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Araştırma Makalesi / Research Article

Techno-Economic Analysis of A Lead-Acid Battery-Supported Fuel Cell for A Stand-Alone Residential House in Turkey

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ABSTRACT: The penetration rate of renewable energy sources is increasing day by day. However, most depend on the weather conditions such as solar, wind, precipitation, etc. This dependency also creates reliability problems for stand-alone systems. Fuel cells are essential solutions to overcome these issues since they need hydrogen to produce electrical energy, one renewable energy source that does not depend on weather conditions. In this research, an end-user profile, isolated from the grid and provides its energy by using a battery-backed PEM fuel cell, has been technically investigated in the simulation environment within the scope of the scenarios created. So, the systems intended to be implemented in reality have been transferred to the simulation environment. During the operation, to prevent deep discharge and overcharge of the battery pack, the fuel cell is kept in operation between a minimum of 40% and a maximum 90% State of Charge (SoC). Based on this system, initial investment, operation, and maintenance costs for a battery-backed fuel cell supply system are calculated and presented. The battery-supported fuel cell system is 46% expensive for lower consumption cases and 63% more expensive for higher consumption cases than grid prices.

Keywords: Cost-benefit analysis, Fuel cell, Residential application, Stand-alone system.

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1. INTRODUCTION

The penetration of renewable energy sources in the power grid increases day by day because of the depletion of fossil fuels, the awareness of climate change, and increased energy prices. However, most renewable energy sources provide power depending on natural events such as rain, wind, solar radiation, etc., and this limits end-users (Buonomano et al., 2018). Therefore, with their structure independent of natural events, fuel cells have become one of the solutions.

Fuel cells are electrochemical devices that generate electricity, heat, and water using hydrogen and oxygen (O'Hayre et al., 2016). In other words, fuel cells can be used wherever hydrogen can be supplied, regardless of geographical location and natural events. Although there are different types, the most suitable type that can be used for a smaller residential application is Polymer Electrolyte Membrane (PEM). In addition, the produced heat and water can also be used in cogeneration to increase efficiency (Li et al., 2020; Ronaszegi et al., 2020). These fuel cells have the main advantages such as high efficiency in electricity generation, noiseless operation compared to fossil fuel generators, and not producing environmentally harmful chemical wastes (Dorer et al., 2005).

One of the methods to produce hydrogen is electrolysis, and this process requires high power. The electrolysis system could be fed by the power obtained from solar panels (Ghenai et al., 2020). Then, produced hydrogen is stored in a tank and used to obtain electrical energy (Shah et al., 2011; Uzunoğlu et al., 2009). Therefore, fuel cells are generally included in hybrid structures, and they are used as auxiliary power for solar and wind energy. The reason is to get benefit from the fuel cell during the hours when the sun or wind is insufficient (Patterson et al., 2015). In a similar study, a microgrid model also consists of solar panels, fuel cells, and batteries; however, this type of hybrid operation's most challenging part is controlling since the dynamic structure of both the source and demand (Swarnakar et al., 2019). On the other hand, such systems have an opportunity to create a self-sufficient energy cycle if well-designed (Lokar and Virtic, 2020). Besides residentials, this could apply to the commercial end-users. (Tribioli and Cozzolino, 2020).

Fuel cells cannot directly produce the voltage level required by the loads at their output, and therefore they need converters (Doğan and Karaarslan, 2017a). In addition, it must be ensured that they can give a stable output with control circuits since they have dynamic structures (Doğan and Karaarslan, 2017b; Özkara et al., 2017). Thus, the technical capacity of such a system is essential to stability and continuity.

Grid isolated electrical energy systems are designed in different sizes and analyzed with their investment costs. Therefore, the economic analysis should be evaluated to decide on a cost-effective source. So, the study presents the technical analysis of a battery-supported fuel cell stand-alone system with the help of Matlab Simulink simulations. Also, the initial investment, operating, and maintenance cost of the system are determined for a residential house. The results are interpreted technically and economically.

