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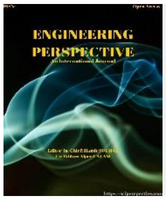

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Review Paper

Investigation of the Use of Fuel Cell Hybrid Systems for Different Purposes

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ABSTRACT

With the increase in global energy demand, air pollution becoming uncontrollable does not fall off the agenda. It is inevitable to use and spread of renewable energy sources to make energy production cleaner, more reliable and sustainable. In studies for this purpose, the use of fuel cell systems comes to the forefront thanks to its many advantages. The use of hybrid systems is becoming more common day by day in order to minimize the efficiency losses that may occur in the energy production, use and waste management process, to ensure energy reliability and to prevent systemic problems. In this study, hybrid systems created with fuel cells are discussed in detail, and examined under three main headings: hybrid systems created with renewable energy sources, created with storage devices, and created for energy recovery. It has been observed that the main purpose of hybrid systems created with renewable energy sources is to ensure energy reliability. In addition, the electrical energy required for the electrolysis of hydrogen used as fuel in fuel cells can be provided by photovoltaic panels or wind turbines, thus eliminating fuel storage and transportation problems. In hybrid systems created with storage devices, it is aimed to prevent instantaneous interruptions in the system by meeting the instantaneous power needed by the system and successful results have been achieved. In the hybrid systems created for energy recovery, it has been seen that it is possible to recover the heat and unburned fuel energy released from the fuel cell with thermophotovoltaic cells, gas turbines and heat exchangers.

Keywords: Efficincy, Fuel Cell, Hybrid System, Hydrogen, Renewable Energy

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1. Introduction

It is observed that the energy crisis and greenhouse effects are increasing day by day. Therefore, the use and spread of renewable energy systems is inevitable for cleaner, more reliable and sustainable energy production [1]. Wind, solar, biomass and fuel cells are at the forefront of renewable energy sources and systems [2]. Renewable energy sources have advantages and disadvantages compared to each other. Solar panels and wind turbines are among the widely preferred renewable energy sources today thanks to their high energy efficiency, no fuel costs and low maintenance costs. However, the energy produced by these systems may vary depending on seasonal and climatic changes and interruptions may occur. In addition, it is difficult to use in mobile applications due to its low power density.

Fuel cell systems are of interest in studies on the use and spread of renewable energy sources. Fuel cells are systems that convert fuel directly into electrical energy using electrochemical methods. With the advancement of technology, the use of these systems, which have many advantages, is becoming more common day by day. Some advantages of fuel cell systems can be listed as high energy density, near-zero CO2 emissions, silence and uninterrupted operation [1,3]. It is possible to use fuel cells in military devices, portable electronic devices, uninterrupted power systems, hybrid electric vehicles, airplanes, submarines and space vehicles [4]. After electricity production in fuel cells, water and heat are released as waste. Fuel cells are divided into three main groups according to their operating temperatures: fuel cells operating at low, medium and high temperatures. Although the heat released from fuel cell systems operating at high temperatures causes a decrease in fuel cell efficiency, it is possible to recover this heat.

Integrated hybrid systems have been developed to take advantage of renewable energy systems and minimize their disadvantages. The most basic criteria in the development of hybrid systems are to increase energy reliability and reduce costs and emission values [5,6]. The use of hybrid energy systems in off-grid, on-grid and mobile applications offers many advantages. Devices, machines and systems with the potential to create hybrid systems are shown in Figure 1 [2]. Biomass, photovoltaic panels, wind turbine, micro hydroelectric power plants, fuel cells, super capacitors and batteries are used in the creation of hybrid systems with renewable energy systems [5,6].

