Energy Proceedings
Vol 47, 2024
ISSN 2004-2965

A Review of Proton Exchange Membrane Fuel Cell Cogeneration Waste Heat Recovery System#

Xin Yuan[1], Baodi Zhang*, Zhentao Wang, Liang Chang
Beijing Key Laboratory of Powertrain for New Energy Vehicle,
School of Mechanical, Electronic and Control Engineering,
Beijing Jiaotong University, Beijing 100044, China
(Corresponding Author: zhangbd@bjtu.eud.cn)

ABSTRACT

Under the current urgent global demand for clean energy and energy security, proton exchange membrane fuel cell (PEMFC) cogeneration systems have attracted much attention and research. The purpose of this paper is to provide a comprehensive overview of the various aspects of fuel cell cogeneration systems, including the composition of the system, the thermal management technology, the composition of the waste heat recovery system, the control strategy, and the form of integration with other energy systems. Through an in-depth analysis of the system components and operation principles, the role and potential of fuel cell cogeneration systems in the energy transition can be better understood.

Keywords: proton exchange membrane fuel cells, cogeneration systems, thermal management, waste heat recovery

1. INTRODUCTION

The current global energy transition is in the spotlight, aiming to promote the transformation of energy production and utilization towards low-carbon, clean and renewable directions to address the challenges of climate change, environmental pollution and energy security. In this context, proton exchange membrane fuel cells (PEMFCs) have attracted much attention as an efficient and clean energy conversion technology, especially in the fields of transportation, industrial and home energy systems, etc. [1]. In order to fully utilize the potential of fuel cells, cogeneration technology has gradually become the focus of research and practice. Utilizing the electricity and waste heat generated from fuel cell power generation, this technology aims to improve energy utilization efficiency and reduce carbon emissions, bringing a wide range of application potentials in fields such as industrial production, energy infrastructure and urban energy networks [2]. Fuel cell cogeneration technology is not only widely used in industrial production, but also plays an important role in energy infrastructure and urban energy networks. In summary, fuel cell cogeneration technology has important economic and environmental benefits, and is of great significance in promoting energy transition and realizing sustainable development [3][4][5]. Figure 1 shows the structure of this review.

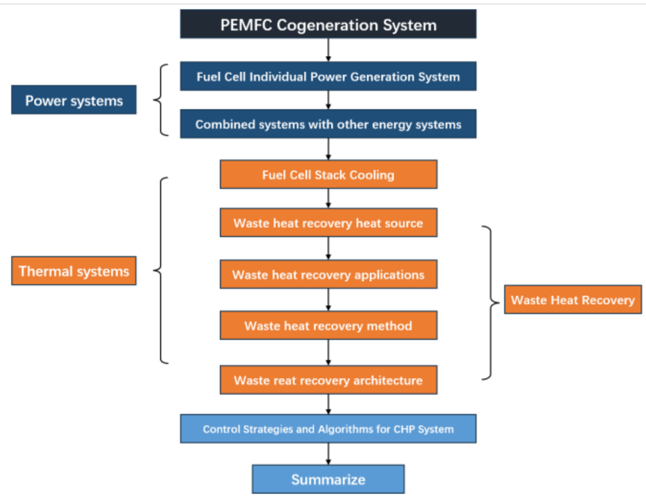

Fig. 1 Structure of this review

2. PEMFC POWER SYSTEM

Under the global energy crisis, improving energy utilization efficiency and reducing carbon emissions have become a major trend. As a result, major energy systems are developing in the direction of combined heat and power (CHP). Fuel cell power generation technology is gradually applied to major power generation scenarios due to its advantages of high efficiency and cleanliness. It is not only more efficient than traditional heat engine power generation, but also reduces pollutant emissions, with the main products being water and heat, which has a significant effect on improving air quality and reducing greenhouse gas emissions. In addition, the low noise

This is a paper for the 10th Applied Energy Symposium: Low Carbon Cities & Urban Energy Systems (CUE2024), May. 11-12, 2024, Shenzhen, China.

level makes it suitable for noise-sensitive environments and enhances the user experience. Flexibility, the application can be designed according to the demand, used alone or combined with other energy technologies to improve the stability and reliability of the system. Modular design makes the system easy to expand and upgrade to meet different needs. Proton exchange membrane fuel cells are usually co-generated with other technologies to improve efficiency, reliability and environmental friendliness [6][7]. Table 1 shows the comparison between fuel cell powered systems and other power generation technologies.

Table 1 Comparison of fuel cell power systems and other power generation technologies

	Reciprocating engine: diesel	**Turbine generator**	**Photovoltaic**	**Wind turbine**	**Coal-fired generation**	**Gas-fired generation**	**Oil-fired generation**	**Fuel cells**
Capacity range	500 kW–50 MW	500 kW–5 MW	1KW-1MW	10KW-1 MW	100MW-1000MW	Tens to hundreds of MW	Tens of KW to hundreds of MW	200kW–2MW
Efficiency	35%	29-42%	6–19%	25%	33-45%	30-40%	25-35%	40–60%
Investment cost ($/kW)	1000-3000	800-2000	1000-3000	1500-3000	1000-3000	500-2000	800-2500	2000-5000
O & M costs ($/kW/year)	30-70	20-50	5-20	15-40	20-50	30-80	30-70	30-60

3. INTEGRATION WITH OTHER ENERGY SYSTEMS

3.1 Combined with photovoltaics

With the increasing global emphasis on renewable energy and environmentally friendly technologies, the combination of solar photovoltaic (PV) technology and proton exchange membrane fuel cell (PEMFC) systems has become a hot research topic in the energy field.This integrated power generation provides a sustainable and environmentally friendly power solution for a variety of application scenarios, and is particularly suitable for situations where a stable power supply needs to be maintained under varying light conditions [8-11].Soni et al [12] provided insights into the performance, economic viability, and environmental impacts of AI technology by evaluating its application in a grid-connected solar PV-fuel cell hybrid power system. While Kasaeian et al [13] provided a comprehensive review of modeling, simulation, experimentation and control optimization for the integration of solid oxide fuel cells and solar systems. The integration of proton exchange membrane fuel cells with solar energy systems has attracted much attention, and a large number of studies have been carried out for this purpose in terms of simulation, experimental validation and performance optimization [14-17]. For example, Zhang et al [18] found that current density and effective area have a significant effect on the PEMFC electric stack by investigating the effect of current density and effective area on the performance of a solar proton exchange membrane fuel cell (PEMFC) cogeneration system. Combining solar energy and PEMFC can increase the tank temperature and keep the indoor heating temperature within the comfort range in winter, while the maximum efficiency of the system can reach 83%.Adhami and Hozhabr [19] proposed a miniature tri-generation system based on a combined proton exchange membrane fuel cell, photovoltaic (PV), and photovoltaic/cogeneration motor, and compared it seasonally with other power generation systems, and the experimental performance metrics such as consumption, system weight, total efficiency, and power were evaluated. Fig.2 shows the basic combination of fuel cell and solar power generation form.

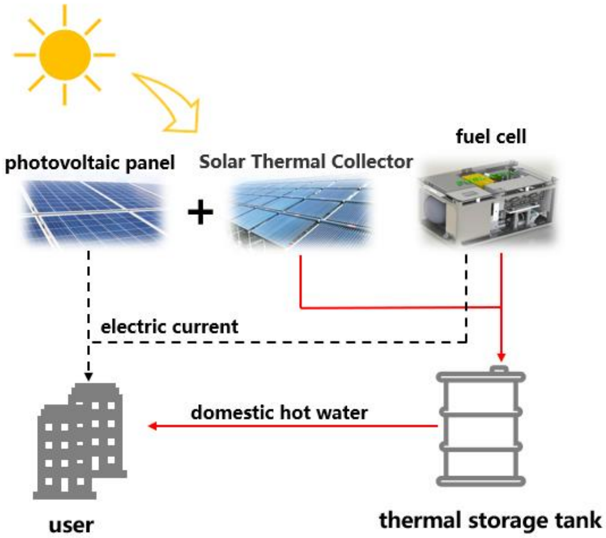

Fig.2 Basic Combination of Fuel Cells and Solar Power Generation

3.2 Combined with wind power technologies

Wind power, as a zero-emission, renewable and clean energy source, shows great potential for development. With the continuous advancement of technology, the efficiency and capacity of wind power generation equipment are constantly improving, providing a broad prospect for its application in the energy system. Combining wind power with proton exchange membrane fuel cells can realize stable power supply, thus playing an important role in energy transition. Fuel cells as a backup power source can make up for the lack of wind resources [20-25], improve the reliability of the system, and reduce the dependence on traditional energy sources. This combination form is feasible and is expected to be widely used in the future. Relevant studies have shown that the coordinated scheduling of a proton exchange membrane fuel cell cogeneration system with wind turbines and photovoltaic (PV) units in a microgrid [26] can effectively address the challenges posed by uncertainties in the power market price, wind speed and solar irradiance. Meanwhile, through the optimal design of hybrid energy systems, multiple objectives such as economics, environmental benefits, and grid interactions can be considered simultaneously [27-29], which provides important support for the stable operation and sustainable development of energy systems.

3.3 Combined with energy storage systems

The integration of fuel cell systems with energy storage systems is one of the important technological measures targeting energy transition and renewable energy integration. With the continuous development of clean energy and the increasing share of renewable energy in the energy mix, the importance of energy storage technology has become increasingly prominent. However, the intermittent and fluctuating nature of renewable energy brings challenges to energy supply and system operation, and an effective way is needed to balance the supply and demand of energy and ensure stable system operation.

Integrating the fuel cell system with the energy storage system can realize the storage and regulation of electric energy, thus improving the energy utilization efficiency and system stability. The fuel cell system can be utilized for charging during low power demand hours, while releasing electrical energy during peak hours [30][31][32]. In the commercial vehicle sector, it is common practice to combine fuel cells with energy storage systems such as batteries [33][34]. Researchers have also explored different combinations, such as combining proton exchange membrane fuel cells with supercells [35] and implementing reinforcement learning energy management strategies to improve efficiency. It has also been shown that combining fuel cell stacks with lithium-ion batteries [36] can provide high efficiency, high speed and significant range. Civilian fuel cell power systems have also been used to regulate power demand through energy storage systems such as batteries and supercapacitors [37][38]. Researchers have also proposed various novel integrated systems, such as biomass gasification integrated systems [40], and control-based hybrid energy storage systems designed to improve the efficiency of renewable energy sources, and validation tests have been conducted to ensure the validity of the models. Figure 3 shows a common energy storage system for fuel cells.