The flow of the article is as follows; The first part includes a literature summary. The materials to be used in the study are explained in the second part. The results of the experiments are given and discussed in the third part. The conclusions drawn from the article are mentioned in the last part.

2. MATERIALS AND METHODS

The study consists of two subsections; technical and economic analysis of a residential house planned to be fed with a battery-supported fuel cell. First, technical analysis is performed via simulations to demonstrate the effectiveness of the system. Second, the cost of the system is calculated to understand the system's feasibility.

2.1 Technical Analysis

The system is presented in Figure 1. The circuit consists of one fuel cell, one inverter, eight 12V-42Ah lead-acid type batteries, and one hydrogen and oxidant. All these are transferred to the simulation environment and performed at Matlab Simulink. Four sets of 24V-42Ah (2 pieces of serial batteries) lead-acid type batteries are connected in parallel to the fuel cell. Thus, a 24 V low voltage busbar is obtained. Also, only batteries can send and receive energy and are represented with a double-sided arrow in the circuit.

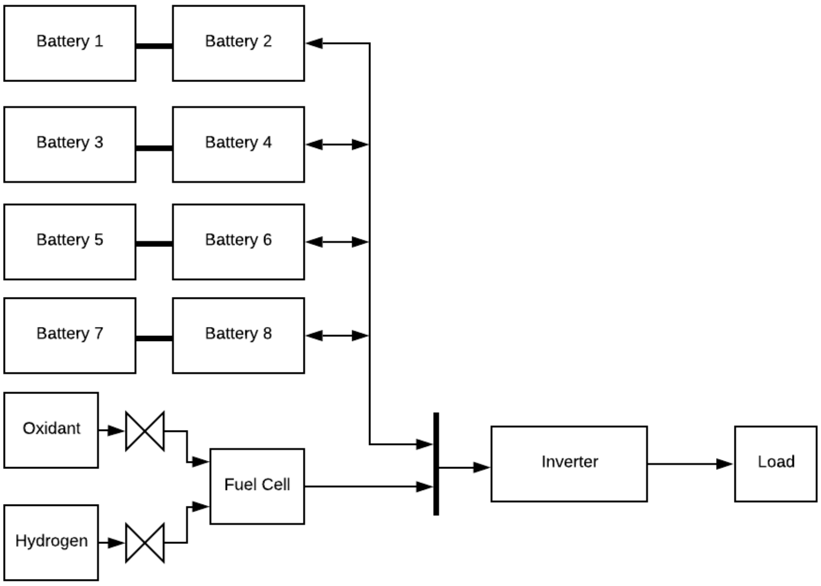

Figure 1. Battery-supported fuel cell system schematic

DuraPEM brand W240 model fuel cell is used as a primary energy supplier, and the fuel cell block is configured with actual specifications in the simulation environment. The nominal power of the fuel cell is given as 2.4 kW. However, it can produce power for a short time above its nominal power (Figure 2). The fuel cell needs hydrogen and oxidant as a source. A 50 L industrial tank supplies hydrogen, and a centrifugal fan supplies the oxidant.

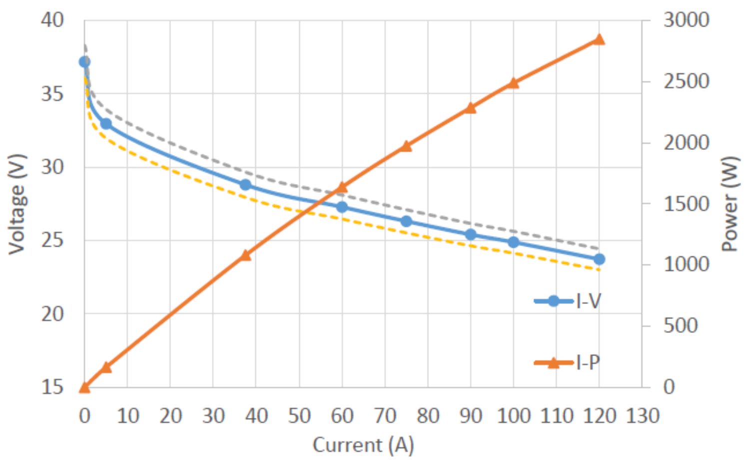

Figure 2. DuraPEM W240 current, voltage, and power graph (APFCT, 2016)

