energies

Review

Performance Analysis and Optimization of SOFC/GT Hybrid Systems: A Review

Qiao Yuan [1], Xiongzhuang Li [1], Shuo Han [1], Sijia Wang [1], Mengting Wang [1], Rentian Chen [1,2], Sergei Kudashev [2], Tao Wei [1,*] and Daifen Chen [1,*]

[1] School of Energy and Power, Jiangsu University of Science and Technology, Zhenjiang 212003, China; justyuanqiao@163.com (Q.Y.); 192210807124@stu.just.cn (X.L.); samhan1997@163.com (S.H.); 221110801102@stu.just.edu.cn (S.W.); 221210801105@stu.just.edu.cn (M.W.); crt01999@163.com (R.C.)

[2] Institute of Mechanics and Energy, National Research Ogarev Mordovia State University, Saransk 430000, Russia; kudaschev@mail.ru

* Correspondence: wt863@just.edu.cn or wt863@126.com (T.W.); dfchen01@163.com (D.C.)

Abstract: This review provides an overview of the solid oxide fuel cell/gas turbine (SOFC/GT) hybrid system, highlighting its potential as a highly efficient and low-emission power generation technology. The operating principles and components of the SOFC/GT system, as well as the various configurations and integration strategies, are discussed. This review also examines the performance, advantages, and challenges of the SOFC/GT system, and discusses the research and development efforts aimed at improving its efficiency, reliability, and cost-effectiveness. This work provides an overview of the research conducted in the area of SOFC-based hybrid systems, which is expected to be beneficial for researchers who are interested in this area.

Keywords: solid oxide fuel cell (SOFC); gas turbine; hybrid system; reformer; fuel utilization

Citation: Yuan, Q.; Li, X.; Han, S.; Wang, S.; Wang, M.; Chen, R.; Kudashev, S.; Wei, T.; Chen, D. Performance Analysis and Optimization of SOFC/GT Hybrid Systems: A Review. *Energies* **2024**, *17*, 1265. https://doi.org/10.3390/en17051265

Academic Editor: Antonino S. Aricò

Received: 20 January 2024
Revised: 24 February 2024
Accepted: 4 March 2024
Published: 6 March 2024

1. Introduction

Under the background of the strategic goal of "carbon peak before 2030 and carbon neutrality before 2060", creating a clean, low-carbon, safe, and efficient energy system is attracting the attention of an increasing number of researchers [1–5]. Since alkali metal ion batteries [3,5–7], solid state batteries [8–13], and lithium metal batteries [14–18], however, are all energy storage technologies, developing new and clean energy conversion technologies is still an urgent requirement around the world [2,19]. The solid oxide fuel cell (SOFC) transforms the chemical energy of fuel and oxidizer directly into electrical energy; it can be coupled with gas turbines (GT) and steam turbine to create an effective and clean hybrid power system because of its advantages in high power generation efficiency, high waste heat level, and low pollution [20–22]. The development of SOFC/GT can be traced back to the early 1990s. During this period, fuel cell technology began to receive widespread attentions, leading to numerous research and projects to explore the potential of SOFC/GT system [23]. Currently, the literature about SOFC/GT primarily centers on thermodynamics investigation [24–26], multi-objective optimization [27–29], system configuration [30,31], eco-technoeconomic analysis [32], numerical study [33–35], control system design [36–40], renewable energy source utilization [41], mobile applications [42], CO_2 capture [27,43], and other prospective research [44]. However, the reviews about SOFC/GT hybrid systems have rarely been reported, thus this work mainly focuses on this topic.

A SOFC/GT hybrid cycle is simple to understand. SOFC stacks can replace conventional burners to heat air streams, which is subsequently expanded in the turbine to produce power through a pressured Brayton cycle. Based on this fundamental concept, numerous alternate SOFC/GT hybrid system topologies have been proposed [45,46].

Several important parameters that affect the layout of SOFC/GT hybrid systems including (Figure 1):

- Power output: According to the power output requirements, determine the size and performance of the main components of SOFC stack and GT.
- Fuel type: Considering the compatibility of the fuel system design with fuel cells and gas turbines, there are a variety of fuel options that can be used in place of hydrogen such as biomass, methane, kerosene, and ammonia.
- Heat recovery: To optimize the power plant's total energy efficiency, incorporate heat recovery systems (such as heat exchangers) into the layout.
- Balance of plant components: Optimizing the placement of components such as fuel reformers, air compressors, heat exchangers, and power electronics to minimize energy losses and optimize system performance.
- Operating temperature: The operating temperature affects the power generation efficiency of the hybrid system, but higher temperature can cause damage to the system, so it is essential to choose a reasonable operating temperature.
- Operational flexibility: Designing the layout to allow for operational flexibility, such as adjusting power output, accommodating different load demands, and facilitating maintenance and repairs without impacting the overall operation of the power plant.

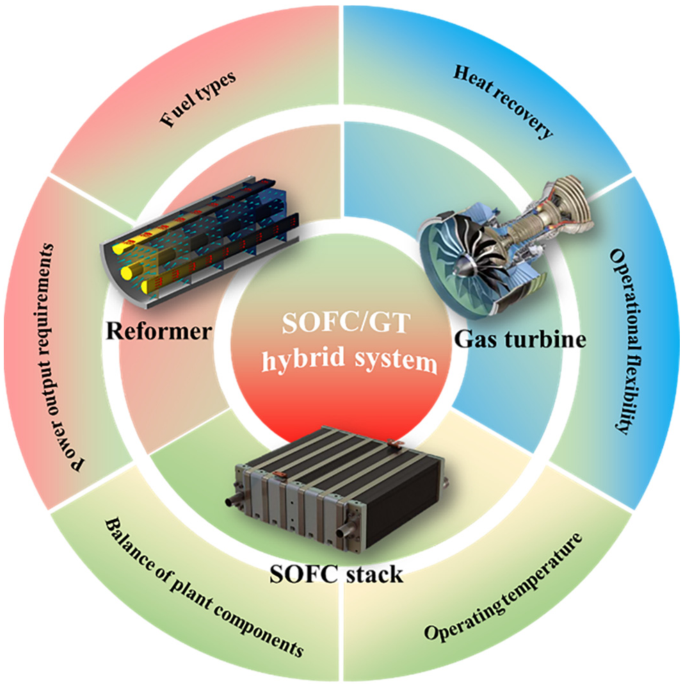

Figure 1. Diagram of main parameters affecting SOFC/GT hybrid systems.

The above-mentioned points are just some examples of design parameters that influence the layout selection of a SOFC/GT power plant. Specific requirements and priorities may vary depending on the project and application.

In this paper, we provide a detailed description of the working principle and structure of SOFC and GT, respectively. In addition, we provide a comprehensive overview of the working principle of SOFC/GT-integrated technology, aiming to explore the key factors affecting the system and propose measures to improve its efficiency; and finally, we provide referential comments and insights into the future development of SOFC/GT hybrid systems. Through this comprehensive analysis, we hope to contribute to the promotion of sustainable energy development.

2. Overview of SOFC and GT Technologies

2.1. Brief Introduction of SOFC

As a high-temperature fuel cell, a single cell of SOFC is mainly composed of anode, cathode, and electrolyte; the working mechanism is shown in Figure 2 [47]. Where O^{2-} is the ionic conductor in the electrochemical reaction, the fuel (H_2, CO) oxidizes at the anode and releases electrons to the external circuit, and the oxidizer (O_2) receives the electrons from the external circuit at the cathode side and conducts the reduction reaction. The main chemical reactions equations are as follows:

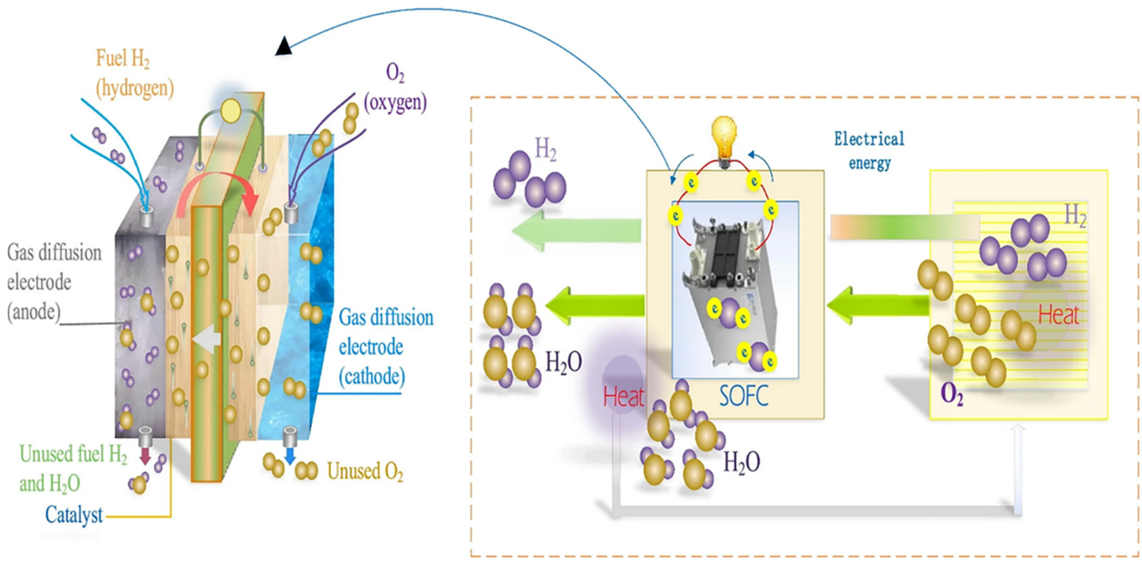

Figure 2. Schematic principle of SOFC [47].

Anode side reaction equation:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \quad (1)$$

Cathode side reaction equation:

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \quad (2)$$

Total reaction equation:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (3)$$

When hydrogen is utilized as a fuel source, the only resulting byproduct is water, making the power generation process nearly emission-free. This makes hydrogen a high-efficiency fuel option. However, the production, storage and transportation of hydrogen are all challenges. So, methane has become a common fuel for SOFCs, in which methane undergoes reforming with hot steam in a reforming plant to produce hydrogen and carbon monoxide, which subsequently react to produce energy [48]. In addition, SOFCs can be internally converted with natural gas and other hydrocarbons to produce the required hydrogen, thus eliminating the need for external equipment [49].

Depending on the physical structure, SOFCs can be divided into tubular (TSOFC) and planar (PSOFC) [50]. Their structures are shown in Figure 3 [51], the TSOFC, developed by Westinghouse company in 1980, demonstrated remarkable durability by resolving the challenge of high temperature sealing. However, its power output was relatively low and the cost was high. In contrast, the PSOFC presented a more cost-effective solution with superior power density and performance, making it the most prevailing commercial SOFC type.

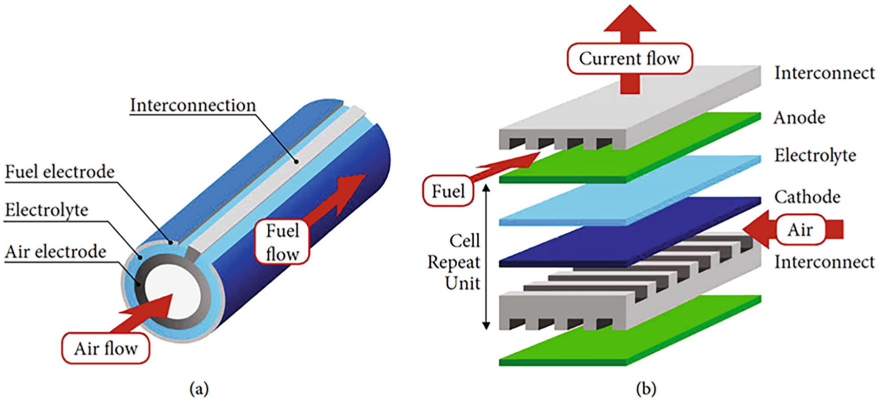

Figure 3. (**a**) Tubular and (**b**) planar structures for SOFCs [51].

The SOFC exhibits remarkable fuel flexibility due to its ability to withstand high operating temperatures [52,53]. This allows for in-fuel reforming reactions to take place at the anode, enabling the use of hydrocarbon fuels like CH_4 and biofuels as reactants. Powered by SOFC technology, Bloom Box micro-power station of Bloom Energy stands out for its capability to utilize a wide range of hydrocarbon fuels, such as ethanol, bio-oil, biogas, and natural gas for electricity generation. Notably, when fossil fuels such as natural gas and oil are used, they produce only 40% of the carbon emissions of conventional power plants, and CH_4 is often chosen as the fuel for SOFC/GT hybrid systems because of its higher efficiency and ease of handling compared to H_2. The incorporation of CH_4 as a fuel in SOFC/GT systems requires an initial fuel reforming procedure. This reforming reaction can take place in various locations, thereby dividing the SOFC system into two categories: internal fuel reforming (IR) and the incorporation of an external fuel reformer. IRSOFC systems are frequently utilized as they do not need an extra reformer, which in turn leads to cost efficiency. Moreover, the fuel reforming reaction, an endothermic process inherent in SOFC stacks, offers a cooling effect [46].

