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Optimal Sizing and Management of Hybrid Renewable Energy System for DC-Powered Commercial Building

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Abstract: DC power may be more efficient than AC power in certain applications, especially when it comes to local generation and storage. This is because AC power requires extra equipment to convert it to DC power, which can lead to energy losses. Using DC power, on the other hand, makes it easier for devices to use it directly, resulting in higher energy efficiency. Additionally, using DC power can reduce equipment capital costs as it eliminates the need for additional AC–DC conversion equipment. Finally, DC power systems can offer new communication capabilities, including plug-and-play for generation and storage devices, making it simpler to integrate these systems into existing infrastructure. This paper analyzes the optimal size of a photovoltaic/PEM fuel cell system to supply a certain DC commercial load in NEOM city. To identify the best size of the PV/PEMFC, minimizing the cost of energy (COE) and minimizing the net present cost (NPC) are considered. The paper studies three sizes of PEMFCs: 15 kW, 20 kW, and 25 kW. In addition, five different PV modules are selected: Axitec 450 Watt, Jinko 415 Watt, REC Solar 410 Watt, Seraphim 310 Watt, and Tongwei 415 Watt. The results of the study confirmed that the best size of the hybrid system comprises a 15 kW PEMFC, a 267 kW Tongwei PV array, a 60 kg electrolyzer, and a 20 kg hydrogen tank. Under these conditions, the COE and NPC are 0.293 USD/kWh and 498,984 USD, respectively.

Keywords: NEOM city; commercial building; photovoltaic; renewable energy

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1. Introduction

Buildings use a considerable amount of primary energy, making up around 40% of the world's total energy consumption, and thus, there is an increasing demand to create buildings that consume no net energy or "Net Zero Energy Buildings" [1]. The future of building design and energy management is expected to involve complete system solutions that enable net zero energy buildings [2]. These buildings are designed to produce as much energy as they consume annually [3]. Achieving this requires the incorporation of various technologies and strategies [4], including (1) building automation systems that are capable of real-time monitoring and optimization of energy consumption across all building systems [5,6]; (2) energy-efficient building envelope design to minimize energy losses through heat transfer [7]; (3) the integration of on-site renewable energy to generate sufficient energy to meet the building's needs [8,9]; (4) energy storage systems to store excess power from on-site renewables for later use throughout periods of sharp loads or low generation [10]; (5) smart-grid integration that allows buildings to interact with local utility grids and participate in demand response programs to balance supply and demand and avoid the construction of new power plants [11,12]; (6) support for the electrification of transportation to minimize greenhouse gas emissions and overall energy consumption [13,14]; and (7) increased financial incentives from the government in order to promote broader adoption of green technologies [15].

Direct current (DC) microgrids have the potential to eliminate large numbers of wasteful converters that are typically used to convert alternating current (AC) power to DC power in commercial buildings [16]. By utilizing DC power for the entire building's infrastructure, including lighting, high-voltage AC systems, and other devices, the need for multiple converters to switch AC to DC power is eliminated [17]. This results in higher energy efficiency and lower costs. Additionally, DC microgrids can be connected to energies, further reducing dependence on traditional power grids and non-renewable energy sources. This reduces energy losses that may be incurred when converting power between DC and AC and eliminates the need for AC–DC converters and inverters. Additionally, this reduces the amount of hardware required, leading to lower capital costs and greater simplicity in design and operation. With fewer components to maintain and repair, maintenance becomes easier. Furthermore, DC power systems can incorporate durable and efficient very high frequency (VHF) GaN switching technology to reduce energy waste, hardware requirements, and maintenance needs. VHF GaN switching provides higher power efficiency, higher switching frequency, and greater durability than conventional switching technologies, resulting in more efficient and reliable DC power systems [18].

Energy storage is a promising solution to address the challenge of intermittent generation from renewable energy sources on the electric grid [19,20]. Both batteries and hydrogen storage systems can complement or substitute for each other depending on the energy storage application. Although batteries are the most commonly used energy storage system in photovoltaic/battery systems, the degradation of their efficiencies from cycle to cycle (charge/discharge) results in decreased lifetimes and, thus, higher cost. Such conditions have led researchers and industries to investigate alternative storage options. One of the recommended solutions is hydrogen storage [21]. Researchers have concluded that hydrogen storage systems will effectively complement batteries in various commercial applications in the future. For instance, hydrogen can serve as a long-term storage solution in renewable source-based energy generation plants, while batteries can serve as medium- and short-term storage solutions [22].

The utilization of hydrogen storage in HES is growing in popularity across various purposes. For example, a study conducted by Singh et al. [23] investigated the possibility of utilizing an HES that combines a hydrogen fuel cell with solar photovoltaic units to power a building in India. Through the use of a fuzzy logic computing program, they determined that hydrogen fuel cells and battery storage are essential components for meeting high energy demands, particularly during late-night and early-morning hours. Another study by Khemariya et al. [24] applied HOMER to optimize the power system for an unelectrified village in India that integrated solar photovoltaic, battery, and fuel cell technologies. Similar work was reported by Salameh et al. on a big scale, i.e., the city of Khorfakkan [25], and at the small level of an office building [25] in UAE. Furthermore, Chadly et al. [26] highlighted how battery and hydrogen fuel cell storage systems can enhance the reliability, resilience, and economic feasibility of power energy systems.

The goal of this paper is to show a techno-economic feasibility study of using PV/PEMFC to feed a certain commercial load located in NEOM city. The software program HOMER (version HOMER pro 3.14.2.) is used to assess various system configurations and identify the most viable solution considering several factors, such as net present value, the levelized cost of energy and hydrogen, and operating cost. HOMER utilizes a repetitive algorithm process to determine the best combination of system configuration and parameters that results in the lowest economic costs and the greatest benefits in order to establish a practical and workable system configuration. To determine the best size of PV/PEMFC, two metrics are utilized: minimizing the cost of energy (COE) and minimizing the net present cost (NPC). Three different sizes of PEMFCs are examined: 15 kW, 20 kW, and 25 kW. In addition, the study employs five different types of PV panels, including Axitec 450 Watt, Jinko 415 Watt, REC Solar 410 Watt, Seraphim 310 Watt, and Tongwei 415 Watt.

