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Advances in Waste Heat Recovery Technologies for SOFC/GT Hybrid Systems

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Abstract: Solid oxide fuel cell/gas turbine (SOFC/GT) hybrid systems have been recognized as a promising solution in the pursuit of high-efficiency and low-emission power generation, offering electrical efficiencies exceeding 60% and notable fuel flexibility. However, the substantial amount of high-temperature exhaust gas (typically in the range of 700–800 K) released during operation has presented ongoing challenges in effective thermal energy recovery, thereby constraining further improvements in overall system efficiency. In recent years, various waste heat recovery technologies have been explored for their applicability to SOFC/GT systems. Among the most studied are the supercritical carbon dioxide (SCO_2) cycle, the transcritical carbon dioxide cycle (TRCC), the organic Rankine cycle (ORC), the Kalina cycle (KC), and the steam cycle (ST). In this review, the thermodynamic principles, performance metrics, and thermal integration compatibility associated with each technology were critically examined. In addition, a novel waste heat recovery configuration optimized for SOFC-GT hybrid systems was proposed and discussed. This approach was conceptually validated to enhance total system efficiency and to facilitate the development of advanced combined heat and power (CHP) systems. The results contribute to the broader efforts in clean energy system design and offer technical insights into the next generation of high-performance, low-emission power technologies.

Keywords: SOFC/GT; Waste heat recovery; CHP; Energy efficiency; Low-carbon systems

1 Introduction

The global energy transition and carbon neutrality goals have led to a focus on reducing dependence on fossil fuels and lowering carbon emissions, which have become the core issues for energy technology innovation. The significant carbon footprint and low efficiency of conventional energy systems must be addressed with utmost urgency, and fuel cell technology exhibits considerable potential as a pivotal means of clean energy conversion. In comparison to alternative fuel cell technologies, solid oxide fuel cells (SOFCs) utilize a solid ceramic electrolyte that facilitates the conduction of oxygen ions. The operating temperature of SOFCs, ranging from 800 to 1000℃, enables high-temperature reactions and the generation of high-quality waste heat. SOFCs have efficiencies exceeding 60%, exhibiting extremely fast reaction kinetics and internal reforming, which are critical technologies for achieving high-efficiency and low-carbon energy systems [1, 2]. The ability to utilize a diverse range of fuels, including hydrogen, carbon monoxide, methane, methanol, ethanol, and complex fuels with higher carbon content, endows SOFCs with a distinct advantage over proton exchange membrane fuel cells (PEMFCs) in terms of fuel flexibility. SOFCs' enhanced operational temperature and their capacity to generate high-quality waste heat have been identified as key advantages compared to PEMFCs [3].

However, the high exhaust temperature of the SOFC when operating in isolation and direct venting results in the dissipation of energy, which can be further utilized in the hybrid cycle to enhance the performance of the overall system [4]. Integration of a gas turbine (GT) in the form of an SOFC/GT hybrid system has been demonstrated to yield an SOFC/GT capable of operating with high electrical energy efficiency exceeding 60% with near-zero NOx pollution [5]. This configuration has been validated through theoretical and demonstration-based studies [6]. Effatpanah et al. [7] proposed a new zero-carbon CHP energy system based on pressurized SOFC/GT and carbon capture and sequestration processes, resulting in energy and exergy efficiencies of 58.09% and 38.58%, respectively. Furthermore, Caliandro et al. [8] investigated dry biomass gasification integrated with SOFC/GT systems for small and medium applications (100 kW and 8 MW dry biomass input). Their analysis indicated that such power plants possess considerable potential in terms of economic and thermodynamic feasibility. Their calculations indicated that the wood biomass power conversion efficiency (cogeneration efficiency) of this system would exceed 70%. However, Kumar and Singh [9] identified inefficiencies in a combined configuration involving SOFCs with an intercooled-reheated GT cycle, Vapor Absorption Refrigeration System (VARS), and ORC to generate electricity and cooling. This investigation employed a second-law-based approach to analyze the system's performance. In contrast, Vojdani et al. [10] presented a novel integrated energy system comprising a multi-effect desalination (MED) unit with SOFC/GT for power generation and freshwater production. This proposed integrated system enhances system power generation, exergy discharge efficiency, and normalized emissions by 6.5%, 8.42%, and 5.8%, respectively, in comparison to the standalone SOFC/GT integrated system.

The synergistic effect of SOFCs with other power units has been shown to significantly improve energy conversion efficiency. Yadav et al. [3] proposed that SOFC-GT configurations can improve the overall system efficiency by 36.8% compared to conventional stand-alone SOFC systems. The combined efficiency of the SOFC, ORC, and GT system is approximately 34% higher than the basic GT cycle and 6% higher than the SOFC-GT hybrid subsystem. Waste heat cycles, such as ORC, KC, steam turbine, and TRCC, have been shown to enhance the efficiency of SOFC/GT systems by approximately 11%, 6%, 15%, and 9%, respectively. Moreover, the waste heat can be utilized for diversified applications, such as absorption refrigeration and seawater desalination, thereby facilitating multi-energy cogeneration of electricity, heat, cooling, and fresh water.

The prevailing focus of contemporary research endeavors is on the thermodynamic optimization and integrated design of SOFC/GT systems. However, there is a paucity of in-depth exploration into the multi-cycle synergistic mechanism, local thermal management, and full life-cycle economics. The objective of this study is to review the latest progress in SOFC/GT waste heat recovery technologies, analyze the performance gains and limitations of different waste heat utilization modes, and provide theoretical support for the design of future high-efficiency and low-carbon energy systems.

2 Classification and Principles of Waste Heat Recovery Technologies

2.1 Carbon Dioxide (CO_2) Cycle

2.1.1 SCO_2 cycle

The SCO_2 thermal cycle system was first developed in the mid-1960s. In their seminal research, Feher [11] constructed a novel energy conversion system, establishing CO_2 (304.13 K/7.377 MPa) as the operation benchmark. Their pioneering introduction of a waste heat recovery device enhanced the overall energy utilization efficiency. When analyzed from the thermodynamic principles, the system belongs to the improved Brayton cycle system, whose core process contains four key stages: isentropic pressurization of the working fluid, constant pressure heat absorption, adiabatic expansion, and constant pressure cooling. In comparison to the conventional steam Rankine cycle (SRC), this technology effectively circumvents the latent heat loss that occurs during phase change by preserving the mass within the supercritical region. This not only significantly reduces the power consumption of the compressor but also results in a substantial increase in the net output power of the system [12]. The SCO_2 cyclic power generation system comprises a heat source, a turbine, a compressor, a recuperative heat exchanger, a pre-cooler, a generator, and other components, as illustrated in Figure 1.

Exploration of SOFC/GT/SCO_2 hybrid systems remains in its nascent stages. In the realm of SOFC/GT/CO_2 hybrid systems, the majority of designed systems are configured to place the CO_2 cycle subsequent to the SOFC/GT subsystem [13, 14]. This configuration is designed to prevent interference from the CO_2 cycle on the core subsystem through physical isolation, thereby significantly enhancing the stability of system operation. However, this design has clear limitations. The power output of the CO_2 cycle system is strictly constrained by the upstream exhaust gas temperature, resulting in limited room for improvement in overall thermal efficiency. Xia et al. [15] conducted a structural optimization study for the SOFC/GT system, and the SCO_2 recycling unit was innovatively embedded into the SOFC/GT subsystem. The design scheme constructs a multi-energy-coupled thermal cycle architecture by recovering the high-temperature tail gas waste heat for inlet gas preheating, which significantly improves the thermodynamic coupling efficiency while optimizing the energy level matching. The specific system architecture is shown in Figure 2.

The SCO_2 cycle power generation system demonstrates notable technological superiority in comparison to conventional thermal power generation systems. Furthermore, the critical point of CO_2 [16] (31℃, 73.7 bar) is considerably lower than that of water. In addition, SCO_2 demonstrates broad application prospects in multiple energy conversion fields due to its near-liquid density, excellent compressibility, stable chemical properties, and low corrosiveness. These fields include, but are not limited to, fossil-fueled power plants, solar photovoltaic systems, nuclear energy units, industrial waste heat recovery, and new energy storage systems. In regard to thermodynamic performance, when the inlet temperature of the system exceeds 600℃, the power generation efficiency is considerably higher than that of SRC under equivalent working conditions [17].

