Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

Semnan University

ISSN: 2383-3068

Review Article

Recent Advances in Renewable Energy-Integrated Thermodynamic Cycles: A Comprehensive Review

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ARTICLE INFO

Article history:

Received: 2025-04-12
Revised: 2025-08-19
Accepted: 2025-08-31

Keywords:

Thermodynamic cycles;
Renewable energy;
Optimization algorithms;
Hydrogen production.

ABSTRACT

The global transition to sustainable energy systems presents the critical challenge of efficiently integrating renewable sources to mitigate climate change. Developing and optimizing energy conversion technologies is paramount to this effort. This research provides a comprehensive review of the latest progress in combining thermodynamic cycles with renewable energy sources, offering valuable insights into system design, performance, and optimization. To this end, we introduce thermodynamic and combined cycles, classify renewable energy inputs, and evaluate their integration, including an analysis of hydrogen production processes. A central focus is the significant impact of single- and multi-objective optimization algorithms on promoting sustainability and reducing emissions. Our analysis reveals that the Rankine cycle is the most commonly applied thermodynamic cycle (43% of cases), with solar energy being the leading renewable input (37%). Furthermore, genetic algorithms are the predominant optimization method (50% usage rate). These findings highlight current trends and suggest that future research should focus on developing novel hybrid cycles and advancing multi-objective optimization frameworks to simultaneously balance economic viability and environmental impact, paving the way for the next generation of clean energy systems.

1. Introduction

Rising global energy consumption has brought humanity face-to-face with two major crises: environmental pollution and the rapid depletion of energy resources. Problems like pollution, climate change, and the limited availability of fossil fuels stem from unsustainable development, inefficient energy use, and a growing global population. The drive for greater societal prosperity and higher per capita GDP is fueling this trend. If it continues, it could seriously harm the natural environment, forcing us to find sustainable solutions. Understanding thermodynamic cycles plays a key role in developing these solutions. These cycles form the foundation of many energy systems, such as heat engines and gas turbines, and are crucial for improving the efficiency of converting heat into mechanical energy.

While previous studies offer deep insights into their respective niches, a comprehensive and comparative analysis that bridges these interconnected topics is still lacking. Previous reviews have tended to focus on either a specific renewable input (like solar), a particular cycle

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Cite this article as:

Vafaeenezhad, M., Abedini Esfahlani, A., Rahbar, N., Rafiei, M. and Jamshidi, E., 2026. Recent Advances in Renewable Energy-Integrated Thermodynamic Cycles: A Comprehensive Review. *Journal of Heat and Mass Transfer Research*, 13(3), pp. 315-334.
https://doi.org/10.22075/JHMTR.2025.37312.1718

technology (like ORC), or a set of optimization techniques. This specialization leaves a critical gap: a holistic understanding of how different combinations of cycles, energy sources, and optimization methods perform against one another. This makes it challenging for researchers and engineers to identify the most promising system configurations for diverse applications and sustainability goals.

This review aims to fill this gap by providing a broad, multi-faceted analysis of the field. Our novel contribution lies in the synthesis and systematic comparison of three crucial pillars—thermodynamic cycles, renewable energy inputs, and optimization algorithms—within a single, unified framework. By analyzing the trends, strengths, and weaknesses across these domains, this work provides unique insights into the most prevalent and effective system integrations. We identify key performance metrics and prevailing methodologies to offer a clear roadmap for future research and development. The paper is organized as follows: Section 2 introduces thermodynamic cycles and energy sources. Section 3 details the integration of these systems and their outputs, such as hydrogen. Section 4 analyzes the application of optimization algorithms, and finally, Section 5 concludes the paper with key findings and future outlooks.

2. Thermodynamic Cycles

Thermodynamic cycles operate by converting energy from one form to another and exchanging heat between the system and its surroundings. The performance of these cycles depends on changes in the state of matter, involving processes such as expansion and compression. During these processes, heat is either transferred from a source to the matter or from the matter to the surroundings. Additionally, mechanical work is performed on the matter throughout the cycle. These cycles are governed by the laws of thermodynamics, including the principle of conservation of energy and the concept of entropy. Fig. 1 illustrates the classification of various thermodynamic cycles.

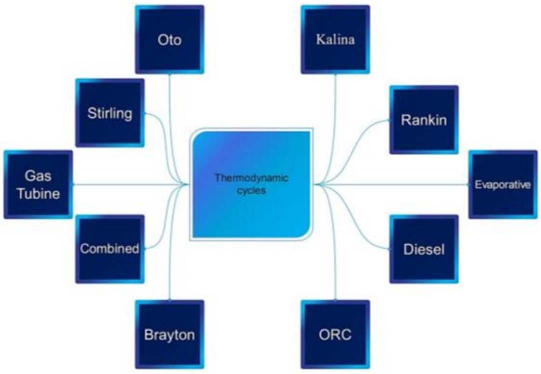

Fig. 1. Different thermodynamic cycles

2.1. Brayton Cycle

The Brayton cycle is a thermodynamic cycle consisting of four processes. Initially, in an adiabatic compression process, air or gas is compressed in a compressor, leading to an increase in both pressure and temperature without any heat transfer to the surroundings. Subsequently, the compressed gas enters a combustion chamber where fuel is added and burned at constant pressure. This reaction elevates the gas temperature without altering its pressure. In the adiabatic expansion process, the hot, high-pressure gas enters a turbine and expands. This expansion results in a decrease in both temperature and pressure, generating mechanical work that can be harnessed for useful purposes such as electricity production. Finally, in a constant-pressure heat rejection process, the gas exiting the turbine is cooled, transferring excess heat to the surroundings [1].

2.2. Rankine Cycle

The Rankine cycle is a thermodynamic cycle composed of four primary stages. Initially, in an adiabatic compression process, the working fluid, in a liquid state, is compressed in a pump, resulting in a significant increase in pressure without a notable change in temperature. Subsequently, the high-pressure fluid enters a boiler where it is heated at constant pressure until it vaporizes. This stage involves the absorption of thermal energy from a heat source. In an adiabatic expansion process, the high-pressure steam enters a turbine and expands, leading to a decrease in both pressure and temperature, thereby generating mechanical work. Finally, in a constant-pressure heat rejection process, the steam exiting the turbine enters a condenser, where it is cooled and condensed back into a liquid state, releasing excess heat to the surroundings [2].

Combined cycles are employed due to their high efficiency and optimal utilization of energy. By integrating two thermodynamic cycles, typically the Brayton and Rankine cycles, these systems offer superior performance compared to independent cycles. The following sections will examine these cycles.

