Exergy destruction rate percentage for the different parts of the studied system

Table 5 presents thorough results of exergoeconomic analysis for the proposed multigeneration system which incorporates both cost rate and investment cost rate calculations for every system component.

Figure 3 displays the influence of compressor pressure ratio on the thermal and exergy performance of the multigeneration cycle. The increase in pressure ratio from 5 to 10 enhances both efficiency levels at different gradual rates. The thermal efficiency increases to 20.63% because a higher fluid temperature and pressure passing through the turbine facilitates better extraction of energy. Exergy efficiency increases from 17.48% to 18.1% due to improved coupling between compressor input and turbine output. However, further performance gains are limited, as higher pressure ratios also lead to increased irreversibilities – primarily during the combustion and expansion processes – which hinder additional improvements. The relationship between efficiency improvement and pressure ratio exists until a specific threshold where additional gains become limited.

Figure 4 illustrates the variation in total system cost with respect to the compressor pressure ratio. As the pressure ratio increases from 5 to 10, the total system cost rises to 98.15 $/s. This increase is primarily due to the need for more advanced and energy-intensive compressors required to handle higher pressure levels. Higher pressure ratios reduce overall exergy destruction throughout the system yet lead to growing exergy losses in the compressor component. Higher work input along with increased entropy generation occurs because of non-ideal operation. Increasing turbine pressure ratio boosts overall system efficiency yet it drives up both localized inefficiencies and total system expenditure. Economic operation depends on choosing the right pressure ratio to maintain efficiency levels.

Table 5. Cost rate and investment cost rate results from the exergoeconomic analysis of the multigeneration system.

Component	Z (\$)	$\dot{Z}$ (\$/s)
Compressor	67552	0.0381
Gas Turbine	171143	0.0966
Solar Tower	1440000	0.215
HRVG	7911	0.00446
Steam Turbine	1348228	0.7613
Pump 1	18350	0.0103
DWH	5568	1.21×10^{-5}
Generator	4291362	2.424
Condenser	165333	0.09336
Evaporator	332048	0.1875
Absorber	41958	0.02369
Pump 2	4595	0.00259
PEM	566446	33×10^{-7}
RO	668617	0.0014