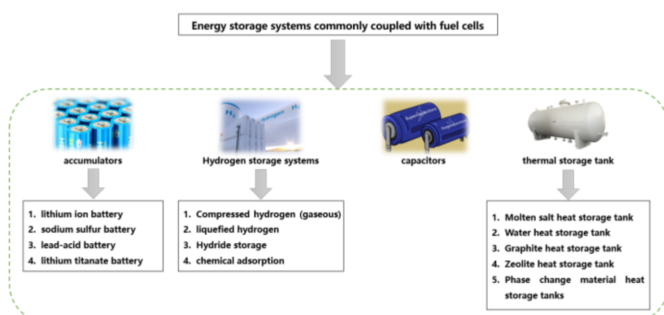

Fig.3 Energy storage systems commonly coupled with fuel cells

3.4 Combined with biomass power

This section refers to biomass power generation as distinguished from biomass fuel cells (BFCs), which utilize biomass as the main feedstock and convert the chemical energy in the biomass into electricity through biochemical processes or thermochemical conversion processes, whereas BFCs use biomass as a fuel, for example, biomass wastes, organic wastes or biomass fermentation products. Biomass power technology is known for its renewability, reduction of greenhouse gas emissions, waste treatment and resource utilization, localized energy production, and diversified energy supply. When combined with proton exchange membrane fuel cells, it not only stabilizes the power supply and enhances the reliability of the system, but also reduces the dependence on traditional energy sources and promotes energy transition and sustainable development [41-45]. This combination demonstrates the potential to play an important role in the clean energy sector, contributing positively to the realization of a cleaner and more sustainable energy future. Hoseini, Hamed et al [46] analyzed an innovative and practical biomass-fuel-driven fuel cell including an improved gas turbine cycle, a supercritical CO2 cycle, a transcritical CO2 cycle, a proton exchange membrane electrolyzer (PEME) and a proton membrane fuel cell unit (PMCU). Proton Membrane Fuel Cell Unit (PEMFC) multi-generation system. Hai, Tao et al [47] utilized biomass to drive cogeneration of hydrogen and electricity while utilizing a cooled absorption unit to recover the waste heat in order to improve the efficiency, reduce fossil energy consumption, and maximize the integration of renewable energy sources. Zhang et al [48] proposed an innovative and practical system that considers a high temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC) and Solid Oxide Fuel Cell (SOFC) biomass cogeneration (CCHP) system, which utilizes a biomass gasifier to provide fuel for the fuel cell system.

3.5 Combined with other hydrogen production systems

In addition to the combined systems mentioned above, gas supply systems for fuel cells are often combined with other hydrogen production technologies, such as electrolyzers and reforming hydrogen production technologies. Reforming technologies for hydrogen production cover a wide range of feedstocks, including natural gas, diesel or petroleum fuels, biomass materials, and coal, etc. Hwang et al [49] proposed and analyzed a mobile proton exchange membrane fuel cell diesel power system. The system consists of a balance of self-heating reformer, proton exchange membrane fuel cell and plant components, and its emissions were compared with those of an alternative system (hydrogen-fueled proton exchange membrane fuel cell system). Chen et al [50] investigated a hybrid power system consisting of a proton exchange membrane fuel cell/electrolyzer hybrid system and an auxiliary power source, as well as its energy management strategy (EMS). The auxiliary power source consists of photovoltaic cells and batteries. Fan et al [51] proposed a cogeneration system based on a 50 kW class high temperature proton exchange membrane fuel cell fueled by on-site hydrogen production, which integrates steam methane reforming with the thermal energy from the fuel cell. Li et al [52] proposed a novel methanol-fueled cogeneration system based on a proton exchange membrane fuel cell/engine for applied to the marine sector. The system generates hydrogen through on-line reforming of methanol to provide high calorific value fuel for the PEM fuel cell. The cogeneration efficiency and power generation efficiency of the proposed cogeneration system are as high as 81.84% and 50.46%, respectively, which is 19.55% higher than that of a single engine.

3.6 Combined Systems Summary

Proton Exchange Membrane Fuel Cells (PEMFCs) have a wide range of integration potential in the renewable energy sector. In addition to integrating with equivalent power generation technologies such as photovoltaic, wind and energy storage systems to supply electricity, it can also be combined with front-end gas supply systems such as electrolyzers and reforming technologies for hydrogen production. This multifaceted integration of individual or even multiple systems not only improves the flexibility and reliability of the energy system, but also helps to realize the efficient use of energy and the reduction of carbon emissions. With the continuous development and popularization of renewable energy technologies, proton exchange membrane fuel cells, as a key component of clean energy, will play an increasingly important role in the energy transition. Its integrated application can not only promote the transformation and upgrading of energy structure, but also is expected to make an important contribution to the realization of the sustainable development goals, thus promoting the global energy landscape towards a cleaner and more sustainable direction. There have been a number of studies on systems with multiple combinations, among which, Taghizadeh, Mahdi et al [53] proposed a new hybrid isolated network topology that employs wind turbines (WTs), proton exchange membrane fuel cells (PEMFCs), photovoltaics (PVs), ultracapacitors (UCs), and battery energy storage systems (BESSs), and a new intelligent fuzzy controllers to handle power demand fluctuations and thus maintain the balance between power generation and consumption.Onar, O.C. et al [54] focused on a combination of wind turbine WT), photovoltaic PV), fuel cell (FC), and ultracapacitor (UC) systems for grid-independent applications. The dynamic behavior of the proposed hybrid system was tested under various wind speed, solar radiation and load demand conditions.Ahmed, Nabil A. et al [55] proposed a hybrid energy system combining variable speed wind turbine, solar PV, and fuel cell power generation systems to provide continuous power for residential power applications in the form of standalone loads. The wind and photovoltaic systems are used as primary energy sources while the fuel cell is used as a secondary or backup energy source. Fig.4 shows the hierarchical relationship between the proton exchange membrane fuel cell system and each of the other systems in terms of material and energy flow relationships.

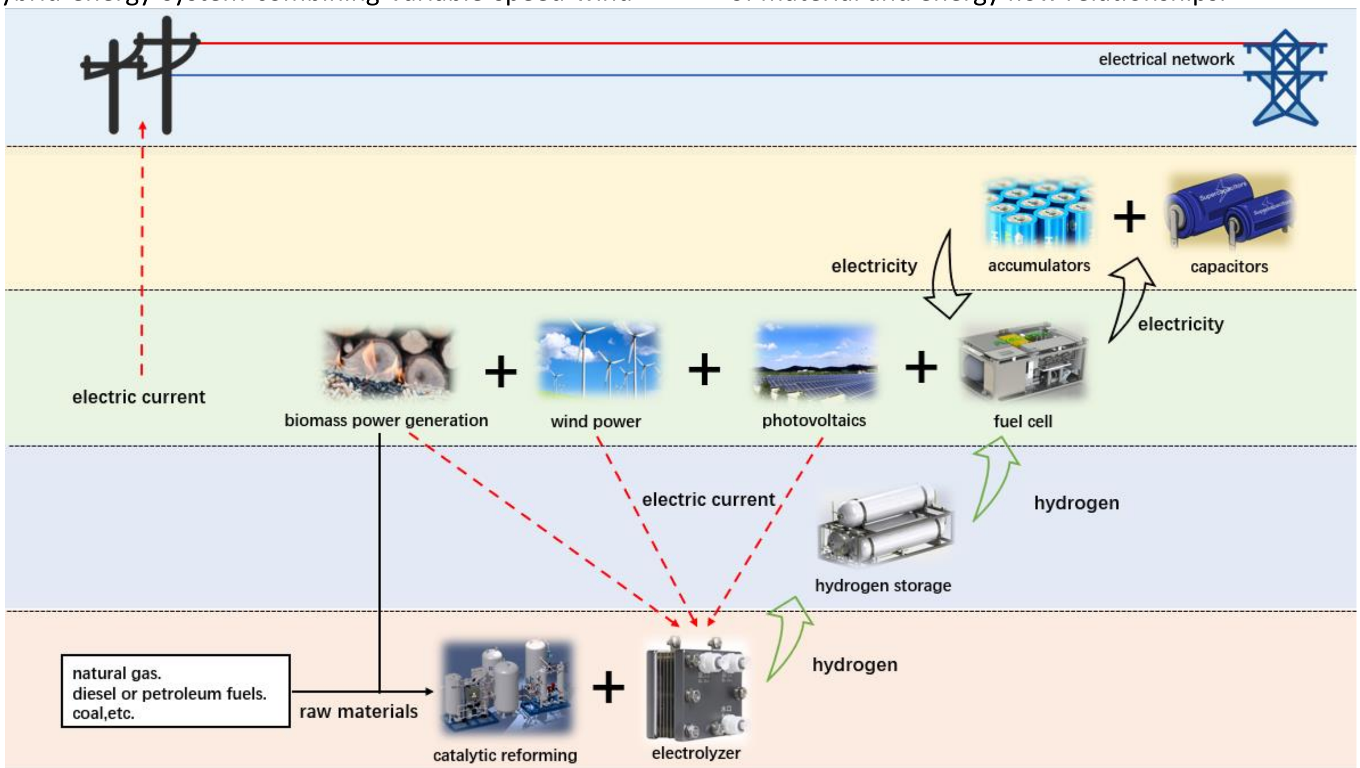

Fig. 4 Combined fuel cell power generation system

4. FUEL CELL STACK COOLING METHOD

The necessity of cooling the electric stack of a proton exchange membrane fuel cell is self-evident, and a good cooling system can improve cell efficiency, enhance stability, and prolong the lifetime [56]. The heat generated by the proton exchange membrane fuel cell in the working process is unavoidable. If the heat cannot be discharged effectively, the temperature of the electric stack will increase, leading to a decrease in the rate of electrochemical reaction, and in severe cases, the structure of the electric stack may even be damaged [57]. Therefore, realizing effective cooling is crucial to maintain the stability and performance of the battery. Traditional cooling techniques such as direct water cooling and indirect cooling have been widely used, while novel techniques such as microchannel cooling and phase change material cooling are being explored [58][59]. Integrated intelligent control systems allow real-time monitoring and regulation of temperature and cooling flow rate to further optimize the system performance. These advances will promote the application of proton exchange membrane fuel cell technology in various fields [60]. Figure 5 shows the common forms of electric stack cooling for fuel cell electric stacks. Table 2 describes the corresponding cooling forms in comparison.