2.3. Brayton-Kalina Cycle

As depicted in Fig. 2, the combined Brayton-Kalina cycle incorporates two condensation stages. In the initial stage, the turbine exhaust steam is continuously absorbed by a secondary fluid in its liquid phase. The heat absorbed by this fluid is subsequently transferred to a cooling water source in the condenser. The secondary fluid is a variable mixture of water and ammonia, formed from the turbine exhaust steam, although its exact composition is of secondary importance as the principle lies in the absorption process. In this process, a pump pressurizes the mixture of the secondary fluid and turbine exhaust steam. Consequently, minimal energy is required for the pump after liquid condensation. The condensed fluid is then heated by the turbine exhaust steam, causing the secondary fluid to revaporize and enabling the turbine to perform additional work. When the fluid is at a higher pressure relative to the turbine exhaust steam, it can be condensed by the cooling water [3].

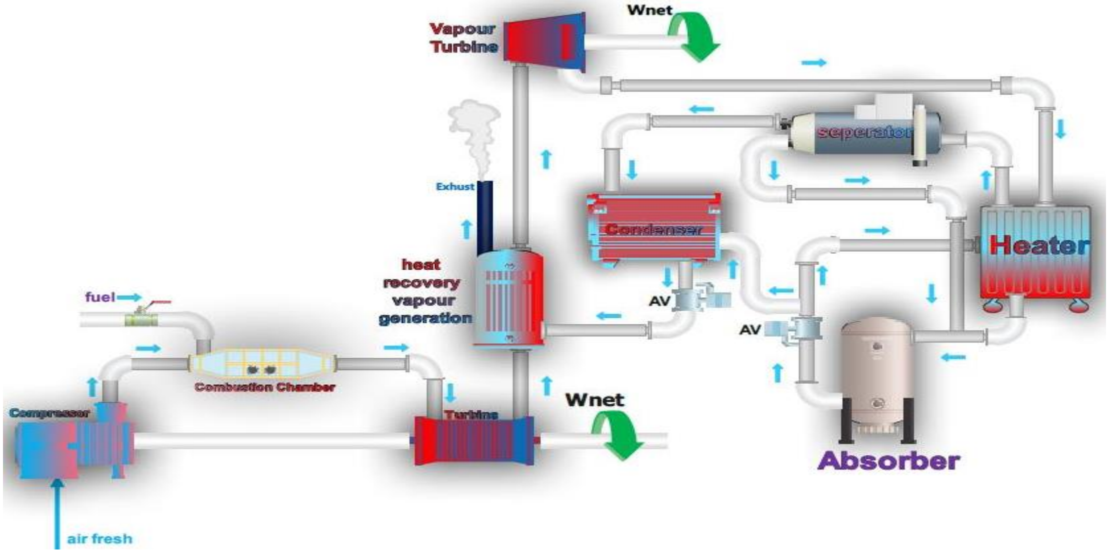

Fig. 2. Schematics of Brayton-Kalina cycle

2.4. Brayton-Brayton Cycle

As depicted in Fig. 3, the Brayton cycle can be integrated with an air-to-gas heat exchanger. In this configuration, the turbine gas exhaust is directed to the heat exchanger, where it heats the returning air for the second-cycle gas turbine. The heated air then expands through the turbine, generating additional power.

In contrast to conventional combined cycles, this design eliminates the need for bulky steam equipment such as boilers, steam turbines, condensers, and water treatment units. Recent research indicates that this system is feasible and, depending on the number of intercoolers, can enhance power output by 18 to 30% and improve efficiency by up to 10% [3].

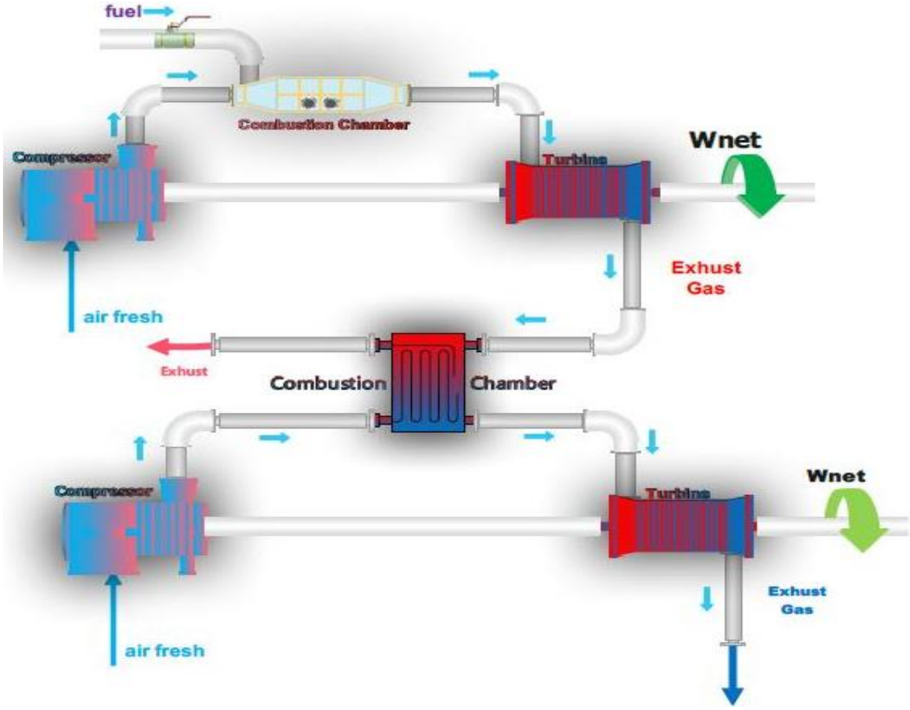

Fig. 3. Schematics of the Brayton-Brayton cycle

2.5. Brayton-Rankine Cycle

The combined Brayton-Rankine cycle is a configuration that integrates two distinct cycles to enhance overall efficiency and power output. In this system, a gas undergoes expansion in a Brayton cycle, passing through a gas turbine. Subsequently, the hot exhaust from this turbine is directed to a heat exchanger where the generated heat is utilized to produce steam in a Rankine cycle. The produced steam is then channeled into a steam turbine, where it expands, generating additional power. Compared to the standalone Brayton cycle, this combined configuration yields a higher overall system efficiency as the waste heat from the Brayton cycle is effectively recovered and utilized in the Rankine cycle.

Furthermore, this combination necessitates the incorporation of a condenser and additional cooling systems within the Rankine portion, contributing to improved efficiency and greater power generation. Fig. 4 presents a schematic of this combined cycle [3].