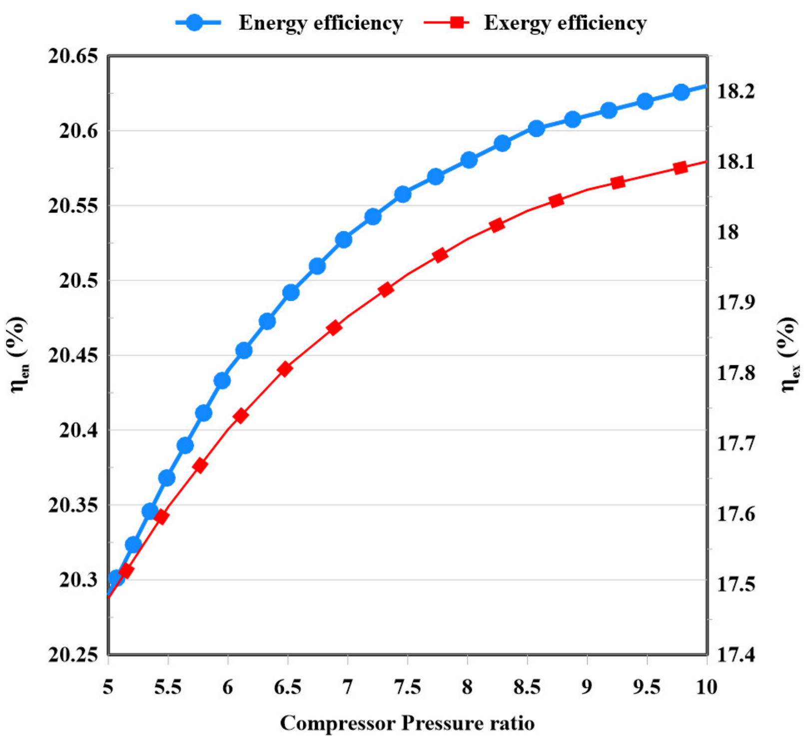

Fig. 3. Variation of energy and exergy efficiency with compressor pressure ratio

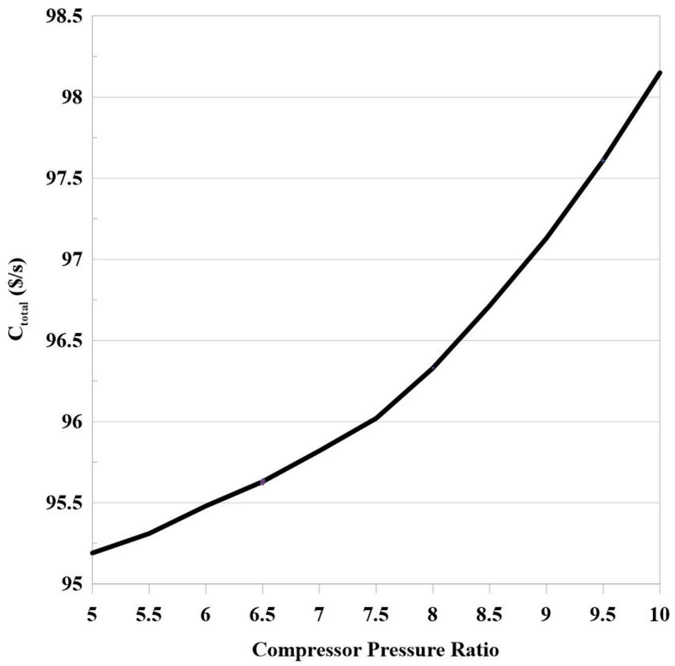

Fig. 4. Total system cost as a function of compressor density ratio.

The integrated energy system achieves optimal performance when the compressor pressure ratio is properly adjusted. As the pressure ratio increases from 5 to 10, power generation capacity decreases from 7,356 kW to 6,983 kW, while the coefficient of performance (COP) of the absorption chiller improves from 0.8491 to 1.11, as shown in Figure 5 Although gas turbine power output increases, the system's total power decreases due to a rise in compressor power consumption and a reduction in Rankine cycle power output. As the pressure ratio increases, the chiller's evaporator load remains steady, while the generator's heat input decreases, resulting in an improved COP. A higher thermal efficiency is achieved when less heat input is required to produce one unit of cooling output.

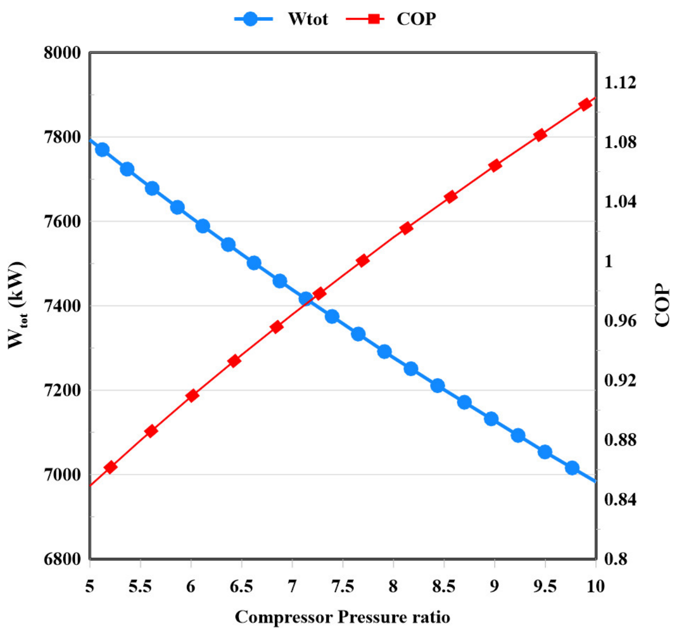

Fig. 5. Variation of total produced power and COP with compressor pressure ratio

An increase in compressor pressure ratio from 5 to 10 creates differently affected hydrogen and freshwater outputs according to Figure 6. Hydrogen output rises to 0.03216 kg/s, while freshwater generation drops to 7.892 kg/s. The two components differ in their power source distribution because the PEM electrolyzer draws power from the gas turbine system while the Rankine cycle operates the RO desalination unit. The optimal performance of multi-generation systems depends on selecting the correct operative conditions to balance output requirements.

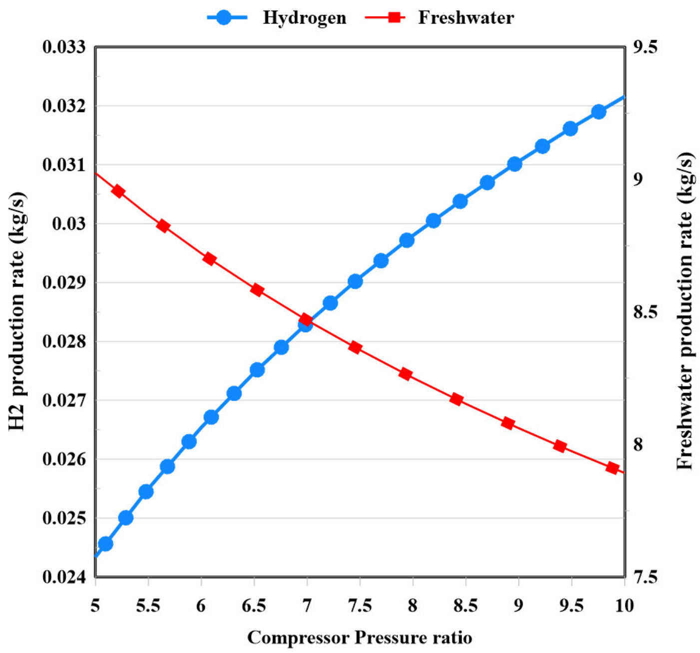

Fig. 6. Variation of hydrogen and freshwater production rates with compressor pressure ratio