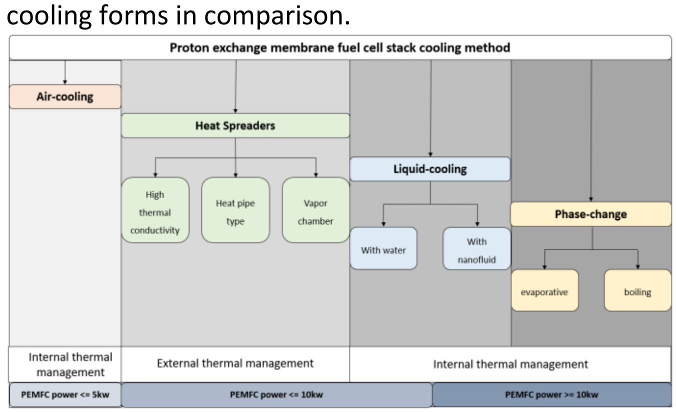

Fig. 5 Common forms of stack cooling for fuel cell stacks

Table. 2 Introduction and Comparison of Common Cooling Forms for Fuel Cell Reactors

Cooling Form	Categorization	Technical Introduction	Advantages	Disadvantages	Reference
Air-cooling	air flow	Convection heat transfer by air flow; Air flow channels integrated into the stack	Simple, reliable, low cost, compact, lightweight.	Limited heat dissipation capacity, difficult temperature control, affected by environment	[61][62][63][64][65].etc
Heat Spreaders	High thermal conductivity materials	Heat sinks and plates made of highly thermally conductive materials, etc.	Efficient heat dissipation, high stability, greater durability.	Higher weight, higher cost, uneven heat transfer.	[66][67][68][69][70].etc
	Heat-pipe type	Working media evaporation and condensation, heat convection or heat radiation	Efficient heat dissipation, uniform temperature, compact design, reliable and wide application	Higher cost, complex design, liquid evaporation or leakage	[71][72][73][74][75].etc
	Vapor chamber	Cyclic phase changes in water	Efficient cooling, uniform temperature, wide applicability	Larger volume, requires liquid water management, additional energy consumption	[76][77][78][79][80].etc
Liquid-cooling	Via water	Circulating water flowing in cooling plates or cooling channels	Efficient and flexible, stable, energy-saving and environmentally friendly	System complexity, maintenance costs, high size and weight	[81][82][83][84].etc

	Via nanofluids	Nanoparticles with high surface area and thermal conductivity	High-efficiency, excellent heat transfer, reduced volume and mass, energy saving	Particle deposition, higher cost, stable and reliable	[85][86][87][88].etc
Phase-change cooling	Evaporation cooling	Cooling by absorption or release of latent heat during phase transitions	Stable temperature control, simplified design and greater stability	Temperature control, cooling efficiency life insurance, periodic maintenance	[85][89][90][91].etc
	Boiling Cooling	Cooling by boiling during phase transitions	High efficiency and stability, suitable for high power	Phase change material selection, design complexity, foam plugging risk	[92][93][94][95].etc

5. FUEL CELL WASTE HEAT RECOVERY

In the field of fuel cell technology, waste heat recovery has attracted much attention as a key technology to improve energy utilization efficiency. As an efficient and clean energy conversion technology, although fuel cells can produce electricity and water through the reaction between hydrogen and oxygen, they also generate a large amount of waste heat during their operation. The importance of waste heat recovery technology lies in the effective utilization of this wasted heat energy, thus improving the overall energy utilization efficiency of the system [96]. This technology not only helps to reduce the environmental impact, energy consumption and operating costs, but also improves the stability and reliability of the system. In the context of the development of fuel cell technology, the research and development of waste heat recovery technology is of great significance in promoting the progress of fuel cell technology and improving its competitiveness in various applications [97]. Therefore, various forms of waste heat recovery technologies, including heat exchangers, heat pipes, heat pumps, etc., have been continuously and intensively researched and applied, aiming to effectively convert waste heat into electricity, heat or other usable forms of energy in order to improve the energy utilization efficiency of the system [98][99].

5.1 Type of waste heat source

Waste heat here refers to the operating waste heat of the fuel cell system alone, excluding the rest of the heat from other combined systems (e.g., photovoltaic, wind, etc.), and there are three main heat sources in the fuel cell system, the gas supply part of the heat source, the heat produced by the operation of the electric reactor, and the reaction gas waste heat.Luo Yang et al. [100] investigated the temperature distribution characteristics of the proton exchange membrane fuel cell and the influence of the structural parameters of the components (PEM, gas diffusion layer, microporous layer, bipolar plate) on the heat dissipation and temperature distribution uniformity. gas diffusion layer, microporous layer, bipolar plate) structural parameters on heat dissipation and temperature distribution uniformity. For the gas supply system, in the process of compressing the gas to the required pressure level through the compressor, the compressor will generate heat when compressing the gas, and this part of heat will be transferred to the air inlet system. Therefore, the front-end air intake part of the fuel cell has received much attention, and a large number of studies have been devoted to optimizing the air intake system of fuel cell systems, especially for the air compressor part [101][102]. The electrical efficiency of proton exchange membrane fuel cell (PEMFC) is usually between 40% and 60% depending on factors such as operating temperature, cell size, and reactant pressure.Özdemir et al [103] simulated and analyzed the thermal system of PEMFC and investigated the thermal control under static, and dynamic loads. The reactor exhaust gas carries away some of the heat, and for proton exchange membrane fuel cells, the heat in the exhaust gas is usually low because of their relatively low operating temperatures (usually between 80°C and 100°C), and the heat in the exhaust gas is correspondingly low. In solid oxide fuel cells, on the other hand, the heat in the exhaust gas is relatively high because of their higher operating temperatures (usually between 700°C and 1000°C), which can usually reach higher temperature levels. The heat in the fuel cell tail gas usually accounts for a portion of the total heat, and the exact percentage depends on the design and operating conditions of the fuel cell system. In some cases, the heat in the tail gas can reach about 10% to 20% of the total heat.

5.2 Waste heat recovery applications

Fuel cell is an efficient and clean energy conversion technology, but its power generation process will produce a large amount of waste heat. In order to maximize the use of this waste heat and improve the efficiency of energy use, fuel cell waste heat recovery technology is widely used. Waste heat from the fuel cell stack itself can be used for cell preheating, fuel pretreatment, moisture and humidity control (heating or humidification through the air intake system), which is very important to ensure efficient and normal operation of the fuel cell.Zhang et al. [104] modeled, validated, and analyzed a sub-zero cold-starting fuel cell vehicle, and with the help of the power enhancement of the external heater, the cold-starting time was reduced by 70%, greatly shortened the starting time. Fuel cell stack systems can provide additional thermoelectric services in addition to their own needs.Oh, Jinwoo et al [105] realized a cascade utilization of waste heat for a fuel cell system based on an organic Rankine cycle and an absorption chiller to satisfy the dynamic energy demand of the region.Capuano, Margherita et al [106] analyzed the performance of a fuel cell system integrating a high temperature Proton Exchange Membrane Fuel Cell (HT - PEMFC) and air source heat pump technologies for residential space heating systems.Shen, Yongting et al [107] used thermoelectric heaters to obtain results more than double the system's capacity to heat domestic hot water than by directly utilizing electrochemical waste heat. The direct utilization of thermal energy and power conversion, the diverse waste heat utilization methods bring different directions and possibilities for fuel cell waste heat recovery, which is of great help in improving the overall energy utilization efficiency and advancing the commercialization of fuel cells [108]. Fig.6 summarizes the common uses of waste heat recovery in power reactors.

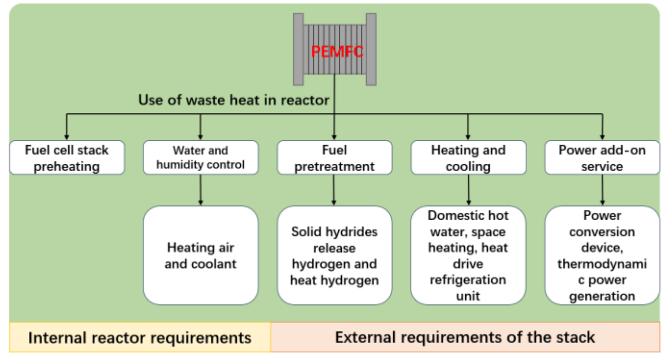

Fig. 6 Fuel cell waste heat recovery applications

5.3 Utilization of waste heat

The architecture of the Proton Exchange Membrane Fuel Cell Waste Heat Recovery System (PEMFC WHC) mainly consists of a waste heat recovery device and a power conversion device, in which the waste heat recovery device mainly consists of a heat exchanger, a heat recovery cycle, and a heat pump technology, and the power conversion device mainly involves a hot spot conversion technology (TEG), and a mechanical device that can use the waste heat to drive a turbine and a piston, etc., and the utilization and conversion of the waste heat are shown in Figure 7.

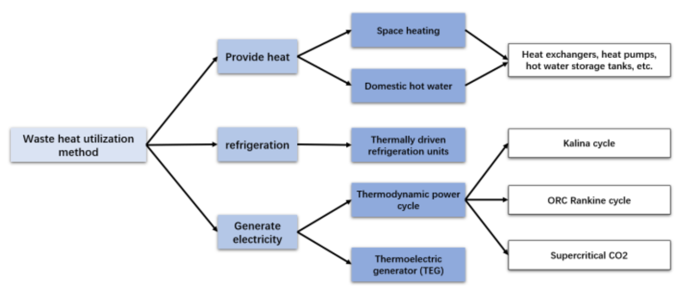

Fig. 7 Fuel cell waste heat utilization method

5.4 Waste Heat Recovery Architecture

Waste heat recovery devices include heat exchangers, heat recovery cycles, and heat pump technology. Heat exchangers utilize tube, plate, or spiral construction to maximize the heat transfer area for efficient heat transfer [109][110]. Heat recovery cycles such as the ORC Rankine cycle [111], Kalina cycle [112], and supercritical CO2 cycle [113][114] utilize a workmass circulated under different temperature and pressure conditions to convert waste heat into mechanical or electrical energy. Heat pump technology absorbs waste heat generated by low-temperature fuel cells through the process of evaporation and condensation of the work mass and provides thermal energy for other uses. In terms of power conversion devices, thermoelectric conversion (TEG) technology [115][116] utilizes the thermoelectric effect of semiconductor materials to convert thermal energy directly into electrical energy.TEG modules are connected in parallel or series to achieve the desired voltage and power output. In addition to TEG technology, other mechanical devices can also utilize waste heat to drive mechanical devices such as turbines or pistons [117][118] to generate mechanical energy and convert it into electrical energy through a generator. Heat pumps utilize the waste heat generated by fuel cells to raise the temperature of the working fluid by compressing and expanding it, and then use the high-temperature thermal energy to heat water or air [119]. The combined use of these devices can efficiently convert waste heat generated by low-temperature fuel cells into electrical, thermal, or mechanical energy to improve the comprehensive utilization and sustainability of system energy. According to the specific needs and technology maturity, the appropriate combination of devices is selected to achieve the best possible waste heat recovery and energy conversion results [120-124]. Table 3 summarizes the form of the combined architecture of common heat recovery devices, and Fig 8 depicts the basic architecture in Table 3.