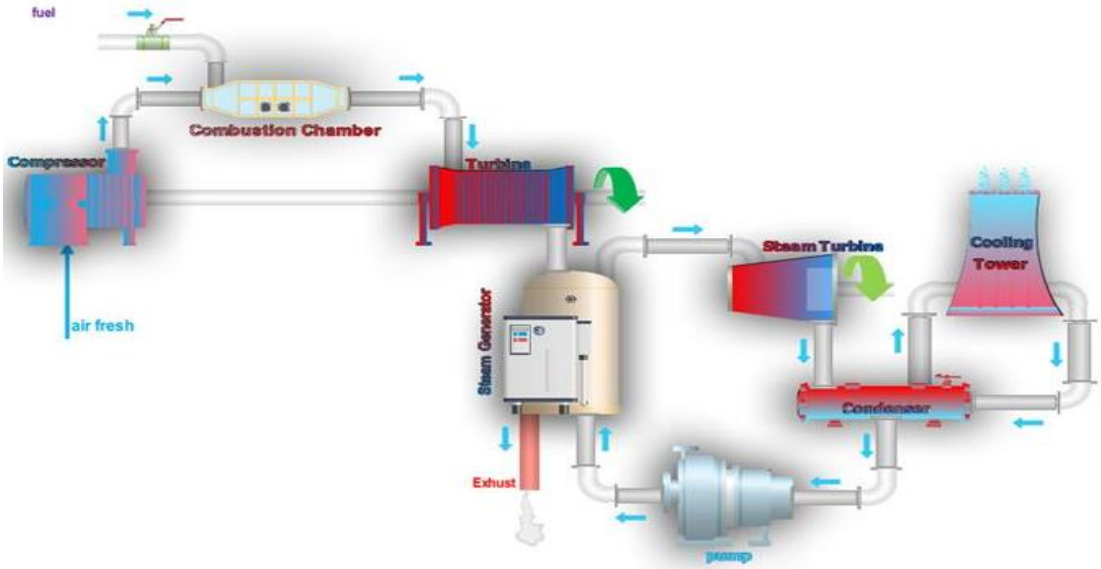

Fig. 4. Schematics of Brayton-Rankine cycle

3. Energy Sources

Energy sources serve as primary inputs in thermodynamic cycles to generate energy forms such as electricity, heat, or motion. These sources can be broadly categorized into renewable and non-renewable sources. Each category possesses distinct advantages and disadvantages, and the choice depends on factors such as availability, cost, environmental impact, and energy demands. Fig. 5 provides a comprehensive schematic representation of this classification [4]. The following sections examine renewable energy sources in detail.

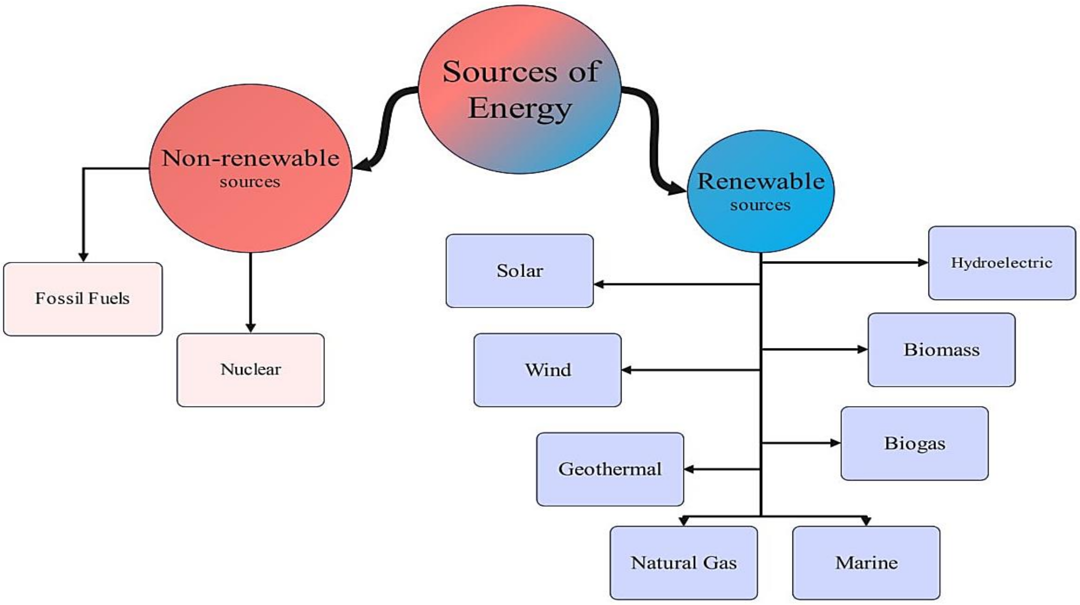

Fig. 5. Classification of energy sources

3.1. Solar Energy

A primary application of solar energy is the generation of electrical power, achievable through both direct and indirect methods. Direct conversion involves the use of photovoltaic cells that directly transform solar energy into electricity. These systems operate without the need for thermodynamic cycles or working fluids but often incur higher production costs. In contrast, indirect conversion involves an initial transformation of solar energy into thermal energy, followed by its conversion into electricity via a thermodynamic cycle. This process is commonly employed in solar thermal power plants. Unlike photovoltaic systems, these methods require a working fluid to transfer the absorbed heat and its subsequent conversion into electrical power.

Heat transfer can occur via two primary mechanisms: In the first method, the working fluid directly absorbs solar energy and transfers this heat to a turbine, which, upon rotation, generates electricity. In the second method, an intermediate fluid, known as a heat transfer fluid, absorbs solar energy and subsequently transfers this energy to the working fluid of the cycle in a heat exchanger. In this scenario, the intermediate fluid solely serves as a heat transfer medium, while the primary working fluid is responsible for generating electrical power. The utilization of an intermediate fluid enhances process control and system efficiency, as fluids with superior thermal properties can be employed to absorb and transfer solar heat [5].

Fig. 6 illustrates the various methods of power generation in solar thermal power plants [6].