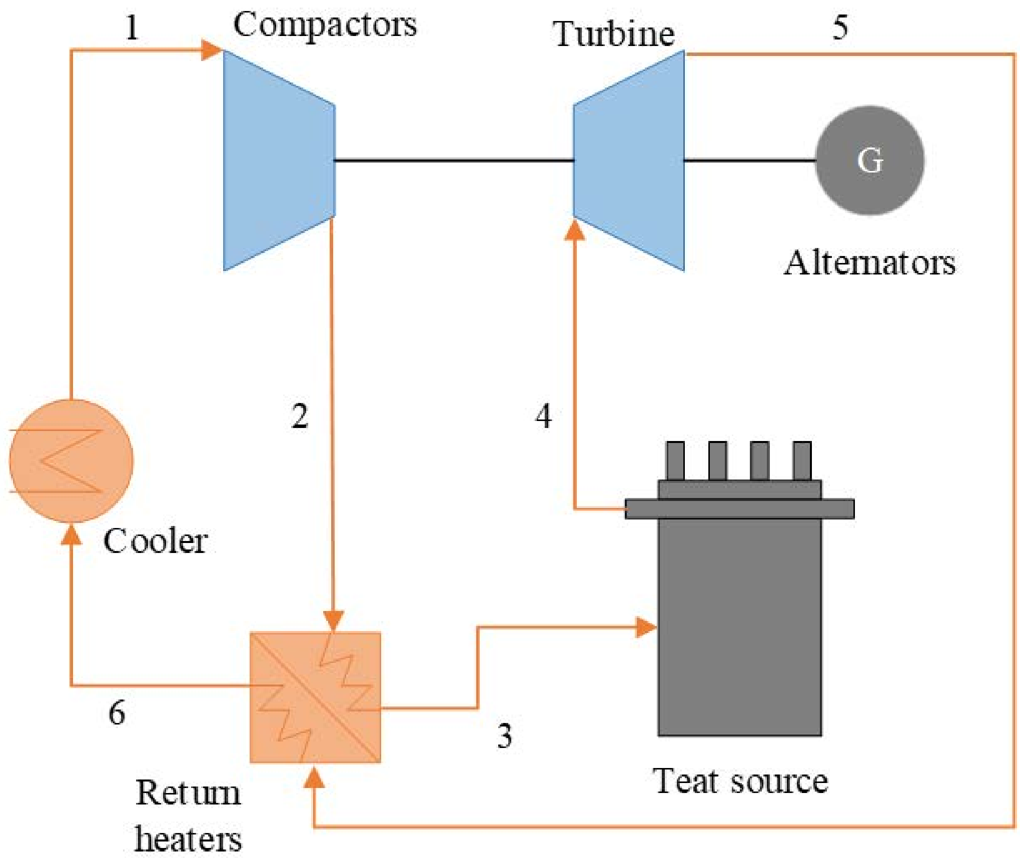

Figure 1. SCO_2 simple regenerative cycle process [12]

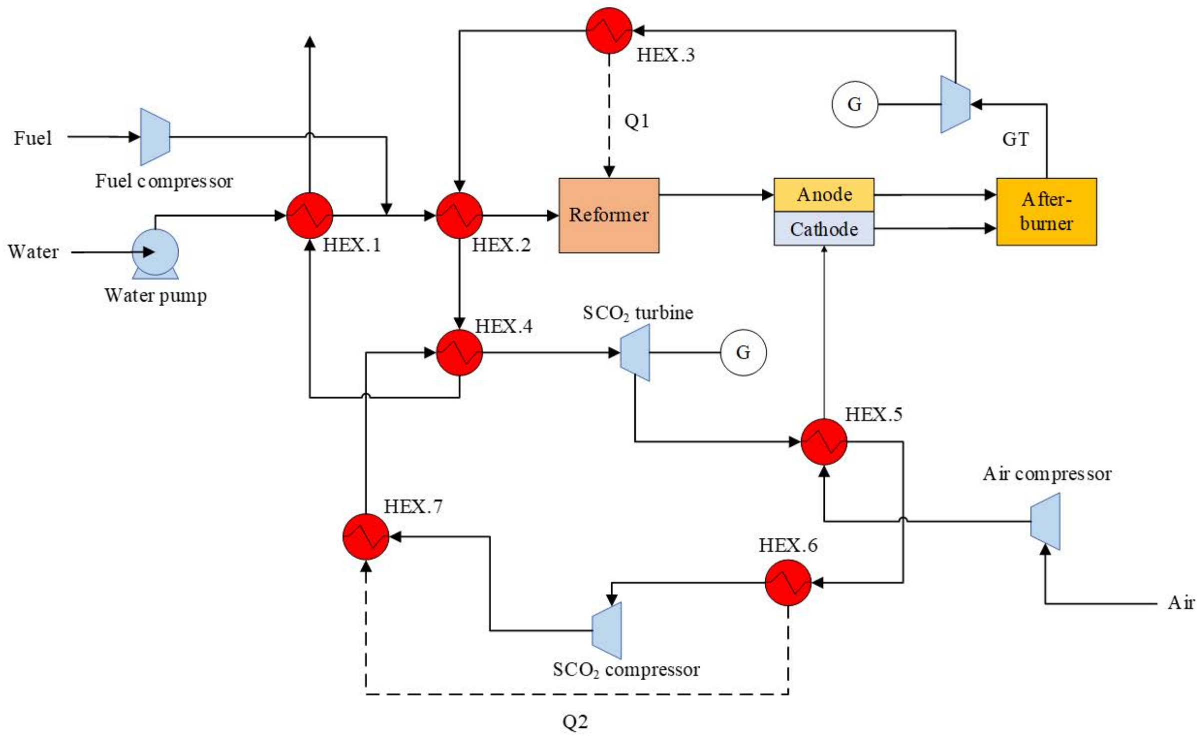

Figure 2. SOFC/GT/SCO_2 system [16]

2.1.2 TRCC

Conventional waste heat recovery devices have been found to utilize work masses that possess substantial greenhouse gas properties. In the event of system failure, such as the escape of the work mass or unregulated disposal, these substances enter the atmosphere, thereby exacerbating the greenhouse effect [18]. Among the novel CO_2 mass waste heat recovery technologies, two architectures are of particular relevance: the SCO_2 cycle and TRCC. While the thermodynamic cycle mechanisms of these two systems bear commonalities, a distinguishing feature of TRCC is that its heat release process is accomplished under operating conditions where the work mass pressure is below a critical point [19].

A standard TRCC system comprises a compressor, a gas cooler, a throttle valve, and an evaporator. A notable distinction of TRCC lies in the configuration of the heat exchanger on the high-pressure side of the recirculation system. In lieu of a medium phase change, which is characteristic of other subcritical cycles, TRCC utilizes a gas cooler in place of a condenser [20]. The underlying working principle of the system is illustrated in Figure 3.

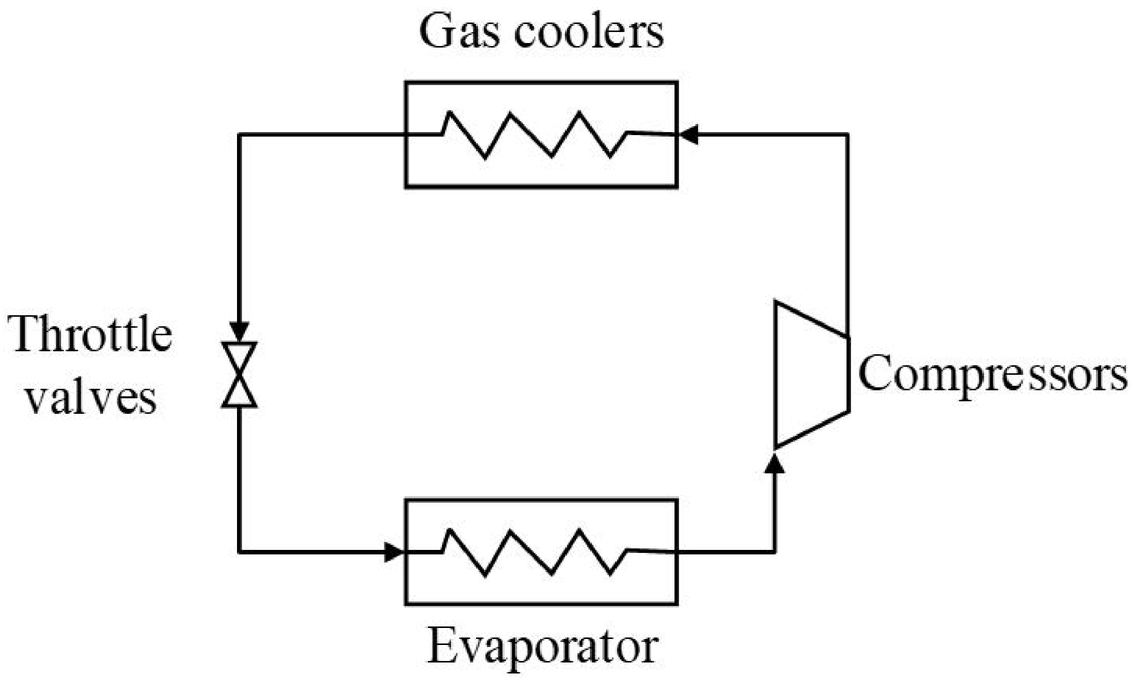

Figure 3. Single-stage TRCC with a throttle valve cycle [20]

In order to ensure the practical application performance of the TRCC system, two main solutions are currently available: (a) replacing pure CO_2 with a CO_2 mixture to increase the critical temperature and reduce the critical pressure; and (b) combining the CO_2 power cycle with a refrigeration cycle to condense CO_2 and further utilize the low-temperature waste heat in the exhaust gas.