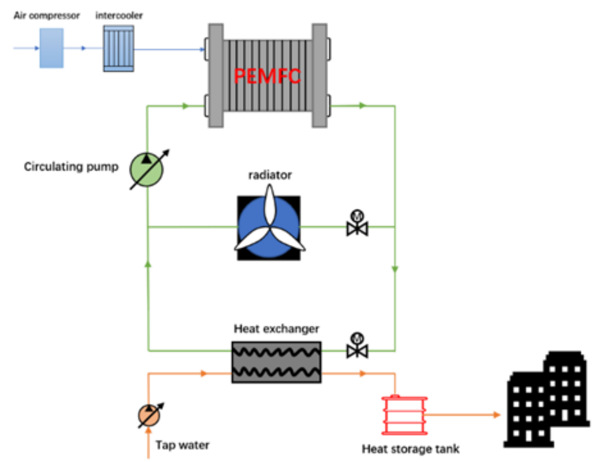

Fig. 8 Basic architecture of waste heat recover

Table 3 PEMFC WHR Module Common Combination Architecture System

	Basic Configuration	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5	Configuration 6
Heat exchanger	√	√	√	√		√	√
Organic Rankine cycle		√					√
Kalina cycle			√	√			
TEG					√		
Supercritical CO2						√	
Thermally driven-cooling units				√			
Heat pumps							√

6. CONTROL STRATEGIES AND ALGORITHMS FOR PEMFC COGENERATION SYSTEMS

Extensive research has been done in the field of controlling the performance and state of the fuel cell itself.Kumar et al [125] classified, summarized and compared the different controllers used in fuel cells. In terms of the control of the fuel cell inlet section, Qin et al [126] used adaptive sliding membrane control technology for the proton exchange membrane fuel cell inlet system, which realized the dynamic control of the oxygen excess ratio, hydrogen excess ratio and differential pressure on both sides of the membrane with strong chatter suppression, which is conducive to the efficient and stable operation of the system. Meanwhile, Zhang et al [127] also studied the control strategy of the air intake system to coordinate the control of air flow and pressure to ensure that the PEMFC stack provides appropriate pressure and flow. In terms of the main body of the electrostack, studies have focused on cell cathode and anode pressure control, differential pressure, voltage and temperature, and membrane humidity [128-132]. In addition, other researchers have summarized and reviewed in detail various control strategies for proton exchange membrane fuel cell systems [133][134].

As the development of fuel cell cogeneration waste heat recovery system is getting more and more attention, the experiments on control strategies and algorithms for cogeneration system are also being carried out in a deeper and deeper way. Figure 9 shows the structural relationship of the cogeneration control system for proton exchange membrane fuel cells. Common control strategies and algorithms include Model Predictive Control (MPC), Proportional Integral Derivative (PID), Fuzzy Logic Control (FLC) and Artificial Neural Network Control (ANN). Control (Artificial Neural Network Control, ANN Control), Dynamic Linear Programming, Load-based scheduling algorithms, Reinforcement learning, etc [135-138]. The corresponding control subsystem of the fuel cell cogeneration system consists of electrical system, thermal system, cooling system, user and grid coordination, etc. Asensio, F.J et al. [139] proposed a control model based on the combination of artificial neural network (ANN) with nonlinear autoregressive configurations and a three-dimensional look-up table (LUT) for the cogeneration system of a polymer electrolyte membrane fuel cell (PEMFC) with cooling system. control model for the cooling system.Yoshida, Akira et al [140] proposed a home energy management system (HEMS) to manipulate electricity consumption with a large number of HMES as a networked control system.A networked supervisory control system was constructed based on the fundamental study of distributed structured control algorithms, which used a stochastic model predictive control scheme to analyze the impact of primary energy consumption on the The sensitivity of the energy demand prediction update interval and operation strategy is analyzed.Wang, Xianlian et al [141] considered the energy management of a sustainable residential cogeneration system consisting of a fuel cell, a battery bank, photovoltaic (PV), a thermal energy system (TES), and a heat pump, and a stochastic dynamic programming (SDP) algorithm is used to minimize the system operation cost.The simulation results show that the control strategy derived at each stage of the process is more efficient in the fuel cell and heat pump. control strategies are energy efficient in managing the power output of the fuel cell and heat pump.

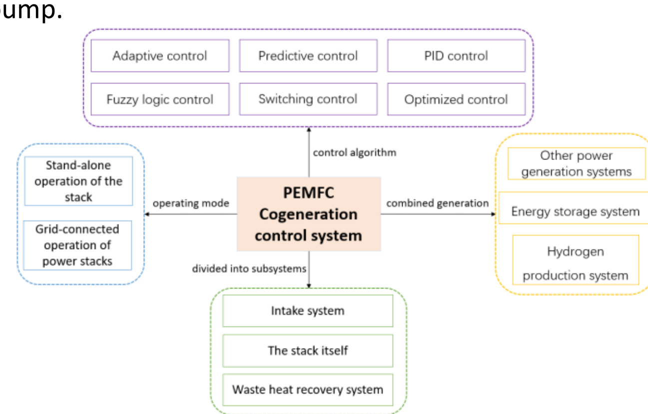

Fig. 9 PEMFC cogeneration control system

7. CONCLUSIONS

This review examines the cogeneration waste heat recovery system for proton exchange membrane fuel cells, dividing it into two key components: heat and electricity. The operation of the power stack generates electrical energy while also releasing heat energy, which needs to be cooled. We connect these cogeneration systems in series and explore the different forms of the power supply system, including the way in which the proton exchange membrane fuel cell can supply power alone and in combination with other systems to generate electricity, as well as the relationship of energy and material flow between them. In the thermal energy section, we summarize and classify the heat sources for waste heat recovery from power reactors, the uses of the recovery, and the technologies and system architectures for the recovery. Finally, we introduce common control strategies and algorithms for cogeneration systems, but unfortunately, we do not provide a more detailed elaboration of the system's control system, or a better generalization of the components, requirements, and functional hierarchical relationships of the control subsystems, as well as more detailed and clearer explanations of the strategies, algorithms, strengths, weaknesses, and possible solutions adopted by each subsystem, and the progress of the research. It is hoped that this paper can bring some help to the subsequent related research.

ACKNOWLEDGEMENT

This project is supported by the National Key R&D Program of China (No.2023YFB4005901).

REFERENCE

[1] H. Tariq, S. A. A. Kazmi, M. Hassan, S. A. Muhammed Ali, and M. Anwar, “Analysis of fuel cell integration with hybrid microgrid systems for clean energy: A comparative review,” International Journal of Hydrogen Energy, vol. 52, pp. 1005–1034, Jan. 2024, doi: 10.1016/j.ijhydene.2023.07.238.

[2] Cigolotti, V.; Genovese, M.; Fragiacomo, P. Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. Energies 2021, 14, 4963. https://doi.org/10.3390/en14164963.

[3] C. Ghenai, T. Salameh, and A. Merabet, “Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region,” International Journal of Hydrogen Energy, vol. 45, no. 20, pp. 11460–11470, Apr. 2020, doi: 10.1016/J.IJHYDENE.2018.05.110.

[4] Akinyele D, Olabode E, Amole A. Review of Fuel Cell Technologies and Applications for Sustainable Microgrid Systems. Inventions. 2020; 5(3):42. https://doi.org/10.3390/inventions5030042.

[5] Li, Z., Zheng, Z., Xu, L. et al. A review of the applications of fuel cells in microgrids: opportunities and challenges. BMC Energy 1, 8 (2019). https://doi.org/10.1186/s42500-019-0008-3.

[6] N. Bizon, “Hybrid Power Systems,” Green Energy and Technology, pp. 17–55, 2020, doi: 10.1007/978-3-030-40241-9_2.

[7] A. N. Akpolat and E. Dursun, “Performance Analysis of PEMFC Based Grid-connected Distributed Generation System,” Research Square, Oct. 2020, doi: 10.21203/rs.3.rs-95537/v1.

[8] H. Bazargan Harandi, A. Asadi, Z. Shen, and P.-C. Sui, “Integration of Direct-Contact Membrane Distillation with Flat-Plate Solar Collector versus Proton-Exchange Membrane Fuel Cell: Dynamic Simulations and Comparative Analysis,” Journal of Energy Engineering, vol. 148, no. 2, Apr. 2022, doi: 10.1061/(ASCE)EY.1943-7897.0000825.

[9] M. H. Khoshgoftar Manesh, N. Abbasi, and M. J. Mehrabian, “Optimal design of a novel hybrid solar tower-gas turbine combined cycle with proton exchange membrane polygeneration system: Application of machine learning,” Environmental Progress and Sustainable Energy, vol. 42, no. 3, Jun. 2023, doi: 10.1002/ep.14029.

[10] N. Zheng, H. Zhang, L. Duan, and Q. Wang, “Comprehensive sustainability assessment of a novel solar-driven PEMEC-SOFC-based combined cooling, heating, power, and storage (CCHPS) system based on life cycle method,” Energy, vol. 265, Feb. 2023, doi: 10.1016/j.energy.2022.126343.