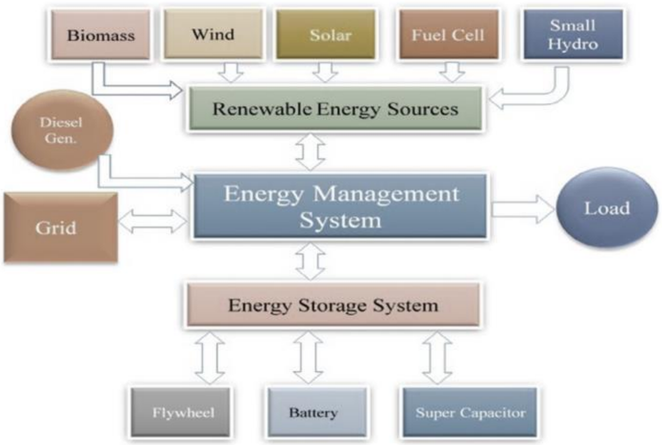

Figure 1. Hybrid renewable energy system [2]

There are many technologies and systems that can convert different primary energy sources into electrical energy and heat. A few-step processes are carried out until the desired energy form is achieved. In the production of electrical energy with fuel cells, heat release as waste is also inevitable. This heat energy can be recovered as electrical energy with various recycling systems [7].

In the literature research, hybrid systems to be created with the use of fuel cells are seen as the best solution in order to ensure energy reliability, which is the biggest problem of renewable energy sources. In this study, information about the types of hybrid systems created with fuel cell integration, their working principles and studies related to this subject are given. Renewable energy sources and storage devices used by hybrid systems created with fuel cell systems and energy recovery methods applied to these systems are mentioned in detail.

2. Fuel Cell Hybrid Energy Systems

In off-grid, on-grid and mobile systems, hybrid systems are used in order to increase the reliability of electrical energy, reduce the cost and improve the emission values [8]. Today, it is aimed to use renewable energy sources as much as possible to meet the load demand in energy production systems [9,10]. In hybrid systems created with renewable energy sources, integrating the fuel cell into the system is one of the most effective methods to ensure energy reliability [11,12].

There are three basic methods in the creation of fuel cell hybrid systems. In this study, hybrid systems created with fuel cells were examined under three headings: hybrid systems created with renewable energy sources, hybrid systems created with storage devices and hybrid systems created for energy recovery.

2.1 Hybrid systems created with renewable energy resources

The biggest disadvantage of renewable energy sources other than fuel cells is that they cannot provide energy reliability. Especially in wind and solar energy, generating electrical energy without using any fuel is an important advantage compared to the fuel cell. On the other hand, fuel cells stand out with their uninterrupted generation of electrical energy as long as fuel is supplied to the system. Energy can be produced from solar energy with photovoltaic panels and from wind energy with wind turbines. In order to ensure energy reliability in these systems, hybrid systems are created with fuel cells. The most common hybrid systems in which fuel cells are used with renewable energy sources are divided into two basic groups: FC (Fuel Cell)-PV (Photovoltaic) and FC (Fuel Cell)-PV (Photovoltaic)-WT (Wind Turbine). In addition to these, different combinations can also be applied.

Fuel cell-Photovoltaic hybrid systems

Hybrid systems created with photovoltaic and fuel cell systems are widely used in on-grid and off-grid systems, and they can also be used in mobile applications. These systems are more useful thanks to their simple structure and high efficiency [13]. Today, one of the most important limitations in the use of photovoltaic systems is the difficulties in storing the generated electrical energy. Due to this limitation, PV systems can only be used in summer and sunny hours in regions with low solar energy potential. In regions with high solar energy potential, it carries a high risk of interruption due to weather conditions [14].

The FC and PV hybrid system is shown in Figure 2. The basic elements of the system are the photovoltaic panel and the fuel cell. The battery or battery pack is used to prevent interruptions that may occur in the system during the transition phase and high power demand. Photovoltaic panels provide energy to the system under appropriate conditions, and the excess energy they produce is stored in the battery pack. The fuel cell, on the other hand, activates when an extra energy is required to feed the system. However, in mobile systems, this power control may be different. If the system shown in Figure 2 is used on a mobile system, FC becomes the primary power source [15]. PV feeds the system continuously. The battery pack stores the excess energy produced by the FC power supply and PV panels and feeds the system when the system needs instant power [15].