As seen in Figure 2, the fuel cell can supply a low DC voltage, which is inversely proportional to the amount of current drawn by the system. Then, an inverter with an input voltage of 24 V is connected to the fuel cell, and 220 Vrms is produced. Therefore, a Mervesan brand inverter with 24 V input nominal voltage and 3 kW output nominal power is selected to convert DC into AC. This inverter has an internal DC-DC chopper circuit and increases the voltage to 250 V DC. Then, it inverts the DC into positive and negative square waves (modified sinus). So, this process is simulated with the same output.

Vacuum cleaner, halogen light, laptop charger, heater, oven, and monitor are selected as possible residential loads, and they are presented in Table 1 with their nominal power values. They have different electrical characteristics. For example, resistive such as a heater and inductive like a vacuum cleaner. In addition to these, there are loads fed with power electronic circuits such as monitors (Akarslan ve Doğan, 2020). All of these loads operate with 220 Vrms nominal voltage.

Table 1. Possible residential loads

Load	**Nominal power [W]**
Halogen light	40
Vacuum cleaner	400
Laptop charger	65
Monitor	25
Oven	2000
Heater	1000

As aforementioned above, the fuel cell can provide 2.4 kW nominal power, the inverter can supply 3 kW nominal power, and the battery block has a total energy limit of 4 kWh. When these situations are considered in combination, the demand power should not exceed 3 kW, which may result in failing the inverter. In addition, if the demand is between 2.4 kW and 3 kW, the power flow can continue with the battery support for a limited time. Therefore, there will be a risk of deep discharge of the battery and deformations in the fuel cell. Thus, the demand factor should be below 68%, 2.4 kW, represented by combinations presented in Table 2.

Table 2. Load configuration for different power levels

Load configuration	**Load Status**	**Demand Power [W]**	**Demand Factor[%]**
Halogen Light-Laptop charger-Monitor	Low	130	3.6
Halogen Light-Vacuum Cleaner-Heater	Mid	1440	40.7
Halogen Light- Laptop Charger-Monitor-Oven	High	2130	60.3

Since the battery block is used in the circuit, the fuel cell is not affected by the instantaneous change in the desired load current. Here, the circuit, first, feeds the loads over the battery, and when the battery state of charge (SoC) drops below 40%, the fuel cell is activated. Then, batteries start to charge, and the load is fed. In addition, system efficiency is increased by ensuring that the energy produced is used at the highest level. Afterward, the fuel cell is deactivated when the battery SoC level reaches 90%. Thus, batteries are protected from overcharging, and the fuel cell is operated at the maximum level. The battery-supported fuel cell system algorithm is represented in Figure 3.

2.2 Cost Analysis

There is a trade-off between renewable energy sources, and one of the determining factors is the overall cost of the system. For example, solar energy has higher initial investment costs and lower operating and maintenance costs. However, diesel generators have lower initial investment costs and higher operating and maintenance costs. Thus, the cost is analyzed under three separate sections: initial investment, operating, and maintenance costs.