Presently, TRCC finds primary application in the absorption of waste heat from SOFC/GT exhaust, with the system's fundamental configuration depicted in Figure 4. Meng et al. [21] constructed an integrated system containing SOFC/GT and demonstrated that the net electrical energy efficiency of the system was 69.26%. Shu et al. [22] conducted a comparative study between the overall efficiency of the ORC system and the single-stage TRCC system, and the results showed that the peak thermal efficiency of the single-stage TRCC system was 24%, which was 3% higher than that of the ORC system. In the study by Kim et al. [23], the heat recovery capability of three distinct CO_2 power generation cycles was examined: single-stage, two-stage, and split-flow CO_2 cycles. The results showed that the thermal efficiencies of the two-stage and split-flow CO_2 cycles were increased by 3.7% and 7.1%, respectively, compared to the single-stage CO_2 cycle.

The integration of TRCC and SOFC/GT has been demonstrated to enhance the power generation capacity of the system. However, the thermodynamic properties of subcritical CO_2 working fluids complicate their condensation with conventional cooling water, thereby limiting the practical application of TRCC [24]. The absence of a suitable low-temperature cooling medium imposes constraints on the implementation of TRCC. Consequently, the implementation of combined cycles integrating SOFC/GT and TRCC faces similar constraints.

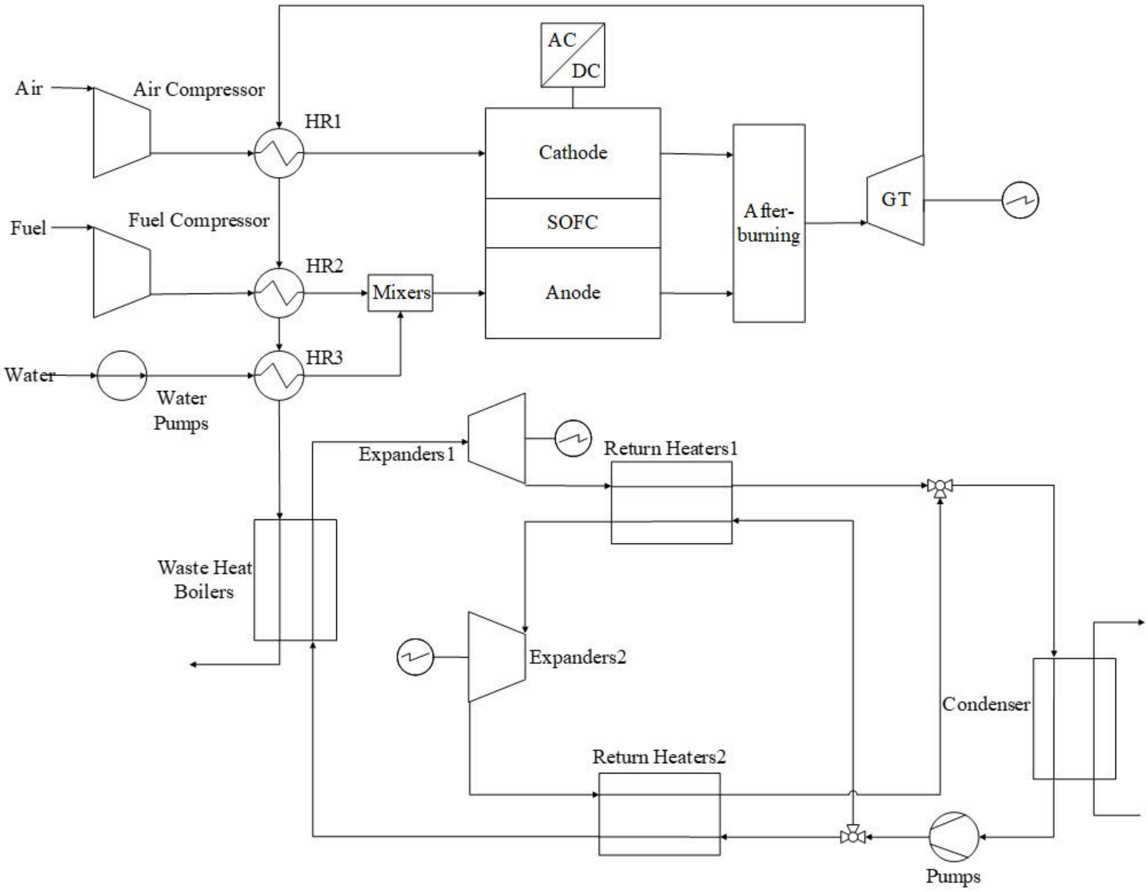

Figure 4. Schematic diagram of the combined system based on SOFC/GT/TRCC [21]

2.2 ORC

The utilization of ORC to recover waste heat from SOFC/GT systems has emerged as a prominent area of research interest. The ORC systems exhibit notable advantages over conventional waste heat recovery technologies, particularly in low-temperature heat source conditions. They are distinguished by their high efficiency, reliability, and adaptability to variable waste heat conditions [25].

While ORC shares similarities with SRC in terms of core components such as the evaporator, the expansion unit, the condenser, and pumps, a key distinction lies in the replacement of the working fluid with organic compounds, including hydrocarbons, refrigerants, ethers, and siloxanes. The fundamental principles of the ORC system are illustrated in Figure 5 [26].

In instances where the turbine outlet temperature is elevated, the thermal efficiency of the simple ORC can be enhanced by incorporating a heat exchanger (internal heat exchanger) between the turbine outlet and the condenser inlet. This heat exchanger employs the waste heat from the turbine to preheat the working fluid prior to its entry into the evaporator. The configuration of the heat exchanger is depicted in Figure 6 [27].

The SOFC/GT system is coupled with the ORC system, whereby the exhaust gas of the GT is used as the heat source for the ORC system. This gas enters the evaporator, where it evaporates the organic working fluid. The heat energy is then converted into mechanical energy of the shaft, thereby enabling waste heat recovery. The configuration of the system is depicted in Figure 7.

As demonstrated in some studies [29, 30], the integration of an intercooler system within the combined unit has been shown to enhance the overall efficiency of the system. This enhancement is attributed to the reduction in power consumption necessary for compressor operation, as well as the strategic utilization of the heat generated by the intercooler. Cai et al. [31] explored and analyzed ammonia-fueled SOFC/GT/ORC systems, investigated them in terms of energy conversion, efficiency, economic analysis, and optimization, and demonstrated that increasing the temperature and pressure at the SOFC inlet improves system performance. In a related study, Al-Hamed and Dincer [32] proposed an ammonia-based SOFC/GT/ORC system integrated with an absorption cooler, targeting clean rail electric transportation applications. The optimized system energy efficiency and exergy efficiency reached 71.0% and 76.8%, respectively.

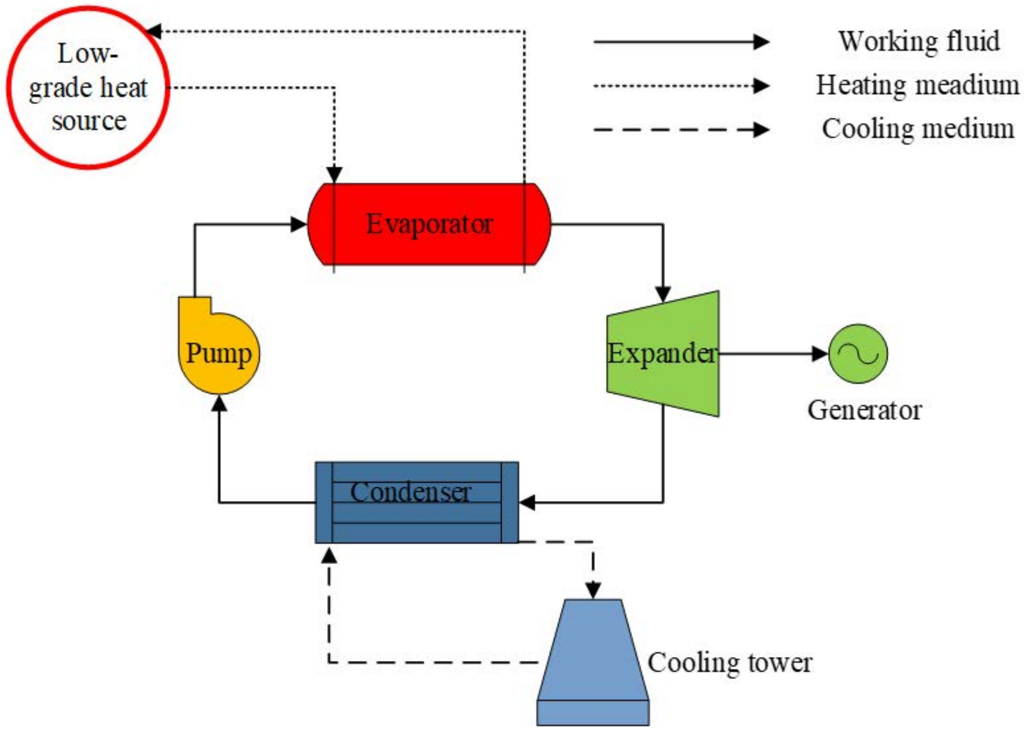

Figure 5. Schematic of the simple ORC layout [26]