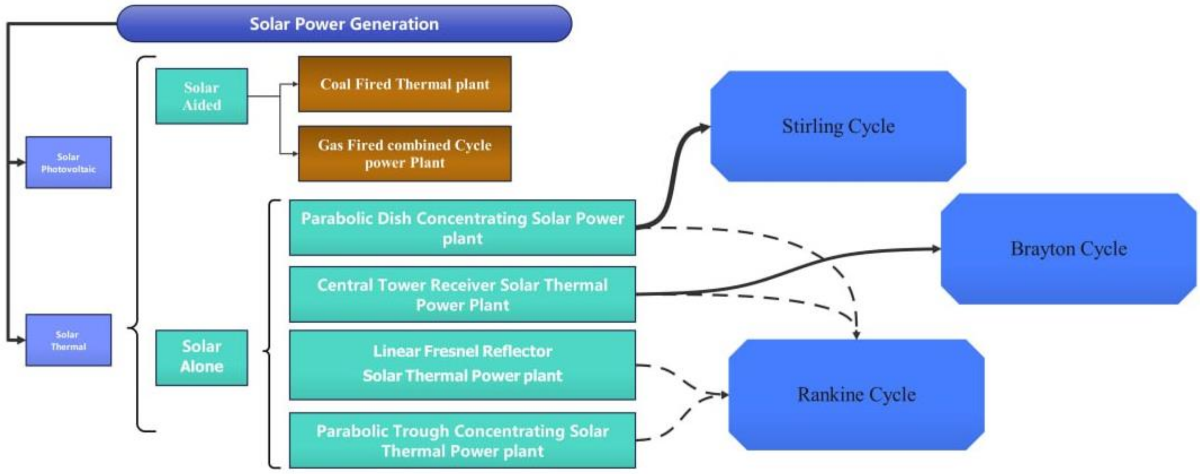

Fig. 6. Different power generation methods in solar systems

3.2. Biomass Energy

Biomass refers to biological matter synthesized through the process of photosynthesis, involving the conversion of water, carbon dioxide, and solar energy into organic compounds. This category encompasses all organic substances found in nature, both living and recently deceased organisms. In contrast to non-renewable energy sources, which are formed through prolonged geological processes involving chemical transformations of organic matter under specific conditions of pressure and temperature, biomass is continuously replenished, thereby qualifying as a renewable energy source. The composition of biomass is diverse, encompassing animals, plants, their associated waste and residues, and organic waste materials. While fossil fuels originated from biomass in the distant past, the carbon within these fuels is effectively removed from the Earth's biological carbon cycle. The combustion of fossil fuels consequently disrupts the atmospheric carbon dioxide equilibrium, preventing them from being classified as biomass [7].

3.3. Ocean Wave Energy

Ocean wave energy, produced by the interaction of wind with the sea surface, represents a substantial component of marine energy resources. Together with tidal energy, it forms a significant portion of renewable energy sources. It is estimated that the global distribution of wave power is around 2500 gigawatts, a figure comparable to that of tidal energy. The irregular, oscillatory nature and low-frequency characteristics of wave energy necessitate conversion to a frequency of 60 hertz before integrating into the electrical grid [8].

3.4. Geothermal Energy

Geothermal energy is a renewable and clean energy source that harnesses the heat from the Earth's interior for electricity generation and heating. Studies indicate that the temperature of rocks increases steadily with depth. On average, at depths of 80 to 100 kilometers below the Earth's surface, rock temperatures can reach 650 to 1200 degrees Celsius. The primary source of this heat is the decay of radioactive materials within the Earth's core. This energy is transferred to the Earth's surface through various mechanisms, including volcanic eruptions, geothermal hot springs, and conductive heat transfer in the deeper layers of the Earth [9].

The integration of thermodynamic cycles with renewable energy sources offers a versatile approach to producing a range of valuable products, including electricity, freshwater, hydrogen, and other energy carriers. Among these products, hydrogen stands out as a promising energy carrier with the potential to meet the increasing demand in various industrial processes such as methanol synthesis, power generation, ammonia production, aniline production, petroleum refining, fuel cell applications, transportation, and power plants.

4. Hydrogen

Hydrogen can be produced from a variety of feedstocks, including fossil and renewable sources. Diverse technologies such as chemical, biological, electrolytic, photolytic, and thermochemical processes can be employed for hydrogen production. Processes utilizing renewable resources for hydrogen production can be categorized based on the use of water and biomass. Fig. 7 illustrates the classification of hydrogen production processes using renewable resources [10].

5. Overall Paper Review

A thorough review of the literature on hydrogen production reveals that the study conducted by Azizimehr et al. [11] provided a comprehensive overview of the field and introduced a novel parameter to aid in the selection of the most suitable production method. Their methodology serves as a foundation for our study, which aims to identify the optimal thermodynamic cycle and input energy source to maximize the performance and efficiency of hydrogen production systems. Studies have shown that the Rankine cycle exhibits greater compatibility for integration with other thermodynamic cycles. Yan Kao et al. [12] conducted a study on the optimization of a two-stage organic Rankine cycle system coupled with geothermal energy and a proton exchange membrane electrolyzer using a genetic algorithm. Results indicated improvements of 2-3% in energy efficiency, 35-41% in hydrogen production, and a 9.5-12% reduction in the cost of hydrogen exergy. R123 was found to be the most suitable working fluid. However, the study did not explore the system's performance under varying geothermal source conditions or alternative electrolyzer configurations, leaving opportunities for further investigation into the scalability and robustness of the proposed system. Anastasovski et al. [13] investigated an organic Rankine cycle integrated with biomass, employing a genetic algorithm and a water-air mixture. Their findings demonstrated the suitability of organic Rankine cycle units for converting low-temperature heat into electricity. However, the study primarily focused on system optimization using a single working medium and did not evaluate the impact of alternative working fluid mixtures or variations in biomass feedstock properties, leaving room for further exploration of these aspects. Mohammadi Doust et al. [14] studied thermodynamic cycles integrated with biomass, using an air-water mixture and optimizing the system using artificial neural networks (ANN). With wheat straw as the biomass, increasing temperature led to higher production of hydrogen, methane, and carbon monoxide, while methane production decreased. Additionally, the water flow rate significantly influenced hydrogen production. However, the study did not address the impact of alternative biomass feedstocks or the scalability of the system under varying operational conditions. Furthermore, the robustness of the ANN optimization in the presence of real-world uncertainties, such as feedstock variability or operational disruptions, was not explored, presenting opportunities for further research.

Asareh et al. [15] conducted a comprehensive study on an organic Rankine cycle (ORC) solar power system, employing R134a and R123 as working fluids and utilizing the teaching-learning-based optimization (TLBO) algorithm for optimization. Through multi-objective optimization using TLBO for R123, significant enhancements were achieved, including a 27.85% increase in thermal efficiency, a 27.66% increase in exergy efficiency, and a 9.90% reduction in cost. However, the study did not explore the system's performance with other emerging low-GWP working fluids, which could provide more environmentally sustainable alternatives. Additionally, the long-term operational stability and the feasibility of integrating the system into larger hybrid energy networks remain unaddressed, indicating potential directions for further investigation. Meltemes et al. [16] carried out a similar investigation on an ORC solar power system using R123 but employed the particle swarm optimization (PSO) algorithm. Multi-objective optimization using PSO for R123 resulted in comparable improvements, with a 27.65%

increase in thermal efficiency, a 27.46% increase in exergy efficiency, and an 11.98% reduction in system cost. However, the study did not evaluate the comparative performance of PSO and other optimization algorithms under varying operational scenarios, leaving the broader applicability of PSO unaddressed. Furthermore, the environmental impact and potential lifecycle benefits of the system with R123 were not analyzed, highlighting opportunities for future research on eco-friendly working fluids and optimization strategies. Meltemes et al. [17] explored the integration of solar and geothermal energy, utilizing PSO for optimization and an air-water mixture as the working fluid. A solar combined cooling, heating, and power (CCHP) system coupled with a PEM electrolyzer and fuel cell was simulated and optimized to meet hydrogen demand. The results indicated notable improvements in energy efficiency (22.32%) and exergy efficiency (8.61%) in the first scenario, while the second scenario demonstrated a 6.65% reduction in total system cost. Table 1 provides a summary of recent research studies in this field.