2.2. Brief Introduction of GT

A GT is a type of machinery that utilizes the combustion of gas to generate high-temperature, high-pressure gas for driving the turbine and producing power. Typically, it comprises a compressor, combustion chamber, turbine, and generator. GTs are extensively utilized in power generation, aviation, marine, and industry due to their remarkable efficiency, quick start-up, low emissions, and versatility.

GTs can be categorized into two main types: single cycle GT and combined cycle GT. The single cycle GT structure is shown in Figure 4. It consists of a single turbine, with the gas being compressed by the compressor and then directly burned in the combustion chamber, driving the turbine to spin. The configuration of the combined cycle GT is depicted in Figure 5, which incorporates a waste heat boiler and steam turbine on top of the single cycle setup, utilizing waste heat to enhance energy efficiency. Common fuels include natural gas, gasoline, diesel, and other similar options.

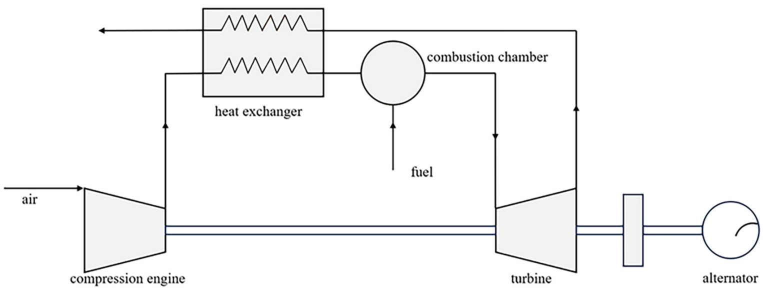

Figure 4. A single cycle gas turbine (including heat exchanger).

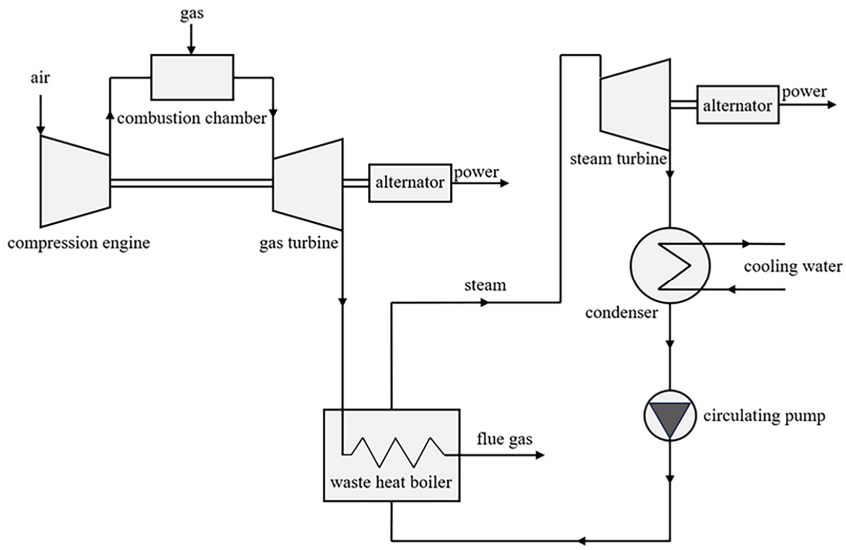

Figure 5. Flow chart of gas and steam combined cycle power generation system.

3. SOFC-GT Integrated Technology

The idea of combining SOFC and GT is actually very simple. The gas stream at the outlet of the anode of SOFC has high energy, which can be utilized to form a hybrid system in combination with GT. The combination mechanism of SOFC and GT can realize the efficient conversion and utilization of energy and improve the overall performance of the system as well as the environmental protection performance [54].

3.1. Layout of SOFC/GT Hybrid System

According to the different locations of SOFC and GT, SOFC/GT hybrid systems can be divided into two categories: top cycle and bottom cycle. In the top cycle, the SOFC stack is placed in front of the GT, and the high-temperature gas flow from the SOFC reaction enters the GT combustion chamber to expand, generating electricity externally through a generator. Whereas the bottom cycle is the opposite of the top cycle: the SOFC stack is placed at the back of the GT, and the high-temperature gas released by the GT serves as a source of air for the cathode of the SOFC stack [55].

Due to the different working pressures of fuel cells, the top cycle is also called pressurized SOFC/GT system (Figure 6), and the bottom cycle is also called atmospheric pressure SOFC/GT system (Figure 7). Among them, the efficiency of the bottom cycle is lower than that of the top cycle, and the cost of heat exchanger components of the bottom cycle is higher. Therefore, the top cycle is often used in SOFC/GT hybrid systems.

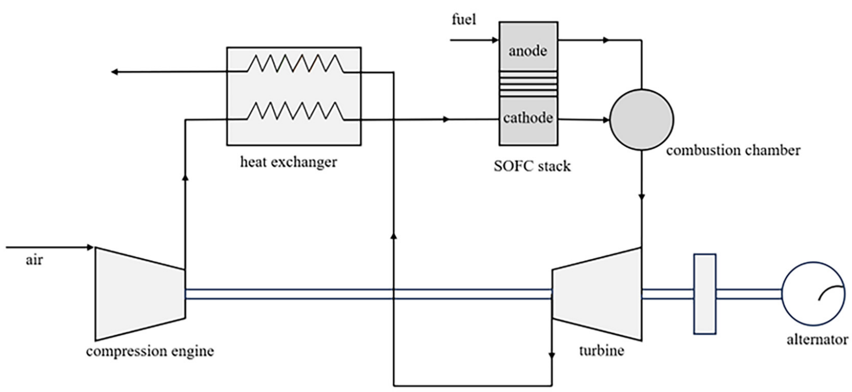

Figure 6. Pressurized SOFC/GT hybrid system.

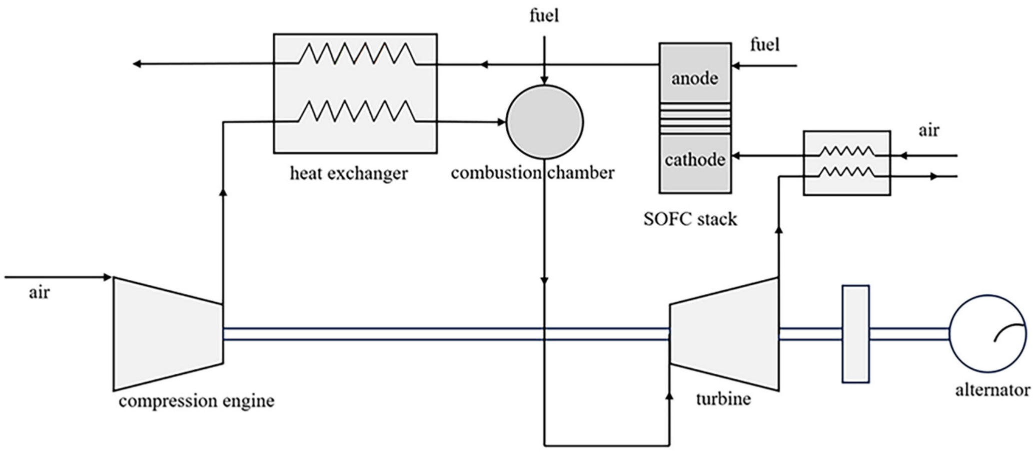

Figure 7. Non-Pressurized SOFC/GT hybrid system.

In recent years, researchers have been working on different SOFC/GT designs in the effort to improve electrical efficiency and reduce initial investment [26,56]. The efficiency and dependability of the system are greatly impacted by the fuel cell's operating pressure choice. If a fuel cell is to be simple and reliable, it should operate at atmospheric pressure [57]. In this scenario, the SOFC functions autonomously from the GT, with a heat exchanger separating the two subsystems. This configuration ensures the safe operation of SOFC and GT. Specifically, the GT can operate properly with an additional burner that adds heat to the air discharged by the SOFC heat exchanger, thereby stabilizing the gas turbine inlet temperature (TIT) value. In addition, the heat transfer between SOFC exhaust gas and incoming air results in lower TIT values compared to pressurized configurations where SOFC exhaust gas goes directly into a gas turbine. Therefore, in terms of power generation efficiency, pressurized design is the best choice. In this setup, the SOFC chimney generates additional power by acting as a burner in the Brayton cycle [58]. Additionally, since this configuration does not require an expensive heat exchanger, it is expected to be more cost-effective than the atmospheric one. However, the trial runs have shown how difficult the direct linked (pressurized) SOFC/GT is. This is mostly because of the limited operational range of a traditional GT power plant with regard to mass flow rates and pressures, which results from the unique characteristics of the turbomachinery. Therefore, the generating capacity of SOFC/GT plants is also limited by the SOFC stack rather than the combustor.

Next, it is essential to select the appropriate thermodynamic cycle (e.g., Brayton, IGCC, Rankine, etc.) and the reforming process [58]. Internal Reforming (Direct, DIR or Indirect, IIR) is the preferred option because of its higher overall efficiencies and lower capital cost. However, in this scenario, controlling the methane conversion rate under all operating conditions may prove to be challenging. Additionally, the DIR configuration may result in significant temperature gradients within the cells, as this process is highly endothermic [30,59–61].

3.2. SOFC/GT Systems That Are Powered by Fuels Other Than Natural Gas

Unlike other fuel cell types that are restricted to hydrogen, SOFCs may use a variety of fuels, including hydrogen, methane, carbon monoxide, biogas, and syngas. Because of their adaptability, SOFC/GT systems may be integrated into a wide range of applications, such as the gasification of biomass, landfill gas, and reformed liquid fuels. Because they are readily available and inexpensive, biomass and syngas generated from coal are typically regarded as the most viable alternative fuels for SOFC/GT systems.

3.2.1. Alternative Fuels: Biomass

Biomass energy is the fourth largest renewable energy source in the world today, and is also an important renewable energy source [62]. Recent studies indicate that biomass and waste collectively account for approximately 10% of global primary energy generation. Crucially, biomass offers a sustainable solution to environmental pollution as it is a carbon-neutral source of fuel. Through partial combustion, biomass can be transformed into producer gas or syngas. The development of power generation systems based on biomass gasification provides a promising and environmentally friendly way to meet the ever-growing demand for electricity.

An analysis of the energy-exergy and sustainability of a new biomass-fueled SOFC/GT hybrid configuration published by A.A. Sinha et al. [63] is compared. A schematic of the proposed hybrid arrangement cycle is shown in Figure 8. Three different biomass fuel types—pine sawdust, aspen sawdust, and apricot shells—are suggested by the research to power this cutting-edge hybrid system. MATLAB-based simulations were used in the study to evaluate the fuel cell hybrid cycle's performance. To assess the system's performance, three important performance metrics were examined: pressure ratio, turbine input temperature, and current density. Each cycle component, as well as the entire system, was assessed using the energy-(exergy) method and the first and second laws of thermodynamics. It was determined that the SOFC/GT hybrid system could achieve maximum efficiency using all three biomass fuels at a pressure ratio of 6 and a turbine input temperature of 1250 K. Pine sawdust demonstrated the highest exergy damage (2653.14 kW), environmental impact (0.91), and the lowest sustainability index (2.09), while also boasting the highest thermal efficiency (63.12%) [64,65]. The findings suggest that biomass fuels have the potential to become an important source of energy for solving the energy crisis and mitigating climate change.

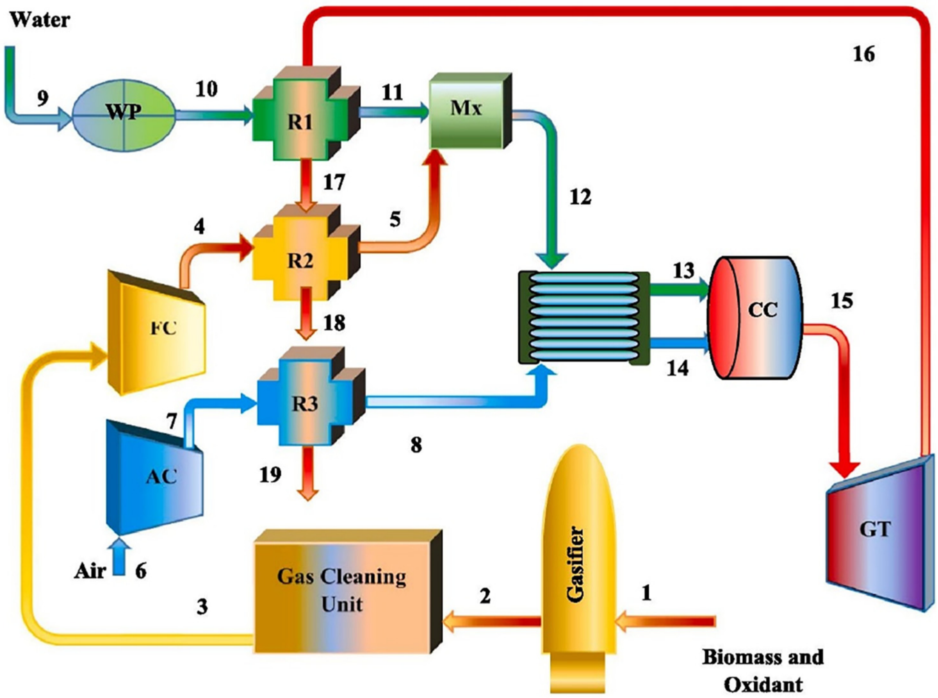

Figure 8. Schematic diagram of the hybrid system design with three different biomass fuels [63].