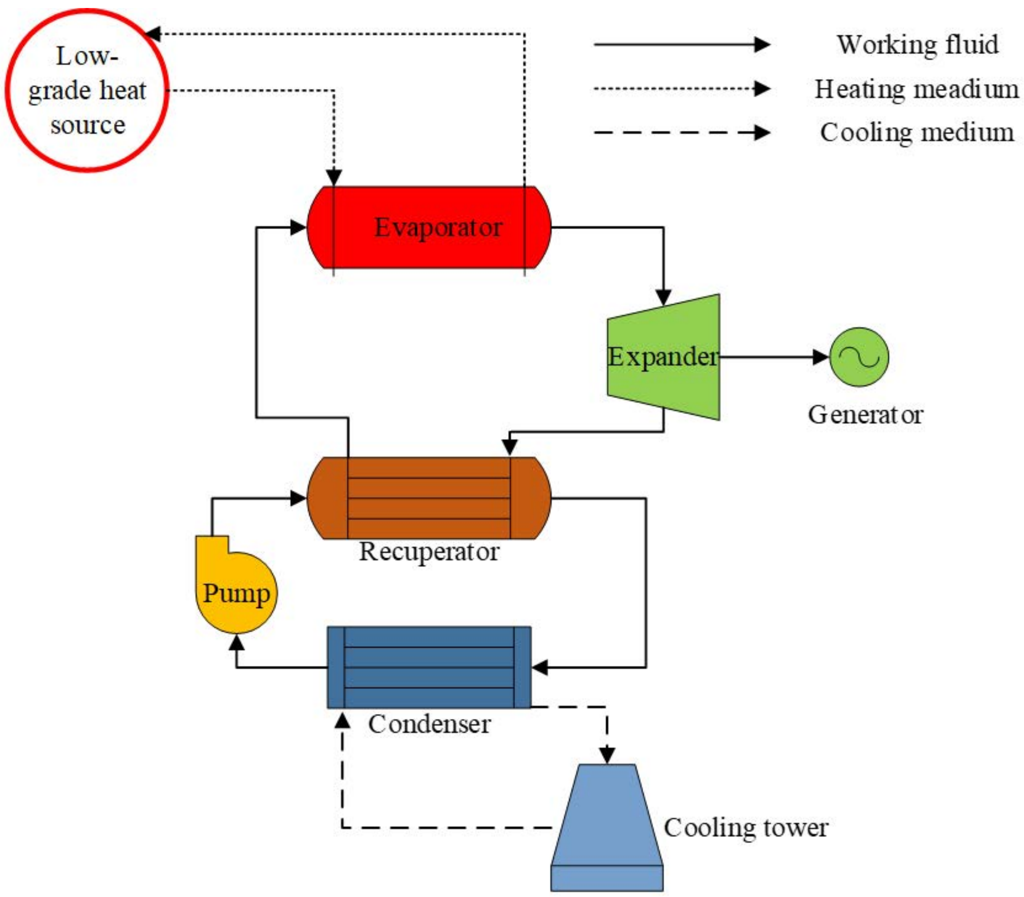

Figure 6. Schematic of the recuperated ORC layout [26]

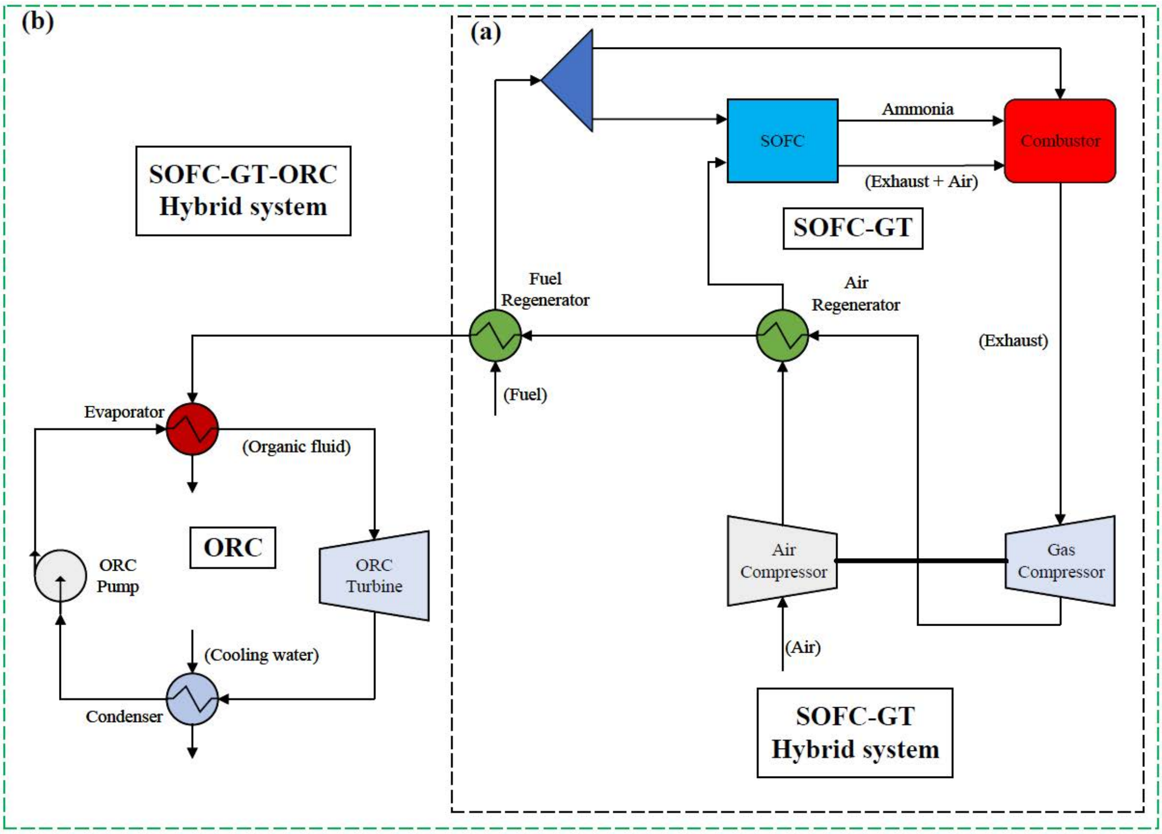

Figure 7. Diagram of (a) SOFC/GT and (b) SOFC/GT/ORC hybrid systems for ammonia-fueled ships [28]

A comparison of ORC with other systems reveals its distinct advantages. ORC stands out due to its simplicity, reliability, cost-effectiveness, and ease of maintenance. In contrast to SRC, which necessitates a superheating device, the high working pressure of the SCO_2 cycle, and the costly and inefficient thermoelectric generator, ORC boasts a number of key benefits. However, as a waste heat recovery device, ORC exhibits low energy efficiency and is susceptible to degradation at high temperatures, thus limiting its application to the recovery of low-temperature waste heat.

2.3 KC

The KC system, which utilizes an ammonia-water mixture as the working fluid, exhibits a favorable match between the heat absorption process of the working fluid and the heat release process of the heat source due to its variable temperature evaporation characteristics. This property reduces irreversible losses in the heat transfer process, enhances the efficiency of waste heat utilization, and demonstrates promising application prospects in low- and medium-temperature waste heat utilization [33].

Since its inception in 1983 by Alexander Kalina, the unique thermodynamic properties of the cycle have garnered significant interest from scholars worldwide. In comparison with the conventional Rankine cycle, KC has achieved significant advancements in the selection of working fluids and the optimization of thermal processes. The ammonia-water system exhibits three distinct advantages. Primarily, its broad phase transition temperature range is well-suited for the temperature glide of low- and medium-temperature heat sources, and its nonlinear heat absorption mode enhances the temperature matching of cold and heat sources. Secondly, in comparison with organic working fluids, ammonia-water solutions offer a substantial economic advantage and exhibit remarkable environmental sustainability. Furthermore, the similarity of physical parameters between ammonia (molecular weight 17.031) and water (molecular weight 18.015) allows the design of the turbomachinery to inherit the well-established water-steam turbine technology system [34].

There are several configurations of KC, including the KC System 1 (primary distillation Kalina), basic Kalina, KC System 11 (KCS 11, suitable for medium-temperature geothermal heat sources around 150℃), and KC System 34 (KCS 34, suitable for low-temperature geothermal heat sources around 100℃) [34]. Given the high exhaust temperature of the SOFC/GT system, the utilization of a primary distillation KC is a prevailing practice, as illustrated in Figure 8.