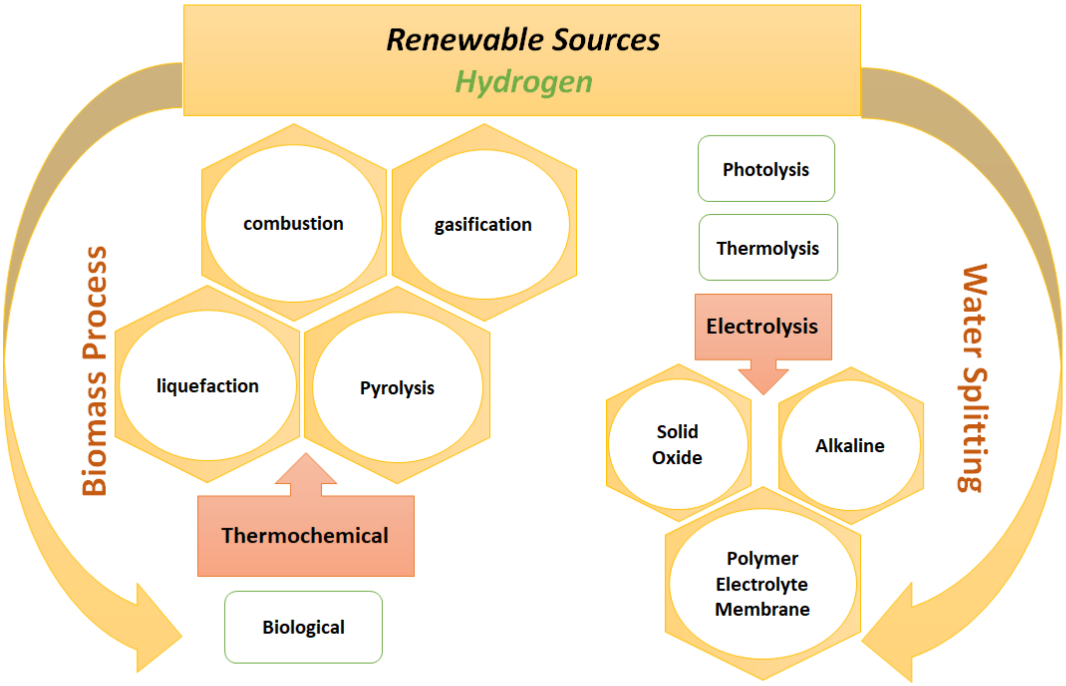

Fig. 7. Classification for hydrogen production processes using renewable resources

Table 1. A comprehensive review of recent literature regarding the combination of different thermodynamic cycles using novel technologies

Ref.	Cycle(s)	Input energy	Algorithm(s)	Working Fluid(s)	Novel technology	Output	Result(s)
[18]	Brayton Rankine	Hybrid solar biomass	Genetic	Air Helium Water	Integration of PEM electrolyzer & electricity from PVT panels	Hydrogen production	↓ CO_2 & biomass consumption; ↑ power generation capacity
[19]	Organic Rankine	geothermal	Particle swarm optimization	Pentane/Butene, Pentane/Butane, Pentane. R245fa	integration of ORC & zeotropic mixtures presents	Power & hydrogen production	Pentane /Butene combination→ max energetic & exergy efficiency; ↑ generator pinch point temp →↓ ORC power generation
[20]	Organic Rankine	geothermal	genetic	R114	Integration of a thermoelectric generator unit & PEM	Power & hydrogen production	↑degree of superheat at the turbine inlet → ↑hydrogen production rate

Ref.	Cycle(s)	Input energy	Algorithm(s)	Working Fluid(s)	Novel technology	Output	Result(s)
[21]	Organic Rankine	Biomass Solar energy	-	Air Water	Integration of solar heliostat, four-step Cu-Cl cycle & absorption cooling system design with cost analysis using Aspen plus V9 & Aspen plus Economic Analyzer V9	Power & hydrogen production	Energy COP of absorption cooling system: 0.51; energetic COP: 0.3; hydrogen production: 59.45 moles electric power: 8.3 MW
[22]	Organic Rankine	Biomass Solar energy	-	Air Water	solid oxide fuel cell-based multi-generation system	Electrical power, cooling, freshwater & hydrogen	energy & exergy efficiencies: 77.58% & 47.14%; ↑fuel utilization factor→↓voltage of each SOFC cell
[23]	Orc /storage tank	Solar energy	-	H_2O $2LiF/BeF_2$	Simultaneous use of linear Fresnel collector & solid oxide electrolyzer cell with thermochemical storage tanks to produce hydrogen	Hydrogen production	hydrogen production: 50.4 kg/hour; thermal energy storage period ↑ to one year→ energy & exergy efficiencies reach to 20.17% & 13.73%, respectively
[24]	Rankine cycle	Biomass Solar energy	-	Air Water	Integrated hybrid biomass-solar system: GT, Rankine cycle, PVT & PEM units	Hydrogen production	↑ number (area) of solar PVTs →↑output power & ↓ CO_2 emissions
[25]	Rankine cycle	Solar energy	-	Amonnia Water	Rankine cycle coupled + concentrated photovoltaic thermal system→hydrogen production by PEM electrolyzer plant	Hydrogen production	CPV/T system → ↑energy/exergy efficiencies & hydrogen production at different rates for all parameter values
[26]	Rankine cycle	Biomass	-	Air Water	Integrated MCFC; Stirling engine; ORC cogeneration system	Cogeneration (Combined heat and power)	Exergy efficiency: 50.18%; CO_2 emission: 0.289 t/MWh; highest exergy destruction: gasifier & fuel cell