Fuel suitability analysis of an intermediate temperature solid oxide fuel cell (IT-SOFC) and GT hybrid system fueled by biomass gas is discussed by Ding et al. [66]. Figure 9 shows the schematic diagram of the IT-SOFC/GT hybrid system, which mainly consists of IT-SOFC, single-axis GT, external reformer, catalytic combustor, fuel compressor, water needle pump, and generator. This study presents the design of an IT-SOFC/GT hybrid system for small-scale distributed generation, with an intended output power scale of around 180 kW. After being heated, the biomass gas is sent into the reformer, where it is reformed and sent onto the SOFC's anode side to participate in the electrochemical process. To deliver O_2 to the electrochemical process, the compressed air is first heated to high temperature and pressure by heat exchangers 1 and 2, which then introduce it to the cathode side of the SOFC. The catalytic combustion combustor receives the exhaust gas from the SOFC reaction and burns it entirely. The gas turbine then receives the high-temperature, high-pressure outlet gas, which produces output power.

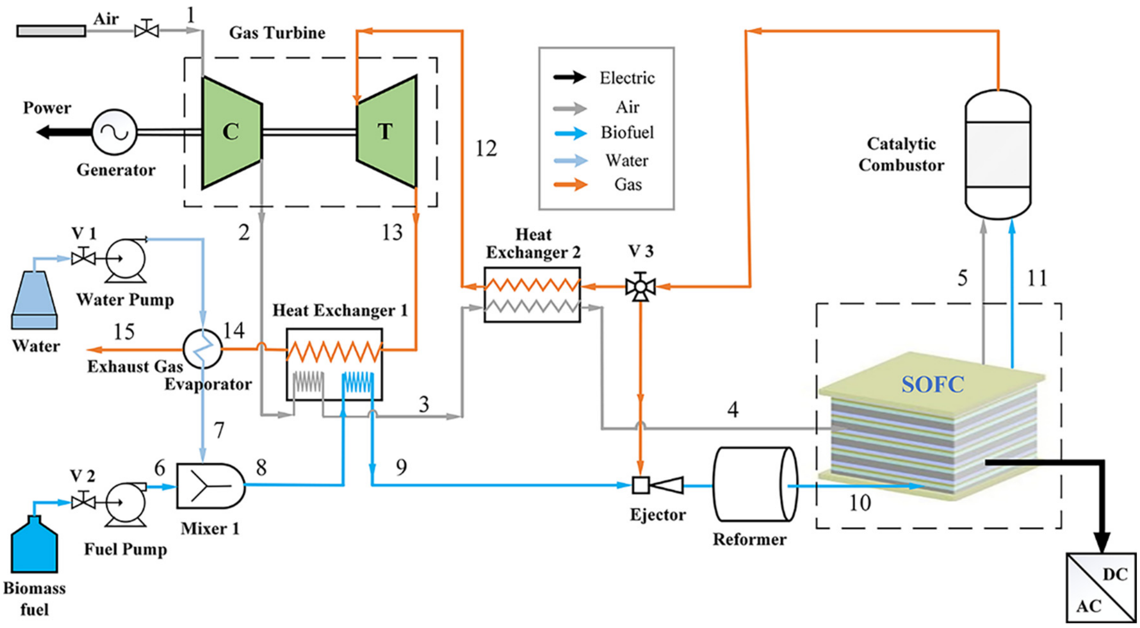

Figure 9. Diagram of an IT-SOFC/GT hybrid system with different biomass fuels expected power scales of 180 kW [66].

The study conducted a thermodynamic analysis of systems using different types of biomass gases as fuel, taking into account component fluctuations. The study compares the system's performance and safety evaluations when dealing with variations in the composition of wood chip gas and farm biogas. Findings indicate that the system can achieve high efficiency using wood chip gas, but its efficiency decreases with farm biogas due to composition fluctuations. The study emphasizes the significant impact of fuel composition variations on system performance and safety and discusses the potential for the use of biomass fuels in hybrid systems [67]. In addition, the literature review emphasizes the limited research that has been conducted on the analysis of system suitability and safety in response to fluctuations in the composition of a wide range of biomass fuels. Regional factors affecting biomass fuel quality are also mentioned.

A parametric study of a recently suggested biomass-based SOFC integrated with GT was carried out by Behzadi et al. [27], The model consists of three primary components: a dual-effect LiBr-H_2O absorption chiller, a reverse osmosis (RO) unit, and SOFC/GT hybrid system (Figure 10). To enhance overall energy efficiency, surplus heat from the SOFC/GT is utilized in a dual-effect cooling system. Additionally, the RO unit utilizes the excess power generated by the GT to produce clean water.

To reduce environmental pollution, the system incorporates a reverse osmosis desalination unit, GT, SOFC, double-effect absorption chiller, and CO_2 recycling. To find the ideal operating conditions, the study uses multi-objective optimization and parametric analysis [68]. The findings demonstrate that, under ideal operating conditions, the suggested system achieves an exergy efficiency of 38.16% and a total product unit cost of 69.47 $/GJ.

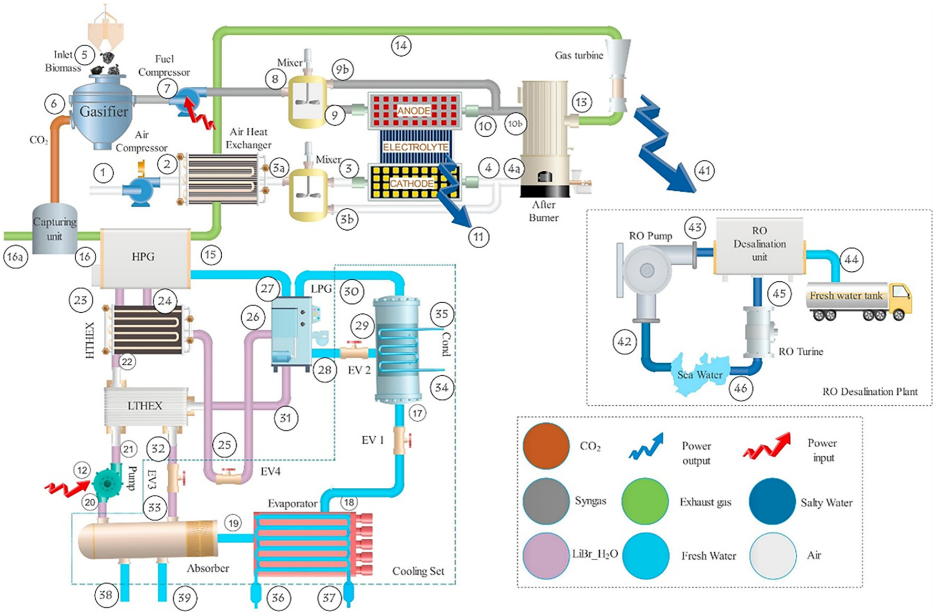

Figure 10. Schematic structure of biomass-based SOFC/GT/double-effect absorption cooler/RO hybrid desalination system with CO_2 cycle [27].

3.2.2. Alternative Fuels: Coal

Numerous research works in the body of the current literature investigate the potential use of coal syngas in SOC/GT hybrid systems. Zhao et al. [69] explored this option. For the effective integration of a syngas-fueled SOFC and GT in a hybrid power plant, the author has described the construction of a thermodynamic modeling and optimization framework (Figure 11). Using an optimization technique, this method links an irreversible GT model with a syngas-fed SOFC model to analyze operating circumstances. The system as a whole is analyzed in terms of energy and entropy balance in order to see how irreversibility is distributed and what role each component plays. In addition, parameter sensitivity analyses were performed to examine the optimal behavior of the system and to predict the sensitivity of system performance to changes in key design and operating parameters [70]. This approach provides a new perspective for the optimal integration of fuel cells, GTs, and other system components in an atmospheric SOFC/GT hybrid cycle.

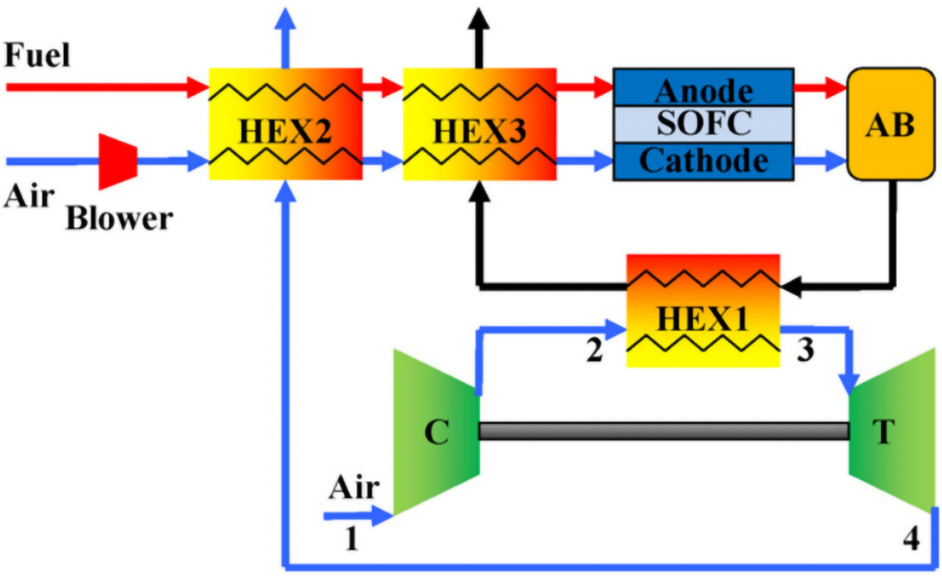

Figure 11. Schematic diagram of the integrated atmospheric syngas-fueled SOFC-GT hybrid system structure [69].

Grigoruk and Kasilova [71] discussed a study of the thermal configuration parameters of a SOFC hybrid system using coal gasification products. The study focused on the efficiency of the system and the effect of different parameters on its performance (Figure 12). The study indicates that the gasification setup with dry particulates has a higher electrical efficiency compared to a water-coal mixture, resulting in a 3–5% decrease due to the reduced calorific value of the fuel gas. In addition, pressurized SOFCs are more electrically efficient, and when the operating pressure of the SOFC stack drops to atmospheric pressure, the electrical efficiency decreases by 5–10%, resulting in a decrease in power output [72]. Furthermore, an increase in efficiency is achieved with a regenerative air preheater, which minimizes heat loss from the SOFC exhaust gases and raises the temperature of the gas supplied to the GT.

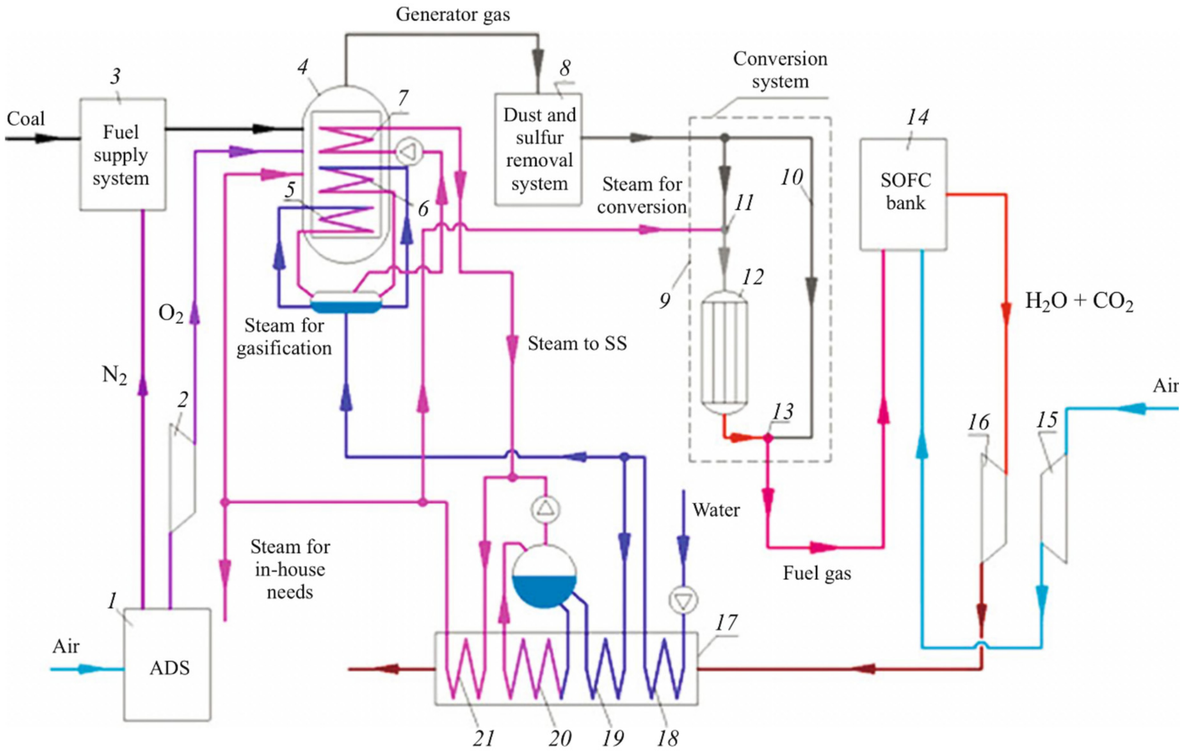

Figure 12. An illustration of a hybrid system's thermal configuration using fuel cells and coal gasification products without CO_2 capture [71].