The initial investment includes amounts incurred before the investment starts operating, which can cause mistakes in understanding the overall cost of the system. In general, the initial investment costs in energy systems are high, and it also depends on the size and type of the system. The primary considerations in operating costs are consumables, and the only consumable used here is hydrogen. To understand the operating costs, the cost required for 1 kWh energy production needs to be determined. Therefore, it is necessary to calculate how many hours the tank that supplies hydrogen to the fuel cell can output hydrogen gas at 0.35 bar level, producing the maximum power. The tank contains 50 L of hydrogen gas, and the volume of this gas is 8.88 m^3. Its total pressure is 250 bar. The hydrogen gas pressure consumed during fuel cell use should be 5 psi (0.35 bar). The time required for the tank to fully empty at this adjusted pressure level is calculated with the help of Equation 1 and Equation 2. First, the gas flow rate at the tube outlet was calculated with the Weymouth Formula (Amani et al., 2016).

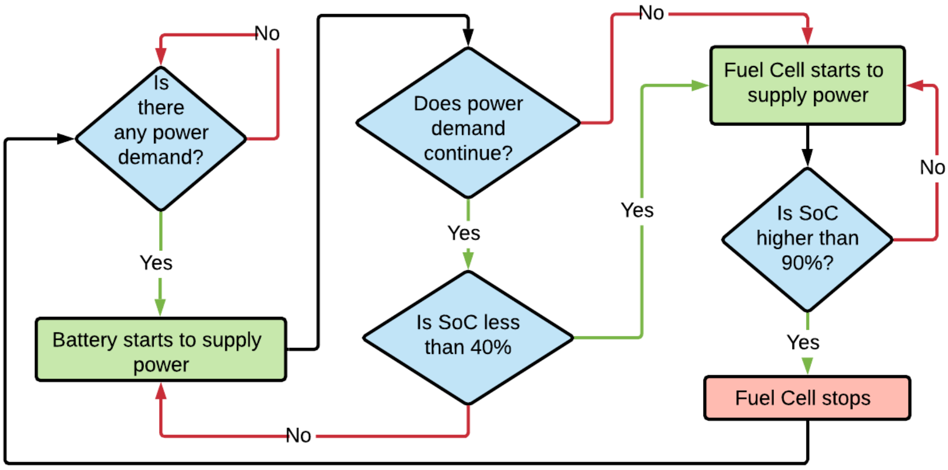

Figure 3. Battery-supported fuel cell system algorithm

$$Q = 2.61 * 10^{-8} * D^{2.667} * \sqrt{\frac{(P_1^2 - P_2^2)}{S * L} * \frac{288}{T}} \quad (1)$$

In this equation, Q is the flow rate (m^3/h), D pipe inner diameter (mm), L pipe length (km), P_1 and P_2 inlet and outlet pressure (Pa), S hydrogen gas density (kg/Nm^3), and T temperature (K). As a result, Q = 8.074 m^3/hour is calculated when the inner pipe diameter is 6 mm, the pipe length is 0.002 km, the inlet gas pressure is 35 000 Pa, the outlet gas pressure is 0 Pa, the hydrogen gas density is 0.089 kg/Nm^3, and the temperature is 20 K.

In Equation 2, the volume of the gas under 250 bar in the tube at normal ambient pressure is calculated.

$$P_{tube} * V_{tube} = P_{air} * V_{air} \quad (2)$$

Here, P_{tube} is given 250 bar, V_{tube} as 8.88 $m^{3,}$ and P_{air} as 1.01325 bar. It was calculated that the hydrogen gas in the tube occupies a volume of 2,191 m^3 in the open air. As a result, this tank needs 271.3 hours to empty.

Maintenance expenses are the costs that do not appear at first and are encountered after a while. Because they emerge under different times and conditions, they are usually calculated over their life cycles.

3. RESULT AND DISCUSSION

To evaluate the battery-backed fuel cell system, analyses are conducted in two stages. First, the effectiveness of the system in low, mid, and high-power consumption cases is investigated. Then, the overall cost of the system is determined.

3.1 Simulation Results

Low, mid, and high-power demand cases are described in Table 2. During simulations, it is assumed that all loads are running simultaneously. So, the demand power is 130, 1440, and 2130 W, respectively. Figure 4, 5, and 6 show the 60-second simulation result of fuel cell current, battery charging current, and inverter input current when the SoC level drops 40% for each case. At that moment, the fuel cell is activated, and the batteries transform to charging mode. It ensures that the efficiency obtained from the fuel cell is maximized.