The goal of the paper can be summed up as follows:

- ✓ The optimal design and size of the PV/PEMFC system to provide DC power to a specific commercial load in NEOM city is proposed;
- ✓ Different types of PV modules are considered to reduce the COE;
- ✓ Techno-economy and feasibility study of the proposed system is presented.

The rest of this paper is arranged as follows: The case study is explained in detail in Section 2. Section 3 describes the PV array, PEMFC, electrolyzer, and hydrogen tank sizing and modeling. Section 4 goes over the criteria for determining the optimum size of PV/PEMFC. Section 5 discusses the findings, and Section 6 summarizes the main findings.

2. Location and Load Profile

As the world's first project of its kind on such a vast scale, NEOM city in Saudi Arabia will run entirely on renewable energy [27]. In addition to lowering carbon emissions, this will pave the way for internationally sustainable projects. The fact that the price of renewable energy will be affordable for both consumers and businesses, ensuring that everyone has access to clean energy, is also promising. The location of NEOM city, as shown in Figure 1, is 29°08′ latitude and 34°55′ longitude. The average solar radiation levels on a horizontal surface are shown in Figure 2a. The months of July/January and June/December, respectively, have the greatest/lowest average temperatures and radiation levels. The case study's load is a commentary building in NEOM city that uses DC electricity. The typical DC primary load demand is shown in Figure 2b, with an average daily consumption of 300 kWh and a maximum output of 43 kW.

Figure 1. NEOM city location, https://neom.directory/where-is-neom, accessed on 30 June 2023.

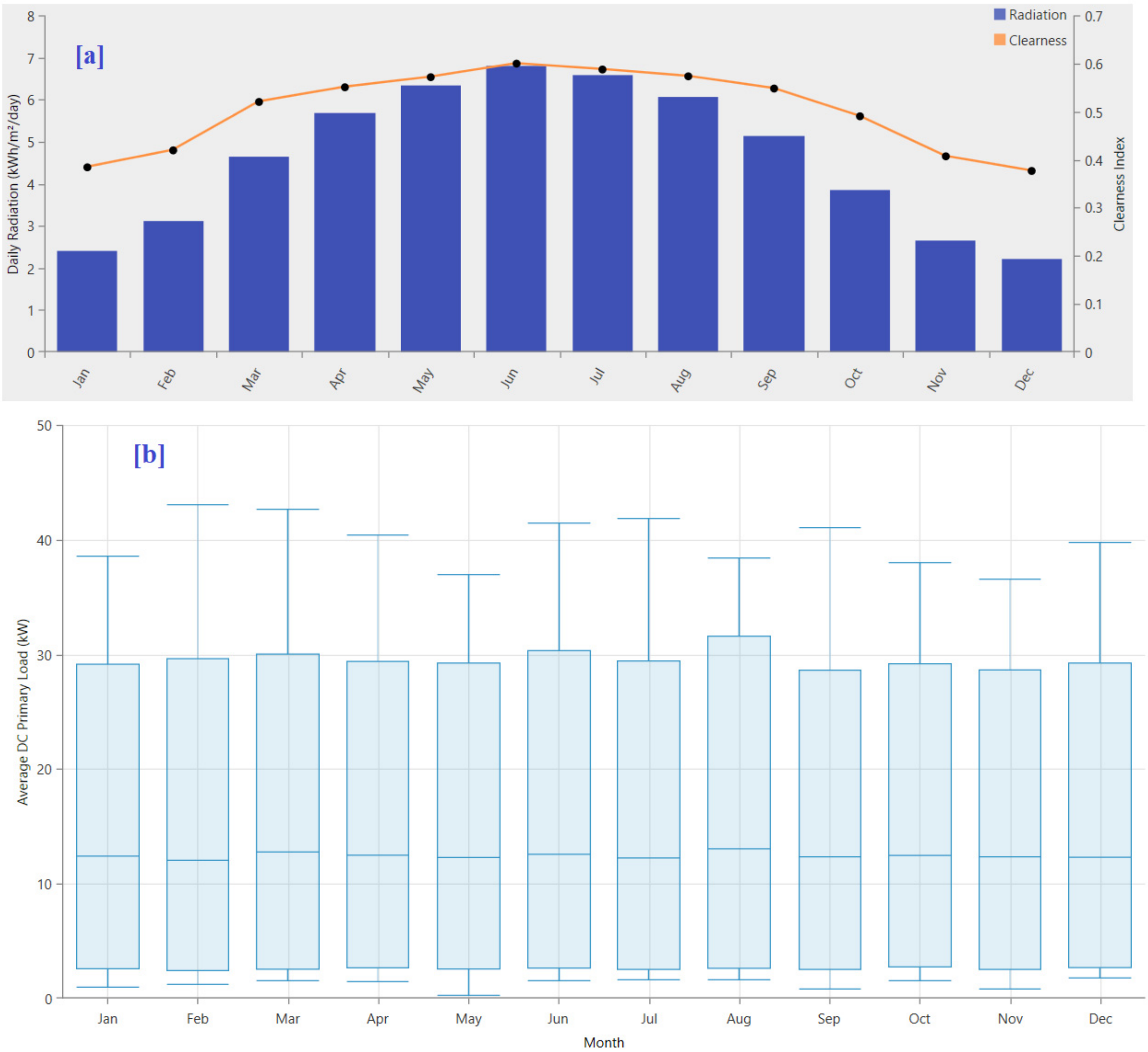

Figure 2. (**a**) Average global solar radiation and (**b**) average DC primary load demand.

3. System Description

A PV/PEMFC is employed used to power a specified load to commercial buildings in NEOM city, as shown in Figure 3. The photovoltaic cells convert sunlight into DC electricity, which can be used immediately or stored for later use by the fuel cells. The electrolyzer is used to generate hydrogen from excess electricity generated by the photovoltaic cells during sunny periods or low power demand. This hydrogen supplies the fuel cells during the deficit periods, when the demand for electricity exceeds the power generated by the photovoltaic cells. This hybrid system offers a more stable and reliable source of renewable energy that can provide power even throughout intervals of low sunlight or high demand. Furthermore, the system produces no greenhouse gas emissions, which promotes sustainability and reduces environmental impact. Three sizes of PEMFC are considered: 15 kW, 20 kW, and 25 kW. In addition, five PV modules are used: Axitec 450 Watt, Jinko 415 Watt, REC Solar 410 Watt, Seraphim 310 WattTongwei 415 Watt. The reason for changing the size of PEMFC and the type of PV module is to identify the best configuration for the case under study corresponding to minimum COE and NPC. PV modules have different efficiencies, temperature coefficients of power, and prices. These factors mainly influence the cost of energy.