4 Synergies and Trade-offs in Multigeneration System Design

The solar-gas turbine-based multigeneration system uses both thermodynamic and economic benefits through successive usage of generated energy outputs. The first application of high-grade solar energy occurs for electricity generation through gas turbine and Rankine cycles. The heat energy discarded from these cycles activates the absorption chiller for cooling and supports the operations of hydrogen manufacturing and desalination systems. The resource utilization rate reaches maximum levels while system-wide efficiency improves significantly according to the determined energy and exergy efficiency values of 20.52% and 17.87%. An integrated electricity and cooling and hydrogen and freshwater production system distributes financial expenses and management expenses throughout all system components. A distributed cost analysis based on exergy content and flow provides improved economic benefit assessment of multiple product operations through exergoeconomic methods. System operation simultaneously benefits from numerous synergies as well as it presents unavoidable trade-offs. A higher distribution of low-grade heat to the absorption chiller results in decreased availability of thermal energy for hydrogen and freshwater production which leads to impacts on their product quantity or operational efficiency. System costs will increase while the compressor pressure ratio optimization improves both thermal and exergy efficiencies although it modifies the overall system output distribution. The study quantifies trade-offs through detailed investigations based on energy, exergy, and exergoeconomic analyses of the system. We assess the operational parameters such as compressor pressure ratio to establish the performance and cost behaviors of each subsystem through which variations in one output generate effects on other outputs regarding their efficiency and economic outcomes. The system follows a design approach which balances performance through operational setting optimizations that maximize overall efficiency and cost-effectiveness without transforming practical outputs from any product. Multi-objective optimization technology represents a potential method to optimize the performance balance of such applications based on specific operational needs.

5 Conclusion

The research develops an innovative multigeneration solar-gas turbine system into which the standard gas turbine combustion chamber has been substituted by a solar tower receiver to enable fully sustainable renewable energy inputs. The system achieves simultaneous power generation and hydronomics production by uniting a gas turbine system with steam Rankine and lithium bromide absorption cooling dynamics and PEM electrolyzers. A complete thermodynamic analysis along with an exergoeconomic review examined the relationship between operation efficiency and economic costs through pressure ratio optimization of the system compressor. The proposed solar-assisted multigeneration system operates at total efficiencies of 20.52% in terms of energy and 17.87% when measuring exergy. The solar tower section accounts for 51.11% of total exergy loss and follows closely by the steam turbine section at 18.33%. Total power output declines while system cost reaches 98.15 $/s when the compressor pressure ratio expands from 5 to 10. The combined system generates 5,704 kW via the gas turbine and 4,406 kW using the Rankine cycle along with 1,523 kW cooling power (COP 0.959) while producing 0.0281 kg/s hydrogen and 8.49 kg/s freshwater. Increasing pressure ratio increases hydrogen yields while decreasing the amount of freshwater generated. The system shows promising capabilities for long-term sustainable power operations however optimization work needs to improve both its efficiency and financial aspects.

5.1 Recommendations

- Substituting combustion chambers with solar tower receivers cuts operational pollution but the complete environmental assessment must review the entire product life cycle. Solar tower units together with electrolyzers produce major environmental effects through their production process because their components have challenging manufacturing requirements and material demands. Future research should involve conducting an LCA that evaluates sustainability of the proposed system according to research team criteria. A combination of thermosyntetic analysis with Life Cycle Assessment methodology enables complete environmental trade-off analysis for sustainable design approaches to multiple-energy-production systems.
- The thermodynamic and exergoeconomic performance of the integrated solar-gas turbine multigeneration system is the main focus of this research yet HTF management needs additional study as a future investigation priority. To improve system functionality, researchers should develop dynamic HTF circulation control methods which preserve stable thermal outputs and maintain system safety under different solar and load conditions. The system reliability needs improvement through extensive studies that examine HTF thermal degradation mechanisms as well as HTF long-term stability at high operating temperatures. The implementation of practical solar tower-based multigeneration systems depends on sustainably addressing current operational and technological difficulties.

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