Ref.	Cycle(s)	Input energy	Algorithm(s)	Working Fluid(s)	Novel technology	Output	Result(s)
[27]	Brayton Rankine cycle	Biomass	-	Air Water	Membrane distillation for freshwater production; hydrogen compression unit with 2 compressors for storage	Hydrogen production; electricity; heating & clean water	Energy & exergy efficiencies: 52.84% & 46.59%, respectively; total hydrogen generation rate: 0.074 kg/s
[28]	Brayton Rankine Kalina cycle,	Biomass Solar energy	-	Carbon Nitrogen	Combined power plant used a dish collector & a biomass gasifier is designed to produce liquefied hydrogen	Power; liquid hydrogen, heating-cooling; hot water	The total electricity, cooling, heating, hydrogen & hot water are obtained as nearly 3.9 MW, 6584 kW, 4206 kW, and 0.087 kg/s
[29]	Organic Rankine cycle	-	-	Seawater	Integration of LNG & TGs for hydrogen production	Hydrogen production	By increasing values, ↓thermal efficiency & so ↓ hydrogen production
[30]	co-fired cycle	Biomass Solar energy	-	Hot water Oxygen/ water	Cycle processes: gas turbine with natural gas & hydrogen injection into the combustion chamber; steam turbine cycle; biomass gasification plant; PVT; hydrogen production with PEM	Hydrogen; Electricity; heating production	The main advantages of hydrogen injection → ↓ exergy destruction by 0.24% , exergy destruction cost rates by 3.36% & ↓ CO_2 discharge rate by 2%.respectively
[31]	Organic Rankine cycle	Biomass	-	Air Water	Biomass gasification power plant integrating SOFC module externally fired gas turbine & ORC	Hydrogen; electricity production	System yields: highest efficiency 49.47%; lowest cost of electricity of 0.086 $/kWh; Max CO_2 emission reduced up to 3564 t/year
[32]	Post-fired combined cycle	Biomass Solar energy	-	Air Water	Photovoltaic combined cycle with biomass post-firing & hydrogen production	Hydrogen; electricity production	↓CO_2 discharge rate, exergy destruction rate in the combustion chamber, system

Ref.	Cycle(s)	Input energy	Algorithm(s)	Working Fluid(s)	Novel technology	Output	Result(s)
							product cost & energy efficiency; ↑PV thermal system area → ↓energy & exergy efficiencies
[33]	double-stage Rankine cycle,	Biomass	-	Air Water	Entrained flow gasifier; CAS unit; double-stage Rankine cycle; WGSR; combined gas–steam power cycle & PEM electrolyzer	Hydrogen; Electricity; heating production	Electrical power output: 1.4 MW; energy efficiency: 53.7%; exergy efficiency: 45.5%
[34]	-	Flare gas recovery	-	Air Water	Four power generation scenarios: Gas Turbine Cycle, Combined Gas Turbine Cycle, Reciprocating Internal Combustion Engine Cycle & SOFC/Gas Turbine Cycle	Electricity production	RICE & SOFC/GT cycles have the best & worst economic performance; flow rate & gas composition could be determinative factors in the economic profitability of the scenarios; RICE showed the best performance in evaluated scenarios of atmospheric pollutant emissions
[35]	Steam Rankine Cycle	flare gas	-	Air Water	The oil extrusion process uses Basic mathematics to estimate the potential energy of flare gas	Carbon footprint of crude oil production; electricity production	This solution saved about 50 million tons of carbon dioxide annually as per today's production rates.
[36]	-	-	-	Air Water	VSA/PSA process used for CO_2 capture & H_2 production from SMR gas mixture	Ultra-pure hydrogen & high-purity CO_2 production	The first stage process could produce 95.31% CO_2 with a recovery of 90.93% & the second stage could produce 99.9952% H_2 with an overall recovery of 71.16%.

Ref.	**Cycle(s)**	**Input energy**	**Algorithm(s)**	**Working Fluid(s)**	**Novel technology**	**Output**	**Result(s)**
[37]	Organic Rankine cycle	Biomass Solar energy	-	R125 R218 R143a etc.	Comparison of four CO_2 cycle configurations & four ORC layouts using a working fluid from 47 candidates	Electricity production	↑ Cycle maximum pressure & temperature is profitable at all times while the cycle
[38]	-	flare gas	-	Air Water	Investigation of hydrogen & CO_2 recovery in a methanol plant; Proposing a three-step membrane-based separation process. Developing a mathematical model for the process	Hydrogen, methanol production	↑ Methanol production →↓CO_2 emissions; the strategy eliminates 2500 kmol/day CO_2 from flare gas & recovers 4050 kmol/day CO_2 via CO conversion, contributing to further reduction.
[39]	KC Brayton	Renewable energy	-	Water	PEM	H_2	↑ Exergy efficiency by 9.76 % & ↓ total product unit cost by 6.63 % $
[40]	Brayton	Air	GA	Dry air	ETM-OA	-	↑ two typical flight conditions 34.1 % & 48.4% ; ↓entropy generation by 30.2 % & 51.1 %
[41]	ORC	GAS	-	FLUE GAS	SCFG	Sinter waste heat recovery	Showing remarkable energy-saving effect 64.86 %
[42]	ORC	Solar	MOPSO SPEA-II NSGA-II	Water	PEM	H_2	Two optimization algorithms: exergy efficiency 2.11 % & 21.14 $/h cost rate
[43]	ORC Brayton	Carnot battery	GA	Water	-	Electrical energy	↓ Grid electricity, operating costs & CO_2 emissions by 16.5%, 29% & 44% respectively
[44]	ORC KC	Fuel cell	GA ANN	-	PEM MED	Electrical energy	Product unit cost & environmental impact: 65.78%, 86.28% & 4.33% $/h

Ref.	Cycle(s)	Input energy	Algorithm(s)	Working Fluid(s)	Novel technology	Output	Result(s)
[45]	ORC	Hybrid renewable energy	-	Wind	PEME HRES	Electrical energy	Hybrid plant: exergy efficiency 47.35 % ; environmental damage index 0.0104
[46]	Claude ORC	fossil fuel	ANN	water	HDH PEM	H_2	Optimum state: 0.840 exergy environmental index; 0.869 exergy stability factor
[47]	Brayton ORC	nuclear power	-	He-gas	HTR-PM	Electrical energy	Output power ↑ from 1424.9 to 1443.8 MW; ↑ isentropic efficiency of gas turbine to 90–94 %
[48]	KC ORC	Renewable energy	GA	CO_2	PEM	electrical energy	Optimized exergy of LTGMES : 64.54 % & 40.96 % energy & exergy efficiency
[49]	Rankin - ORC	Electrical power	-	CO_2	PEM	Methanol – Methane	Electricity, methanol 36.8%, 92.8$/MWh & methane 37.6%, 79.4 $/MWh
[50]	VCC	Fossil Fuels	Genetic	Air - R-134a	-	CO_2 - minimization weight	↑ Small-scale radial compressors 85%
[51]	GTC	Solar	-	Water	PEM	H_2	↑ Fuel & environmental cost 54.76%
[52]	-	Fossil Fuels	Genetic - NSGA-II	Air helium	PEM	Electrical energy	Cost and heat ↓ 34.6%, ↓ 597 ∘ C
[53]	Brayton	Solar	Genetic	Water	PEME	-	↑ Energy 22.05 %; ↑ exergy 15.93 %
[54]	LCC	Solar	-	Water	-	Air desiccant – CO_2	↓ Operation Cost 58.4%
[55]	ORC	Solar	Genetic	Water	PEM	cooling load	↑ Exergy performance 10.3% ; ↓ total annual Cost 21.6%
[56]	Brayton	Fossil Fuels	SGA-II	Water	-	Thermal energy	↑ Efficiency 0.94
[57]	Brayton	Fossil Fuels	NSGA-II	Air	-	cooling load	↑ Exergy efficiency