3.2.3. Alternative Fuels: Ammonia

Ammonia, with the chemical formula NH_3, functions as a hydrogen storage medium. There are a number of ways to use the stored energy, including quick combustion and ammonia dissociation and separation for the recovery of H_2. A fuel cell can then be powered by the hydrogen that has been collected. Ammonia can also be blended with diesel fuel to reduce emissions by 8 tons of CO_2-equivalent and provide a more affordable fuel option for hybrid systems. In addition, ammonia is more economical compared to diesel fuel, and there are several other advantages of ammonia [73,74]:

- Energy Storage: Ammonia serves as a method for storing and transporting hydrogen, which can be extracted from the ammonia to produce power in fuel cells, positioning it as a potential energy carrier.
- Scalability: Compared to hydrogen, ammonia can be produced in large quantities, making it a scalable energy storage and transportation option.
- Versatility: Ammonia has a variety of uses, including as a fuel for internal combustion engines, fuel cells, and as a feedstock for the production of various chemicals.

- Safety: Ammonia boasts a high energy density and can be stored and transported with relative safety, making it a feasible option for energy storage and distribution.

Al-Hamed et al. [75] presented a new integrated system for clean railway electric transport using direct ammonia SOFCs and GTs (Figure 13). The article examines the energy and exergy efficiency of the system and conducts parametric studies to enhance its performance. The utilization of a supercritical ammonia-organic Rankine cycle enhances efficiency in comparison to ammonia-based systems. The article highlights the advantages of using ammonia as a fuel, such as cost-effectiveness, environmental friendliness, and high energy density. The article also discusses the potential for lowering SOFC operating temperatures and the feasibility of using ammonia as a direct fuel.

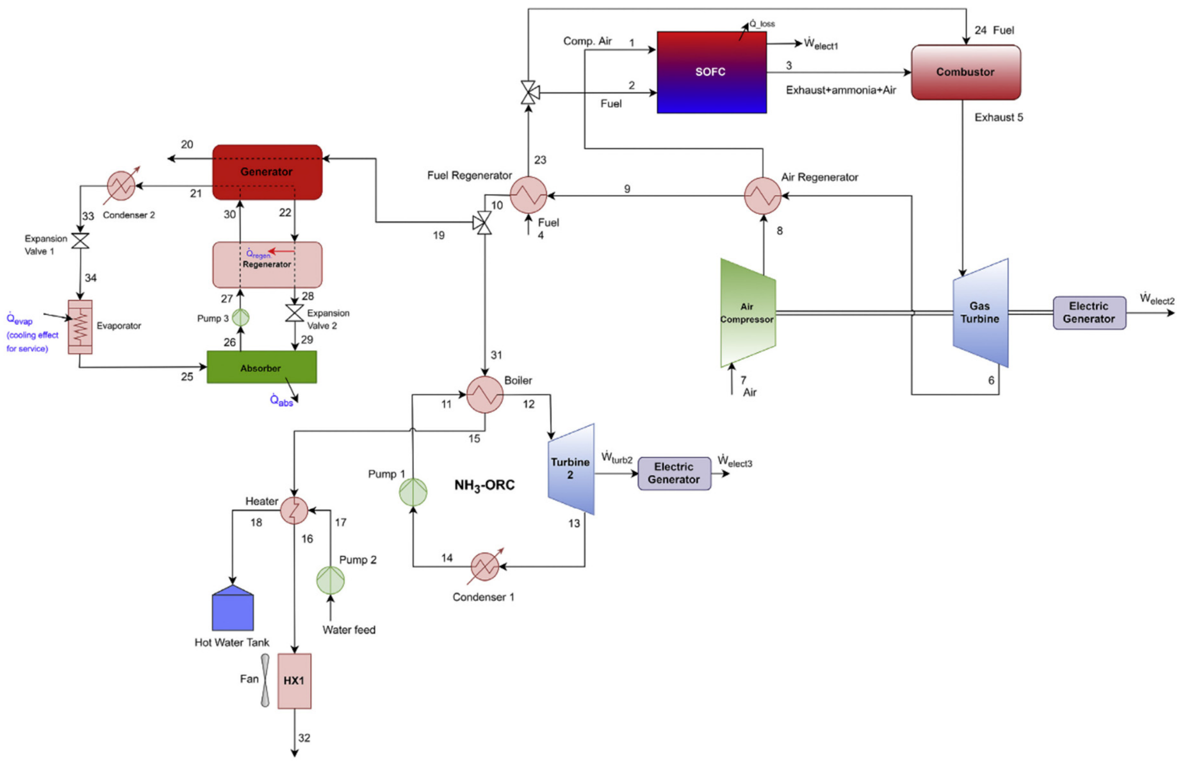

Figure 13. A diagram illustrating the complete ammonia-based SOFC-GT-ORC system with an absorption chiller [75].

F. Ishak et al. [76] presented the integration of a direct ammonia SOFC with a GT in a combined cooling, heating, and power cycle (Figure 14). The comparative analysis is conducted between the integration strategies of oxygen ion-conducting solid oxide fuel cells (O-SOFC) and hydrogen proton-conducting solid oxide fuel cells (H-SOFC or PCFC). The system is aimed at utilizing the cooling properties of ammonia to minimize complexity and cost. A comprehensive study was carried out to evaluate the impact of different operational conditions on energy and exergy efficiencies. The findings indicate that the integrated H-SOFC system outperforms the O-SOFC option. The study also elaborates on the operation of the DA-SOFC and the integrated DA-SOFC/GT systems. The system employs pressurized ammonia for immediate delivery and integrates a closed-loop heat exchanger for thermal exchange. The ammonia extracted is preheated prior to entering the fuel cell stacks, and the heat generated during the electrochemical reaction is utilized. The research offers a comprehensive analysis of the integrated system and its performance under different conditions.

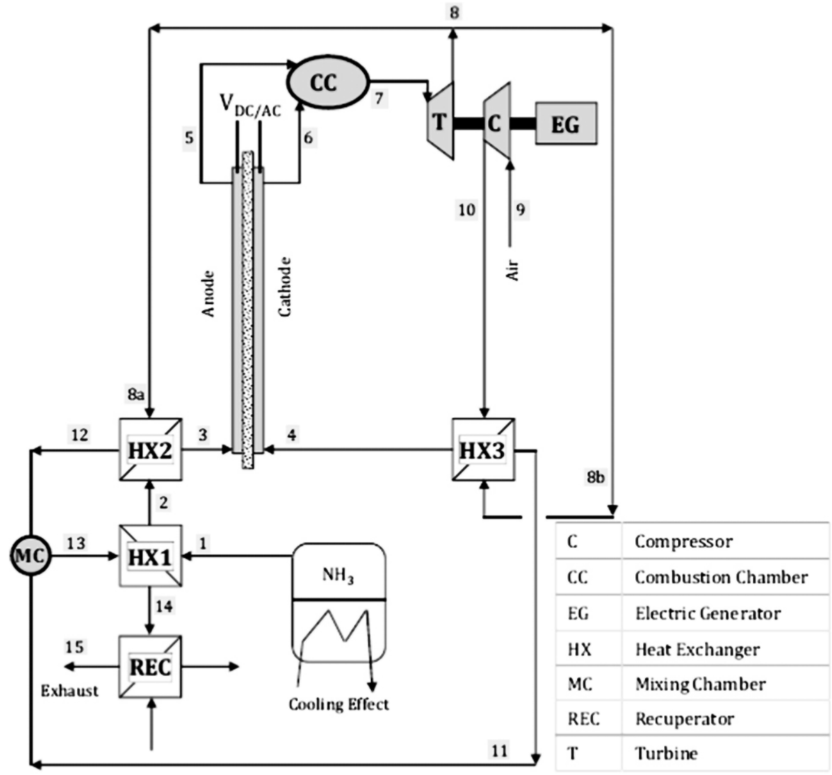

Figure 14. Schematic diagram of integrated DA-SOFC/GT system [76].

In general, SOFC-GT hybrid systems can use a variety of alternative fuels, and there is no doubt that hydrogen, as a clean energy source with water vapor as a by-product, is one of the most suitable fuels, but there are many problems with its manufacture, storage and transportation. In recent years, many researchers have done a lot of research on biomass fuel, coal and ammonia.

The above analysis shows that the use of biomass fuel can reduce the dependence on fossil fuels and reduce greenhouse gas emissions. At the same time, it faces challenges such as high production cost, unstable supply, and low energy density. In the future, as biomass energy technology continues to advance, it is expected to become a more sustainable energy option. As for coal energy, despite its abundant resources and low cost, problems such as its high carbon emissions and serious air pollution make it an unsustainable energy choice, and improving combustion efficiency and carbon dioxide capture capacity is one of the major challenges for future development. Ammonia, as a clean, high-energy-density fuel, has the potential to be the fuel of choice for SOFC-GT systems. However, challenges in terms of its safety, production cost, and supporting facilities need to be addressed to realize the wide application of ammonia in the energy sector. With continued technological advances and cost reductions, ammonia may play an important role in the energy transition.

3.3. Performance Analysis of the SOFC/MGT Hybrid System

In the energy sector, GTs and micro gas turbines (MGTs) are two different types of gas turbines. The dividing line between them is usually based on power levels and application areas. Typically, GTs are more powerful and are used for large-scale energy production and industrial applications, while MGTs are less powerful and are mainly used for micro-energy systems, distributed energy sources, and portable energy devices.

As distributed power generation systems rapidly develop, MGT systems have also progressed. Due to their unique features, MGT can seamlessly integrate with SOFC systems. At present, SOFC/MGT hybrid systems are crucial in the field of distributed power generation. It can improve efficiency and reduce environmental impact, promising to meet the growing demand for distributed energy systems.

L. Fryda et al. [77] investigated the integration of autothermal biomass gasification with SOFC and MGT in small-scale combined heat and power (CHP) systems (Figure 15). Three configurations are compared: gasification at different pressures with SOFC, MGT, or both. The study uses process simulation software to model the system components and conducts an exergy analysis to evaluate system performance. The results show that the electrical efficiency of SOFC/MGT configuration is the highest, reaching 35.6%. The research aims to develop more efficient biomass fuel energy systems and explore the potential of biomass gasification and SOFC technologies for small-scale CHP applications.

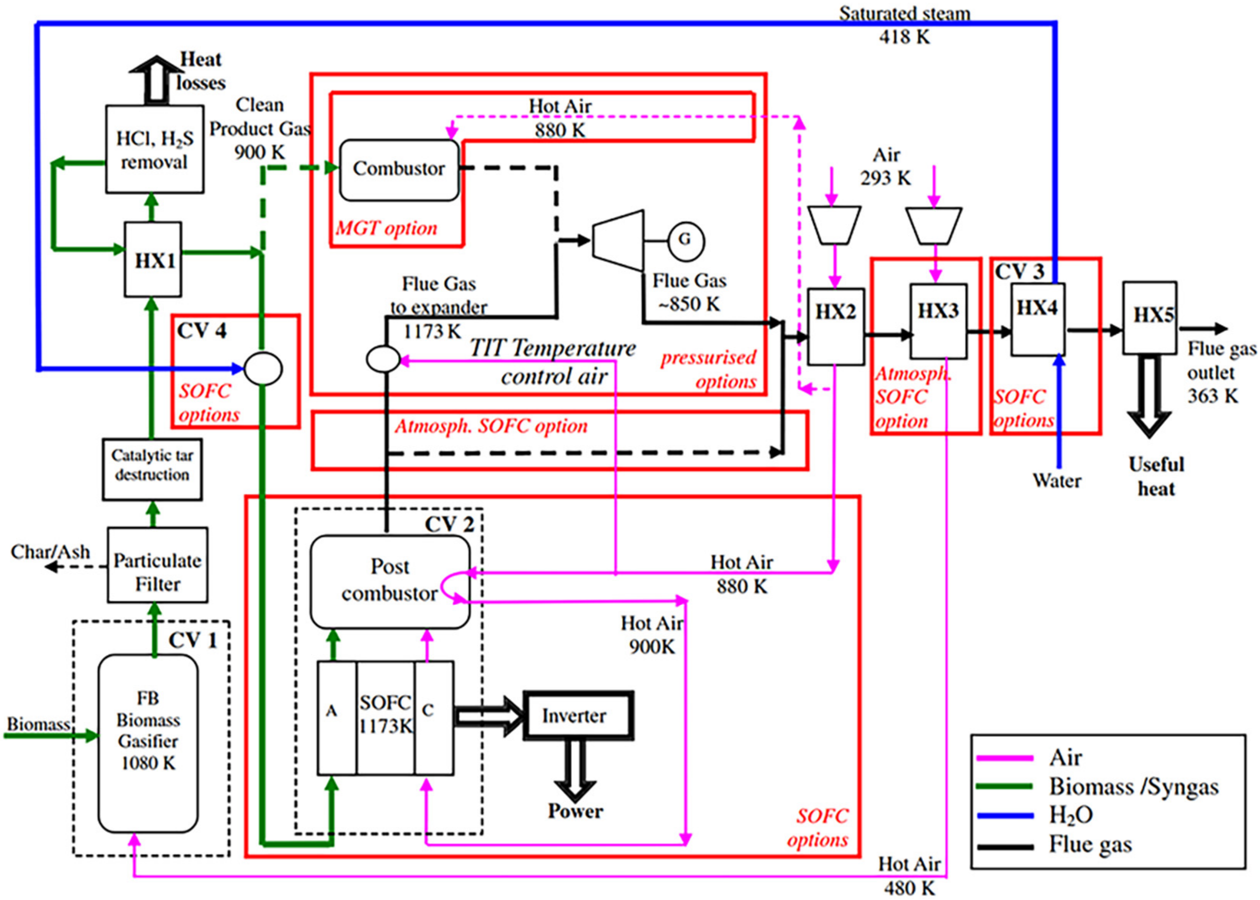

Figure 15. A diagram of the biomass gasification CHP with SOFC and/or MGT [77].