Figure 4 presents the low-power demand case current waveforms. The average charging current is noted as 100 A. It indicates that batteries are charged faster than the other load cases since the charging current is the maximum for the battery group. In this case, the fuel cell operates shorter than in the other cases.

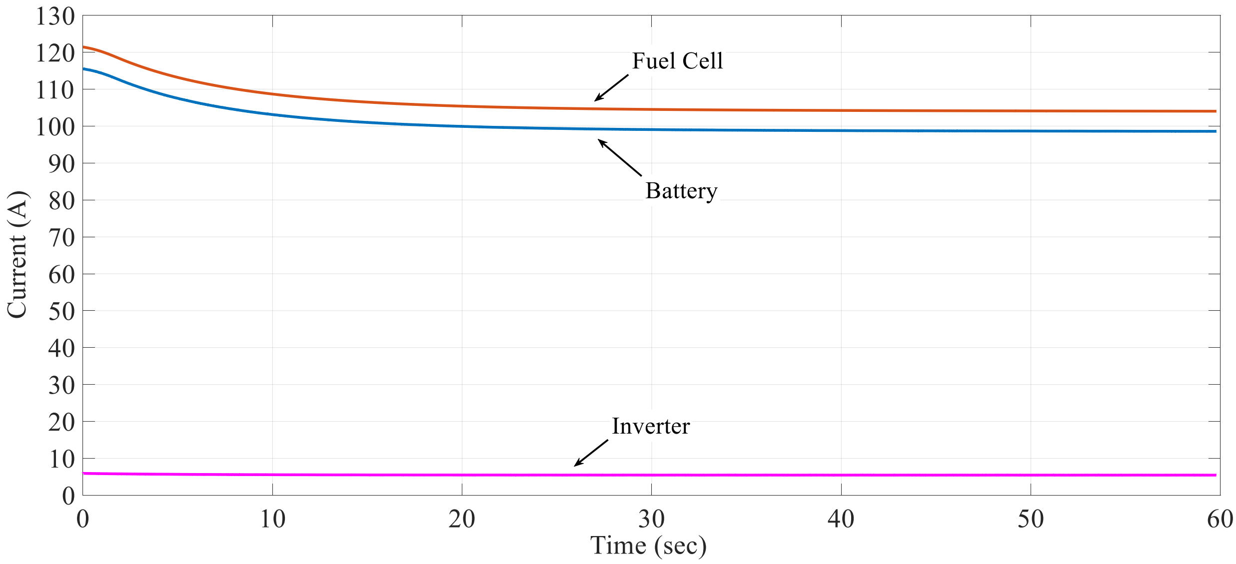

Figure 4. Low-power load case currents

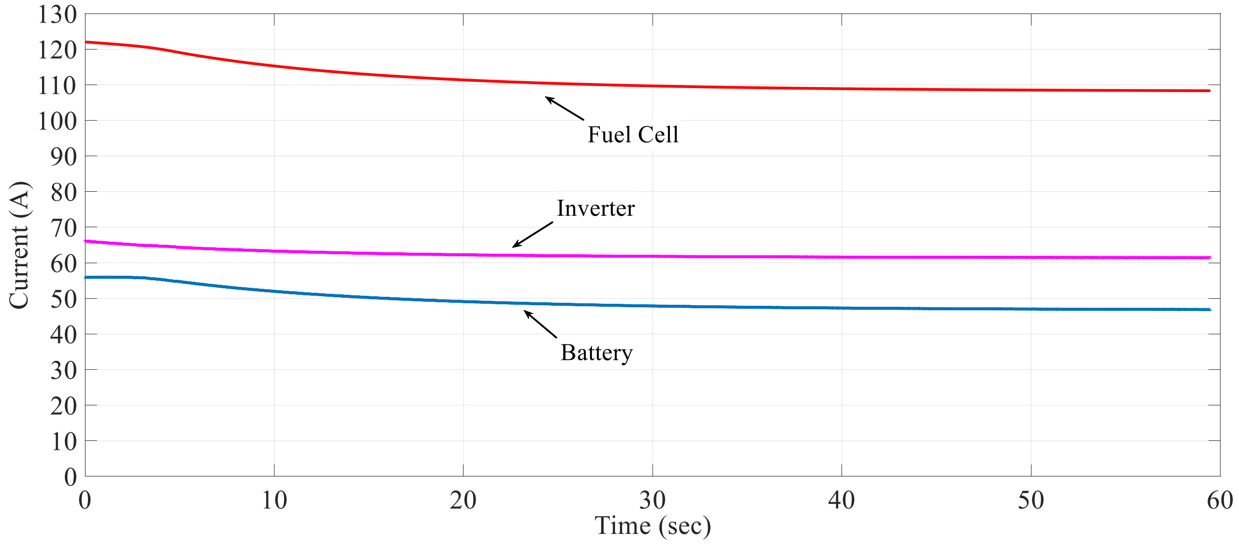

Figure 5. Mid-power load case currents

Figure 5 shows the mid-power demand case current waveforms. For this case, the higher portion of the produced energy by the fuel cell is transferred to the inverter since the demand increased more than ten times in comparison to the low-power case. The rest of the energy is delivered to batteries, and the average charging current is noted as 47 A.