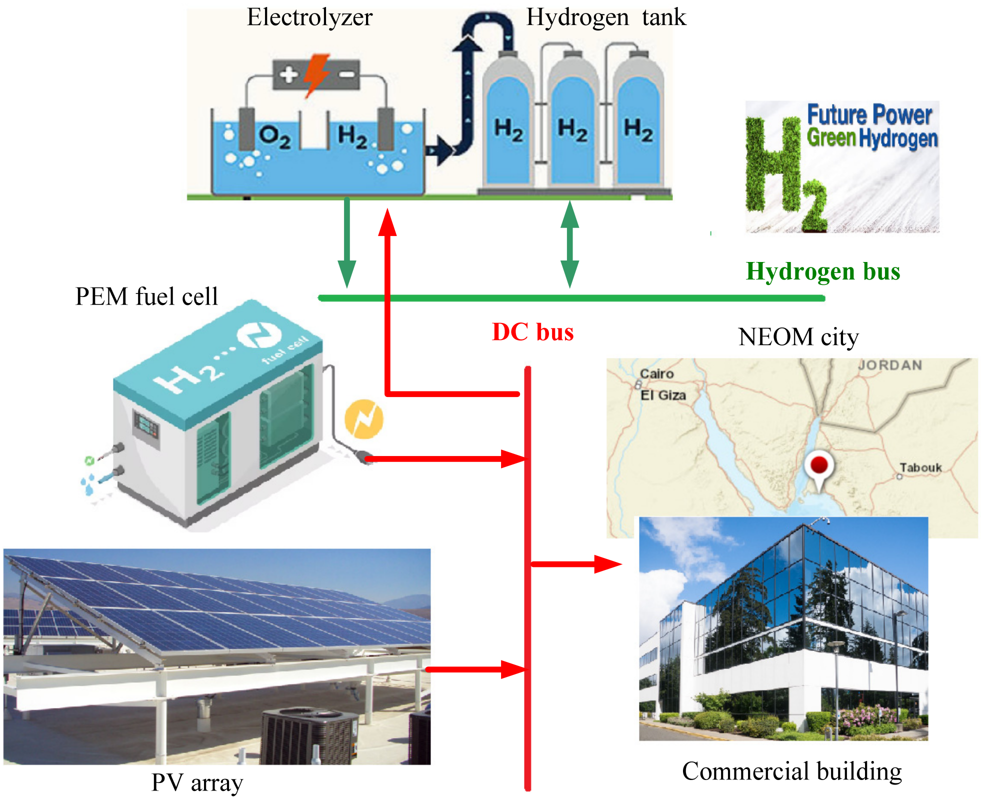

Figure 3. Schematic diagram of PV/PEMFC system.

The following subsections provide a description of the components of the PV/PEMFC system: PV array, PEMFC, electrolyzer, and hydrogen tank.

3.1. Photovoltaic System

The output power of a PV module is often inversely related to temperature and directly related to the solar energy impacting it. Because of the PV panel's decreased efficiency at higher temperatures, output power drops as temperature rises. On the other hand, as solar radiation rises, output power rises as more light photons may be converted into electrical power. The output of the PV array can be determined using the following relation:

$$P_{pv} = Y_{pv} f_{pv} R(1 + \alpha(T_c - T_{stc})) \tag{1}$$

- Y_{pv} is the rated capacity of the PV array;
- R is solar irradiance, T_c is the temperature of solar cells, and T_{stc} is the reference temperature;
- f_{pv} is the derating factor.

The derating factor is a scaling factor that HOMER uses to calibrate the PV array's power output. This change is needed to account for the fact that the PV panel's output will be lower in real-world conditions, which may be different from the conditions under which it is rated. If temperature effects are not explicitly modeled in the system, they can also be added to the derating factor.

α is called the temperature coefficient of power for PV systems. α is a measurement of how much the power output from the PV array varies as a result of the temperature of the cells, which is equivalent to the surface temperature of the array. Since reduced power production occurs at higher temperatures, the value is often negative. The temperature coefficient of power, power temperature coefficient, and maximum power temperature coefficient are typical names for this value used by manufacturers in the product literature. The five PV panels' specifications are listed in Table 1. PVs have a lifespan of 25 years.

Table 1. Specification of considered photovoltaic panels [28].

Parameter	PV Module Type				
	Axitec 450 Watt	**Jinko 415 Watt**	**REC Solar 410 Watt**	**Seraphim 310 Watt**	**Tongwei 415 Watt**
Maximum power, P_{max}, (W)	450	415	410	310	415
Voltage at maximum power (V)	41.60	30.79	49.4	33.2	31.49
Current at maximum power (A)	10.82	13.48	8.30	9.34	13.18
Open-circuit voltage, V_{oc}, (V)	49.40	37.31	59.2	40.4	38.08
Short-circuit current, I_{sc}, (A)	11.52	14.01	8.81	9.69	13.87
Efficiency (%)	20.70	21.25	21.2	18.85	21.3
No. of cells	144	108	-	60	108
Nominal operating cell temperature	45 °C	45 °C	44 °C	45 °C	45 °C
Temperature coefficients of P_{max} (%/°C)	−0.35	−0.35	−0.26	−0.36	−0.341
Temperature coefficients of V_{oc} (%/°C)	−0.27	−0.28	−0.24	−0.28	−0.262
Temperature coefficients of I_{sc} (%/°C)	0.048	0.048	0.04	0.05	0.054
Price (USD)	266	310	372	190	200

3.2. PEM Fuel Cell

PEMFCs, "Proton-exchange membrane fuel cells", offer numerous advantages, such as operation at low temperatures enabling quick start-up and shutdown; compactness due to high power density; environmentally friendly operation, as they produce water as a byproduct; and widespread commercial availability, particularly for automotive applications. PEMFCs are distinguished by the presence of a proton-conducting polymer electrolyte membrane. PEMFCs generate electricity by combining hydrogen and oxygen, which is the inverse of electrolysis. Although hydrogen fuel cells are highly efficient and only produce water as a byproduct, their production is expensive. During this process, hydrogen gas is oxidized in the fuel cell's anode section, releasing electrons and forming positive hydrogen ions. The lifetime of a fuel cell is 40,000 h.