Ref.	**Cycle(s)**	**Input energy**	**Algorithm(s)**	**Working Fluid(s)**	**Novel technology**	**Output**	**Result(s)**
[58]	ORC	solar	Genetic	Water	TOPSIS	Electrical energy	↑ power output 19.1% for every 5 °C
[59]	lifecycle	Renewable sources	Genetic	DowthermTM A	hybrid energy	H_2	Cost of energy for standalone: $0.22 per kWh
[60]	ORC	Solar	Genetic	Water	Dry cooling	Cooler	Output power 7994.541 kW ; thermal efficiency 53.365 %
[61]	Rankine	Renewable energy	MOPS	Water	Traditional cooling	Electrical energy - Cooler	Exergy efficiency 51.28 USD/(kWh)
[62]	Brayton	Ideal gas	-	air	PDs in flow	Power & efficiency optimizations for an open	Optimal values: PD 0.32 & PR 14.0; ↓ to double max dimensionless PP of 1.75
[63]	Rankine	Steam-water	NSGA-II	-	Recovers wasted heat, generates mechanical power	Maximizing the net power	Power of the SFT-ORC system after single-Objective optimization ↑ by up to 7.9% compared SFD-ORC system
[64]	Rankine	Fue gas	-	R236ea -R245fa	double carbon	Recover waste heat, generate mechanical power	-
[65]	Brayton	Nuclear power	-	Helium	Cooled reactors & nuclear energy	Carbon-free electricity generation	Combined cycle: ↑12.4% efficiency & ↓9.7% LCOE vs. GT-MHR power plant
[66]	Brayton	Nuclear power	-	CO_2	Optimization of a novel CO_2	Leading to better overall output from an integrated single	Demonstrates a ↑12.56% exergy efficiency while ↓the total product unit cost by 6.32% compared to stand-alone
[67]	Kalina	Fossil fuel	-	Toluene - R143a - R1233zd	CCP system,in a KC & double-effect absorption chiller driven by exhaust gas of an ICE	Optimize net power output & condenser pinch point locations	First enhanced Kalina cycle: energy & exergy efficiencies ↑32% & ↑63.2 % respectively

Ref.	Cycle(s)	Input energy	Algorithm(s)	Working Fluid(s)	Novel technology	Output	Result(s)
[68]	Recompression Partial cooling	CO_2	-	CO_2	Optimization of a novel cryogenic CO_2 capture process	In a partial cooling cycle, min pressure has the most significant impact on thermal efficiency	2% variation in effectiveness recuperator → ↑3% change in cycle
[69]	Combined	Oil - gas	-	Seawater - Na	More compact & lightweight OTSG with smaller bend diameter than current design	Combined heat & power production in a FPSO system	Installation of bottoming cycles → ↓ 25% CO_2 emission per retrofitted platform
[70]	Brayton	Solar	Pso	air	Crimped-spiral rib inside a triple-tube heat exchanger with a nanofluid	Reheating ↑ turbine work output by ↑ average specific volume & cycle efficiency	Network output with dual recuperative system ↑33.5% vs. single recuperator for same flow rate
[71]	ORC	Solar - geothermal	-	R113 -R123	Solar-driven direct contact membrane-based water desalination system	Clean water & electricity production	Power production ↑19% & coal consumption ↓ by up to 0.3 million tons annually

6. Statistical Analysis Results

The results suggest a significant preference for the Rankine cycle, likely due to its high efficiency and well-established integration with renewable energy systems such as solar thermal and geothermal sources. The findings indicate that the Rankine cycle is the most frequently employed thermodynamic cycle in recent studies, with a utilization rate of 43%, followed by the Brayton cycle at 32%. The Brayton cycle, accounting for 32% of the studies, demonstrates its growing popularity, particularly in applications involving high-temperature renewable sources, such as concentrated solar power and biomass gasification systems. Further statistical insights reveal that the remaining 25% of thermodynamic cycle usage is distributed among other cycles, including Kalina, Organic Rankine, and Stirling cycles, which are utilized in more niche or specialized applications.

Additionally, Fig. 8 illustrates the visual disparity, emphasizing the dominance of the Rankine and Brayton cycles.

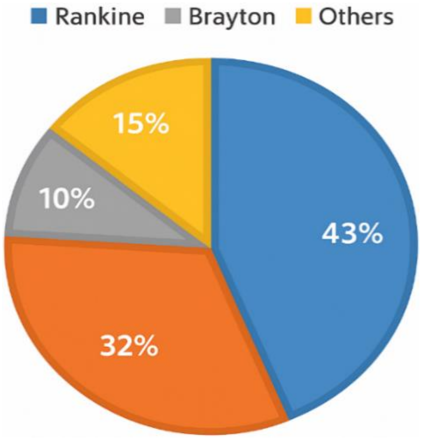

Fig. 8. Prevalence of thermodynamic cycles in recent research

The Rankine cycle's dominance in recent research is further emphasized by its strong integration with renewable energy sources.

Solar power, representing 37% of the studies involving the Rankine cycle, underscores its versatility and efficiency in harnessing abundant and sustainable energy.

This prevalence can be attributed to advancements in solar thermal technologies and their compatibility with the Rankine cycle's heat-to-power conversion process. Biomass, accounting for 20% of the studies, highlights its significance as a reliable and renewable input energy source, particularly in regions with abundant agricultural or forestry residues. A comparative analysis of the Rankine cycle's input energy sources reveals a notable disparity in preferences. Solar power's 37% share is nearly double that of biomass, showcasing its leading role in renewable energy integration. Other sources, including geothermal energy and waste heat recovery, collectively make up the remaining 43%, reflecting their more specialized applications. Fig. 9 further illustrates this distribution, visually emphasizing solar power's dominance and the emerging role of biomass as a complementary renewable input. This pattern underscores the importance of tailoring thermodynamic cycles to region-specific energy potentials and technological advancements.