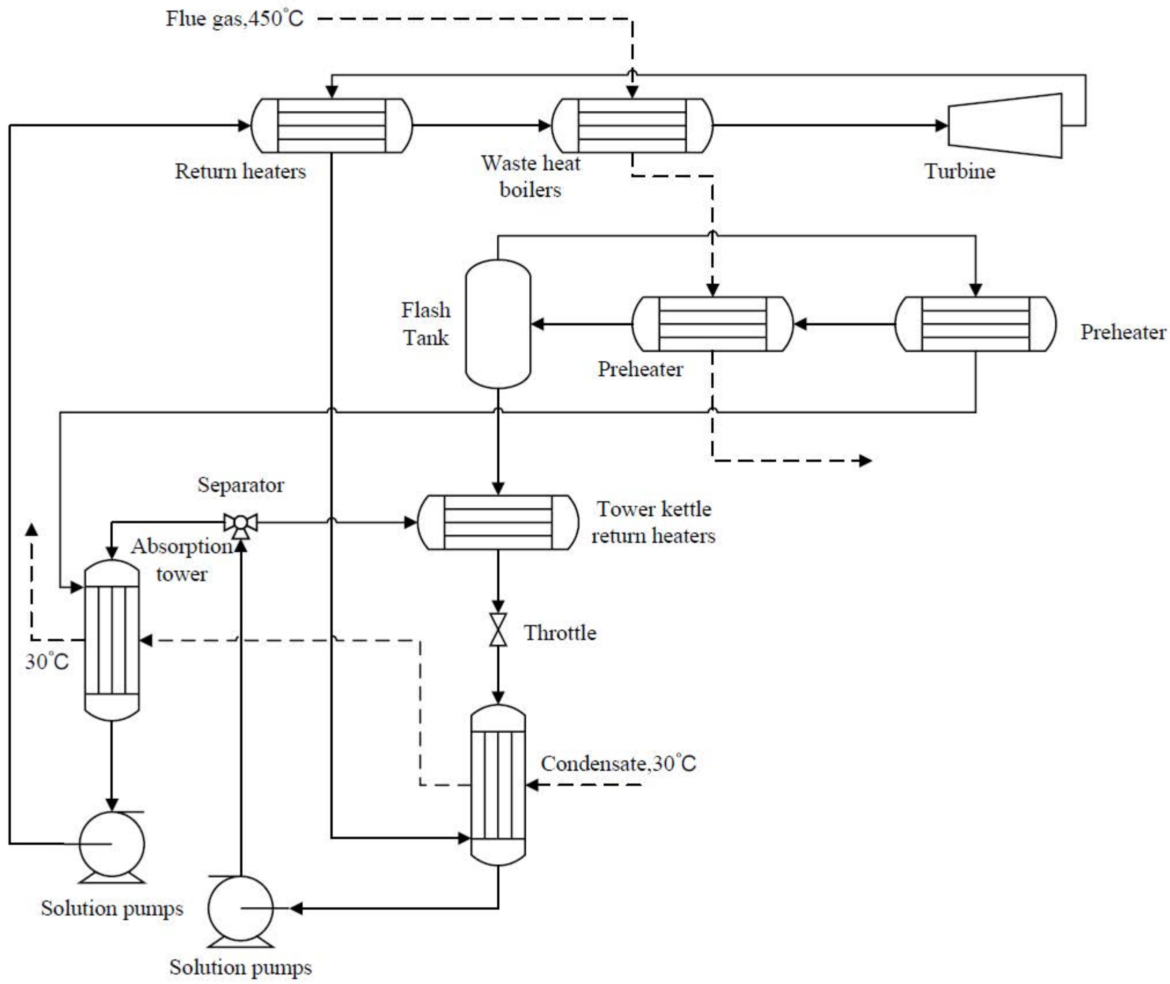

Figure 8. One grade distilled KC [33]

A paucity of studies currently exists on the recovery of SOFC/GT waste heat using KC and the comprehensive performance analysis of SOFC/GT/KC systems. In a notable study, Wang et al. [35] explored the application of the conventional KC in the context of exhaust waste heat recovery for SOFC/GT systems. The findings of this study indicated that the total system power generation efficiency attained 70%, marking a 7.3% increase compared to the efficiency of SOFC/GT systems. Zhao et al. [36] examined the performance of an SOFC/GT/KC system and identified the impact of key parameters on its effectiveness. Their analysis revealed that the integrated system exhibited high electrical efficiency, and that enhancing the pressure ratio, ST inlet pressure, and ammonia concentration could further boost the system's performance. Zhao et al. [37] employed KC as a bottom cycle to recover the waste heat of GT and generate electricity. The superiority of KC in waste heat recovery was substantiated by comparing it with the SOFC/GT/ST system, which was utilized as a reference system. The main structure of the system is depicted in Figure 9. The system's waste heat is utilized as follows: exhaust gas from GT is employed to preheat the air, which then flows into KC to continue its use. This realizes the graded utilization of energy and enhances the efficiency of the entire system. As stated in the study by Yang et al. [38], an innovative ammonia-fueled SOFC cascade power generation system was proposed, and the influence of key operating parameters (fuel ammonia mass fraction, fuel utilization rate, SOFC operating pressure, etc.) on the thermo-economic performance parameters of the new cascade system was revealed. In addition, Yue et al. [39] investigated the effects of parameter variations such as air flow rate, fuel utilization, fuel flow rate, pressurizer pressure ratio, and water-steam-carbon ratio on the system performance by introducing a KC with an ammonia-rich steam return heater in an SOFC/GT system. This development provides a basis for the advancement of SOFC/GT/KC systems. Wang et al. [40] proposed a new type of high-temperature solar thermochemical and methane-complementary SOFC/GT/KC composite power system. This system utilizes high-temperature solar heat to drive methane reforming to produce hydrogen. It also converts solar energy into chemical energy in the synthesis gas of hydrogen-rich fuel. The hydrogen generated drives the SOFC/GT/KC composite system to generate electricity, realizing the stepwise utilization of energy.

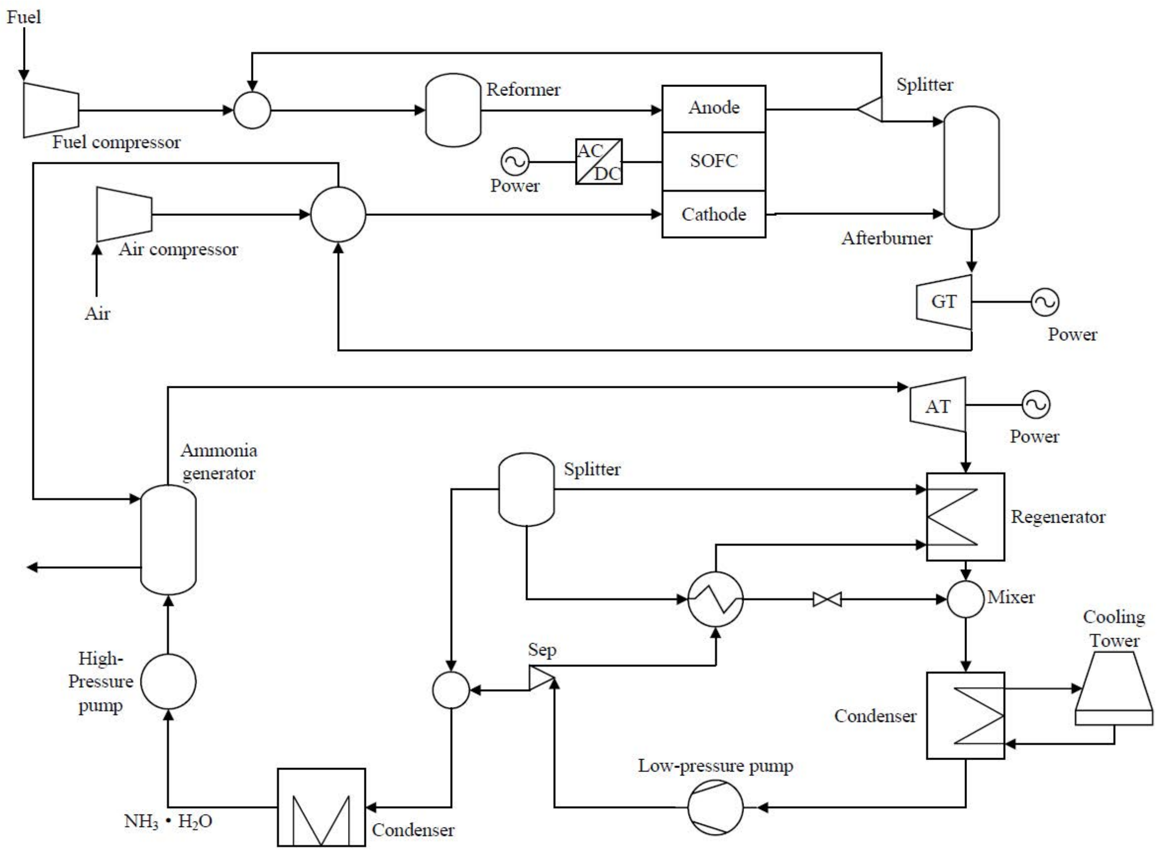

Figure 9. Flow chart of the proposed SOFC-GT-KC system [37]

The potential for KC to enhance the energy efficiency of SOFC/GT systems is substantial; however, its implementation necessitates a compromise between efficiency gains and associated costs, complexity, and technical risks. A meticulous selection process, encompassing considerations such as waste heat temperature, system dimensions, and economic evaluations, is imperative to ensure optimal outcomes. As material technology and control strategies continue to advance, the applicability of KC in the field of high-temperature waste heat is poised to expand further.