[11] E. Baniasadi, M. Ziaei-Rad, M. A. Behvand, and N. Javani, “INTEGRATION OF PEM ELECTROLYZER AND FUEL CELL TO A SOLAR-GEOTHERMAL COMBINED SYSTEM FOR A ZERO-ENERGY BUILDING: AN EXERGYECONOMIC ANALYSIS,” Proceedings of WHEC 2022 - 23rd World Hydrogen Energy Conference: Bridging Continents by H2, pp. 964–966, 2022, [Online]. Available: https://www.engineeringvillage.com/share/document.url?mid=cpx_17ab7f71864c89d2aaM7ebd1017816363&database=cpx

[12] P. Soni and V. Dave, “‘An In-Depth Comparison of Ai-Powered Techno-Economic Analysis for Hybrid Power Systems Integrating Grid-Tied Solar Pv and Fuel Cells,’” SSRN, Feb. 2024, doi: 10.2139/ssrn.4730304.

[13] A. Kasaeian, M. Javidmehr, M. R. Mirzaie, and L. Fereidooni, “Integration of solid oxide fuel cells with solar energy systems: A review,” Applied Thermal Engineering, vol. 224, Apr. 2023, doi: 10.1016/j.applthermaleng.2023.120117.

[14] T. Kwon et al., “Ce(III)-Based Coordination-Complex-Based Efficient Radical Scavenger for Exceptional Durability Enhancement of Polymer Application in Proton-Exchange Membrane Fuel Cells and Organic Photovoltaics,” Advanced Energy and Sustainability Research, vol. 3, no. 7, Jul. 2022, doi: 10.1002/aesr.202200011.

[15] L. Chen, H. Huang, P. Tang, D. Yao, H. Yang, and H. Roohbakhsh, “A combined energy system for generating electrical and thermal energies using concentrating Solar System, fuel cell and organic Rankine cycle; energy and exergy assessment,” Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 2022, doi: 10.1080/15567036.2022.2043957.

[16] B. R. S. Reddy, V. C. V. Reddy, and M. V. Kumar, “Modelling and analysis of DC-DC converters with AI based MPP tracking approaches for grid-tied PV-fuel cell

system," Electric Power Systems Research, vol. 216, Mar. 2023, doi: 10.1016/j.epsr.2022.109053.

[17] Y. Wang and J. Hasani, "Energy generation from a system based on solar energy and fuel cell technology with the option of storing electrical energy," Energy Reports, vol. 8, pp. 4988–5004, Nov. 2022, doi: 10.1016/j.egyr.2022.03.199.

[18] J. Zhang, Y. Lu, G. Xie, S. Li, and Z. Wan, "Research on combined heat and power system based on solar-proton exchange membrane fuel cell," International Journal of Green Energy, vol. 19, no. 4, pp. 410–423, 2022, doi: 10.1080/15435075.2021.1946818.

[19] H. Adhami, "Designing and analysis of the micro-trigeneration systems based on combined proton exchange membrane fuel cell with photovoltaic and photovoltaic/thermal prime movers in portable applications," Applied Thermal Engineering, vol. 180, Nov. 2020, doi: 10.1016/j.applthermaleng.2020.115779.

[20] R. K. Parida, "PEM Fuel Cell based PV/Wind Hybrid Energy System," 2022 OPJU International Technology Conference on Emerging Technologies for Sustainable Development, OTCON 2022, 2023, doi: 10.1109/OTCON56053.2023.10114038.

[21] M. Temiz and I. Dincer, "Development of solar and wind based hydrogen energy systems for sustainable communities," Energy Conversion and Management, vol. 269, Oct. 2022, doi: 10.1016/j.enconman.2022.116090.

[22] K. Sarker, D. Chatterjee, and S. K. Goswami, "A modified PV-wind-PEMFCS-based hybrid UPQC system with combined DVR/STATCOM operation by harmonic compensation," International Journal of Modelling and Simulation, vol. 41, no. 4, pp. 243–255, 2021, doi: 10.1080/02286203.2020.1727134.

[23] E. Ganesan, S. S. Dash, and C. Samanta, "Modeling, control, and power management for a grid-integrated photo voltaic, fuel cell, and wind hybrid system," Turkish Journal of Electrical Engineering and Computer Sciences, vol. 24, no. 6, pp. 4804–4823, 2016, doi: 10.3906/elk-1404-409.

[24] M. H. Shahverdian, A. Sohani, M. Zamani Pedram, and H. Sayyaadi, "An optimal strategy for application of photovoltaic-wind turbine with PEMEC-PEMFC hydrogen storage system based on techno-economic, environmental, and availability indicators," Journal of Cleaner Production, vol. 384, Jan. 2023, doi: 10.1016/j.jclepro.2022.135499.

[25] J. Man, T. Ma, Y. Yu, and H. Ren, "Levelized costs and potential production of green hydrogen with wind and solar power in different provinces of mainland China," Journal of Renewable and Sustainable Energy, vol. 16, no. 2, Mar. 2024, doi: 10.1063/5.0183511.

[26] M. Bornapour, R.-A. Hooshmand, A. Khodabakhshian, and M. Parastegari, "Optimal stochastic coordinated scheduling of proton exchange membrane fuel cell-combined heat and power, wind and photovoltaic units in micro grids considering hydrogen storage," Applied Energy, vol. 202, pp. 308–322, 2017, doi: 10.1016/j.apenergy.2017.05.133.

[27] M. H. Fakhr, A. R. Ariaei, and R. Ahmadi, "Power Generation Dynamics, Using Polymer Membrane Fuel Cell, Solar Panel, Wind Turbine, and Generator in Zahedan with Trnsys Software and Comparison of Hybrid Systems Performance with Single Systems," SSRN, Jul. 2022, doi: 10.2139/ssrn.4171565.

[28] X. Zhu, P. Gui, X. Zhang, Z. Han, and Y. Li, "Multi-objective optimization of a hybrid energy system integrated with solar-wind-PEMFC and energy storage," Journal of Energy Storage, vol. 72, Nov. 2023, doi: 10.1016/j.est.2023.108562.

[29] H. Liu, C. Wang, and J. Zhu, "Joint optimized operation of large-scale electric hydrogen production and new energy stations based on proton exchange membrane fuel cells," 2023 4th International Conference on Smart Grid and Energy Engineering, SGEE 2023, pp. 569–575, 2023, doi: 10.1109/SGEE60678.2023.10481748.

[30] A. Abdollahi Arjanaki, A. Dehestani Kolagar, and M. R. Alizadeh Pahlavani, "A two-level power management strategy in a DC-coupled hybrid microgrid powered by fuel cell and energy storage systems with model predictive controlled interface converter," Journal of Energy Storage, vol. 52, Aug. 2022, doi: 10.1016/j.est.2022.104861.

[31] C. A. Beltran, L. H. Diaz-Saldiernat, P. R. Martinez-Rodriguez, R. Cisneros, G. Vazquez-Guzman, and D. Langarica-Cordoba, "Adaptive IDA-PBC for Output Voltage Regulation of a Fuel Cell Hybrid Storage System," 2022 IEEE International Autumn Meeting on Power, Electronics and Computing, ROPEC 2022, 2022, doi: 10.1109/ROPEC55836.2022.10018669.

[32] R. Pedicini, M. Romagnoli, and P. E. Santangelo, "A Critical Review of Polymer Electrolyte Membrane Fuel Cell Systems for Automotive Applications: Components, Materials, and Comparative Assessment," Energies, vol. 16, no. 7, Apr. 2023, doi: 10.3390/en16073111.

[33] I. Yahia, C. ben Salah, A. S. Saidi, M. F. Mimouni, and A. Alshahrani, "Contribution to energy management of fuel cell/battery hybrid electric vehicles," Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, vol. 237, no. 2, pp. 388–398, Apr. 2023, doi: 10.1177/09544089221124451.

[34] A. Loskutov, A. Kurkin, A. Shalukho, and I. Lipuzhin, “New Trends and Prospects for Developing Local Power Sources Based on Fuel Cells and Power Storage Units for Critical Infrastructure Customers,” Energies, vol. 16, no. 1, Jan. 2023, doi: 10.3390/en16010197.

[35] A. Khadhraoui, T. Selmi, and A. Cherif, “Energy Management and Performances Evaluation of Proton Exchange Membrane Fuel Cell Battery Electric Vehicle,” 2022 13th International Renewable Energy Congress, IREC 2022, 2022, doi: 10.1109/IREC56325.2022.10002040.

[36] H. Fathabadi, “Combining a proton exchange membrane fuel cell (PEMFC) stack with a Li-ion battery to supply the power needs of a hybrid electric vehicle,” Renewable Energy, vol. 130, pp. 714–724, Jan. 2019, doi: 10.1016/j.renene.2018.06.104.

[37] H. Rezk and A. Fathy, “Hydrogen reduction-based energy management strategy of hybrid fuel cell/PV/battery/supercapacitor renewable energy system,” Journal of Energy Storage, vol. 86, May 2024, doi: 10.1016/j.est.2024.111316.

[38] Y. Achour, I. Chibane, D. Beziane, M. Aissani, and F. Benyamina, “Standalone power Plant based on PEMFC,” 2022 2nd International Conference on Advanced Electrical Engineering, ICAEE 2022, 2022, doi: 10.1109/ICAEE53772.2022.9962072.

[39] H. A. Ozgoli, S. Safari, and M. H. Sharifi, “Integration of a biomass-fueled Proton Exchange Membrane Fuel Cell system and a Vanadium Redox Battery as a power generation and storage system,” Sustainable Energy Technologies and Assessments, vol. 42, Dec. 2020, doi: 10.1016/j.seta.2020.100896.

[40] M. Vijayan, R. R. Udumula, T. Mahto, and L. Bhamidi, “Dynamic Operation of Islanded DC Microgrid with Fuel Cell Using Hybrid Energy Storage Systems,” Lecture Notes in Electrical Engineering, vol. 1117, pp. 249–259, 2024, doi: 10.1007/978-981-99-9235-5_18.

[41] S. Sharafi laleh, M. Zeinali, S. M. S. Mahmoudi, S. Soltani, and M. A. Rosen, “Biomass co-fired combined cycle with hydrogen production via proton exchange membrane electrolysis and waste heat recovery: Thermodynamic assessment,” International Journal of Hydrogen Energy, vol. 48, no. 87, pp. 33795–33809, Oct. 2023, doi: 10.1016/j.ijhydene.2023.05.137.

[42] Z. Mohammadi, P. Ahmadi, and M. Ashjaee, “Proposal and multi-criteria optimization of a novel biomass-based and PEMfuel cell system for generating clean power for building applications,” Energy, vol. 277, Aug. 2023, doi: 10.1016/j.energy.2023.127352.