The worst case is presented in Figure 6. In this case, the inverter current reaches the highest level. When the fuel cell is active, the average charging current is around 20 A. Therefore, batteries have the longest charging and the shortest discharging time. Even in the worst-case scenario, the simulation results show that it can operate and stay stable as a stand-alone system when such a system is installed.

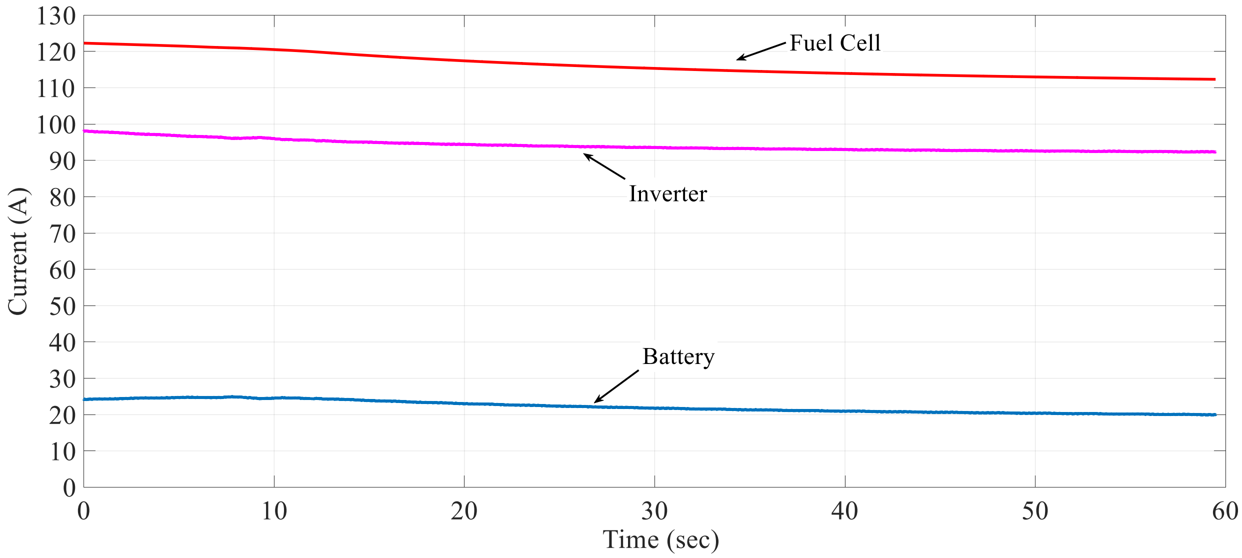

Figure 6. High-power load case currents

3.2 Cost Analysis

First, the initial investment cost of the system is investigated. The list of materials to be used in the system and their costs are presented in Table 3. The fuel cell constitutes 84% of the installation cost, the most expensive component. The reason behind this is the fuel cell manufacturing process.