2.4 ST

Currently, there are two SOFC/GT/ST system structures. The first one is the SOFC/"GT+ST" system proposed in the study by Cheng et al. [41], in which the cathode and anode of the fuel cell enter into the GT and steam turbine, respectively, to do work. The SOFC cathode and anode lack a gas-mixing combustion part, which is canceled in this system, and the cathode spent gas is directly passed into GT for expansion work, while the anode spent gas is passed into ST for expansion work. Compared with the SOFC/GT system, the total power of the SOFC/ "GT+ST" system increases to 73.3 MW, which is 5.74% higher than the original system, and the power generation efficiency reaches 60.13%. The main structure of the system is shown in Figure 10.

The second one is the SOFC/GT/ST combined cycle power system innovatively constructed by the researchers [42–44]. The residual fuel after the SOFC reaction is utilized to fully react with cathode residual oxygen in a secondary combustion unit, and the generated high-temperature flue gas is shunted and regulated to realize multi-stage energy conversion. As shown in Figure 11, part of the exhaust gas is first diverted to the pre-reforming unit and the cathode channel to participate in the recirculation process through a three-way valve. The other exhaust gas passes through GT for power generation. In terms of waste heat management, the system adopts multi-stage heat exchange technology to realize deep energy recovery. The flue gas in the medium temperature section preheats the raw gas, combustion air and circulating medium in turn, and then enters the waste heat boiler system, where the high-pressure feed-water is converted into superheated steam to drive the turbine to do work through the process of phase change, and then becomes liquid water to be pressurized and discharged back to the waste heat boiler through the pump to form a cycle. The SOFC/GT/ST combined cycle power system was simulated and analyzed in terms of the compressor pressure ratio, fuel utilization rate, and the influence of operating temperature on the system performance. It was found that the system performance was optimal at a pressure ratio of 14, a steam-to-carbon ratio of 2.1, a fuel utilization rate of 0.85, and an SOFC operating temperature of not higher than 950℃. Pirkandi et al. [45] investigated nine different ST configurations and concluded that the triple hybrid cycle is the thermodynamically best-performing cycle, showing that by adding an ST to the SOFC/GT system, the triple system produces a 200% increase in net power with respect to the simple GT cycle, and a 15% increase with respect to the SOFC/GT system.

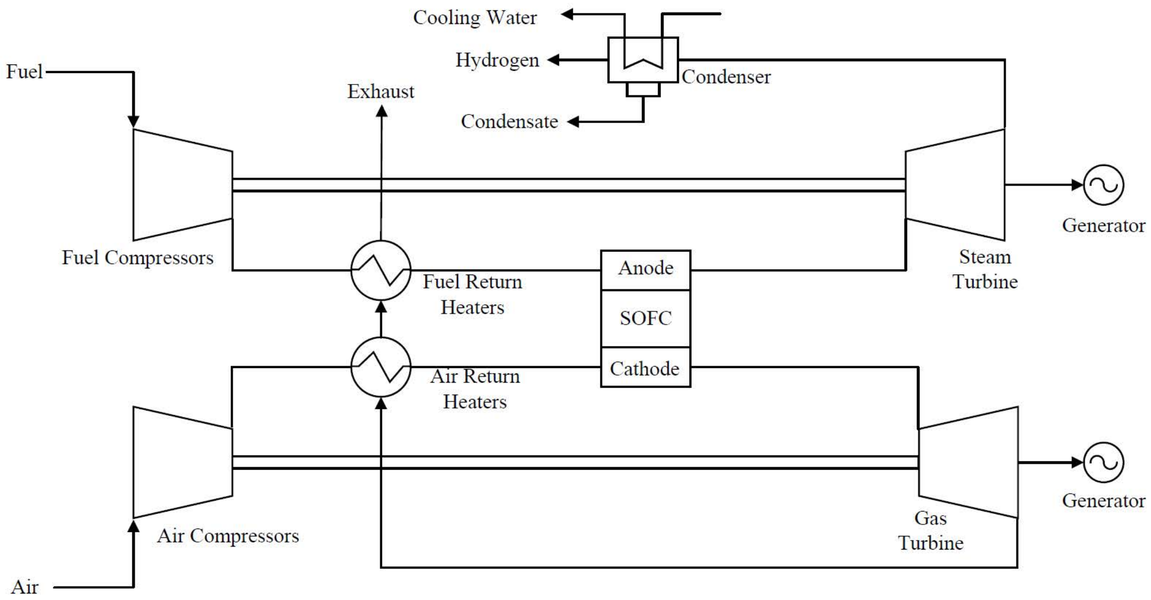

Figure 10. SOFC/"GT+ST" system [41]

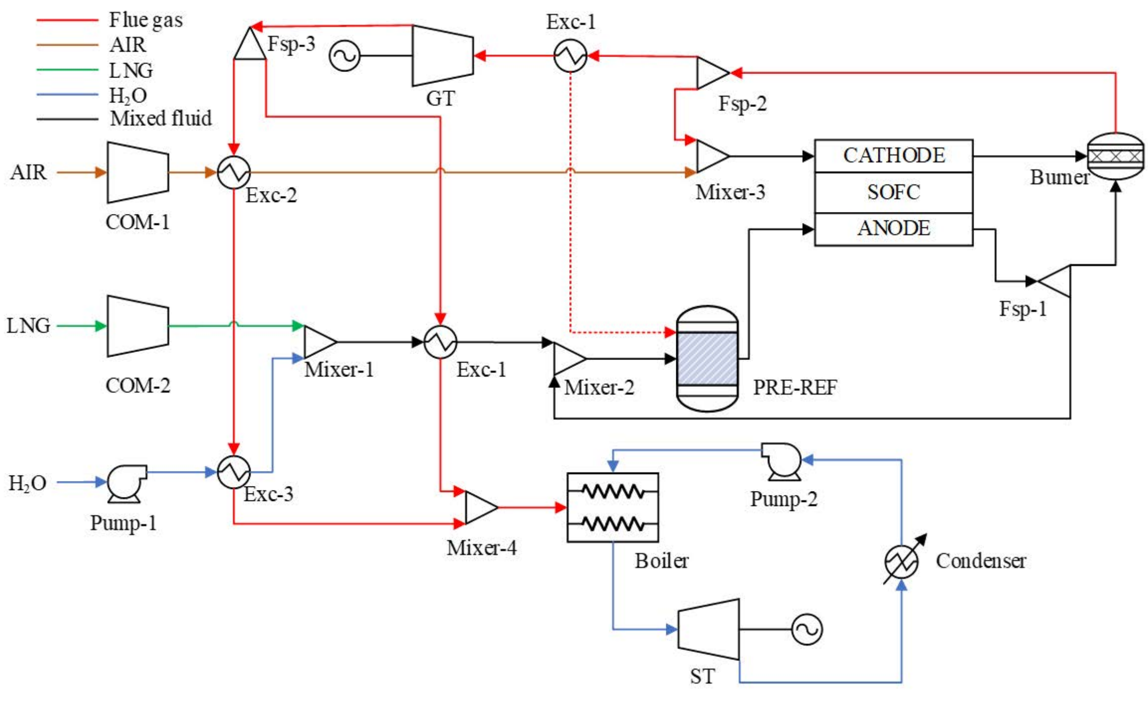

Figure 11. SOFC/GT/ST combined cycle power system [44]

The SOFC/GT/ST combined cycle system demonstrates a notably high energy conversion efficiency. However, the system is also confronted with numerous challenges. These challenges encompass system complexity, the necessity of coordinating diverse physicochemical processes, the complexity of the design, the high initial investment required, the high cost of materials, the requirement of high-temperature alloys for equipment, the high costs of operation and maintenance, the material degradation that results from high-temperature operation, the need for frequent maintenance, the prolonged start-up time, the lagging overall response, and its incompatibility with frequent start-stop or load fluctuation scenarios.