Anode equation:

$$2H_2 = 4H^+ + 4e^- \tag{2}$$

Cathode equation:

At the cathode of a fuel cell, oxygen combines with electrons from the electrodes and positive hydrogen ions from the electrolyte and water. This process produces water as a byproduct, which is removed from the cell.

$$O_2 + 4e^- + 4H^+ = H_2O \tag{3}$$

$$O_2 + 2H_2 = 2H_2O + heat + dc\ power \tag{4}$$

3.3. Electrolyze

The electrolyzer converts electrical power to chemical, producing hydrogen through electrolysis, a well-known method of producing hydrogen. Water is decomposed into hydrogen and oxygen using electricity during electrolysis. Surplus energy from the PV array initiates an electrochemical reaction within the electrolyzer.

Anode reaction

$$H_2O \to O_2 + 4H^+ + 4e^- \tag{5}$$

Cathode reaction

$$4H^{+} + 4e^{-} \rightarrow 2H_2 \quad (6)$$

3.4. Hydrogen Tank

A direct solution is to store hydrogen as compressed gas. A storage system is critical in standalone energy systems to meet load demand during periods of insufficient energy production. For long-term storage, hydrogen gas storage systems offer both technical and economic advantages over battery storage systems. The ratio of the hydrogen tank's energy capacity to the electric load is referred to as the tank's autonomy. The next relation is used to estimate the hydrogen tank's autonomy:

$$A_{\text{htank}} = \frac{Y_{\text{htank}} LHV_{H_2} (24\ \text{h/d})}{L_{prim,ave} (3.6\ \text{MJ/kWh})} \quad (7)$$

where Y_{htank} denotes tank capacity, $L_{prim,ave}$ denotes the average primary load (kWh/d), and LHV_{H_2} denotes the lower heating value.

The lower heating value is the amount of heat that is released after the fuel has burned completely, assuming that the water created during combustion does not turn to vapor. The LHV for hydrogen is 120 MJ/kg.

4. Evaluation Criterion

The COE and the NPC are the two primary metrics taken into account while determining the ideal size of PV/PEMFC. Energy costs are a useful statistic for determining how competitive a renewable energy system is compared to other energy sources. It aids in locating chances for cost-cutting and performance enhancement. The total annualized cost is divided by the total electric load served to determine the COE. The equation reads as follows:

$$\text{COE} = \frac{\text{TAC}}{\text{TEL}} \quad (8)$$

where TAC denotes the total annualized cost of the system. The total amount of electric load served by the system over its lifetime is referred to as TEL.

The net present cost of a project is calculated by applying the project's discount rate to all anticipated future costs and revenues. The cost of capital, which is a representation of the possible return on investment in another project or venture, is factored into the discount rate. The following formula can be used to determine the NPC:

$$\text{NPC} = \frac{C_{ann,tot}}{\text{CRF}_{(i,n)}} \quad (9)$$

where $C_{ann,tot}$ is the yearly expense, i stands for the discount rate, and n represents the number of years.

CRF is the capital recovery factor, and it can be written as

$$\text{CRF}(i, N) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10)$$

The CRF formula requires that future cash flows be discounted in order to account for their present-day value. This procedure is applied to estimate the annual amount needed to repay a loan or to calculate the annual cost of a project.

5. Results and Discussion

HOMER allows you to identify the best size and layout for the system. The program takes into account energy requirements, available resources, and financial constraints to identify the cost-effective feasible solution that reduces the system's NPC or COE. This is accomplished through the methodical assessment of different system settings, equipment sizes, usage patterns, and distribution approaches. The HOMER iterative optimization process involves changing variables and evaluating scenarios in order to identify the most efficient solution. In order to identify the best size of PV/PEMFC, three sizes of PEMFC (15 kW, 20 kW, and 25 kW) were considered. Also, five PV panels were used: Axitec 450 Watt, Jinko 415 Watt, REC Solar 410 Watt, Seraphim 310 Watt, and Tongwei 415 Watt. Table 2 demonstrates the optimized results using different PV module types and sizes of FC. The COE values range from 0.293 USD/kWh to 0.41 USD/kWh, and the NPC values range from 498,984 USD to 69,679 USD, depending on the size of the FC and the type of PV module. Ultimately, the best size of FC was determined to be 15 kW. Figure 4 presents the COE with varying the size of FC and the type of PV module. It was found that the Tongwei 415 Watt panel combined with 15 kW of FC yielded the lowest COE of 0.293 USD/kWh, followed by Axitec 450 Watt with the same size of FC. The worst COE of 0.41 USD/kWh was obtained using REC Solar 410 Watt.

Table 2. Optimized results using different PV module types and sizes of FC.

PV	FC	Electrolyzer (kg)	H2 Tank (kg)	NPC (USD)	COE (USD/kWh)	O&M (USD/yr)	Capital Cost (USD)	Fuel (Kg/yr)
PV module type: Axitec 450 Watt								
276	15	60	20	520,938	0.305	17,982	237,671	1649
201	20	60	110	557,916	0.327	20,371	237,030	1771
196	25	60	130	632,960	0.371	24,068	253,836	1789
PV module type: Jinko 415 Watt								
268	15	60	40	571,530	0.335	18,389	281,186	1660
193	20	60	130	594,525	0.349	20,637	269,451	1781
201	25	40	170	666,637	0.393	23,790	291,896	1741
PV module type: REC Solar 410 Watt								
268	15	60	40	615,634	0.361	18,458	324,869	1659
193	20	60	130	626,030	0.368	20,675	300,348	1780
169	25	60	200	696,791	0.41	24,166	316,120	1832
PV module type: Seraphim 310 Watt								
268	15	60	40	570,050	0.334	20,578	245,899	1660
193	20	60	130	593,462	0.349	22,209	243,612	1781
202	25	40	170	666,826	0.393	25,465	265,698	1740
PV module type: Tongwei 415 Watt								
276	15	60	20	498,984	0.293	18,502	207,532	1649
214	20	60	80	540,903	0.317	20,949	210,912	1755
217	25	60	80	615,151	0.359	24,749	225,294	1763