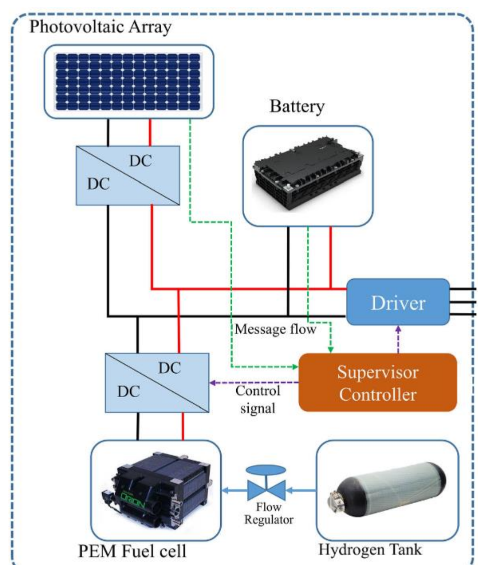

Figure 2. FC and PV hybrid system [15]

Yeşilata et al. analyzed the use of hybrid systems created with PV and FC in their studies. The hybrid system consists of PV panel, electrolysis unit, hydrogen tank and fuel cell. The electrical energy supplied from the PV panel is used for hydrogen production in the electrolysis unit. In cities with high solar energy potential, it has been seen that it is possible to produce hydrogen, needed by the fuel cell, with the electrical energy produced in the PV panel in 6 months. However, it has been concluded that extra electrical energy is required in the remaining months. It has been stated that the efficiency is very low since the electrical energy produced from solar energy goes through electrolysis and fuel cell processes. [14]. Ezzat et al. investigated the hydrogen consumption of the hybrid system consisting of FC and battery and the hybrid system consisting of PV, FC and battery under the same conditions. It has been obtained that the hybrid system consisting of PV, FC and battery consumes 561 g less hydrogen compared to the other system when it is operated for 3 hours at 98.32 kW power conditions. It has been concluded that the PV system reduces hydrogen consumption by 11.2% [16].

Fuel cell-Photovoltaic-Wind turbine hybrid systems

Supporting batteries and diesel generators with wind or solar energy reduces fossil fuel consumption. Replacing diesel generators and batteries with fuel cells offers a great opportunity to prevent environmental pollution and reduce operating and maintenance costs. As a promising alternative, the fuel cell can be used as an efficient energy conversion device for a hybrid generation system [17]. Alternative energy conversion systems such as photovoltaic panels and wind turbines can be operated in conjunction with fuel cells in a variety of on-grid systems [18]. FC, PV and WT hybrid systems are preferred to be used in regions with high solar and wind energy potential.

The hybrid system consisting of photovoltaic panels, wind turbines and fuel cell is shown in Figure 3 [8]. PV and WT systems on the hybrid system are used as primary sources in electricity generation. A battery pack is used to prevent instantaneous power interruptions in the system. When PV and WT systems cannot produce enough electrical energy, FC steps in and supports electricity generation [12,19].

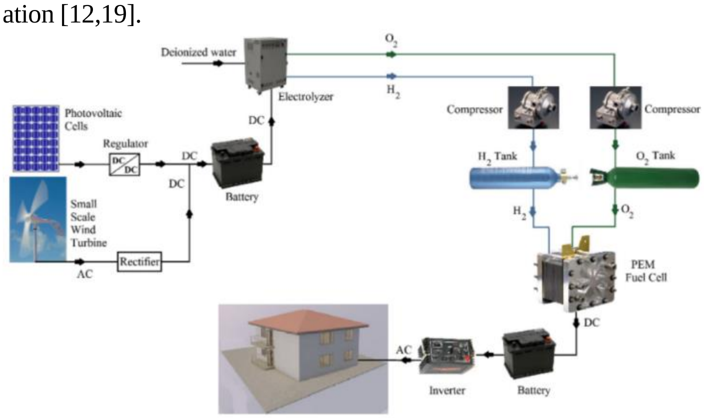

Figure 3. FC, PV and WT hybrid system [8]