[43] S. M. Beheshti, H. Ghassemi, and R. Shahsavan-Markadeh, “An advanced biomass gasification-proton exchange membrane fuel cell system for power generation,” Journal of Cleaner Production, vol. 112, pp. 995–1000, Jan. 2016, doi: 10.1016/j.jclepro.2015.05.106.

[44] S. Zhang, W. Jian, J. Zhou, J. Li, and G. Yan, “A new solar, natural gas, and biomass-driven polygeneration cycle to produce electrical power and hydrogen fuel; thermoeconomic and prediction approaches,” Fuel, vol. 334, Feb. 2023, doi: 10.1016/j.fuel.2022.126825.

[45] K. Guerra, R. Gutiérrez, and P. Haro, “THE ROLE OF BIOMASS IN THE FUTURE POWER SYSTEM: BIOMASS-BASED HYDROGEN AND BIOMASS-FUELED POWER PLANTS,” European Biomass Conference and Exhibition Proceedings, pp. 434–436, 2022, [Online]. Available: https://www.engineeringvillage.com/share/document.url?mid=cpx_M33f43b80184e40be525M79061017816355&database=cpx.

[46] H. Hoseini, M. M. Keshtkar, and A. Abbaslo, “Comprehensive 4E evaluation of an innovative multi-generation system driven by biomass fuel based on integration of GT-SCO2-TCO2-PEME-PEMFC,” Energy Conversion and Management: X, vol. 22, Apr. 2024, doi: 10.1016/j.ecmx.2024.100587.

[47] T. Hai et al., “An innovative biomass-driven multi-generation system equipped with PEM fuel cells/VCl cycle: Throughout assessment and optimal design via particle swarm algorithm,” International Journal of Hydrogen Energy, vol. 51, pp. 1264–1279, Jan. 2024, doi: 10.1016/j.ijhydene.2023.03.356.

[48] X. Zhang et al., “Comprehensive performance assessment of a novel biomass-based CCHP system integrated with SOFC and HT-PEMFC,” Energy, vol. 295, May 2024, doi: 10.1016/j.energy.2024.131112.

[49] H. Hwang, J. Yoon, and W. Choi, “Mobile Proton-Exchange Membrane Fuel Cell Powered by Diesel Fuel: System Simulation and Life Cycle Analysis,” International Journal of Energy Research, vol. 2023, 2023, doi: 10.1155/2023/3849631.

[50] J. Chen, F. Lin, H. He, and Y. Wang, “Proton Exchange Membrane Fuel Cell/Electrolyzer Hybrid Power System Modeling and Load Tracking Strategy,” Diangong Jishu Xuebao/Transactions of China Electrotechnical Society, vol. 35, pp. 636–643, Dec. 2020, doi: 10.19595/j.cnki.1000-6753.tces.191551.

[51] R. Fan, Z.-Q. Li, H.-M. Zhang, and W.-Q. Tao, “Analysis of a combined heating and power system based on high-temperature proton exchange membrane fuel cell and steam methane reforming: From energy, exergy and economic point of views,” Applied Thermal

Engineering, vol. 247, Jun. 2024, doi: 10.1016/j.applthermaleng.2024.123075.
[52] C. Li et al., "4E analysis of a novel proton exchange membrane fuel cell/engine based cogeneration system with methanol fuel for ship application," Energy, vol. 282, Nov. 2023, doi: 10.1016/j.energy.2023.128741.
[53] M. Taghizadeh, M. Mardaneh, and M. S. Sadeghi, "Frequency control of a new topology in proton exchange membrane fuel cell/wind turbine/photovoltaic/ultra-capacitor/battery energy storage system based isolated networks by a novel intelligent controller," Journal of Renewable and Sustainable Energy, vol. 6, no. 5, Sep. 2014, doi: 10.1063/1.4897940.
[54] O. C. Onar, M. Uzunoglu, and M. S. Alam, "Modeling, control and simulation of an autonomous wind turbine/photovoltaic/fuel cell/ultra-capacitor hybrid power system," Journal of Power Sources, vol. 185, no. 2, pp. 1273–1283, Dec. 2008, doi: 10.1016/j.jpowsour.2008.08.083.
[55] N. A. Ahmed, M. Miyatake, and A. K. Al-Othman, "Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems," Energy Conversion and Management, vol. 49, no. 10, pp. 2711–2719, Oct. 2008, doi: 10.1016/j.enconman.2008.04.005.
[56] R. Singh, A. S. Oberoi, and T. Singh, "Factors influencing the performance of PEM fuel cells: A review on performance parameters, water management, and cooling techniques," International Journal of Energy Research, vol. 46, no. 4, pp. 3810–3842, Mar. 2022, doi: 10.1002/er.7437.
[57] Y. Wang, K. S. Chen, J. Mishler, S. C. Cho, and X. C. Adroher, "A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research," Applied Energy, vol. 88, no. 4, pp. 981–1007, Apr. 2011, doi: 10.1016/j.apenergy.2010.09.030.
[58] Z. Yong, H. Shirong, J. Xiaohui, X. Mu, Y. Yuntao, and Y. Xi, "3D multi-phase simulation of metal bipolar plate proton exchange membrane fuel cell stack with cooling flow field," Energy Conversion and Management, vol. 273, Dec. 2022, doi: 10.1016/j.enconman.2022.116419.
[59] G. Zhang, H. Yuan, Y. Wang, and K. Jiao, "Three-dimensional simulation of a new cooling strategy for proton exchange membrane fuel cell stack using a non-isothermal multiphase model," Applied Energy, vol. 255, Dec. 2019, doi: 10.1016/j.apenergy.2019.113865.
[60] K. Zhou, Z. Liu, M. Qi, J. Huang, and X. Yan, "Evaluation criterion of cathode flow field in air-cooling proton exchange membrane fuel cells," Journal of Power Sources, vol. 603, May 2024, doi: 10.1016/j.jpowsour.2024.234409.
[61] X. Bai and Q. Jian, "Decoupling strategy for react-air supply and cooling of open-cathode proton exchange membrane fuel cell stack considering real-time membrane resistance estimation," Journal of Cleaner Production, vol. 410, Jul. 2023, doi: 10.1016/j.jclepro.2023.137288.
[62] H. Pei, J. Chen, L. Sun, W. Zhu, L. Xing, and Z. Tu, "Influence of Cathode Air Supply Mode on the Performance of an Open Cathode Air-Cooled Proton Exchange Membrane Fuel Cell Stack," SSRN, Jul. 2023, doi: 10.2139/ssrn.4524727.
[63] X. Yu, S. Cai, X. Luo, and Z. Tu, "Barrel effect in an air-cooled proton exchange membrane fuel cell stack," Energy, vol. 286, Jan. 2024, doi: 10.1016/j.energy.2023.129668.
[64] H. Chang, F. Cai, Z. Yang, C. Duan, and Z. Tu, "Experimental study on the endplate effect on the cold-start performance of an open-cathode air-cooled proton exchange membrane fuel cell stack," International Journal of Hydrogen Energy, vol. 48, no. 40, pp. 15215–15228, May 2023, doi: 10.1016/j.ijhydene.2023.01.003.
[65] G. Zhang, Z. Qu, H. Yang, Y. Mu, and Y. Wang, "Integrating full fan morphology and configuration in three-dimensional simulation of air-cooled proton exchange membrane fuel cell stack," Fuel, vol. 368, Jul. 2024, doi: 10.1016/j.fuel.2024.131628.
[66] A. Faghri, Z. Guo, Challenges and opportunities of thermal management issues related to fuel cell technology and modeling, Int. J. Heat Mass Transfer 48 (1920) (2005) 3891–3920 Pergamon.
[67] Y. Wang, D.F. Ruiz Diaz, K.S. Chen, Z. Wang, X.C. Adroher, Materials, technological status, and fundamentals of PEM fuel cells a review, Mater. Today 32 (2020) 178–203 Elsevier B.V
[68] C.Y. Wen, G.W. Huang, Application of a thermally conductive pyrolytic graphite sheet to thermal management of a PEM fuel cell, J. Power Sources 178 (1) (2008) 132–140.
[69] C.Y. Wen, Y.S. Lin, C.H. Lu, Performance of a proton exchange membrane fuel cell stack with thermally conductive pyrolytic graphite sheets for thermal management, J. Power Sources 189 (2) (2009) 1100–1105.
[70] C.-Y. Wen, Y.-S. Lin, C.-H. Lu, and T.-W. Luo, "Thermal management of a proton exchange membrane fuel cell stack with pyrolytic graphite sheets and fans combined," International Journal of Hydrogen Energy, vol. 36, no. 10, pp. 6082–6089, May 2011, doi: 10.1016/j.ijhydene.2011.02.052.