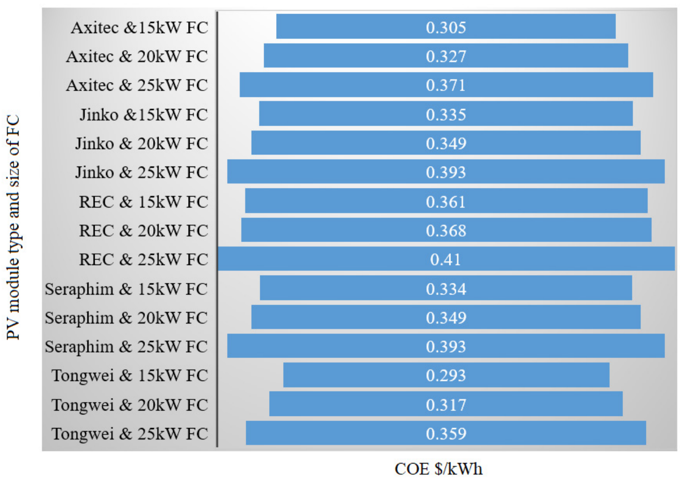

Figure 4. The COE with varying the size of FC and the type of the PV module.

According to Table 2, the best size of PV/PEMFC comprises a 276 kW PV, a 15 kW FC, a 60 kg electrolyzer, and a 20 kg H2 tank. The initial cost is USD 207,532. Table 3 presents the details of the NPC for different components of the PV/PEMFC. For instance, in the case of Tongwei 415 Watt, the total NPC is USD 498,984. The largest portion of the total NPC is the NPC of the FC, which amounts to USD 211,148.16 or roughly 42.3%, followed by the NPC of the photovoltaic array, with the NPC of the hydrogen tank being the lowest at 1.4%.

Table 3. Economical assessments for various components considering 15 kW PEMFC.

Component	Capital	Replacement	O&M	Salvage	Total
			Axitec 450 Watt		
Electrolyzer	USD 30,000.00	USD 16,847.52	USD 0.00	(USD 3822.59)	USD 43,024.93
Fuel Cell	USD 163,171.30	USD 0.00	USD 96,629.29	USD 0.00	USD 259,800.58
H2 Tank	USD 37,500.00	USD 52,415.44	USD 128,185.13	(USD 6988.17)	USD 211,112.40
PV	USD 7000.00	USD 0.00	USD 0.00	USD 0.00	USD 7000.00
System	USD 237,671.30	USD 69,262.95	USD 224,814.41	(USD 10,810.76)	USD 520,937.90
			Jinko 415 Watt		
Electrolyzer	USD 30,000.00	USD 16,847.52	USD 0.00	(USD 3822.59)	USD 43,024.93
Fuel Cell	USD 37,500.00	USD 52,583.66	USD 128,988.50	(USD 6744.48)	USD 212,327.68
H2 Tank	USD 14,000.00	USD 0.00	USD 0.00	USD 0.00	USD 14,000.00
PV	USD 200,363.96	USD 0.00	USD 101,813.31	USD 0.00	USD 302,177.26
System	USD 281,863.96	USD 69,431.18	USD 230,801.81	(USD 10,567.07)	USD 571,529.87
			REC Solar 410 Watt		
Electrolyzer	USD 30,000.00	USD 16,847.52	USD 0.00	(USD 3822.59)	USD 43,024.93
Fuel Cell	USD 37,500.00	USD 52,563.04	USD 128,893.99	(USD 6773.15)	USD 212,183.88
H2 Tank	USD 14,000.00	USD 0.00	USD 0.00	USD 0.00	USD 14,000.00
PV	USD 243,368.90	USD 0.00	USD 103,054.93	USD 0.00	USD 346,423.84
System	USD 324,868.90	USD 69,410.56	USD 231,948.92	(USD 10,595.74)	USD 615,632.64
			Seraphim 310 Watt		
Electrolyzer	USD 30,000.00	USD 16,847.52	USD 0.00	(USD 3822.59)	USD 43,024.93
Fuel Cell	USD 37,500.00	USD 52,583.66	USD 128,988.50	(USD 6744.48)	USD 212,327.68
H2 Tank	USD 14,000.00	USD 0.00	USD 0.00	USD 0.00	USD 14,000.00
PV	USD 164,398.52	USD 0.00	USD 136,298.46	USD 0.00	USD 300,696.98
System	USD 245,898.52	USD 69,431.18	USD 265,286.96	(USD 10,567.07)	USD 570,049.59
			Tongwei 415 Watt		
Electrolyzer	USD 30,000.00	USD 16,847.52	USD 0.00	(USD 3822.59)	USD 43,024.93
Fuel Cell	USD 37,500.00	USD 52,420.41	USD 128,208.76	(USD 6981.00)	USD 211,148.16
H2 Tank	USD 7000.00	USD 0.00	USD 0.00	USD 0.00	USD 7000.00
PV	USD 133,032.13	USD 0.00	USD 104,778.74	USD 0.00	USD 237,810.87
System	USD 207,532.13	USD 69,267.92	USD 232,987.50	(USD 10,803.59)	USD 498,983.96

Table 4 presents details on the electrical energy of a PV/PEMFC that uses a 15-kW PEMFC. When the Tongwei 415 Watt is used, the total annual energy production is 380,180 kWh. The PV array generates 92.8% of this energy, while the fuel cell produces the remaining 7.23%. The PV array has an average power output of 40.3 kW and generates 699 kWh of electricity daily. Its capacity factor is 14.6%, and it operates for 4277 h each year. Using the Tongwei module reduces the levelized cost of energy by 32.38% compared to using a REC Solar 410 Watt solar PV module, lowering it from USD 0.0633/kWh to USD 0.0428/kWh. Figure 5 illustrates the mean PV power output over time, with annual maximum outputs of 215 kW and 141 kW being recorded in March and December, respectively. The fuel cell operates for 5426 h each year and has 406 starts/yr. Its expected operational life and capacity factor are 7.37 years and 20%, respectively. Figure 6 shows the hourly output power of the PEMFC, with a mean electrical output of 5.06 kW.