Devrim et al. analyzed the use of a hybrid system consisting of FC, PV and WT devices for a 150 m2 house in Ankara. Since the use of PV and WT system for this house cannot provide uninterrupted electrical energy, FC has been integrated into the system. In the study, solar and wind energies were used as the primary energy source, and PEMFC (Proton Exchange Membrane Fuel Cell) was used as the supporting power source. In the hybrid system, there is a wind turbine with a power of 3 kW, photovoltaic panels with an area of 17.97 m2 and a fuel cell with a power of 1 kW. Considering the daily energy requirement of the examined house as 5 kWh, it is seen that the hybrid system meets the electricity need uninterruptedly throughout the year, except for November. In the other months, the energy requirement of the house is more than met and it can be used for cooling and heating of the house [8].

2.2 Hybrid systems created with storage devices

Fuel cells are constantly exposed to temporary power surges and dynamic loads according to their usage areas. Fuel cell systems have many effective advantages. Despite these advantages, it has longer start-up time and slow dynamic response compared to electronic systems due to the limitation of chemical reaction and fuel delivery system [20]. For this reason, hybrid systems are created by integrating electronic storage sources such as battery packs or capacitors into fuel cell systems [4]. The creation of hybrid systems with fuel cells and storage devices is generally carried out with three different combinations: FC-Battery, FC-Capacitor or FC-Battery-Capacitor.

Fuel cell-Battery hybrid systems

Batteries can effectively increase power performance by responding to rapid transient power pulses. FC stack characteristic is more suitable for working under constant loads. For this reason, hybrid systems consisting of fuel cell and battery have been created. The hybrid system created from the fuel cell-battery is shown in Figure 4 [20]. When the power demanded from the system is less than the fuel cell power, the excess energy produced is stored in the battery pack. When the power demanded from the system is more than the power of the fuel cell, the energy stored in the battery pack is supplied to the system and the need for power fluctuations is met uninterruptedly. In addition, fuel cell efficiency increases in this hybrid system. If the system where the electrical energy is transmitted needs constant power, such a hybrid system may not be necessary [4,20].

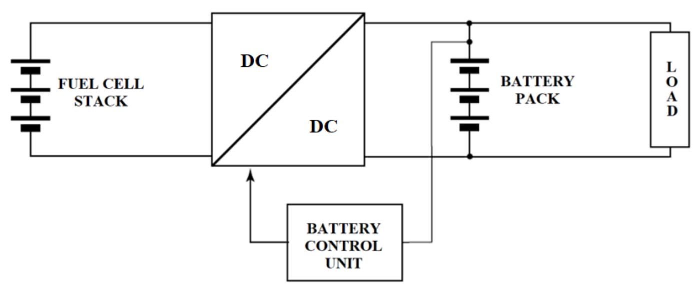

Figure 4. FC and battery hybrid system [20]

Gonzalez et al. experimentally investigated the fuel cell-battery hybrid system developed for use in an unmanned ground vehicle. The battery pack formed with lithium phosphate battery cells and the PEM fuel cell stack with 200 W power are connected in series. When the battery charge rate drops below a certain level, the fuel cell is activated. Approximately 49% of the energy produced by the fuel cell was transmitted to the power system for propulsion of the vehicle and 59% to the battery pack for storage. In the tests, it was determined that the average energy efficiency of the PEM fuel cell stack was 39%. As a result of the study, it was concluded that the energy required for the unmanned ground vehicle was successfully provided in the system created with the fuel cell and battery [21].

Fuel cell-Capacitor hybrid systems

Due to the slow dynamics of fuel cells, it is not suitable for use alone in systems with sudden fluctuations. The use of fuel cells alone in such systems shortens the life of the fuel cell and may cause instant interruptions in the system. Hybrid systems have been developed by combining fuel cells with capacitors to avoid this problem [22]. Hybrid systems created with FC-Capacitor devices are shown in Figure 5 [26]. There are some advantages and disadvantages of using a capacitor instead of a battery in the system. Although battery packs start to lose their efficiency after about 10 thousand charge-discharge cycles, capacitors can maintain performance for about one million cycles [23]. In addition, capacitors have a higher power density than batteries and can absorb higher power waves. Despite these advantages of capacitors, the biggest disadvantage is their low energy density [24]. However, this disadvantage does not prevent the use of capacitors with fuel cells. FC-Capacitor hybrid system is more suitable for mobile systems and is widely used [25].