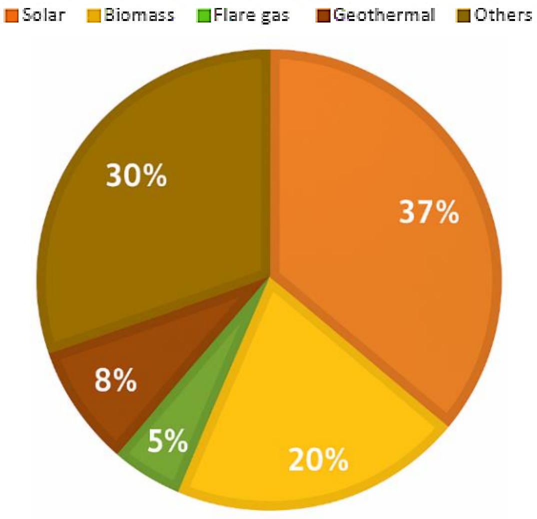

Fig. 9. Prevalence of renewable energy sources integrated with thermodynamic cycles in recent research

The 50% utilization rate of the genetic algorithm highlights its importance as a robust and versatile tool for thermodynamic cycle optimization. Its widespread adoption is likely due to its ability to efficiently navigate complex, non-linear optimization problems that involve multiple objectives, such as minimizing exergy destruction while reducing costs. This adaptability makes it particularly well-suited for balancing the competing demands of performance and economics in exergoeconomic optimization. Table 2 highlights the distribution of other optimization techniques, such as particle swarm optimization (PSO) and simulated annealing (SA), which collectively account for the remaining 50%. A closer look reveals that PSO is the second most frequently used method, with a 25% share, while SA and other techniques, such as ant colony optimization and gradient-based methods, occupy smaller portions of the distribution. Additionally, the dominance of the genetic algorithm can be attributed to its flexibility in handling constraints and multi-objective functions, which are often encountered in thermodynamic cycle optimization. Fig. 10 could further support these findings by providing a visual representation of the comparative popularity of optimization techniques. This emphasis on genetic algorithms highlights the ongoing trend towards computationally intensive, yet highly effective, optimization methods in thermodynamic and exergoeconomic analyses.

Table 2. The distribution of different optimization algorithms used in thermodynamic cycle optimization

Algorithm(s)	Percentage
Genetic	50%
NSGA-II	7%
PSO	16.5%
TLBO	10%
Others	16.5%

The air-water mixture, representing 40% of the studies, is the most common working fluid, demonstrating its versatility and effectiveness across various thermodynamic cycle applications. This dominance can be attributed to its favorable thermophysical properties, such as a high specific heat capacity and ease of phase change, which contribute to efficient heat transfer and energy conversion. Its compatibility with both low-temperature and high-temperature cycles further solidifies its widespread adoption. Comparatively, other working fluids, including organic refrigerants, supercritical CO_2, and ammonia, share the remaining 60% of the studies. Organic refrigerants account for 25%, likely due to their suitability in organic Rankine cycles (ORCs) for low-grade heat recovery applications. Supercritical CO_2, with a 20% share, highlights its growing prominence in high-efficiency, compact systems, while ammonia and other fluids collectively make up 15%, reflecting their niche applications in absorption and other specialized cycles.

Fig. 10 visually reinforces these findings, emphasizing the dominance of air-water mixtures while showcasing the diverse range of alternative fluids employed in specific contexts. These patterns suggest that while the air-water mixture remains a standard choice, innovations in working fluids are driving new opportunities in niche thermodynamic applications.

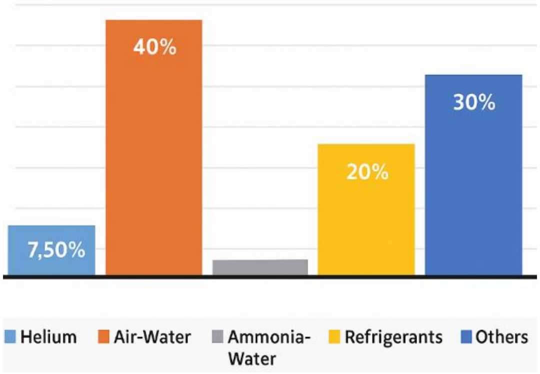

Fig. 10. Prevalence of different working fluids used in thermodynamic cycles in recent research

7. Conclusions

This comprehensive review on the integration of thermodynamic cycles with renewable energy sources and optimization techniques has yielded several key findings that highlight the current state and future direction of the field. The main conclusions are summarized as follows:

- The Rankine cycle is the most widely adopted thermodynamic cycle, featured in 43% of the reviewed studies. It is most frequently paired with solar energy, which stands out as the leading renewable input source, also accounting for 37% of the analyzed systems. This combination represents the dominant configuration in current research.
- The application of optimization algorithms is a critical trend for enhancing system performance. Among the various techniques, the genetic algorithm (GA) is the most prevalent method, employed in 50% of the systems studied, underscoring its robustness for solving complex, non-linear problems in thermodynamics.
- The systematic use of optimization techniques, particularly heuristic algorithms like GA, has a proven and significant impact. As demonstrated in the literature, these methods can lead to substantial improvements in system efficiency and cost-effectiveness, with reported gains of over 15% in exergy efficiency and 25% in cost reduction for optimized solar Rankine cycles.
- Beyond electricity generation, a key application for these integrated systems is the production of green hydrogen. Renewable-powered thermodynamic cycles are increasingly being investigated as a viable pathway to produce clean fuel, aligning with global decarbonization goals.

8. Future Research Directions

Based on the comprehensive analysis conducted in this review, several key gaps and promising opportunities for future research have been identified to guide the advancement of integrated renewable energy systems. Our review revealed a strong concentration of research on solar-powered Rankine cycles; thus, a critical future direction is the development of hybrid renewable energy systems that combine solar with more stable sources like geothermal, biomass, or thermal storage, as well as exploring underutilized sources like wave and tidal energy. Furthermore, while Genetic Algorithms are prevalent, the next generation of research must evolve towards more holistic multi-objective optimization frameworks that incorporate metrics beyond simple efficiency and cost, such as Life Cycle Assessment (LCA) data, circular economy principles, and social impact factors. To address the operational challenges posed by fluctuating environmental conditions, future work should also move beyond static optimization to focus on dynamic control and real-time optimization through the integration of Digital Twin technology, which allows for continuous adjustment and predictive maintenance. Finally, a pivotal area for future research is to look beyond standalone units towards system-level integration and sector coupling, focusing on how these cycles can be integrated with industrial processes, district heating networks, and transportation infrastructure to maximize resource utilization and contribute to the decarbonization of multiple economic sectors.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Authors Contribution Statement

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Nader Rahbar: Review & Editing.

Mehdi Rafiei: Review & Editing.

Ehsan Jamshidi: Review & Editing.

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