However, efforts are currently being made to develop it and reduce its costs (Nielsen et al., 2019). Therefore, the prices mentioned here are expected to lower over time.

Table 3. The initial cost for materials

Materials	Quantity	Cost (₺)
PEM Fuel Cell	1 piece	60,000
3000W Invertör	1 piece	5,000
12V 42Ah Lead-Acid Battery	8 pieces	3,200
Hydrogen Tank 50L	1 piece	2,000
Miscellaneous Components	1 set	1,000
Total		**71,200**

Second, the operating cost of the system is calculated. For this cost, the consumables have to be considered. Since the only consumable is hydrogen, the operating cost equals the consumption of hydrogen per kWh. Remember that it takes 271.3 hours to empty a hydrogen tank. Hence, the operating cost of the one-hour operation of the system is calculated by Equation 3.

$$M_h = \frac{P_{tank}}{271.3}\ [₺/h] \tag{3}$$

where M_h represents the hourly operating cost, and P_{tank} represents the refilling charge of the hydrogen tank. The cost of refilling a hydrogen tank is 500₺ (November-2021). Based on this information, the cost of hydrogen consumed by the fuel cell during its operation is calculated as 1.843 ₺/h. After calculating the unit cost of hydrogen gas, the operating costs of each demand should be calculated. At this calculation, the demand factor for each is assumed to be 0.5. In other words, loads are assumed to be fully operated 12 hours a day. So, the total energy consumption is calculated using Equation 4.

$$E = P * h \tag{4}$$

where E represents the energy in kWh, P represents the consumption power in kW, and h is the consumption in hours. The amount of energy is calculated as 46.8, 478.8, and 766.8 kWh for low, mid, and high demand cases, respectively. Assuming that the fuel cell operates at full capacity, the total operating time and total operating cost are calculated using Equations 5 and 6, respectively.

$$T_{cs} = \frac{E}{P_{FC}} \tag{5}$$

$$T_{im} = T_{cs} * M_h \tag{6}$$

where T_{cs} is the total operating time in hours, T_{im} is the total operating cost in ₺, and P_{FC} is the nominal power of the fuel cell in kW. T_{cs} is calculated as 19.5, 199.5, and 319.5 hours for low, mid, and high demand cases. Based on calculated T_{cs} values, T_{im} is calculated as 35.94, 367.67, and 588.83 ₺ for low, mid, and high demand cases. All calculations are presented in Table 4.

Table 4. Cost analysis for different demand conditions

Demand	Total Operation Time [h]	Total Energy Consumption [kWh]	Total Operational Cost [₺]
Low	19.5	46.8	35.94
Mid	199.5	478.8	367.67
Large	319.5	766.8	588.83

Last, the maintenance cost for the system is considered. Maintenance costs should be calculated only for the battery, inverter, and fuel cell. However, a maintenance fee has not been determined for batteries since lead-acid batteries are maintenance-free. In addition, the inverter used does not require maintenance as long as it is not exposed to excessive current stresses. There are fuses inside for self-protection in case of malfunctions. In such a malfunction, these fuses may need to be replaced. Since their cost is meager, they are not included in the maintenance costs. Maintenance costs can only be calculated for the fuel cell due to the membranes. The membranes lose their life cycle after a certain period recommended in the user manual. It is reported as 3500 hours for the DuraPemW240 model fuel cell. After, they must be replaced. Anion Exchange Membrane (AEM) with a length of 20x15 cm must be used for its renewal, and 40 of these membranes are required. The price of each is 400₺ and a total of 16000₺.