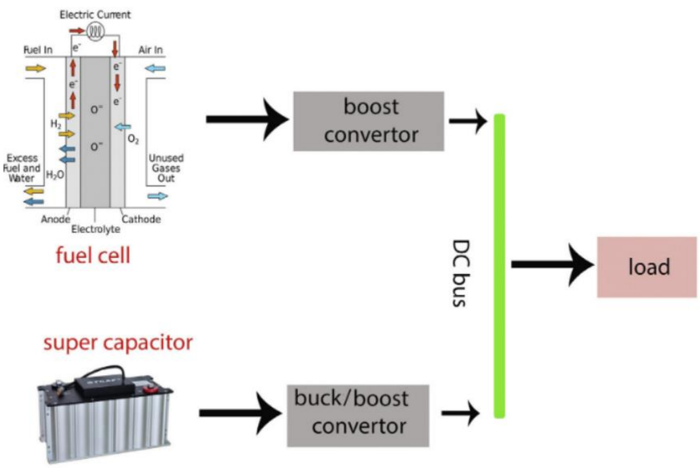

Figure 5. FC and capacitor hybrid system [26]

Allaoua et al. investigated the use of PEMFC as the main energy source and supercapacitor as auxiliary power source in an electric vehicle. MATLAB Simulink software was used in the simulation study. The slow dynamics of PEMFC has been tried to be eliminated with a super capacitor. Thus, it is aimed to improve fuel cell performance and life. In the study, it was concluded that PEMFC and super capacitor work in harmony and the stabilization of the system increased [27].

Fuel cell-Battery-Capacitor hybrid systems

In cases where the power requirement of the system to be energized is very fluctuating, a hybrid system can be created with FC, battery and capacitor. The hybrid system consisting of FC, battery and capacitor is shown in Figure 6 [28].

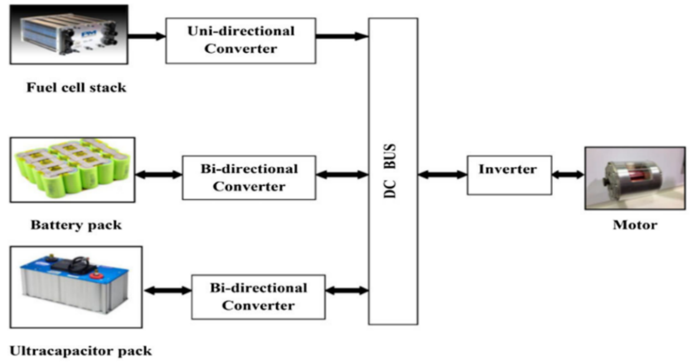

Figure 6. FC, battery and capacitor hybrid system [28]

The fuel cell produces the electrical energy required for the system, the battery and the capacitor store the surplus energy. When the energy need of the system increases, the system is fed by the battery and capacitor.

Chandan et al. simulated a hybrid system consisting of FC, supercapacitor and battery devices on an electric vehicle. A control strategy has been established in order to ensure that the hybrid system can meet the energy needs of the electric vehicle. The results have been obtained that the hybrid system created meets the electrical energy needed by the vehicle and the system works stably [29].

2.3 Hybrid systems created for energy recovery

It is aimed to increase the efficiency of the systems used in the energy production process and to reduce their emission values. As a result of the reactions taking place in fuel cells, high temperatures occur and heat is discharged to the outside. In addition, it is known that not all of the fuel supplied to the anode catalyst can be used. It is possible to recover energy from the heat released as a result of the reaction and from the unused fuel, by using systems outside the fuel cell [30]. Hybrid systems can be created by integrating systems such as gas turbine, thermophotovoltaic cell and heat exchanger into fuel cell systems. These systems, in which the heat and fuel discharged from the fuel cells are recovered with the integrated system, are examined under the title of hybrid systems created for energy recovery [31].

