A TECHNO-ECONOMIC ANALYSIS OF PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC)

S. Saharin[1*], I.S. Gazali[1]

[1] Department of Mechanical & Aerospace Engineering, International Islamic University Malaysia, 53100 Kuala Lumpur Malaysia

Corresponding Author's Email: sanisah@iium.edu.my

Article History: Received 27 November 2025; Revised 29 December 2025; Accepted 15 January 2026

ABSTRACT: *This paper presents a comprehensive analysis of the techno-economic feasibility of Proton Exchange Membrane Fuel Cells (PEMFCs) as a sustainable power generation solution. The study focuses on performance evaluation and cost analysis to assess the viability of PEMFCs in comparison to conventional internal combustion engines. A detailed 3D model of the PEMFC, incorporating various functional regions, is developed and solved using the finite element method. Simulation results validate the model's accuracy, demonstrating a maximum power density of 0.69 W/m² and a peak power output of 21.74 W. The analysis indicates that thinner membranes and higher operating pressures significantly improve power generation performance. Furthermore, an economic feasibility model is established, accounting for capital equipment costs, total cost of ownership, and production volume. The cost analysis highlights the potential for significant cost reductions through economies of scale with increased production. Overall, the findings offer valuable insights into the performance, economic viability, and market potential of PEMFCs, supporting informed decision-making for their broader adoption in future sustainable energy systems.*

KEYWORDS: *PEMFC, Hydrogen fuel cells, Techno-economical Analysis*

1.0 INTRODUCTION

The depletion of conventional fossil fuels and their environmental impact have driven industries and consumers to explore alternative power generation methods. Fuel cells have garnered significant attention as a promising technology due to their high efficiency and potential to replace fossil fuel-based systems. As the demand for cleaner energy sources continues to grow, hydrogen has emerged as a crucial energy carrier, playing a pivotal role in the global transition to a more sustainable energy infrastructure [1]. Hydrogen, a low or zero-carbon energy source, is projected to meet a substantial increase in global demand by 2050 [2-3]. This study focuses on the production of hydrogen for fuel cell technology and conducts a comprehensive techno-economic analysis, with a specific focus on Proton Exchange Membrane Fuel Cells (PEMFCs) compared to other fuel cell technologies. The evaluation takes into account the advancements made in PEMFCs, addressing challenges related to cost and durability. The objective is to analyze the performance characteristics and economic viability of PEMFCs, addressing their current challenges of high costs and low durability [4]. While analyzing the performance characteristics of PEMFCs, including factors such as membrane characteristics, gas diffusion layer (GDL), catalyst, and operating parameters, this study also evaluates the economic viability of implementing Proton Exchange Membrane Fuel Cell (PEMFC) technology by considering key cost factors such as production, maintenance, and system lifespan. Performance analysis is conducted using COMSOL™ Multiphysics simulation software, with the results validated against established literature to ensure accuracy and reliability.

Through this comprehensive approach, the study offers valuable insights into both the performance and economic feasibility of PEMFC systems. The findings support the continued development of PEMFC technology as a sustainable energy solution and provide a foundation for future research and innovation. By integrating techno-economic analysis, the study encourages broader adoption of PEMFCs, contributing to the transition toward a cleaner, more efficient energy future.

2.0 METHODOLOGY

2.1 Geometry Model

The 3D model of a single channel of PEMFC is depicted in Figure 1. This model consists of seven distinct zones, including the anode channel, anode gas diffusion layer (GDL), anode electrode, membrane, cathode electrode, cathode GDL, and cathode channel. The geometric parameters for the model, as provided in Table 1, are sourced from the experimental study conducted by Jourdani et al, 2017 [5].

2.2 Numerical Analysis

The simulation of the PEMFC involved rigorous numerical procedures to accurately capture its behavior. A structured grid was employed to mesh the geometry, resulting in a total of 6890 domain elements, 3656 boundary elements, and 638 edge elements (Figure 2). *COMSOL 6.1* was used along with the finite element method to solve the governing equations and implement appropriate boundary conditions. This computational approach ensured precise and efficient computations, although it required a total calculation time of 50 minutes. The simulation maintained a uniform temperature of 333K, and a standardized pressure reference of 101 kPa. The cell model's geometry is listed in detailed in Table 1, and the operating parameter values, presented in Table 2, were carefully selected based on experimental data and relevant literature sources to ensure accurate and reliable simulations.