2.5 Step Utilization and Hybrid System

In order to fully utilize the waste heat of SOFC/GT, some researchers have proposed a combination of multiple waste heat utilization systems, thereby forming a waste heat cascade utilization system. The prevailing research direction involves the development of a cold, heat, and power cogeneration system, encompassing the joint operation of SCO_2 and the refrigeration cycle, the joint operation of TRCC and the refrigeration cycle, and the joint operation of ORC and the refrigeration system, among others. The enhancement of each efficiency in comparison with the SOFC/GT system alone is evident. Additionally, scholars have explored the utilization of waste heat for desalination, a practice that offers substantial economic advantages.

Various innovative system architectures have been proposed by scholars for the joint operation of SCO_2 and refrigeration cycles. Ran et al. [46] designed a composite system integrating an SCO_2 cycle with lithium bromine single-effect absorption refrigeration, aiming to enhance the efficiency of combined heat utilization in a combined SOFC/GT unit. Tian et al. [47] constructed an integrated energy system consisting of SOFC/GT, ST, ORC, and ammonia absorption refrigeration units, which realized a SOFC power generation efficiency of 55.5%, an integrated power supply efficiency of 76.5%, and a cogeneration efficiency of 92.6% under the baseline conditions, with all the performance indexes significantly improved compared with the conventional system. Liu et al. [48] proposed a polygeneration system, which is a device that realizes heat, power and cooling triple-supply through the SCO_2 cycle, humidification and desalination, and jet refrigeration technology, and its power conversion efficiency, exergy-efficiency, and integrated output ratio reach 68.35%, 67.23%, and 85.25%, respectively. In addition, the hybrid system developed by Yao et al. [49] organically integrates the SCO_2 cycle with ORC and introduces chemical carbon capture technology, and the experimental data show that the system has a net power output of 4743.81 kW, a carbon capture rate of 81.52%, an energy conversion efficiency of 60.56%, and a unit cost of power generation that is controlled at $0.08727/kWh.

In the context of the coupled application of TRCC, Yang et al. [50] developed a cascade absorption refrigeration/TRCC system, which demonstrated notable advantages in terms of refrigeration performance and economic efficiency. Xu et al. [51] proposed a two-stage TRCC with a jet refrigeration composite system that achieves 65.05% net power generation efficiency and 79.90% overall energy efficiency at standard operating conditions. Notably, Liu et al. [52, 53] innovatively combined the SOFC/GT unit with a TRCC and refrigeration dual cycle, evaluated the system performance through the two dimensions of energy consumption and energy efficiency, deeply analyzed the influence law of key operating parameters (including fuel cell operating pressure, working mass flow rate, etc.) on the thermodynamic characteristics of the system, and used the multi-objective optimization method to determine the optimal operation interval. The optimal operation interval was determined using a multi-objective optimization method.

With regard to the collaborative operation of ORC and refrigeration systems, an enhancement in the comprehensive energy efficiency of SOFC-GT systems to 68.79% has been demonstrated through the integration of vapor absorption refrigeration and ORC technologies [54]. A liquefied natural gas (LNG) cold energy utilization system has been proposed that achieves 79.48% integrated energy efficiency and 79.2 kg/h carbon capture capacity [55]. With regard to the integration of renewable energy sources, the developed solar-driven triple-heating system [56] achieves a thermal efficiency of 90% and a cost-effectiveness index of 64.5% through the optimized configuration of ST and the reforming reactor.

In addition to conventional technologies such as absorption chillers, heat supply units, and power cycle systems employed for waste heat recovery in SOFC-GT systems, some researchers have investigated the prospect of utilizing desalination technology as an alternative. Meratizaman et al. [57, 58] pioneered the integration study of a multi-effect distillation-thermal vapor compressor (MED-TVC) system with SOFC/GT, and the economic analysis demonstrated that this solution has substantial advantages over a single power generation system. Mohammadnia and Asadi [59] and Vojdani et al. [10] further validated the feasibility of this technology route. As demonstrated in the study by Liang et al. [60], the technical specifications of 78.56% system thermal efficiency and 829.3 tons of fresh water production per year were achieved through the synergistic application of double-effect absorption refrigeration and MED-TVC. Moreover, the integrated biomass fuel cell system proposed in the study by Behzadi et al. [61] in conjunction with reverse osmosis seawater desalination technology achieved multi-dimensional optimization of energy-economy-environment from the perspective of the whole life cycle.

2.6 Other Waste Heat Utilization Systems

From the perspective of energy utilization and economic cost, absorption refrigeration systems have emerged as the optimal solution for SOFC/GT-based CCP systems, particularly in the context of power generation and refrigeration [62, 63]. Additionally, novel systems have been integrated using the inverse Brayton cycle [64], exhibiting enhanced cost-effectiveness in comparison to SOFC/GT systems. Furthermore, vapor recovery [65] has been employed for integration with SOFC/GT systems, among other methodologies.

2.7 Comparison of Existing Waste Heat Recovery Technologies

This study comparatively analyzes the performance characteristics and technical defects of various waste heat recovery cycle technologies integrated with SOFC/GT systems. Among them, KC utilizes the sliding boiling characteristics of the ammonia-water mixed working fluid and has outstanding performance in low-temperature waste heat recovery, but suffers from the defects of system complexity, high corrosiveness of the working fluid, and insufficient stability of high-pressure operation; ORC, with the advantages of simple structure and low cost, has remarkable economy in low and medium-temperature waste heat scenarios (the power of the SOFC/GT/ORC system is 12.6% higher than that of KC, and the efficiency reaches 67%), but the SCO_2 cycle is ideal for high-temperature waste heat recovery due to its environmentally friendly working fluid, high-temperature efficiency (better than Rankine cycle at >820 K), and compactness, but its supercritical, high-pressure operation (>7.38 MPa) poses a serious challenge to the material's resistance to pressure; TRCC is better suited to low-grade heat sources, with a power output superior to that of ORC, but the thermal efficiency and economic performance are not as good as those of KC, and ORC has the same advantages as SOFC/GT/ORC.

3 Economic Analysis of SOFC Systems

When analyzing the economics of waste heat recovery methods for SOFC/GT systems, a number of factors must be considered, including initial investment costs, operation and maintenance costs, energy efficiency, exergy efficiency, unit cost of electricity generation, payback period, and carbon emissions. As indicated by the data presented in various scholarly publications, the economic performance of SOFC/GT systems exhibits variability. However, the majority of research findings indicate that these systems possess the capacity to substantially enhance overall economic efficiency, contingent upon the effective recovery of waste heat.

The economics of SOFC/GT systems are closely related to the manner in which their waste heat recovery technologies are integrated. The extant literature proposes a variety of options for waste heat recovery, including the SCO_2 cycle, ORC, absorption refrigeration, such as Ejector Refrigeration Cycle (ERC) and Double-Effect Vapor Absorption Refrigeration System (DVARS), seawater desalination, such as Humidification-Dehumidification Desalination (HDH) and MED-TVC, and multi-generation systems, such as Combined Cooling, Heating, and Power (CCHP). The cost-effectiveness of the various technologies under consideration varies significantly. The SCO_2 cycle demonstrates a high degree of economic potential while concomitantly improving energy efficiency. As demonstrated in the study by Xia et al. [15], the power generation cost is reduced to $0.079/kWh, and the payback period is shortened to 2.07 years through the optimization of the layout of the SCO_2 cycle [66]. This is attributed to the cycle's high heat-matching and low-cycle pressure-loss characteristics. The composite system combining SCO_2 and ORC, as documented in the extant literature, has a power generation cost of $0.08727/kWh. This cost is slightly higher than that of a single SCO_2 system; however, the carbon capture rate is improved to 81.52%, which may further improve the economy through the carbon trading mechanism. ORC has an outstanding performance in terms of cost control. The unit power generation cost of the SOFC/GT/ORC system [54] is $1939.93/kW, which is significantly lower than that of the conventional steam Rankine system, but its efficiency improvement is limited (ORC only improves thermal efficiency by 2-6%, but the cost increases by 14-24% [28]). This suggests that ORC is more suitable for short-term projects that are sensitive to initial investment. Polygeneration systems improve overall economics by diversifying output. Liu et al. [48] integrated power generation, refrigeration, and freshwater production at a total cost of $14.01/h, which is higher than a single power generation system but dilutes the cost through product diversification; the biomass-based polygeneration system [67] has a low cost of hydrogen of $4.06/kg and an annual cash flow of $58.42 million, which reflects the advantages of integrated resource utilization.

The levelized cost of energy (LCOE) is the core economic indicator. A review of the relevant literature reveals that the LCOE of SOFC/GT waste heat recovery systems ranges from 0.0599 to 0.13807 USD/kWh. The TRCC/ERC system, with an LCOE of 0.0599 USD/kWh, has been identified as the optimal solution [51]. This cost is comparable to that of conventional coal-fired power generation. Conversely, the ammonia-fueled system [38] is contingent upon a reduction in ammonia prices or policy subsidies to enhance its competitiveness, given the high fuel cost ratio (65.86%) and LCOE of $0.1364/kWh. The payback period is found to be significantly influenced by the complexity of the system and its initial cost. Simple systems, such as the marine hybrid system [66], have a payback period of only 2.07 years. In contrast, the payback period of the polygeneration system [68] extends to 12.5 years due to the high investment in equipment. It has been demonstrated that a payback period of 5.11 years at a total cost rate of $18.53/h has been attained by integrating multi-effect distillation with thermal vapor compression [60]. This finding suggests that effective thermal management can reduce the payback period.