SOFC (Solid Oxide Fuel Cells) and MCFC (Molten Carbonate Fuel Cells) are called HTFC (High Temperature Fuel Cells) because they operate at high temperatures such as 800-1000 °C and 500-700 °C, respectively. The waste heat from these HTFC stacks is of high quality [32]. By integrating HTFC stacks with other thermal energy conversion devices, the overall energy efficiency of the system is increased, and the waste heat energy can be recovered with the hybrid systems created [33].

Thermophotovoltaic cell hybrid systems

TPVC (Thermophotovoltaic Cells) are devices that efficiently convert thermal radiation obtained by the sun, burning fuel or other methods into electricity [34]. The main advantages of TPVCs are their small size, no moving parts, low noise, easy maintenance, high power densities and high heat-electricity conversion [35,36]. Thanks to these advantages, TPVCs are among the common hybrid systems that provide energy recovery by integrating into fuel cells [31,36,37].

A hybrid system formed with HTFC and TPVC is shown in Figure 7 [36]. The HTFC-TPVC hybrid system consists of HTFC, regenerator, emitter, back surface reflector and TPVC. The regenerator heats the air and fuel that are about to enter the fuel cell with some of the heat released from the fuel cell. Thanks to the highly conductive material used between the HTFC and the emitter, heat flow to the emitter occurs. The emitter and the TPVC are separated by a vacuum cavity, and the heat transfer that takes place obeys Stefane Boltzmann's law. The emitter emits photons with thermal power density towards the TPVC. Moreover, a back surface reflector that can reflect photons back is used to increase the efficiency of the hybrid system [38].

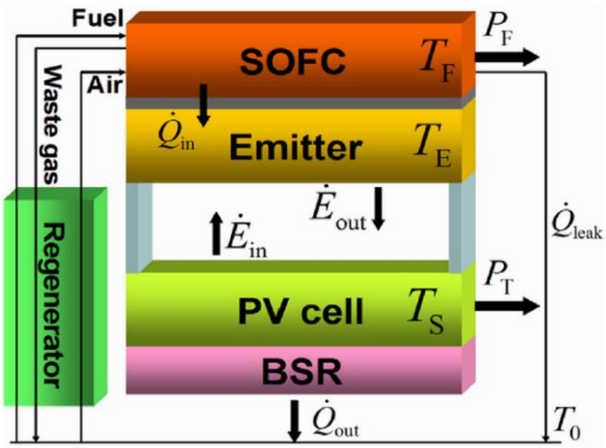

Figure 7. HTFC and TPVC hybrid system [36]

Zhimin Yang et al. numerically modeled and optimized the output power density in a hybrid system created with a DCFC (Direct Carbon Fuel Cell) and TPVC. More than twice the power that DCFC gives alone under the same operating conditions is obtained by this hybrid system. It has been determined that the output power density and efficiency increase as the operating temperature of the DCFC increases [31]. Dong et al. created a hybrid system with SOFC and TPVC. SOFC waste heat was transferred to thermophotovoltaic cells with water. As a result of the study, it was observed that the created hybrid system had higher efficiencies than the use of SOFC alone [39].

Gas turbine hybrid systems

By using HTFC and gas turbine systems together, a hybrid system aimed at energy recovery is obtained [40]. The main reason for using gas turbine hybrid systems is to provide energy production with high efficiency and low emission values. It is possible to achieve 70% efficiency in hybrid systems created by integrating gas turbines with SOFC, and it is almost impossible to achieve this efficiency with conventional fossil fuel systems [41]. With the use of gas turbine hybrid systems, even in power plants with low power outputs (200-400 kW), an efficiency of over 60% can be achieved [42]. The major disadvantages of these hybrid systems are the high initial setup cost and the difficulty of controlling between systems [41].