[71] A. P. Tetuko, B. Shabani, and J. Andrews, “Thermal coupling of PEM fuel cell and metal hydride hydrogen storage using heat pipes,” International Journal of Hydrogen Energy, vol. 41, no. 7, pp. 4264–4277, Feb. 2016, doi: 10.1016/j.ijhydene.2015.12.194.
[72] L. Wang, Z. Quan, Y. Zhao, M. Yang, and H. Jing, “Heat transfer process analysis and performance research of micro heat pipe array applied for the thermal management of proton exchange membrane fuel cells,” Applied Thermal Engineering, vol. 219, Jan. 2023, doi: 10.1016/j.applthermaleng.2022.119531.
[73] Y. Han, W. Zhuge, J. Peng, Y. Qian, P. Ming, and Y. Zhang, “A novel heat pipe bipolar plate for proton exchange membrane fuel cells,” Energy Conversion and Management, vol. 284, May 2023, doi: 10.1016/j.enconman.2023.116945.
[74] N. Shirzadi, R. Roshandel, and M. B. Shafii, “Integration of Miniature Heat Pipes into a Proton Exchange Membrane Fuel Cell for Cooling Applications,” Heat Transfer Engineering, vol. 38, no. 18, pp. 1595–1605, Dec. 2017, doi: 10.1080/01457632.2016.1262722.
[75] P. Marocco, D. Ferrero, A. Lanzini, and M. Santarelli, “Benefits from heat pipe integration in H<inf>2</inf>/H<inf>2</inf>O fed SOFC systems,” Applied Energy, vol. 241, pp. 472–482, May 2019, doi: 10.1016/j.apenergy.2019.03.037.
[76] J. Zhao, J. Han, C. Zhou, X. Cheng, Q. Jian, and C. Chen, “Design and experimental study of a novel vapor chamber for proton exchange membrane fuel cell cooling,” International Journal of Heat and Mass Transfer, vol. 220, Mar. 2024, doi: 10.1016/j.ijheatmasstransfer.2023.124949.
[77] Y. Chen, Q. Jian, Z. Huang, J. Zhao, X. Bai, and D. Li, “Improvement of thermal management of proton exchange membrane fuel cell stack used for portable devices by integrating the ultrathin vapor chamber,” International Journal of Hydrogen Energy, vol. 46, no. 74, pp. 36995–37006, Oct. 2021, doi: 10.1016/j.ijhydene.2021.08.185.
[78] X. Bai, Q. Jian, L. Luo, J. Zhao, and B. Huang, “Application of Vapor Chamber in the Thermal Management of Proton Exchange Membrane Fuel Cell Stack,” Huanan Ligong Daxue Xuebao/Journal of South China University of Technology (Natural Science), vol. 49, no. 2, pp. 25–32, Feb. 2021, doi: 10.12141/j.issn.1000-565X.200345.
[79] Z. Huang, Q. Jian, L. Luo, B. Huang, X. Bai, and D. Li, “Rapid thermal response and sensitivity analysis of proton exchange membrane fuel cell stack with ultra-thin vapor chambers,” Applied Thermal Engineering, vol. 199, Nov. 2021, doi: 10.1016/j.applthermaleng.2021.117526.
[80] Z. Huang, Q. Jian, and J. Zhao, “Thermal management of open-cathode proton exchange membrane fuel cell stack with thin vapor chambers,” Journal of Power Sources, vol. 485, Feb. 2021, doi: 10.1016/j.jpowsour.2020.229314.
[81] X.-H. Yuan, G. Wu, J.-G. Zhou, X. Xiong, and Y.-P. Wang, “MPC-based thermal management for water-cooled proton exchange membrane fuel cells,” Energy Reports, vol. 8, pp. 338–348, Dec. 2022, doi: 10.1016/j.egyr.2022.10.236.
[82] N. Atasay, A. Atmanli, and N. Yilmaz, “Liquid Cooling Flow Field Design and Thermal Analysis of Proton Exchange Membrane Fuel Cells for Space Applications,” International Journal of Energy Research, vol. 2023, 2023, doi: 10.1155/2023/7533993.
[83] Z. Li, B. Yin, J. Wan, S. Xu, and F. Dong, “Numerical study on heat and mass transfer characteristics of a novel cooling channel in PEM fuel cell,” Numerical Heat Transfer; Part A: Applications, vol. 84, no. 10, pp. 1191–1215, 2023, doi: 10.1080/10407782.2023.2174221.
[84] S. M. Baek, S. H. Yu, J. H. Nam, and C.-J. Kim, “A numerical study on uniform cooling of large-scale PEMFCs with different coolant flow field designs,” Applied Thermal Engineering, vol. 31, no. 8–9, pp. 1427–1434, Jun. 2011, doi: 10.1016/j.applthermaleng.2011.01.009.
[85] H. Ma et al., “Effects of PEMFC cooling channel insulation coating on heat transfer and electrical discharge characteristics of nanofluid coolants,” Applied Energy, vol. 357, Mar. 2024, doi: 10.1016/j.apenergy.2023.122514.
[86] I. A. Zakaria, W. A. N. W. Mohamed, N. H. A. Azid, M. A. Suhaimi, and W. H. Azmi, “Heat transfer and electrical discharge of hybrid nanofluid coolants in a fuel cell cooling channel application,” Applied Thermal Engineering, vol. 210, Jun. 2022, doi: 10.1016/j.applthermaleng.2022.118369.
[87] D. K. Madheswaran et al., “Nanofluids as a coolant for polymer electrolyte membrane fuel cells: Recent trends, challenges, and future perspectives,” Journal of Cleaner Production, vol. 424, Oct. 2023, doi: 10.1016/j.jclepro.2023.138763.
[88] F. Sahin, M. C. Acar, and O. Genc, “Experimental determination of NiFe<inf>2</inf>O<inf>4</inf>-water nanofluid thermophysical properties and evaluation of its potential as a coolant in polymer electrolyte membrane fuel cells,” International Journal of Hydrogen Energy, vol. 50, pp. 1572–1583, Jan. 2024, doi: 10.1016/j.ijhydene.2023.07.261.

[89] M. Striednig et al., “Evaporative cooling for polymer electrolyte fuel cells - An operando analysis at technical single cell level,” Journal of Power Sources, vol. 556, Feb. 2023, doi: 10.1016/j.jpowsour.2022.232419.
[90] S. A. Hosseini Baboli, A. Arabkoohsar, and I. Seyedi, “Numerical modeling and optimization of pressure drop and heat transfer rate in a polymer fuel cell parallel cooling channel,” Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 45, no. 4, Apr. 2023, doi: 10.1007/s40430-023-04106-z.
[91] H. Kazemi-Varnamkhasti, I. Khazaee, M. Ameri, and D. Toghraie, “Heat storage and increasing the rate of heat transfer in polymer electrolyte membrane fuel cell by adding nano-encapsulated phase change material to water in the cooling process,” Journal of Energy Storage, vol. 59, Mar. 2023, doi: 10.1016/j.est.2022.106497.
[92] G. Liu, Y. Qin, and D. Ji, “Numerical investigation of organic fluid flow boiling for proton exchange membrane fuel cell cooling and waste heat recovery,” Applied Thermal Engineering, vol. 228, Jun. 2023, doi: 10.1016/j.applthermaleng.2023.120564.
[93] X. Yan et al., “The use of phase-change cooling strategy in proton exchange membrane fuel cells: A numerical study,” Science China Technological Sciences, vol. 64, no. 12, pp. 2762–2770, Dec. 2021, doi: 10.1007/s11431-021-1889-4.
[94] Q. Li et al., “Comparison of organic coolants for boiling cooling of proton exchange membrane fuel cell,” Energy, vol. 266, Mar. 2023, doi: 10.1016/j.energy.2022.126342.
[95] W. Wang, N. Li, J. Zhang, C. Zhang, and L. Zhang, “Thermal Management Analysis of Proton Exchange Membrane Fuel Cell Filled with Phase Change Material in Cooling Channel,” International Journal of Energy Research, vol. 2023, 2023, doi: 10.1155/2023/9077046.
[96] L. Cheng, Z. Guo, and G. Xia, “A Review on Research and Technology Development of Green Hydrogen Energy Systems with Thermal Management and Heat Recovery,” Heat Transfer Engineering, vol. 45, no. 4–5, pp. 300–322, 2024, doi: 10.1080/01457632.2023.2191435.
[97] A. Baroutaji et al., “Advancements and prospects of thermal management and waste heat recovery of PEMFC,” International Journal of Thermofluids, vol. 9, Feb. 2021, doi: 10.1016/j.ijft.2021.100064.
[98] T. Wilberforce et al., “Recovery of waste heat from proton exchange membrane fuel cells – A review,” International Journal of Hydrogen Energy, vol. 52, pp. 933–972, Jan. 2024, doi: 10.1016/j.ijhydene.2022.08.069.
[99] H. Q. Nguyen and B. Shabani, “Proton exchange membrane fuel cells heat recovery opportunities for combined heating/cooling and power applications,” Energy Conversion and Management, vol. 204, Jan. 2020, doi: 10.1016/j.enconman.2019.112328.
[100] L. Yang, N.-N. Nik-Ghazali, M. A. H. Ali, W. T. Chong, Z. Yang, and H. Liu, “A review on thermal management in proton exchange membrane fuel cells: Temperature distribution and control,” Renewable and Sustainable Energy Reviews, vol. 187, Nov. 2023, doi: 10.1016/j.rser.2023.113737.
[101] Y. Wu, H. Bao, J. Fu, X. Wang, and J. Liu, “Review of recent developments in fuel cell centrifugal air compressor: Comprehensive performance and testing techniques,” International Journal of Hydrogen Energy, vol. 48, no. 82, pp. 32039–32055, Sep. 2023, doi: 10.1016/j.ijhydene.2023.04.262.
[102] M. Geng, H. Jiang, L. Jin, D. Cui, and L. Wang, “Design and testing of the fuel cell twin-screw air compressor,” Journal of Physics: Conference Series, vol. 2703, no. 1, 2024, doi: 10.1088/1742-6596/2703/1/012026.
[103] T. H. Ö zdemir and C. F. Yasar, “Proton Exchange Membrane Fuel Cell Thermal System Modeling and Control,” Proceedings - 2023 10th International Conference on Electrical and Electronics Engineering, ICEEE 2023, pp. 491–499, 2023, doi: 10.1109/ICEEE59925.2023.00095.
[104] C. Zhang et al., “Modelling, validation and analysis of preheating strategy of fuel cell vehicle during Subzero cold start,” International Journal of Heat and Mass Transfer, vol. 220, Mar. 2024, doi: 10.1016/j.ijheatmasstransfer.2023.124889.
[105] Oh, Y. Jung, H. Kim, and H. Lee, “Cascade utilization of organic Rankine cycle and absorption chiller assisted phosphoric acid fuel cell waste heat for dynamic building demands,” Energy Conversion and Management, vol. 263, Jul. 2022, doi: 10.1016/j.enconman.2022.115699.
[106] M. Capuano, M. Sorrentino, and M. Agelin-Chaab, “Design and analysis of a hybrid space heating system based on HT-PEM fuel cell and an air source heat pump with a novel heat recovery strategy,” Applied Thermal Engineering, vol. 231, Aug. 2023, doi: 10.1016/j.applthermaleng.2023.120947.
[107] Y. Shen, B. Zhao, T. H. Kwan, and Q. Yao, “Numerical analysis of combined air-cooled fuel cell waste heat and thermoelectric heating method for enhanced water heating,” Energy Conversion and Management, vol. 213, Jun. 2020, doi: 10.1016/j.enconman.2020.112840.
[108] Z. Hbilate, S. Hamham, Y. Naimi, and D. Takky, “Study and analysis of the thermal impact on the overall performance of the proton exchange membrane fuel cell

and its management and the exploitation of PEM fuel cells in a cogeneration system: Review," Proceedings of the 1st International Conference of Computer Science and Renewable Energies, ICCSRE 2018, pp. 115–124, 2018, doi: 10.5220/0009772501150124.