Duan et al. [78] focused on a SOFC/MGT hybrid power system (Figure 16). The study aims to explore and optimize important parameters that significantly affect the overall system performance. It looks into the thermodynamic potential for improving the hybrid system by integrating the SOFC with an advanced thermal cycle system. It also describes how to optimize the main SOFC/MGT hybrid system parameters, with the MGT inlet temperature acting as a constraint. The results indicate that the Turbine Inlet Temperature (TIT) is the primary parameter constraining the electrical efficiency of the hybrid system. In a hybrid system with a fixed number of batteries, increasing the operating temperature of the SOFC can achieve higher power efficiency, but higher operating temperatures can also lead to an increase in TIT. Improving fuel efficiency is seen as an effective method for enhancing the performance of the hybrid system. Additionally, research has shown that as the gas-carbon ratio increases, the electrical efficiency and TIT of the hybrid system will decrease. These findings offer valuable reference points for future research on efficient SOFC/MGT hybrid systems.

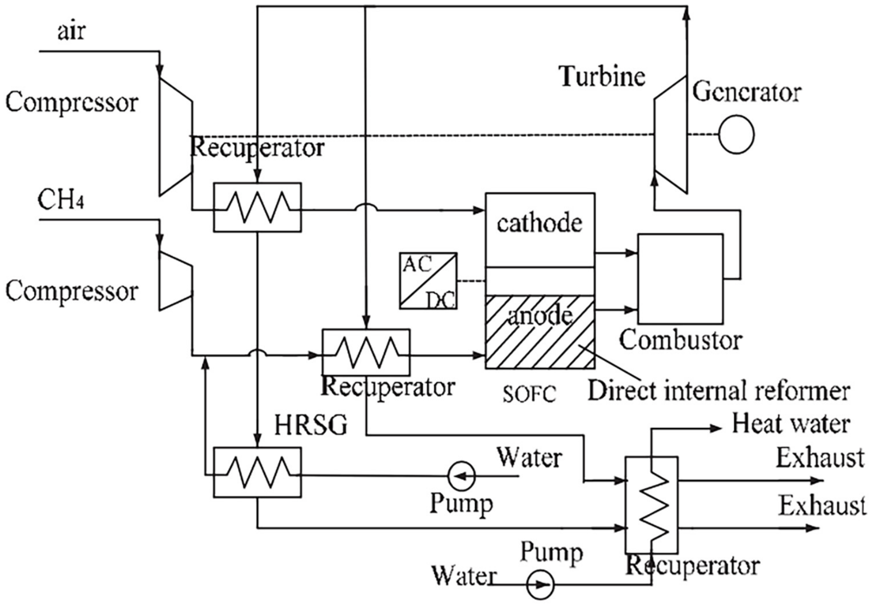

Figure 16. Schematic diagram of the SOFC-MGT hybrid power system [78].

Alessandra Perna et al. [79] examined the performance evaluation of a small-scale hybrid power plant that combines an MGT and a SOFC powered with syngas from a biomass downdraft gasifier (Figure 17). The plant is specifically designed to maximize the production of electric and thermal power, with a focus on decentralized combined heat and power (CHP) plants. The performance evaluation is conducted using a numerical model and validation with experimental data. The research assesses the influence of operational parameters on cogeneration performance, and emphasizes the potential for achieving high electric and cogeneration efficiencies. The article also reviews the growing interest in developing such plants and the need for optimization to increase performance, lower costs, and improve reliability. The study provides valuable insights for the integration of biomass gasification with SOFC/MGT hybrid systems.

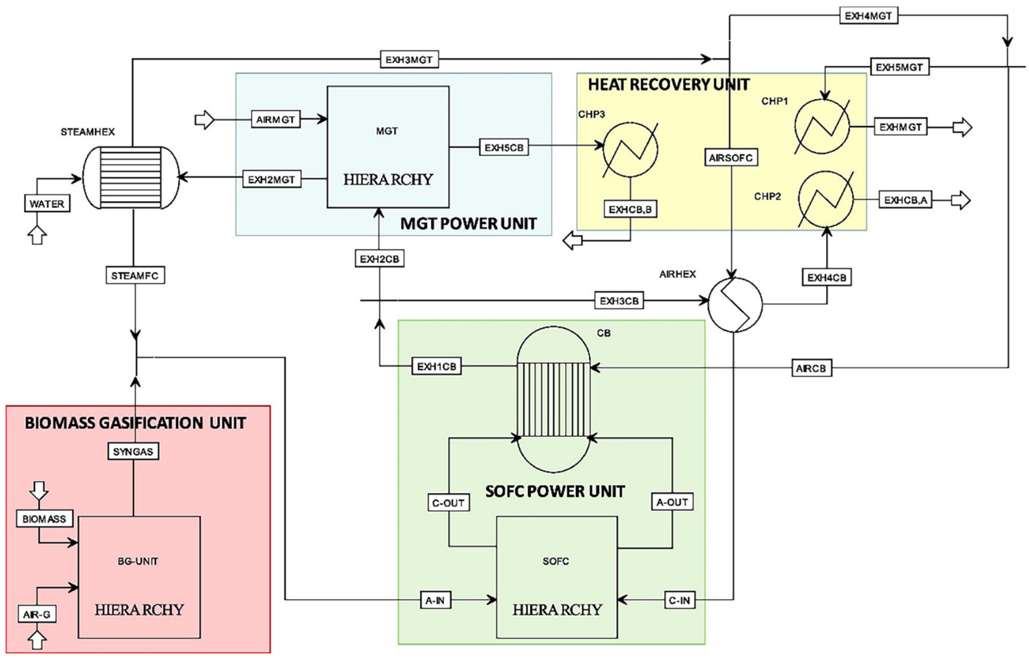

Figure 17. A diagram of the hybrid BG-SOFC/MGT cogeneration plant [79].

Overall, the SOFC-MGT combined cycle system is a highly efficient energy conversion technology with the potential to achieve high power generation and cogeneration efficiencies. However, the high manufacturing and maintenance costs of SOFC-MGT combined-cycle systems make them challenging for commercial applications. Therefore, the development of SOFC-MGT has a long way to go in terms of energy and environmental benefits.

4. Application of SOFC/GT Hybrid System

Fuel cells are indeed an important energy conversion technology, directly transforming chemical energy into electrical energy. They are often regarded as the fourth power generation method, following thermal power, hydropower, and nuclear power. While the application of SOFC/GT technology has gained significant attention in recent years. This advanced power generation system combines the high efficiency of a GT with the clean and reliable energy production of a SOFC.

The SOFC/GT technology has been widely adopted in various industries, such as power generation, aerospace, and military applications (Figure 18). Its versatility and ability to operate on a wide range of fuels, including natural gas, biogas, and hydrogen, make it a sustainable energy solution. In the power generation sector, SOFC/GT systems have demonstrated higher electrical efficiency and lower emissions compared to traditional power plants, making them an attractive option for meeting the increasing demand for clean and efficient energy production. In the aerospace and military sectors, the compact size and high power density of SOFC/GT systems make them suitable for remote or mobile power applications. Their ability to operate on a variety of fuels also provides flexibility in fuel supply logistics. As research and development in this field continue to progress, we can expect to see even greater adoption of this innovative technology in the future, which holds great promise for advancing the efficiency and sustainability of energy production across various industries.

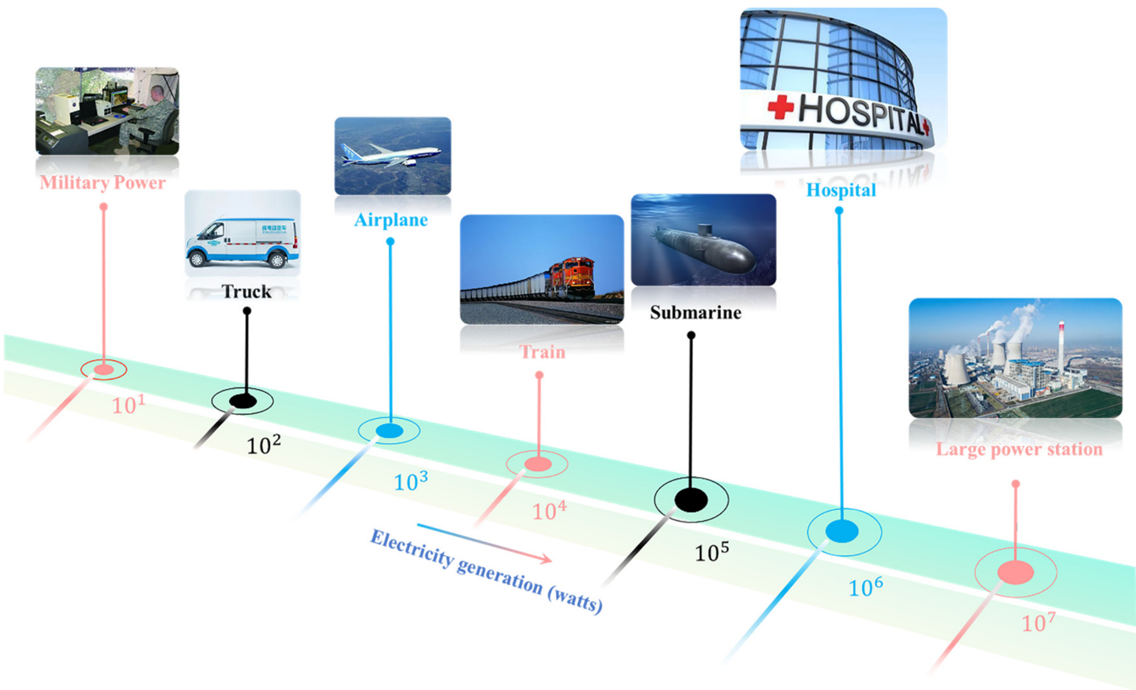

Figure 18. Applications of SOFC/GT.

Mousa Meratizaman et al. [80] propose a combined cycle SOFC/GT (11–42.9 kWe) in the kilowatt range to fulfill the energy needs of household applications. Figure 19 illustrates the layout of the system under examination. The author has developed a proposed system structure based on an industrial model from Siemens Westinghouse (Siemens) to meet the building's demand for electrical energy, cooling, and heating. This system includes a

SOFC, internal reformer, fuel compressor, air compressor, GT, and three heat exchangers. Preheated air and fuel are delivered to the fuel cell, with any excess fuel being burned in the combustor. The resulting high-temperature gas flow is then utilized to power the gas expander for the second stage of power generation. In order to minimize energy waste in the GT stack, the air and fuel are preheated using an air heat exchanger and a fuel heat exchanger before entering the SOFC.