The heat energy required for the gas turbine is provided by the HTFC instead of the heat source used in the Brayton Cycle. In the system, the gas turbine has basic tasks such as generating electricity and giving pressure to the air that the fuel cell needs. In addition, the heat exchangers in the system heat the air and the fuel before entering the fuel cell. In order to obtain the high temperature and pressure gas required for the gas turbine, the heat released as a result of the chemical reaction in the fuel cell and the heat obtained by the re-oxidation of the fuel used in the fuel cell are utilized. One side of the turbine is connected to the compressor and the other side is mechanically connected to the generator. While a small part of the mechanical energy obtained in the turbine is consumed for the compressor, the majority of it drives the generator and produces electricity. Electricity generation with the electrochemical method in the fuel cell has high efficiency and low emission values. For this reason, it is aimed to produce as much of the electrical energy as possible in the fuel cell. The gas turbine hybrid system integrated with HTFC is shown in Figure 8 [40,43].

One type of gas turbine is micro gas turbines. Micro gas turbines are widely used for the conversion of heat energy from a system into electrical energy. Micro gas turbines, which have a lower weight and volume than normal gas turbines, bring gas turbine technology to smaller dimensions [40]. Their usage is quite advantageous for units in the range of 30-200 kW [44].

Mehrpooya et al. have created a hybrid system in which MCFC, gas turbine, steam engine and TPVC are integrated. The efficiency of MCFC was obtained as 44.58% under the conditions of 0.8 fuel consumption coefficient, 1 atm pressure and 650 ºC temperature and 2.5 vapor-carbon ratio. In the hybrid system, which was created by integrating only a gas turbine into the MCFC, the total efficiency was obtained as 54.83%. By adding gas turbine, steam engine and TPVC to MCFC, the total efficiency of the system was increased to 67.3%. It has been observed that a 22.72% increase in total energy efficiency has been achieved with the combined use of MCFC, gas turbine, steam engine and TPVCs [45]. Leal et al. examined a hybrid system with SOFC and gas turbine. The SOFC and gas turbine power ratio in the system is approximately 1.5. As a result of the study, SOFC efficiency was 40.8%, gas turbine efficiency was 27.1% and total efficiency was 62.1%. It has been determined that under the same conditions, the power of SOFC decreases with the increase of gas turbine power and the system efficiency decreases by 7% [46].

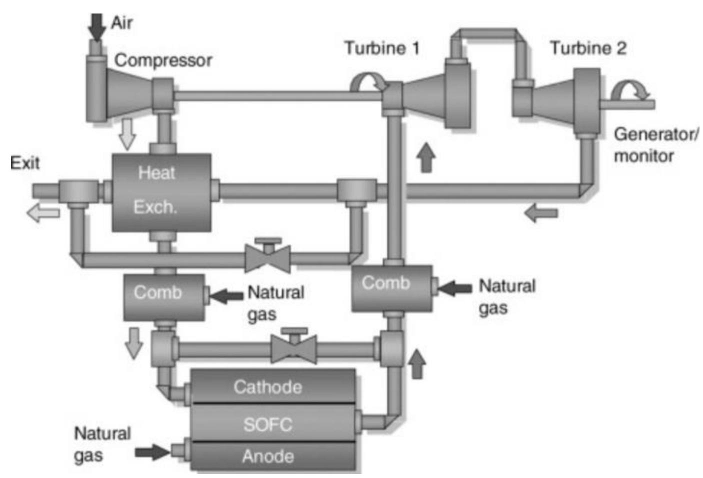

Figure 8. Pressure HTFC and gas turbine hybrid system [43]

Hybrid system with heat exchanger

SOFC and MCFC fuel cells operate at high temperatures and heat dissipation is inevitable. In addition, it is possible to recover some heat energy by reusing the fuel from the fuel cell. A combustor is used in the system to reburn the unused fuel. Although it is aimed to operate this combustor with fuel that has not been used by the fuel cells, some fuel can be added to the system from outside. It is important in terms of energy efficiency that the heat released by high-temperature fuel cells and the heat obtained from the re-burning of unused fuels are converted into useful work with heat exchangers. Hybrid systems with heat exchangers can consist of a single heat exchanger or more than one heat exchanger [30,47].