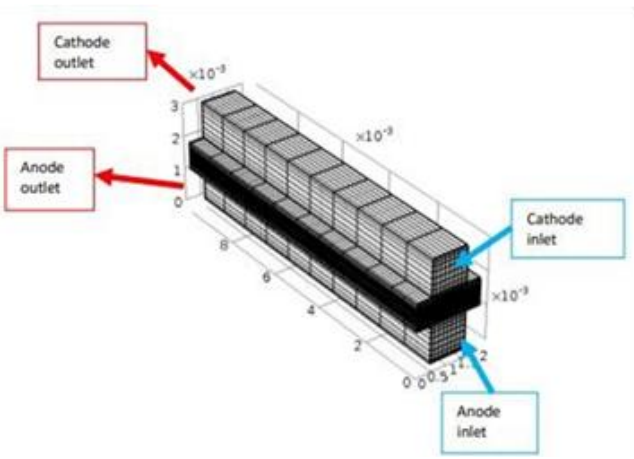

Figure 1. 3D Model Geometry used in present study based on Jourdani et. al [5]

Table 1: Design Parameters for PEMFC

Description		Value
Channel width	W_ch	1.1e-3 m
Cell length	L	0.01 m
Channel Height	H_ch	1.1e-3 m
Rib width	W_rib	0.90932e-3 m
GDL height	H_gdl	380e-6 m
Electrode thickness	H_electrode	50e-6 m
Membrane thickness	H_membrane	30e-6 m

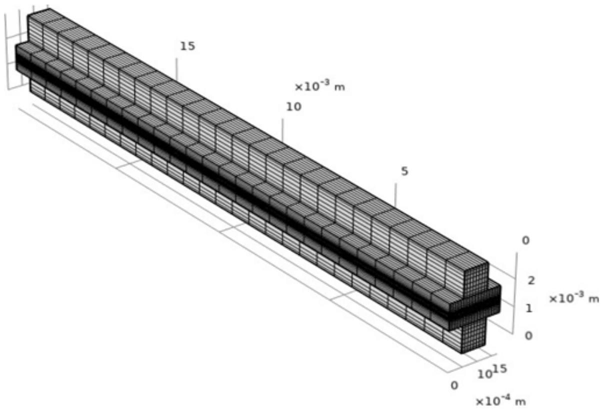

Figure 2. Model structure after meshing.

2.3 Economic Feasibility Model

When considering Proton Exchange Membrane Fuel Cells (PEMFCs) as a future energy solution, it's important to look beyond just how well they perform technically—we also need to understand how practical and affordable they are to produce, use, and maintain. This is where a techno-economic model becomes helpful. It allows us to compare PEMFCs with other energy technologies by looking at both their costs and potential value, helping us see whether they can realistically grow and succeed in the market.

A major part of this evaluation is the cost analysis. Cost is often one of the biggest deciding factors in whether a new technology can move from concept to reality. In this study, we focus mainly on estimating the key costs involved in setting up a basic PEMFC system. Although this is not a full-scale economic assessment, it offers a meaningful overview. The main components contributing to the cost of a PEMFC system are: Fuel Cell Stack, System Assembly and Balance of Plant (BOP).

To estimate these costs, we look at the size and specifications of each part and compare them with available market prices. Alongside these core costs, we also consider additional expenses—like instrumentation, control systems, service infrastructure, and other supporting elements—which are necessary for the system to function properly.

Another important consideration is the Total Cost of Ownership (TCO), especially when comparing PEMFCs with other vehicle technologies such as fuel cell electric vehicles (FCEVs), internal combustion engine vehicles (ICEVs), and battery electric vehicles (BEVs). TCO takes into account not just the purchase price, but also the long-term costs of operating, maintaining, and eventually replacing the vehicle. This gives a clearer and more complete picture of how affordable and sustainable PEMFCs might be over time.