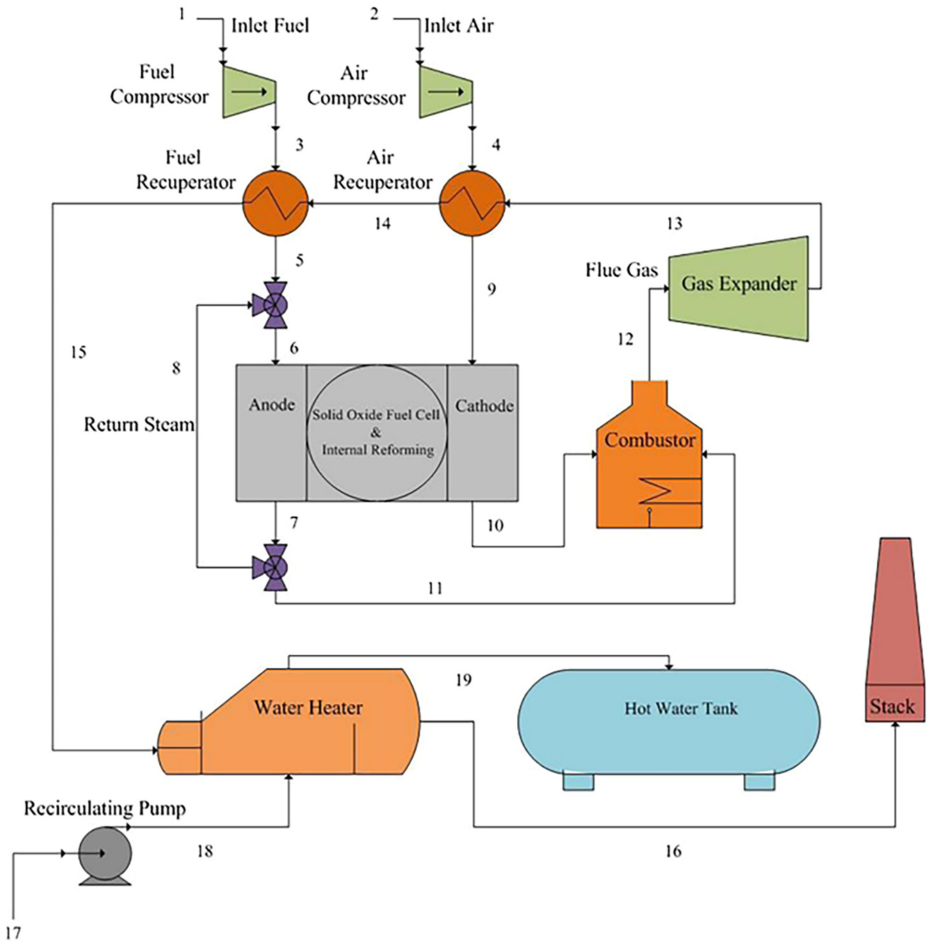

Figure 19. A diagram of SOFC-GT combined heat and power system [80].

While thermodynamic simulations of the SOFC/GT power generation system were carried out, it was also integrated into a four-story building to assess energy consumption. Each floor is 100 square meters. After determining the electrical and thermal load requirements of the building, the scale of the proposed system was determined and an economic assessment was conducted. The study focused on four different climate zones in Iran. The results show that the SOFC/GT system is most economically viable in Ahvaz, where the climate is hot and humid. In Ahvaz, the main cost per KWH of electricity is USD 0.0208 and the payback period is 8.3494 years.

Berend et al. [51] thoroughly examined the key features in the major components of SOFC systems in order to achieve insight into the potential for a marine SOFC power plant. This research explores SOFC stacks, balance of plant components, and combined cycles (Figure 20).

The article examines advancements in SOFC systems, encompassing power plant choices, potential fuel options, and the factors influencing the design of marine power plants. It also discusses the integration of SOFC systems with ships. The article also highlights the need for a holistic approach to improve marine SOFC systems and the potential for hybridization to make ships technically and economically feasible. It emphasizes the significant reduction in greenhouse gases, NO_X, SO_X, PM, and noise emissions that SOFC systems could bring to the shipping industry. The review also identifies the challenges and opportunities for implementing SOFCs in marine applications, providing insights for marine industry stakeholders.

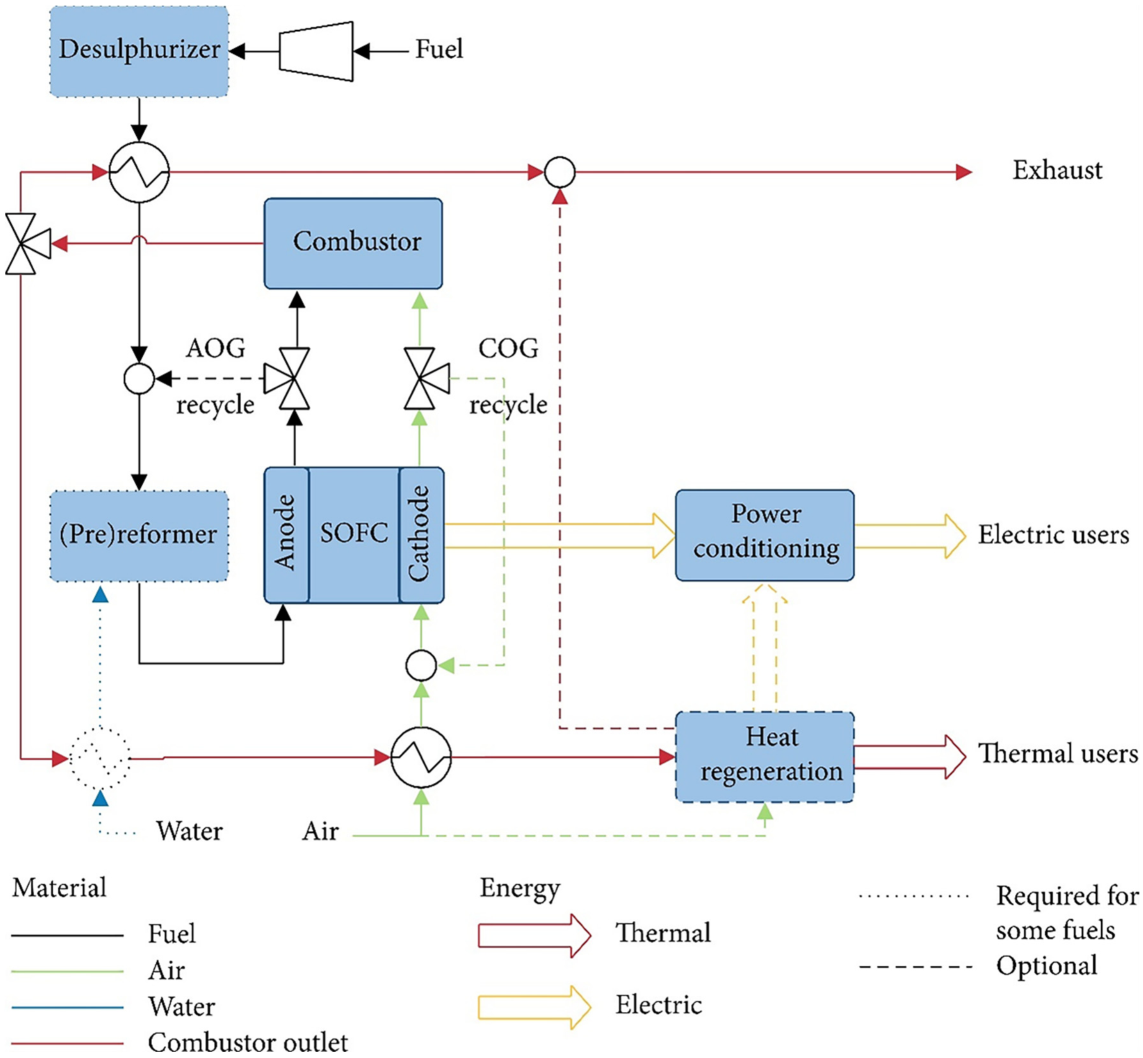

Figure 20. Diagram showing the layout of SOFC power plants. AOG represents anode off-gas, while COG represents cathode off-gas [51].

He et al. [81] conducted a comparative study of different fuel types for SOFC/GT hybrid systems for electric propulsion aircraft (Figure 21). The study evaluates the impact of fuel types on the performance, mass, and storage capacity of the system. It investigates the thermodynamic performance and CO_2 emissions of the system when fueled by hydrogen, ethanol, and various alkanes. The results indicate that methane exhibits the best hydrogen production performance, while n-decane achieves higher electrical efficiency. Additionally, the study considers the impact of fuel types on the aircraft's range and CO_2 emissions. It highlights how crucial it is to assess fuel kinds according to mass and thermodynamic performance, especially for electric aircraft driven by the SOFC/GT hybrid system.

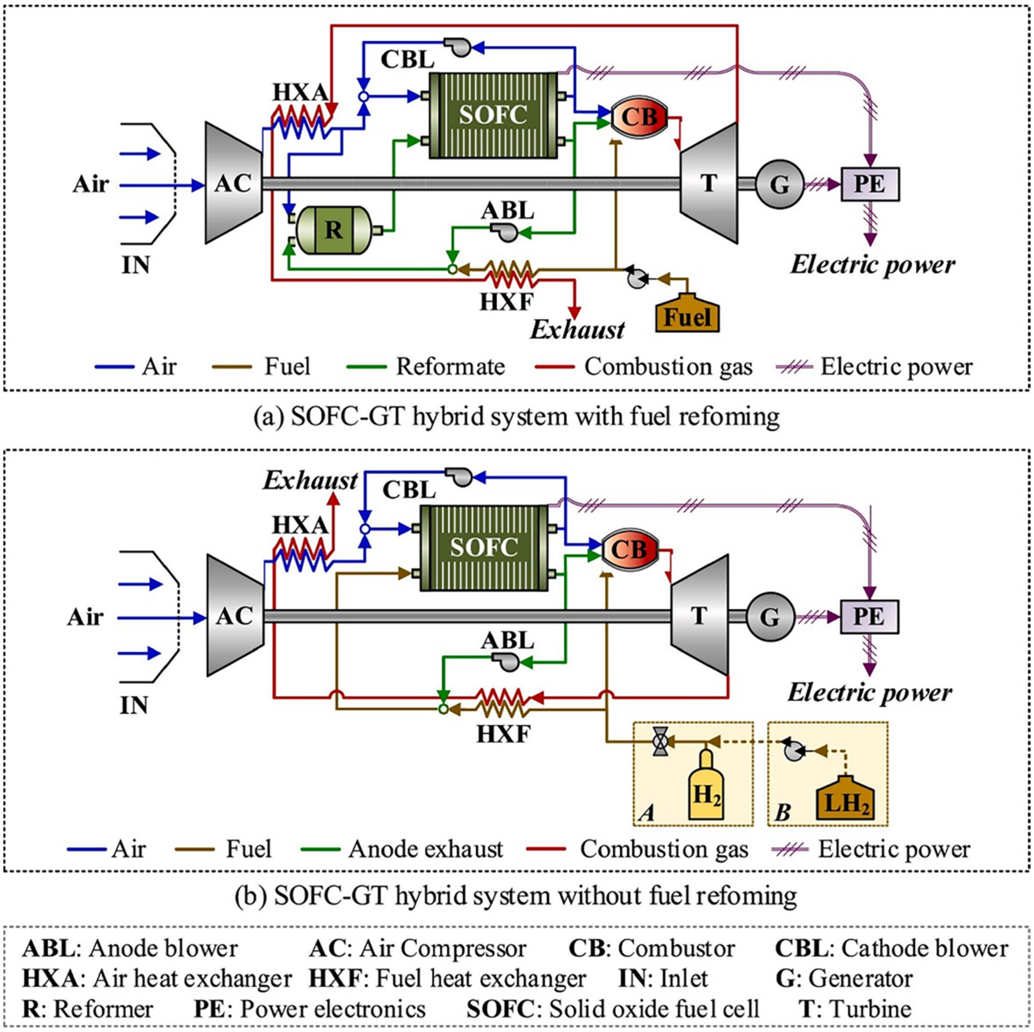

Figure 21. Schematic diagram of SOFC-GT hybrid system with different fuels [81].

5. Conclusions

One of the most promising energy conversion technologies for a long time has been acknowledged as being SOFCs. Regardless of system size, they exhibit remarkable electrical and thermal efficiency while operating at high temperatures. Because of this intrinsic feature, SOFCs—which have the potential to achieve up to 70% theoretical efficiencies—are very appealing for incorporation into hybrid cycles. Consequently, both academia and industry have dedicated substantial research efforts over the past few decades to develop economically viable SOFC systems. This has led to the creation of a wide range of systems, encompassing virtually all possible configurations of hybrid SOFC/GT systems. The potential of SOFCs as a clean and efficient energy source has garnered significant attention, and ongoing research endeavors aim to further refine and optimize these systems for widespread implementation.

Generally, the literature review led to several important results and conclusions, which are summarized as follows:

(1) Most SOFC/GT power plants utilize a pressurized configuration, which enables higher conversion efficiencies and lower capital costs. However, this setup necessitates more complex and restricted operational management. When replacing a conventional gas burner of a Brayton cycle with a SOFC stack in this configuration, it further limits the possible operational range of the hybrid cycle.

(2) In theory, SOFC/GT power plants have the potential to be fueled by a range of fuels beyond natural gas. Of particular interest is the potential to use gasified biomass to

fuel SOFC/GT systems, thereby integrating the use of a renewable energy source. In addition, ammonia as an alternative fuel improves the efficiency of SOFC-GT hybrid systems, increases renewability, and has high supply stability and security.
(3) The SOFC/MGT hybrid system is a promising technology for power generation. It combines the high efficiency of SOFC with the flexibility and reliability of MGT. This system has the potential to provide clean and efficient power generation for various applications. However, further research and development are needed to optimize the performance and cost-effectiveness of the SOFC/MGT hybrid system. Overall, this technology shows great promise for the future of power generation.
(4) SOFC/GT hybrid systems have a wide range of applications in various industries. Additionally, they are also used in distributed power generation for industrial and commercial facilities. The high efficiency and low emissions of SOFC/GT systems make them an attractive option for energy production in environmentally sensitive areas. Furthermore, these systems are increasingly being utilized in the transportation sector for auxiliary power units in ships and aircraft. Overall, the versatility and reliability of SOFC/GT hybrid systems make them a valuable asset in a variety of application areas.