Table 4. Technical details of PV/PEMFC system.

	Axitec 450 Watt	Jinko 415 Watt	REC Solar 410 Watt	Seraphim 310 Watt	Tongwei 415 Watt
		Electrical production			
Annual photovoltaic power, kWh	352,043 (92.8%)	342,216 (92.5%)	347,674 (92.6%)	341,058 (92.5%)	352,704 (92.8%)
Annual PEMFC power, kWh	27,476 (7.24%)	27,664 (7.48%)	27,655 (7.37%)	27,665 (7.5%)	27,475 (7.23%)
Annual total power, kWh	379,519 (100%)	369,880 (100%)	375,329 (100%)	368,723 (100%)	380,180 (100%)
		Electrical consumption			
DC load, kWh year	108,296 (58.5%)	108,318 (58.1%)	108,311 (58.1%)	108,317 (58.1%)	108,295 (58.5%)
Annual electrolyzer power, kWh	76,910 (41.5%)	78,185 (41.9%)	78,156 (41.9%)	78,186 (41.9%)	76,907 (41.5%)
Total, kWh/yr	185,206 (100%)	186,503 (100%)	186,467 (100%)	186,503 (100%)	185,203 (100%)
		PV array			
Mean output, kW	40.2	39.1	39.7	38.9	40.3
Mean output, kWh/d	965	938	953	934	966
Capacity factor, %	14.6	14.6	14.8	14.5	14.6
Maximum output, kW	215	209	318	208	216
PV penetration	322%	313%	255%	311%	322%
Hours of operation, hrs/yr	4277	4277	4277	4277	4277
Levelized cost, USD/kWh	0.0468	0.0561	0.0633	0.0560	0.0428
		Fuel cell			
Hours of operation, hrs/yr	5425	5459	5455	5459	5426
Number of starts, starts/yr	405	407	405	407	406
Operational life, yr	7.37	7.33	7.33	7.33	7.37
Capacity factor,%	20.9	21.1	21.0	21.1	20.9
Mean electrical output, kW	5.06	5.07	5.07	5.07	5.06
Maximum output, kW	15	15	15	15	15
		Electrolyzer			
Mean input, kW	8.78	8.93	8.92	8.93	8.78
Maximum input, kW	60	60	60	60	60
Capacity factor,%	14.6	14.9	14.9	14.9	14.6
Total production, kg/yr	2826	1685	1684	1685	1657
Specific consumption, kWh/kg	46.4	46.4	46.4	46.4	46.6
Hours of operation, hr/ys	1855	1897			
		Hydrogen tank			
Levelized COH, USD/kg	20.0	21.5	23.2	21.5	19.1
Energy storage capacity, kWh	667	1333	1333	1333	667
Tank autonomy, hr	53.3	107	107	107	53.3

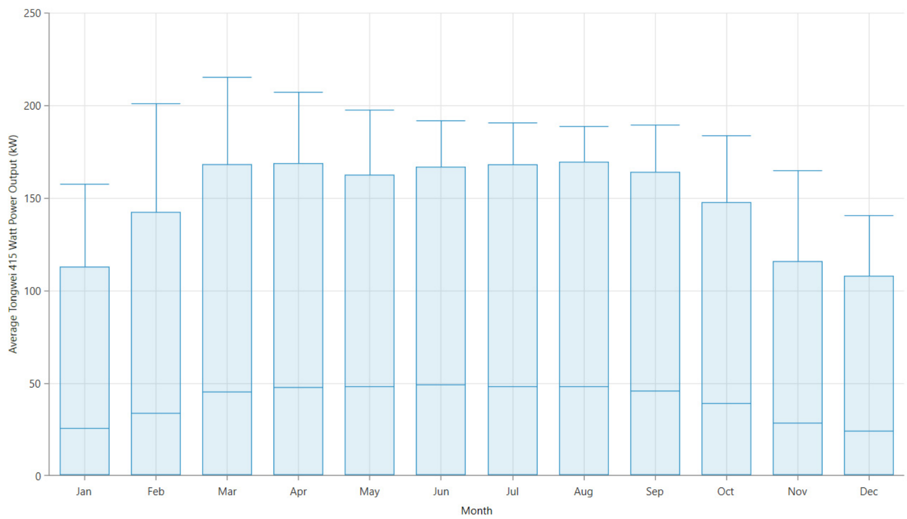

Figure 5. Mean PV power output using Tongwei 415 Watt.

The levelized costs of hydrogen values, shown in Figure 7, range between USD 19.1/kg and USD 24.3/kg. When using a Tongwei 415 Watt with 15 kW, there was a 21.4% decrease in cost compared to a Jinko 415 Watt with 25 kW. As presented in Figure 8, on average, the monthly amount of stored hydrogen is higher when using a Trina solar TSM-430NEG9R.28 with a 30 kW FC. The daily average stored hydrogen ranges between 9.76 kg and 18.79 kg, with the lowest value of 9.76 kg stored in January and the highest value of 18.79 kg stored in June. Figure 9 shows the hourly stored hydrogen.