The analysis of cost components shows that fuel and equipment are the main expenditures. As an example, fuel cost accounts for 65.86%, while SOFC accounts for 58.35% and GT accounts for 20.8% of the equipment cost [31]. Therefore, reducing SOFC manufacturing cost (e.g., scale-up production) and selecting cheap fuel (e.g., biomass gasification) are the key paths for economic optimization. LCOH of the biomass polygeneration system [67] is 4.06 USD/kg, which is close to the green-hydrogen parity threshold (3-5 USD/kg), and it may be profitable when combined with the government subsidy; the unit cost of the product has been reduced to 69.47 USD/GJ through multi-objective optimization [61], which indicates that the biomass system has the potential to be used in a circular economy model. The balance between energy efficiency improvement and cost increase is significant in multiple studies. For example, Khan et al. [69] improved energy efficiency by 36.51% through Heat Recovery Steam Generator (HRSG) and DVARS, but the total cost increased by only 1.76%, indicating that the solution is cost-effective; while the ORC system [28] improves efficiency by 2-6%, but the annual cost increases by more than 138,000 USD, which needs to be amortized over a long period of operation. The integration of carbon capture and storage (CCS) increases the initial investment, but the return can be improved through carbon trading or tax incentives. The carbon capture rate of 81.52% [49] increases the cost of power generation to $0.08727/kWh, but the annual emission reduction benefit can reach tens of thousands of dollars when the carbon price is $30/ton.

A comprehensive examination of the economics of SOFC/GT waste heat recovery systems is imperative, encompassing the selection of technology, cost-sharing mechanisms, and the policy environment. The integration of advanced waste heat recovery technologies, such as the CO_2 cycle, ORC, and the absorption refrigeration cycle, among others, has been demonstrated to facilitate a reduction in the unit cost of power generation and a corresponding shortening of the payback period. This is achieved while ensuring higher energy efficiency. Nevertheless, the initial investment and operational and maintenance costs of the system remain significant factors that hinder its widespread implementation. Consequently, future research endeavors must prioritize the identification of methodologies to further minimize these costs while optimizing the configuration and operation of the waste heat recovery unit. This approach is instrumental in enhancing the economic viability of SOFC/GT systems.

4 SOFC/GT/Molten Salt Waste Heat Recovery Systems

The current technological path for waste heat utilization in SOFC/GT cogeneration systems is mainly based on multi-stage thermal cycling, which realizes electrical energy output by converting medium- and low-temperature heat energy into kinetic energy. Although the exhaust gas after completing the energy gradient utilization has the potential to supply heat, the time-varying characteristics of the heat output make it difficult to meet the stable demand because the current cogeneration units are generally not equipped with heat storage devices. It is worth noting that the startup time of SOFC is usually very long, ranging from several hours to tens of hours, and the temperature rise rate must be limited to 3 K/min. Although the stack temperature has reached the design conditions, it usually takes several minutes to increase the load (i.e., hot start) [70, 71]. Specifically, the startup process of SOFC can be divided into two phases: (a) the cold startup phase: the temperature of the stack is raised from ambient temperature to normal operating temperature by an external heat source; and (b) the hot startup phase: the fuel is passed into the anode channel, which causes an electrochemical reaction at the three-phase boundary (TPB) [72]. Existing studies have shown significant differences in hot start times. A study by Petruzzi et al. [73] for a 3.5 kW on-board auxiliary power system found that hot start takes 20 minutes at 600°C operating temperature; a study by Barzi et al. [74] for a hydrogen-fueled tubular SOFC showed that it takes 2.5 hours to ramp up the system from ambient to a homogeneous temperature of 860°C; while Apfel et al. [75] showed that the complete start-up and shutdown process can take up to several hours for a 5 kW flat plate SOFC system with reformer, heat exchanger and catalytic afterburning chamber.

It has been determined that the gas discharged from the conventional SOFC/GT combined system is approximately 700-800 K [76]. The temperature of this portion of the gas is notably high, and molten salt energy storage has a broad operating temperature range (300-1000°C). It possesses several advantageous properties, including high energy storage density, minimal subcooling, robust thermal stability, a prolonged service life, and low cost [77]. These characteristics align well with the exhaust temperature of the SOFC/GT. The construction of a molten salt heat storage module enables the effective recovery of exhaust waste heat and the utilization of stored thermal energy for fuel cell stack preheating support, thereby establishing a closed-loop energy utilization system.

The optimization design is carried out to address two major technical problems of the existing SOFC cogeneration system. Firstly, the waste heat recovery part of the system generally lacks efficient heat storage devices, resulting in unstable heat output; secondly, the thermal inertia of the fuel cell stack is large in the start-up stage, and the system's response speed is limited. In this study, a multi-energy coupling system architecture of SOFC/GT/molten salt energy storage was innovatively proposed, and the main structure of the system is shown in Figure 12. In the pre-operation stage of the system, pre-heated high-temperature air is used to preheat the SOFC and raise its temperature above 600°C to meet the startup temperature threshold. This method can change the system startup mode from cold startup to hot startup, thus shortening the startup time by 1-2 hours. At the beginning of operation, the molten salt in the hot salt storage tank preheats the fuel and air through a heat exchanger to raise the gas temperature to the design operating point, during which the molten salt medium that has completed the heat exchange is transferred to a low-temperature storage tank for temporary storage. The gas from the SOFC reaction is fully combusted in the afterburning chamber and then enters the GT for power generation in order to recover the high-temperature waste heat. After heat recovery in GT, the temperature of the exhaust gas is still very high. At this point, the low-temperature molten salt in the cold salt tank is heated by a heat exchanger and transported to the hot salt tank. The high-temperature molten salt stored in the hot salt tank is not only used to preheat the gas but also meets the heating demand, thus realizing the cogeneration of the system.

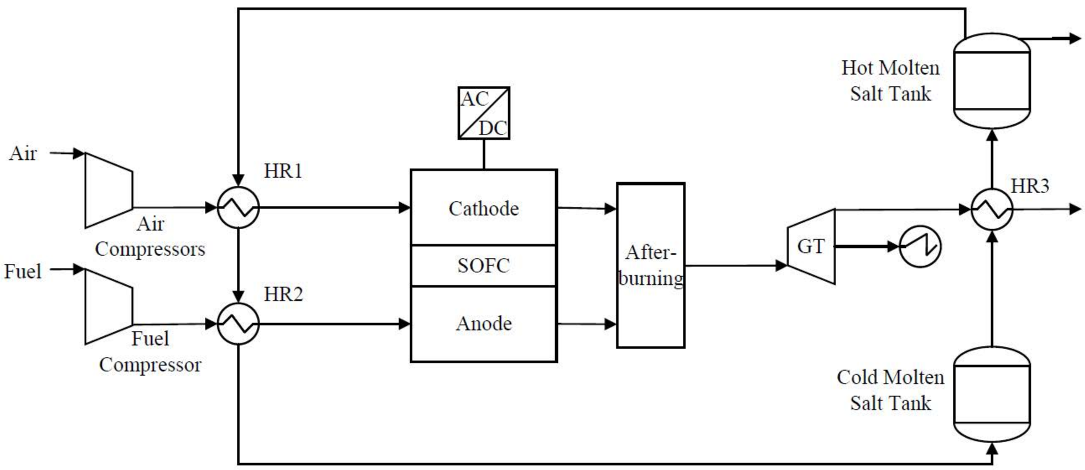

Figure 12. SOFC/GT/molten salt system

5 Conclusion and Outlook

In low-temperature waste heat recovery, ORC is the first choice because of its simplicity and economy, and KC can be chosen if higher thermodynamic efficiency is pursued and complexity and cost can be afforded; SCO_2 is preferred for high-temperature waste heat (>820K) scenarios because of its high efficiency and compactness to maximize the energy conversion; for medium- and low-grade heat sources (e.g., industrial waste heat and solar energy in the mid-temperature section), TCO_2 is more promising because of its wide operating range and environmental friendliness. TCO_2 has more potential due to its wide operating range and environmental friendliness, but further cost reduction is needed. The current technical bottlenecks are focused on the development of high-temperature and high-pressure materials (e.g., corrosion resistance of SCO_2 turbine), optimization of multi-cycle coupling (e.g., design of SCO_2/TCO_2 hybrid systems), and enhancement of stability of the work material (e.g., development of ORC high-temperature-resistant work material), etc. Therefore, it can cover the full range of waste heat and take into account the efficiency and economy. Future research needs to balance thermodynamic efficiency and economy, and promote the development of high-efficiency waste heat recovery technology for ships, nuclear energy, and other fields through hybrid cycle integration and material innovation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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