6. Challenges and Prospects of SOFC/GT Technology

SOFC/GT technology has been gaining attention because its promising solution for clean and efficient power generation. However, it also faces a series of challenges and prospects.

One of the main challenges of SOFC/GT technology is the high cost of materials and manufacturing. The use of expensive materials such as ceramics and precious metals for the fuel cells, as well as the complex manufacturing processes, contribute to the high cost of the technology. Additionally, the need for advanced control systems and integration of the fuel cell and gas turbine components adds to the overall cost.

Another challenge is the durability and reliability of the SOFC/GT systems. The high operating temperatures and thermal cycling can lead to degradation of the fuel cell components, reducing their lifespan and performance. This requires continuous research and development to improve the durability and reliability of the technology.

Despite these challenges, SOFC/GT technology holds great prospects in the future. It offers high electrical efficiency, low emissions, and fuel flexibility, making it an attractive option for power generation. The ability to utilize a wide range of fuels, including natural gas, biogas, and hydrogen, makes it a versatile technology that can adapt to different energy sources.

Furthermore, the potential for combined heat and power generation makes SOFC/GT systems even more appealing, as they can provide both electricity and heat for various applications, such as industrial processes and district heating.

In conclusion, while SOFC/GT technology faces challenges such as high costs and durability issues, its prospects for clean and efficient power generation are promising. With ongoing research and development efforts, it has the potential to become a leading technology in the energy sector.

Funding: This work was financially supported by National Natural Science Foundation of China (Nos. 21701083, 22179054). The key technologies R & D program of Jiangsu Province (BZ2023010).

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sun, Z.; Pan, J.; Chen, W.; Chen, H.; Zhou, S.; Wu, X.; Wang, Y.; Kim, K.; Li, J.; Liu, H.; et al. Electrochemical Processes and Reactions In Rechargeable Battery Materials Revealed via In Situ Transmission Electron Microscopy. *Adv. Energy Mater.* **2023**, *14*, 2303165. [CrossRef]

2. Wang, H.; Wang, Q.; Cao, X.; He, Y.; Wu, K.; Yang, J.; Zhou, H.; Liu, W.; Sun, X. Thiol-Branched Solid Polymer Electrolyte Featuring High Strength, Toughness, and Lithium Ionic Conductivity for Lithium-Metal Batteries. *Adv. Mater.* **2020**, *32*, 2001259. [CrossRef] [PubMed]
3. Wang, Q.; Yang, C.; Yang, J.; Wu, K.; Qi, L.; Tang, H.; Zhang, Z.; Liu, W.; Zhou, H. Stable Li metal anode with protected interface for high-performance Li metal batteries. *Energy Storage Mater.* **2018**, *15*, 249–256. [CrossRef]
4. Wei, T.; Wang, Z.; Zhang, M.; Zhang, Q.; Lu, J.; Zhou, Y.; Sun, C.; Yu, Z.; Wang, Y.; Qiao, M.; et al. Activated metal-organic frameworks (a-MIL-100 (Fe)) as fillers in polymer electrolyte for high-performance all-solid-state lithium metal batteries. *Mater. Today Commun.* **2022**, *31*, 103518. [CrossRef]
5. Wang, Q.; Yang, C.; Yang, J.; Wu, K.; Hu, C.; Lu, J.; Liu, W.; Sun, X.; Qiu, J.; Zhou, H. Dendrite-Free Lithium Deposition via a Superfilling Mechanism for High-Performance Li-Metal Batteries. *Adv. Mater.* **2019**, *31*, e1903248. [CrossRef] [PubMed]
6. Liu, Z.; Liu, X.; Wang, B.; Wang, X.; Lu, D.; Shen, D.; Sun, Z.; Liu, Y.; Zhang, W.; Zhang, Q.; et al. Ultra-thick, dense dual-encapsulated Sb anode architecture with conductively elastic networks promises potassium-ion batteries with high areal and volumetric capacities. *eScience* **2023**, *3*, 100177. [CrossRef]
7. Xiong, Q.; Li, X.; Zhou, M.; Chen, R.; Sun, C.; Zhou, Y.; Wang, S.; Qiu, X.; Song, M.; Wei, T. One-pot hydrothermal synthesis of flower-shaped Zif-67@NiCo-LDH heterostructure as anode materials for lithium-ion batteries. *Ionics* **2023**, *29*, 1741–1749. [CrossRef]
8. Zhang, Q.; Wang, S.; Liu, Y.; Wang, M.; Chen, R.; Zhu, Z.; Qiu, X.; Xu, S.; Wei, T. UiO-66-NH_2@67 Core-shell MOF as Fillers in Solid Composite Electrolytes for High-Performance All-Solid-State Lithium Metal Batteries. *Energy Technol.* **2023**, *11*, 2201438. [CrossRef]
9. Lu, J.; Wang, Z.; Zhang, Q.; Sun, C.; Zhou, Y.; Wang, S.; Qiu, X.; Xu, S.; Chen, R.; Wei, T. The effects of amino groups and open metal sites of MOFs on polymer-based electrolytes for all-solid-state lithium metal batteries. *Chin. J. Chem. Eng.* **2023**, *60*, 80–89. [CrossRef]
10. Zhang, Q.; Wei, T.; Lu, J.; Sun, C.; Zhou, Y.; Wang, M.; Liu, Y.; Xiao, B.; Qiu, X.; Xu, S. The effects of PVB additives in MOFs-based solid composite electrolytes for all-solid-state lithium metal batteries. *J. Electroanal. Chem.* **2022**, *926*, 116935. [CrossRef]
11. Wei, T.; Zhang, Q.; Wang, S.; Wang, M.; Liu, Y.; Sun, C.; Zhou, Y.; Huang, Q.; Qiu, X.; Tian, F. A gel polymer electrolyte with IL@UiO-66-NH_2 as fillers for high-performance all-solid-state lithium metal batteries. *Int. J. Miner. Metall. Mater.* **2023**, *30*, 1897–1905. [CrossRef]
12. Wei, T.; Zhang, Z.H.; Wang, Z.M.; Zhang, Q.; Ye, Y.S.; Lu, J.H.; Rahman, Z.U.; Zhang, Z.W. Ultrathin Solid Composite Electrolyte Based on $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$/PVDF-HFP/LiTFSI/Succinonitrile for High-Performance Solid-State Lithium Metal Batteries. *ACS Appl. Energy Mater.* **2020**, *3*, 9428–9435. [CrossRef]
13. Wei, T.; Zhang, Z.H.; Zhang, Q.; Lu, J.H.; Xiong, Q.M.; Wang, F.Y.; Zhou, X.P.; Zhao, W.J.; Qiu, X.Y. Anion-immobilized solid composite electrolytes based on metal-organic frameworks and superacid ZrO_2 fillers for high-performance all solid-state lithium metal batteries. *Int. J. Miner. Metall. Mater.* **2021**, *28*, 1636–1646. [CrossRef]
14. Wei, T.; Lu, J.; Wang, M.; Sun, C.; Zhang, Q.; Wang, S.; Zhou, Y.; Chen, D.; Lan, Y.-Q. MOF-Derived Materials Enabled Lithiophilic 3D Hosts for Lithium Metal Anode—A Review. *Chin. J. Chem.* **2023**, *41*, 1861–1874. [CrossRef]
15. Wei, T.; Lu, J.; Zhang, P.; Yang, G.; Sun, C.; Zhou, Y.; Zhuang, Q.; Tang, Y. Metal-organic framework-derived Co_3O_4 modified nickel foam-based dendrite-free anode for robust lithium metal batteries. *Chin. Chem. Lett.* **2023**, *34*, 107947. [CrossRef]
16. Wei, T.; Zhou, Y.; Sun, C.; Liu, L.; Wang, S.; Wang, M.; Liu, Y.; Huang, Q.; Zhuang, Q.; Tang, Y. Prestoring lithium into SnO_2 coated 3D carbon fiber cloth framework as dendrite-free lithium metal anode. *Particuology* **2024**, *84*, 89–97. [CrossRef]
17. Wang, Q.; Wan, J.; Cao, X.; Wen, R.; Guo, Y.; Liu, W.; Zhou, H. Organophosphorus Hybrid Solid Electrolyte Interphase Layer Based on LixPO4 Enables Uniform Lithium Deposition for High-Performance Lithium Metal Batteries. *Adv. Funct. Mater.* **2021**, *32*, 2107923. [CrossRef]
18. Wei, T.; Lu, J.; Zhang, P.; Zhang, Q.; Yang, G.; Yang, R.; Chen, D.; Wang, Q.; Tang, Y. An intermittent lithium deposition model based on bimetallic MOFs derivatives for dendrite-free lithium anode with ultrahigh areal capacity. *Chin. Chem. Lett.* **2023**, 109122. [CrossRef]
19. Zhang, Z.-H.; Wei, T.; Lu, J.-H.; Xiong, Q.-M.; Ji, Y.-H.; Zhu, Z.-Y.; Zhang, L.-T. Practical development and challenges of garnet-structured $Li_7La_3Zr_2O_{12}$ electrolytes for all-solid-state lithium-ion batteries: A review. *Int. J. Miner. Metall. Mater.* **2021**, *28*, 1565–1583. [CrossRef]
20. Barelli, L.; Bidini, G.; Ottaviano, A. Integration of SOFC/GT hybrid systems in Micro-Grids. *Energy* **2017**, *118*, 716–728. [CrossRef]
21. Chen, J.; Li, Y.; Zhang, H.; Weng, S. Comparison of different fuel cell temperature control systems in an anode and cathode ejector-based SOFC-GT hybrid system. *Energy Convers. Manag.* **2021**, *243*, 114353. [CrossRef]
22. Harun, N.F.; Tucker, D.; Adams, T.A. II, Technical challenges in operating an SOFC in fuel flexible gas turbine hybrid systems: Coupling effects of cathode air mass flow. *Appl. Energy* **2017**, *190*, 852–867. [CrossRef]
23. Harvey, S.; Richter, H. A detailed study of a gas turbine cycle with an integrated internal reforming solid oxide fuel cell. In Proceedings of the Intersociety Energy Conversion Engineering Conference, Monterey, CA, USA, 7–12 August 1994. [CrossRef]
24. Meng, Q.; Han, J.; Kong, L.; Liu, H.; Zhang, T.; Yu, Z. Thermodynamic analysis of combined power generation system based on SOFC/GT and transcritical carbon dioxide cycle. *Int. J. Hydrogen Energy* **2017**, *42*, 4673–4678. [CrossRef]
25. Singh, O.; Singh, R. Thermodynamic evaluation of SOFC-GT hybrid power and cooling system. *Energy Sources Part A Recovery Util. Environ. Eff.* **2021**, *43*, 1975–1989. [CrossRef]