A hybrid system with heat exchanger is shown in Figure 9 [47]. This hybrid system consists of SOFC stack, combustor, air heater, fuel heater and HRS (Heat Recovery System). In the fuel cell, the unreacted anode and cathode exhaust gases are burned in a combustor to produce heat. The heat generated as a result of the reactions occurring in the fuel cells and the heat generated in consequence of the burning of the unused fuel are collected by the heat exchangers. The heat collected in the heat exchangers can be used to heat the fuel and air that are about to enter the fuel cell [48]. In addition, the collected heat can meet the hot water need of a house in hot seasons and can be used for heating the house in cold seasons [30,47].

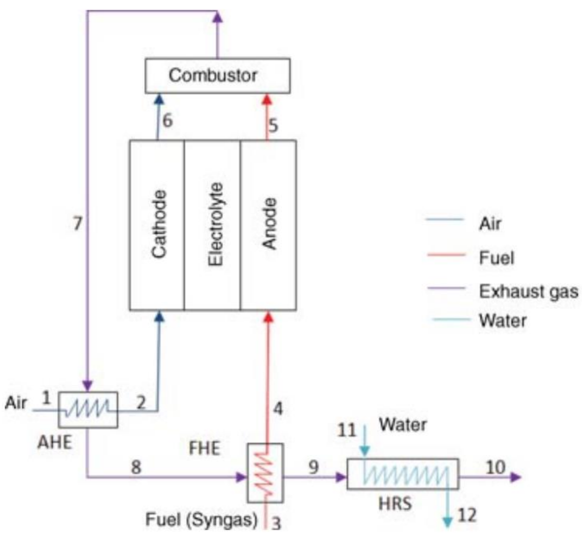

Figure 9. Hybrid system with heat exchanger [47]

Samavati et al. experimentally investigated the energy efficiency of a hybrid system with 5 kW SOFC and heat exchangers. In addition to heating the air and fuel entering the fuel cell with waste heat, the water in the external source is also heated. As a result of the study, the electrical energy efficiency, heat energy efficiency and total efficiency of the system were examined and these values were determined as approximately 20%, 50% and 75%, respectively [47]. Quoc et al. investigated hybrid systems that can be created to recover the heat produced by PEMFC and to use it in different heating/cooling and power cycles. It has been emphasized that with the use of hybrid systems to provide energy recovery in PEMFC, energy efficiency increases, operating costs and greenhouse gas emissions are significantly reduced [48].

3. Results and Discussion

In this study, the working principles, types and effects of hybrid systems created with fuel cells are examined in detail. FC hybrid systems are examined under three headings: hybrid systems created with renewable energy sources, created with storage devices, and created for energy recovery. It has been observed that the main purpose of hybrid systems created with renewable energy sources is to ensure energy reliability. Interruptions in the energy production of PV panels and WT due to seasonal and weather conditions are eliminated by the environmentally friendly structure of the FC. In addition, providing the electrical energy required for the electrolysis of hydrogen, which is used as fuel in FC, with PV panels or WT, eliminates fuel storage and transportation problems. In hybrid systems created with storage devices, it is aimed to meet the instant power needed by the energized system and to prevent instant interruptions in the system. In the studies examined, it has been observed that the interruptions and fluctuations that will occur in the system are absorbed by the use of a battery, capacitor or battery-capacitor together with the FC. Thus, the life of the FC is extended. In the hybrid systems created for energy recovery, it is aimed to recover the heat lost from the FC and the unused fuel energy. This energy recovery is carried out successfully with TPVC, gas turbines or heat exchangers and FC efficiency is increased.

Nomenclature

DCFC	Direct Carbon Fuel Cell
FC	Fuel Cell
HRS	Heat Recovery System
HTFC	High Temperature Fuel Cell
MCFC	Molten Carbonate Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
SOFC	Solid Oxide Fuel Cell
TPVC	Thermophotovoltaic Cell
WT	Wind Turbine

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Tolga Kocakulak: Writing-original draft, Conceptualization, Investigation. **Turan Alp Arslan:** Writing-review & editing, Visualization.

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