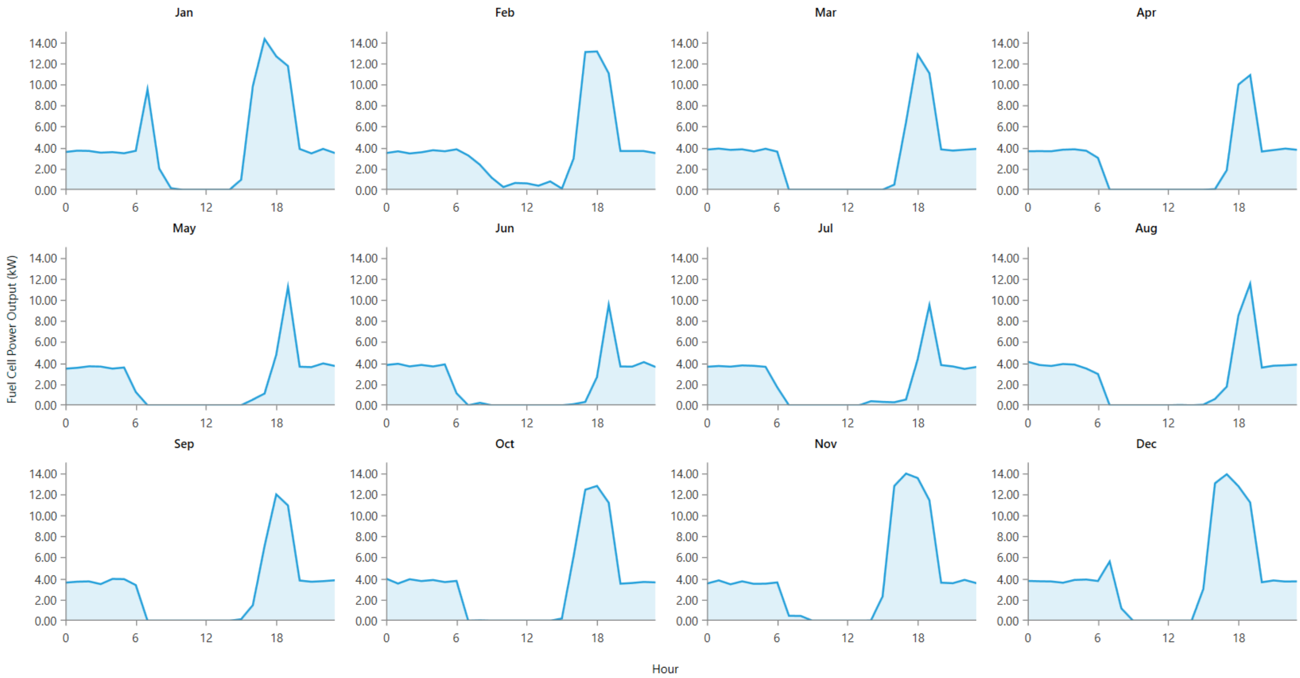

Figure 6. Hourly fuel cell output power.

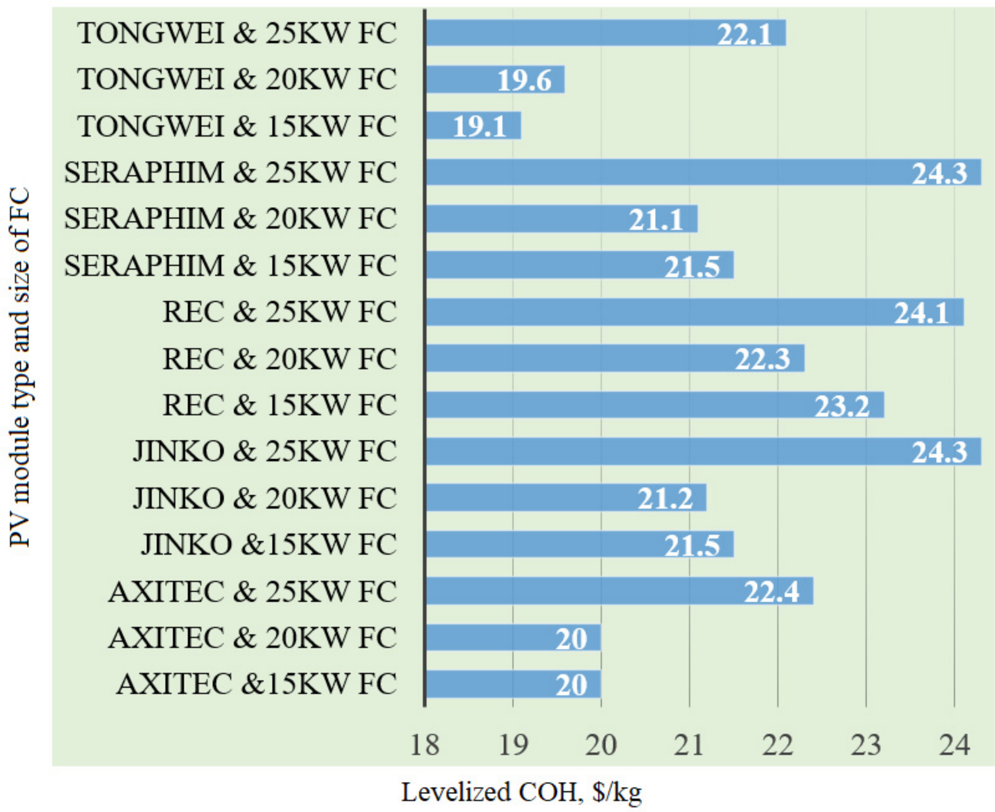

Figure 7. Levelized COH with varying PV module type and size of the FC.

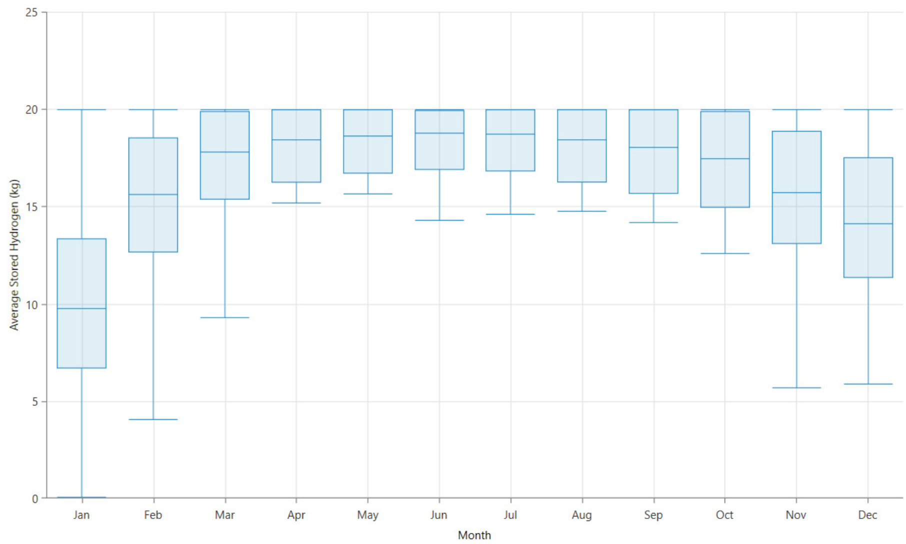

Figure 8. Average monthly stored hydrogen in case of using Tongwei 415 Watt with 15 kW FC.