3.3 Comparison with The Grid Price

As of March 1, 2022, with the transition to the efficiency-oriented cascaded tariff in Turkey, the final price for consumption amounts to 240 kWh per month for residential customers is 1.25 ₺/kWh, and 1.89 ₺/kWh for monthly consumptions above 240 kWh will be applied. Considering the updated tariff, both costs are compared based on consumption, and the results are presented in Table 5.

Table 5 indicates that a battery-supported fuel cell is 46-63% more expensive for a location that can feed over the grid. However, it should be noted here that this study is carried out for a house located in a place where there is no grid, such as a chalet or a vineyard house. Bringing the distribution network here is either impossible or not cost-effective. Therefore, it is unfavorable. Considering such situations, it can be concluded that the fuel cell provides excellent advantages for the reliability of the system.

Table 5. Comparison of battery-supported fuel cell vs. grid

	Battery-supported fuel cell				Grid cost [₺]
	Total consumption [kWh]	Total operating cost [₺]	Total maintenance cost [₺]	Total cost [₺]	
Low	46.8	35.94	88.92	124.86	58.5
Mid	478.8	367.7	909.72	1277.39	751.33
High	766.8	588.83	1456.92	2045.75	1295.6

4. CONCLUSION

Within the scope of this study, computer simulations are performed to demonstrate the effectiveness of the system, and the costs are calculated. The primary aim of this work is to reveal the economic status of such a system.

Simulations prove that a residential consumption of 2.13 kW (high power demand situation) can be supplied by a battery-supported fuel cell and inverter system. With the algorithm applied in the study, firstly, the system is fed via the battery. Then, the fuel cell, which is operated at full capacity, is activated. In this case, the maximum power produced by the fuel cell can be used. Otherwise, the total energy obtained from the fuel cell would have decreased before maintenance. Thus, the situation would increase the cost per generated energy and naturally increase overall costs.

The cost analysis includes initial investment, operation, and maintenance costs. The initial investment cost of such a system is calculated as 71200 ₺. In addition, operating cost is determined as 0.768 ₺ per kWh. Finally, the maintenance cost is calculated. However, the most important criterion that will determine the maintenance cost is the life cycle of the fuel cell, and it has a life cycle that varies according to usage conditions. Based on the life cycle specified in the catalog, there will be a maintenance cost of 16000 ₺ after every 3500 hours of operation, which means an additional cost of 1.9 ₺ per kWh. The battery-supported fuel cell system is 46% more expensive for lower consumption and 63% more expensive for higher consumption cases at the grid price comparison.

As a result, although the natural events required to obtain electricity from renewable energy sources from solar and wind occur in an irregular structure, they are predictable with some parameters (Sarı et al., 2021). However, they cannot be considered a power supply available at the time of need. Although the fuel cell stands out in the search for a renewable energy source independent of natural events, the need for hydrogen as a fuel is one of the most important disadvantages. However, diesel or gasoline generators planned to be used in such cases also need fuels. In addition, there are disadvantages such as very noisy structures and frequent maintenance. Review all, fuel cells stand out because they operate silently and do not require frequent maintenance. In addition, although their initial investment costs are higher than other generators, they are preferred in terms of comfort. Considering that fuel cell prices will decrease with the advancing manufacturing process, it is clear that it will be a significant energy source in the coming years.

Future studies may be towards finding alternative components to reduce the difference between the fuel cell and grid generation regarding electricity cost.

5. CONFLICT OF INTEREST

Authors approves that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

6. AUTHOR CONTRIBUTION

Muzaffer AKTAŞ and Rasim DOĞAN have the full responsibility of the paper about determining the concept of the research, data collection, data analysis and interpretation of the results, preparation of the manuscript and critical analysis of the intellectual content with the final approval.

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