26. Xia, M.; Yao, S.; Ying, C. Analysis and multi-objective optimization of SOFC/GT/SCO2 hybrid power system based on thermodynamics and economics. *Appl. Therm. Eng.* **2023**, *232*, 121033. [CrossRef]
27. Behzadi, A.; Habibollahzade, A.; Zare, V.; Ashjaee, M. Multi-objective optimization of a hybrid biomass-based SOFC/GT/double effect absorption chiller/RO desalination system with CO_2 recycle. *Energy Convers. Manag.* **2019**, *181*, 302–318. [CrossRef]
28. Lei, Y.; Ye, S.; Xu, Y.; Kong, C.; Xu, C.; Chen, Y.; Huang, W.; Xiao, H. Multi-objective optimization and algorithm improvement on thermal coupling of SOFC-GT-ORC integrated system. *Comput. Chem. Eng.* **2022**, *164*, 107903. [CrossRef]
29. Shamoushaki, M.; Ehyaei, M.A.; Ghanatir, F. Exergy, economic and environmental analysis and multi-objective optimization of a SOFC-GT power plant. *Energy* **2017**, *134*, 515–531. [CrossRef]
30. Bao, C.; Shi, Y.; Li, C.; Cai, N.; Su, Q. Multi-level simulation platform of SOFC-GT hybrid generation system. *Int. J. Hydrogen Energy* **2010**, *35*, 2894–2899. [CrossRef]
31. Huang, Y.; Turan, A. Fuel sensitivity and parametric optimization of SOFC—GT hybrid system operational characteristics. *Therm. Sci. Eng. Prog.* **2019**, *14*, 100407. [CrossRef]
32. Lai, H.; Harun, N.F.; Tucker, D.; Adams, T.A., II. Design and eco-technoeconomic analyses of SOFC/GT hybrid systems accounting for long-term degradation effects. *Int. J. Hydrogen Energy* **2021**, *46*, 5612–5629, Correction in *Int. J. Hydrogen Energy* **2022**, *47*, 18530–18531. [CrossRef]
33. Chen, J.; Sun, S.; Chen, Y.; Zhang, H.; Lu, Z. Study on Model Evolution Method Based on the Hybrid Modeling Technology With Support Vector Machine for an SOFC-GT System. *J. Electrochem. Energy Convers. Storage* **2023**, *20*, 011015. [CrossRef]
34. Faleh, S.; Khir, T.; Ben Brahim, A. Energetic Performance Optimization of a SOFC-GT Hybrid Power Plant. *Arab. J. Sci. Eng.* **2017**, *42*, 1505–1515. [CrossRef]
35. Sghaier, S.F.; Khir, T.; Ben Brahim, A. Energetic and exergetic parametric study of a SOFC-GT hybrid power plant. *Int. J. Hydrogen Energy* **2018**, *43*, 3542–3554. [CrossRef]
36. Chen, J.; Li, J.; Zhou, D.; Zhang, H.; Weng, S. Control strategy design for a SOFC-GT hybrid system equipped with anode and cathode recirculation ejectors. *Appl. Therm. Eng.* **2018**, *132*, 67–79. [CrossRef]
37. Chen, J.; Liang, M.; Zhang, H.; Weng, S. Study on control strategy for a SOFC-GT hybrid system with anode and cathode recirculation loops. *Int. J. Hydrogen Energy* **2017**, *42*, 29422–29432. [CrossRef]
38. Waechter, C.; Lunderstaedt, R.; Joos, F. Using Linear Control Theory for Parameterization of a Controller for a SOFC/GT Hybrid Power Plant. *J. Fuel Cell Sci. Technol.* **2010**, *7*, 031003. [CrossRef]
39. Wang, X.; Lv, X.; Mi, X.; Spataru, C.; Weng, Y. Coordinated control approach for load following operation of SOFC-GT hybrid system. *Energy* **2022**, *248*, 123548. [CrossRef]
40. Wu, W.; Chen, S.-A.; Chiu, Y.-C. Design and Control of an SOFC/GT Hybrid Power Generation System with Low Carbon Emissions. *Ind. Eng. Chem. Res.* **2016**, *55*, 1281–1291. [CrossRef]
41. Beigzadeh, M.; Pourfayaz, F.; Ghazvini, M.; Ahmadi, M.H. Energy and exergy analyses of solid oxide fuel cell-gas turbine hybrid systems fed by different renewable biofuels: A comparative study. *J. Clean. Prod.* **2021**, *280*, 124383. [CrossRef]
42. Waters, D.F.; Pratt, L.M.; Cadou, C.P. Gas Turbine/Solid Oxide Fuel Cell Hybrids for Aircraft Propulsion and Power. *J. Propuls. Power* **2021**, *37*, 349–361. [CrossRef]
43. Liu, Y.; Han, J.; You, H. Performance analysis of a CCHP system based on SOFC/GT/CO^2 cycle and ORC with LNG cold energy utilization. *Int. J. Hydrogen Energy* **2019**, *44*, 29700–29710. [CrossRef]
44. Fernandes, A.; Woudstra, T.; Aravind, P.V. System simulation and exergy analysis on the use of biomass-derived liquid-hydrogen for SOFC/GT powered aircraft. *Int. J. Hydrogen Energy* **2015**, *40*, 4683–4697, Correction in *Int. J. Hydrogen Energy* **2016**, *41*, 725–727. [CrossRef]
45. Bao, C.; Wang, Y.; Feng, D.; Jiang, Z.; Zhang, X. Macroscopic modeling of solid oxide fuel cell (SOFC) and model-based control of SOFC and gas turbine hybrid system. *Prog. Energy Combust. Sci.* **2018**, *66*, 83–140. [CrossRef]
46. Eisavi, B.; Chitsaz, A.; Hosseinpour, J.; Ranjbar, F. Thermo-environmental and economic comparison of three different arrangements of solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems. *Energy Convers. Manag.* **2018**, *168*, 343–356. [CrossRef]
47. Yang, B.; Li, Y.; Li, J.; Shu, H.; Zhao, X.; Ren, Y.; Li, Q. Comprehensive summary of solid oxide fuel cell control: A state-of-the-art review. *Prot. Control Mod. Power Syst.* **2022**, *7*, 36. [CrossRef]
48. Wongchanapai, S.; Iwai, H.; Saito, M.; Yoshida, H. Performance evaluation of a direct-biogas solid oxide fuel cell-micro gas turbine (SOFC-MGT) hybrid combined heat and power (CHP) system. *J. Power Sources* **2013**, *223*, 9–17. [CrossRef]
49. Corigliano, O.; Pagnotta, L.; Fragiacomo, P. On the Technology of Solid Oxide Fuel Cell (SOFC) Energy Systems for Stationary Power Generation: A Review. *Sustainability* **2022**, *14*, 15276. [CrossRef]
50. Buonomano, A.; Calise, F.; d'Accadia, M.D.; Palombo, A.; Vicidomini, M. Hybrid solid oxide fuel cells-gas turbine systems for combined heat and power: A review. *Appl. Energy* **2015**, *156*, 32–85. [CrossRef]
51. van Veldhuizen, B.; van Biert, L.; Aravind, P.V.; Visser, K. Solid Oxide Fuel Cells for Marine Applications. *Int. J. Energy Res.* **2023**, *2023*, 5163448. [CrossRef]
52. Azizi, M.A.; Brouwer, J. Progress in solid oxide fuel cell-gas turbine hybrid power systems: System design and analysis, transient operation, controls and optimization. *Appl. Energy* **2018**, *215*, 237–289. [CrossRef]
53. Martinez, A.S.; Brouwer, J.; Samuelsen, G.S. Feasibility study for SOFC-GT hybrid locomotive power part II. System packaging and operating route simulation. *J. Power Sources* **2012**, *213*, 358–374. [CrossRef]
54. Kumar, P.; Singh, O. A review of solid oxide fuel cell based hybrid cycles. *Int. J. Energy Res.* **2022**, *46*, 8560–8589. [CrossRef]

55. Samuelsen, S.; Brouwer, J. Applications—Stationary | Fuel Cell/Gas Turbine Hybrid. In *Encyclopedia of Electrochemical Power Sources*; Garche, J., Ed.; Elsevier: Amsterdam, The Netherlands, 2009; pp. 124–134. [CrossRef]
56. Toonssen, R.; Aravind, P.V.; Smit, G.; Woudstra, N.; Verkooijen, A.H.M. System Study on Hydrothermal Gasification Combined With a Hybrid Solid Oxide Fuel Cell Gas Turbine. *Fuel Cells* **2010**, *10*, 643–653. [CrossRef]
57. Zhang, X.; Su, S.; Chen, J.; Zhao, Y.; Brandon, N. A new analytical approach to evaluate and optimize the performance of an irreversible solid oxide fuel cell-gas turbine hybrid system. *Int. J. Hydrogen Energy* **2011**, *36*, 15304–15312. [CrossRef]
58. Zhang, X.; Chan, S.H.; Li, G.; Ho, H.K.; Li, J.; Feng, Z. A review of integration strategies for solid oxide fuel cells. *J. Power Sources* **2010**, *195*, 685–702. [CrossRef]
59. Calise, F.; d'Accadia, M.D.; Vanoli, L.; von Spakovsky, M.R. Single-level optimization of a hybrid SOFC-GT power plant. *J. Power Sources* **2006**, *159*, 1169–1185. [CrossRef]
60. Calise, F.; d'Accadia, M.D.; Vanoli, L.; von Spakovsky, M.R. Full load synthesis/desigin optimization of a hybrid SOFC-GT power plant. *Energy* **2007**, *32*, 446–458. [CrossRef]
61. Calise, F.; Palombo, A.; Vanoli, L. Design and partial load exergy analysis of hybrid SOFC-GT power plant. *J. Power Sources* **2006**, *158*, 225–244. [CrossRef]
62. Azevedo, S.G.; Sequeira, T.; Santos, M.; Mendes, L. Biomass-related sustainability: A review of the literature and interpretive structural modeling. *Energy* **2019**, *171*, 1107–1125. [CrossRef]
63. Sinha, A.A.; Saini, G.; Sanjay; Shukla, A.K.; Ansari, M.Z.; Dwivedi, G.; Choudhary, T. A novel comparison of energy-exergy, and sustainability analysis for biomass-fueled solid oxide fuel cell integrated gas turbine hybrid configuration. *Energy Convers. Manag.* **2023**, *283*, 116923. [CrossRef]
64. Cocco, D.; Tola, V. Externally reformed solid oxide fuel cell—Micro-gas turbine (SOFC—MGT) hybrid systems fueled by methanol and di-methyl-ether (DME). *Energy* **2009**, *34*, 2124–2130. [CrossRef]
65. Isfahani, S.N.R.; Sedaghat, A. A hybrid micro gas turbine and solid state fuel cell power plant with hydrogen production and CO_2 capture. *Int. J. Hydrogen Energy* **2016**, *41*, 9490–9499. [CrossRef]
66. Ding, X.; Lv, X.; Weng, Y. Fuel-Adaptability Analysis of Intermediate-Temperature-SOFC/Gas Turbine Hybrid System With Biomass Gas. *J. Energy Resour. Technol. Trans. Asme* **2021**, *143*, 022104. [CrossRef]
67. Lv, X.; Gu, C.; Liu, X.; Weng, Y. Effect of gasified biomass fuel on load characteristics of an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system. *Int. J. Hydrogen Energy* **2016**, *41*, 9563–9576. [CrossRef]
68. Behzadi, A.; Gholamian, E.; Houshfar, E.; Habibollahzade, A. Multi-objective optimization and exergoeconomic analysis of waste heat recovery from Tehran's waste-toenergy plant integrated with an ORC unit. *Energy* **2018**, *160*, 1055–1068. [CrossRef]
69. Zhao, Y.; Sadhukhan, J.; Lanzini, A.; Brandon, N.; Shah, N. Optimal integration strategies for a syngas fuelled SOFC and gas turbine hybrid. *J. Power Sources* **2011**, *196*, 9516–9527. [CrossRef]
70. Zhao, Y.; Shah, N.; Brandon, N. In Comparison between two optimization strategies for solid oxide fuel cell-gas turbine hybrid cycles. *Int. J. Hydrogen Energy* **2011**, *36*, 10235–10246. [CrossRef]
71. Grigoruk, D.G.; Kasilova, E.V. Parametric studies of thermal configurations for hybrid systems with coal-gasification-product fuel cells. *Power Technol. Eng.* **2013**, *46*, 496–499. [CrossRef]
72. Gür, T.M.; Homel, M.; Virkar, A.V. High performance solid oxide fuel cell operating on dry gasified coal. *J. Power Sources* **2010**, *195*, 1085–1090. [CrossRef]
73. Giddey, S.; Badwal, S.P.S.; Munnings, C.; Dolan, M. Ammonia as a Renewable Energy Transportation Media. *ACS Sustain. Chem. Eng.* **2017**, *5*, 10231–10239. [CrossRef]
74. Klerke, A.; Christensen, C.H.; Norskov, J.K.; Vegge, T. Ammonia for hydrogen storage: Challenges and opportunities. *J. Mater. Chem.* **2008**, *18*, 2304–2310. [CrossRef]
75. Al-Hamed, K.H.M.; Dincer, I. A new direct ammonia solid oxide fuel cell and gas turbine based integrated system for electric rail transportation. *Etransportation* **2019**, *2*, 100027. [CrossRef]
76. Ishak, F.; Dincer, I.; Zamfirescu, C. Energy and exergy analyses of direct ammonia solid oxide fuel cell integrated with gas turbine power cycle. *J. Power Sources* **2012**, *212*, 73–85. [CrossRef]
77. Fryda, L.; Panopoulos, K.D.; Kakaras, E. Integrated CHP with autothermal biomass gasification and SOFC-MGT. *Energy Convers. Manag.* **2008**, *49*, 281–290. [CrossRef]
78. Duan, L.; He, B.; Yang, Y. Parameter optimization study on SOFC-MGT hybrid power system. *Int. J. Energy Res.* **2011**, *35*, 721–732. [CrossRef]
79. Perna, A.; Minutillo, M.; Jannelli, E.; Cigolotti, V.; Nam, S.W.; Yoon, K.J. Performance assessment of a hybrid SOFC/MGT cogeneration power plant fed by syngas from a biomass down-draft gasifier. *Appl. Energy* **2018**, *227*, 80–91. [CrossRef]
80. Meratizaman, M.; Monadizadeh, S.; Amidpour, M. Techno-economic assessment of high efficient energy production (SOFC-GT) for residential application from natural gas. *J. Nat. Gas Sci. Eng.* **2014**, *21*, 118–133. [CrossRef]
81. Liu, H.; Qin, J.; Xiu, X.; Ha, C.; Dong, P. Comparative study of fuel types on solid oxide fuel cell-gas turbine hybrid system for electric propulsion aircraft. *Fuel* **2023**, *347*, 128426. [CrossRef]