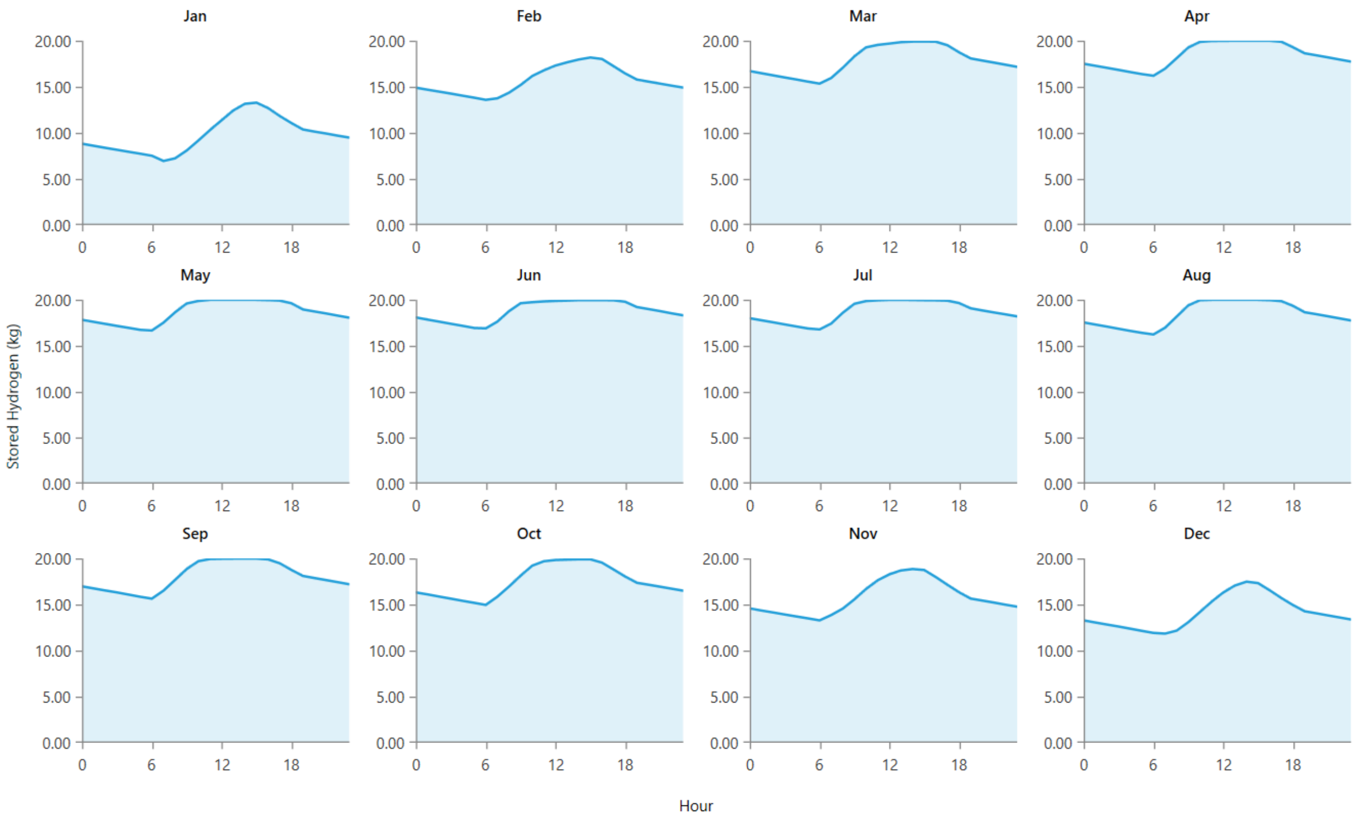

Figure 9. Hourly stored hydrogen in case of using Tongwei 415 Watt with 15 kW FC.

6. Conclusions

The main objective of this work is to size a PV/PEMFC system for powering a commercial load in NEOM city. To determine the best option for the case study, three different sizes of PEMFC were considered, alongside five different types of PV panels. The results illustrate the optimized outcomes that can be achieved through the use of different PV module types and sizes of FC. The COE values range from 0.293 USD/kWh to 0.41 USD/kWh, while the NPC values range from USD 498,984 to USD 69,679, depending on the size of the FC and the type of PV module used. Ultimately, the best size of FC was determined to be 15 kW, with the Tongwei 415 Watt panel and 15 kW of FC being found to yield the lowest

COE of 0.293 USD/kWh, followed by Axitec 450 Watt with the same size of FC. The worst COE of 0.41 USD/kWh was obtained using REC Solar 410 Watt. The optimal size for the case study consists of a 276 kW PV, a 15 kW FC, a 60 kg electrolyzer, and a 20 kg H2 tank. The capital cost for this system is USD 207,532, with the NPC of the FC comprising the largest portion of the total NPC at USD 211,148.16 or roughly 42.3%, followed by the NPC of the PV. The NPC of the hydrogen tank is the lowest at 1.4%. Using the Tongwei module reduces the levelized cost of energy by 32.38% compared to using a REC Solar 410 Watt solar PV module, lowering it from 0.0633 USD/kWh to 0.0428 USD/kWh. Finally, the levelized costs of hydrogen values range between 19.1 USD/kg and 24.3 USD/kg. When using a Tongwei 415 Watt with 15 kW, there is a 21.4% decrease in cost compared to a Jinko 415 Watt with 25 kW. The daily average stored hydrogen ranges between 9.76 kg and 18.79 kg, with the lowest value of 9.76 kg stored in January and the highest value of 18.79 kg stored in June. Finally, it can be concluded that the proposed system is suitable for offices in commercial buildings. The optimal size of the fuel cell and most economical type of the PV module are identified. Furthermore, the study of the load growth in the offices in commercial buildings and the effect of the change of the level of voltage on the losses will be considered in future work.

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