[109] X. Duan, A. Zhou, J. Xiao, S. Wang, and J. Wen, "Numerical simulation and structure optimization of spiral wound heat exchanger with novel spacing bars," Canadian Journal of Chemical Engineering, vol. 102, no. 3, pp. 1341–1352, Mar. 2024, doi: 10.1002/cjce.25110.

[110] J. Cao, X. Wang, Y. Yuan, Z. Zhang, and Z. Xiao, "EXPERIMENTAL INVESTIGATION ON HEAT TRANSFER AND PRESSURE LOSS CHARACTERISTICS OF THE GROOVED HELICALLY COILED TUBE HEAT EXCHANGER," Heat Transfer Research, vol. 55, no. 3, pp. 75–94, 2024, doi: 10.1615/HeatTransRes.2023049039.

[111] W. Jiang, D. Song, H. Jing, and W. Pan, "Organic Rankine Cycle System Variable Condition Analysis," Lecture Notes in Electrical Engineering, vol. 1118, pp. 739–746, 2024, doi: 10.1007/978-981-99-8878-5_73.

[112] A. S. Irani and A. Fattahi, "On the combined Brayton-Kalina cycle with PEM hydrogen production: An exergoeconomic analysis and multi-objective optimization with LINMAP decision maker," International Journal of Hydrogen Energy, vol. 52, pp. 289–304, Jan. 2024, doi: 10.1016/j.ijhydene.2023.05.006.

[113] R. Zhang, X. Wang, S. Yang, and X. Shen, "Thermodynamic Analysis of a Cogeneration System Combined with Heat, Cold, and Electricity Based on the Supercritical CO<inf>2</inf> Power Cycle," Energies, vol. 17, no. 7, Apr. 2024, doi: 10.3390/en17071767.

[114] H. Farajollahi and S. Hossainpour, "Techno-economic assessment of biomass and coal co-fueled chemical looping combustion unit integrated with supercritical CO<inf>2</inf> cycle and Organic Rankine cycle," Energy, vol. 274, Jul. 2023, doi: 10.1016/j.energy.2023.127309.

[115] C. Aoughlis et al., "A Novel Dynamic and Self-Adaptive InCre Technique Based on PI Control and EO Optimization for Hybrid PV-TEG Conversion Systems," Electric Power Components and Systems, vol. 52, no. 9, pp. 1569–1580, 2024, doi: 10.1080/15325008.2023.2296964.

[116] C. Liu et al., "Influence study of bottom cycle ratios and superheat for vessels waste heat cascade recovery based on TEG-ORC combined cycle system employing R245fa," International Journal of Green Energy, vol. 20, no. 7, pp. 734–743, 2023, doi: 10.1080/15435075.2022.2090841.

[117] B. Peris Pérez, M. Ávila Gutiérrez, J. A. Expósito Carrillo, and J. M. Salmerón Lissén, "Performance of Solar-driven Ejector Refrigeration System (SERS) as pre-cooling system for air handling units in warm climates," Energy, vol. 238, Jan. 2022, doi: 10.1016/j.energy.2021.121647.

[118] R. Dixit, "The evolution of thermally driven cooling technologies," World Energy Engineering Congress, WEEC 2018, 2018, [Online]. Available: https://www.engineeringvillage.com/share/document.url?mid=cpx_M685d466616d87c2cf7aM6baf10178163131&database=cpx

[119] R. Lazzarin and M. Noro, "Energy analysis of a heating and cooling plant equipped with a thermally driven heat pump and PVT collectors," Refrigeration Science and Technology, vol. 2020-July, pp. 27–35, 2020, doi: 10.18462/iir.rankine.2020.1107.

[120] Mohammed, MA, Hosseini, SE, Mahlia, TMI and Ong, HC (2014). Advances in Organic Rankine Cycle Research for Small-Scale Solar Power Systems. Renewable and Sustainable Energy Reviews, 32,502-516.

[121] Mohd Alam, Kuldeep Kumar, Viresh Dutta,Dynamic modeling and experimental analysis of waste heat recovery from the proton exchange membrane fuel cell using thermoelectric generator.Thermal Science and Engineering Progress 19 (2020) 100627.

[122] He, T., Shi, R., Peng, J., Zhuge, W., & Zhang, Y. (2016). Waste heat recovery of a PEMFC system by using organic Rankine cycle. Energies, 9(4). https://doi.org/10.3390/en9040267.

[123] Zhong, L., Yao, E., Dang, Z., Hu, Y., Zou, H., & Xi, G. (2021). Conceptual design and performance analysis of a novel CHP system integrated with solid oxide fuel cell and supercritical CO<inf>2</inf> partial preheating cycle. International Journal of Energy Research, 45(3), 3801–3820. https://doi.org/10.1002/er.6033

[124] Liu, W., Sun, B., Lai, Y., Yu, Z., & Xie, N. (2023). Performance improvement of an integrated system with high-temperature PEMFC, Kalina cycle and concentrating photovoltaic (CPV) for low temperature heat recovery. Applied Thermal Engineering, 220, 119659. https://doi.org/10.1016/J.APPLTHERMALENG.2022.119659

[125] R. Kumar, S. Patel, N. P. Patidar, and S. K. Patel, "A Review on Fuel Cell and Different Controller," 2023 IEEE International Students' Conference on Electrical, Electronics and Computer Science, SCEECS 2023, 2023, doi: 10.1109/SCEECS57921.2023.10062988.

[126] B. Qin, X.-L. Wang, L. Wang, F.-W. Pan, W.-M. Chen, and L. Jia, "Adaptive slide mode control of gas feeding of proton exchange membrane fuel cell system," Kongzhi

Lilun Yu Yingyong/Control Theory and Applications, vol. 40, no. 11, pp. 2049–2058, Nov. 2023, doi: 10.7641/CTA.2022.10550.
[127] B. Zhang, D. Gong, Z. Liu, and S. Xu, “Experimental Analysis of Control Strategies on Air Supply System for Proton Exchange Membrane Fuel Cells,” SAE Technical Papers, 2022, doi: 10.4271/2022-01-5096.
[128] H. Wei, C. Du, X. Li, C. Shi, and J. Zhang, “Research on anode pressure control and dynamic performance of proton-exchange membrane fuel cell system for vehicular application,” Fuel, vol. 358, Feb. 2024, doi: 10.1016/j.fuel.2023.130219.
[129] K. R. Ram, S. S. Kumar, V. Léchappé, A. Mohammadi, and M. Cirrincione, “Thermal and Air Management of an Open Cathode Proton Exchange Membrane Fuel Cell Using Sliding Mode Control,” Journal of Electrochemical Energy Conversion and Storage, vol. 21, no. 2, May 2024, doi: 10.1115/1.4063056.
[130] Y. Zhou, H. Lv, and B. Hu, “Research on Control Strategy for Cathode Pressures in Proton Exchange Membrane Fuel Cell,” Proceedings of SPIE - The International Society for Optical Engineering, vol. 12589, 2023, doi: 10.1117/12.2669868.
[131] K. R. Ram, S. S. Kumar, V. Léchappé, A. Mohammadi, and M. Cirrincione, “Thermal and Air Management of an Open Cathode Proton Exchange Membrane Fuel Cell Using Sliding Mode Control,” Journal of Electrochemical Energy Conversion and Storage, vol. 21, no. 2, May 2024, doi: 10.1115/1.4063056.
[132] J. Chang, X. Wang, J. Fang, D. Xie, and C. Wang, “Study on Control Strategy for Anode and Cathode Pressures in Proton Exchange Membrane Fuel Cell,” Qiche Gongcheng/Automotive Engineering, vol. 43, no. 10, pp. 1466–1471, Oct. 2021, doi: 10.19562/j.chinasae.qcgc.2021.10.007.
[133] B. Yang et al., “A critical survey of proton exchange membrane fuel cell system control: Summaries, advances, and perspectives,” International Journal of Hydrogen Energy, vol. 47, no. 17, pp. 9986–10020, Feb. 2022, doi: 10.1016/j.ijhydene.2022.01.065.
[134] K. B. Samal, S. Pati, and R. Sharma, “A review of FCs integration with microgrid and their control strategies,” International Journal of Hydrogen Energy, vol. 48, no. 91, pp. 35661–35684, Nov. 2023, doi: 10.1016/j.ijhydene.2023.05.287.
[135] X. Wang, Q. Hua, P. Liu, and L. Sun, “Stochastic dynamic programming based optimal energy scheduling for a hybrid fuel cell/PV/battery system under uncertainty,” Process Safety and Environmental Protection, vol. 165, pp. 380–386, Sep. 2022, doi: 10.1016/j.psep.2022.07.025.
[136] H. Hu, W.-W. Yuan, M. Su, and K. Ou, “Optimizing fuel economy and durability of hybrid fuel cell electric vehicles using deep reinforcement learning-based energy management systems,” Energy Conversion and Management, vol. 291, Sep. 2023, doi: 10.1016/j.enconman.2023.117288.
[137] J. Peng, T. Ren, Z. Chen, W. Chen, C. Wu, and C. Ma, “Efficient training for energy management in fuel cell hybrid electric vehicles: An imitation learning-embedded deep reinforcement learning framework,” Journal of Cleaner Production, vol. 447, Apr. 2024, doi: 10.1016/j.jclepro.2024.141360.
[138] J. Yang et al., “A novel dynamic load-priority-based scheduling strategy for home energy management system,” Journal of Cleaner Production, vol. 389, Feb. 2023, doi: 10.1016/j.jclepro.2023.135978.
[139] F. J. Asensio, J. I. San Martín, I. Zamora, and O. Oñederra, “Model for optimal management of the cooling system of a fuel cell-based combined heat and power system for developing optimization control strategies,” Applied Energy, vol. 211, pp. 413–430, Feb. 2018, doi: 10.1016/j.apenergy.2017.11.066.
[140] A. Yoshida, J. Yoshikawa, Y. Fujimoto, Y. Amano, and Y. Hayashi, “Stochastic model predictive control of residential fuel cell cogeneration unit with periodic forecast update for distributed architecture,” 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2017, 2017, [Online]. Available: https://www.engineeringvillage.com/share/document.url?mid=cpx_M1e4ec30e16437773e0fM53c01017816339&database=cpx
[141] X. Wang, Y. Zhang, L. Sun, and Z. Su, “Stochastic Dynamic Programming based Energy Management of a Residential Cogeneration System,” Proceedings of 2022 IEEE 5th International Electrical and Energy Conference, CIEEC 2022, pp. 3678–3683, 2022, doi: 10.1109/CIEEC54735.2022.9846563.