Table 2: Operating Parameters

Model parameters	**Values**
GDL porosity	0.4
GDL permeability	1.18 e $^{-11}$ m^2
GDL electric conductivity	222 Sm^{-1}
Inlet H2 mass fraction (anode)	0.743
Inlet H2O mass fraction (cathode)	0.023
Inlet oxygen mass fraction (cathode)	0.228
Anode inlet flow velocity	0.4 ms^{-1}
Cathode inlet flow velocity	0.7 ms^{-1}
Anode viscosity	1.19 e^{-5}Pa.s
Cathode viscosity	2.46 e^{-5}Pa.s
Hydrogen molar mass	0.002 kgmol^{-1}
Nitrogen molar mass	0.028 kgmol^{-1}
Water molar mass	0.018 kgmol^{-1}
Oxygen molar mass	0.032 kgmol^{-1}
H2-H2O Binary diffusion coefficient	1.55 e^{-4} m^{2}s^{-1}
N2-H2O Binary diffusion coefficient	2.95 e^{-5} m^{2}s^{-1}
O2-N2 binary diffusion coefficient	2.75 e^{-5} m^{2}s^{-1}
O2-H2O binary diffusion coefficient	3.23 e^{-5} m^{2}s^{-1}
Cell temperature	333 K
Reference pressure	101e^3 Pa
Cell voltage	0.9 V
Oxygen reference concentration	40.88 molm^{-3}
Hydrogen reference concentration	40.88 molm^{-3}
Membrane conductivity	9.82 Sm^{-1}

3.0 RESULTS AND DISCUSSIONS

3.1 PEMFC Performance Simulation

In a fuel cell, the polarization curve represents the relationship between the voltage and current density. A higher voltage on the curve indicates better performance, as it signifies a higher potential difference generated by the fuel cell. The ideal polarization curve exhibits a gradual increase in voltage with increasing current density, indicating efficient power generation. However, deviations from this trend, such as a decrease in voltage at higher current densities, can indicate factors like ohmic loss and concentration loss impacting the performance of the fuel cell.

In the simulation results shown in Figure 3, the polarization curve of the PEMFC demonstrates a maximum power density of 0.69W/m^2 at a voltage of 0.71V and a current density of 0.98 A/m^2. The peak power output for the PEMFC with a 31.5 m^2 active area is reported as 21.74W.

ISSN 2180-1053 e-ISSN 2289-8123 Vol.18 No.1

These values offer insights into the performance characteristics of the fuel cell system, indicating its power generation capability at different operating conditions.

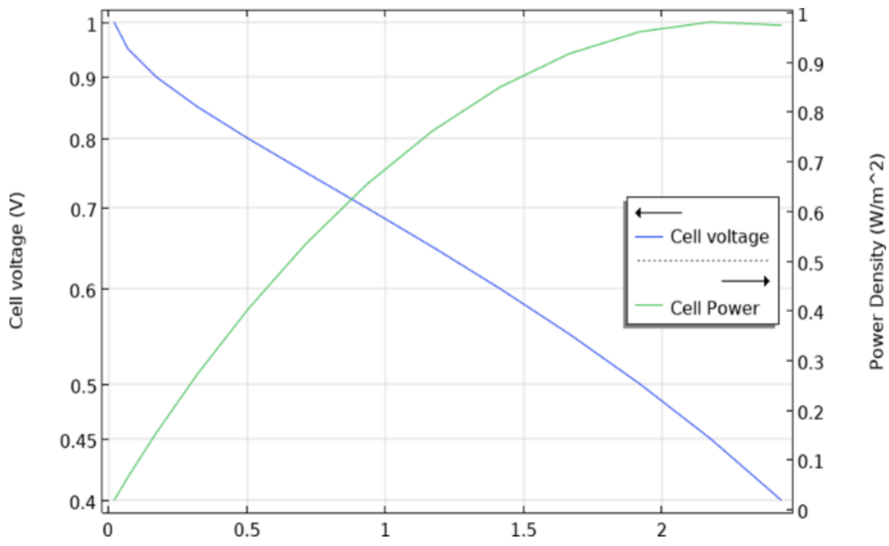

Figure 3. Polarization curve and power curve of PEMFC

Figure 4 shows the overall fuel cell performance in terms of polarization obtained under the four operating membrane thicknesses, meanwhile Figure 5 shows the comparison of power density at different membrane thickness.Two thicknesses under [7] thickness and one above it and this just to understand the performance of PEMFC by choosing thinner or larger membrane thickness. According to the comparison, we see that the PEMFC has the highest cell potential at 3 x 10^{-5} m, especially in the high current density region. A low ohmic loss and a high concentration loss are observed at 6 x 10^{-5} m. Ohmic loss is found to increase with temperature and the loss is due to the high temperatures.

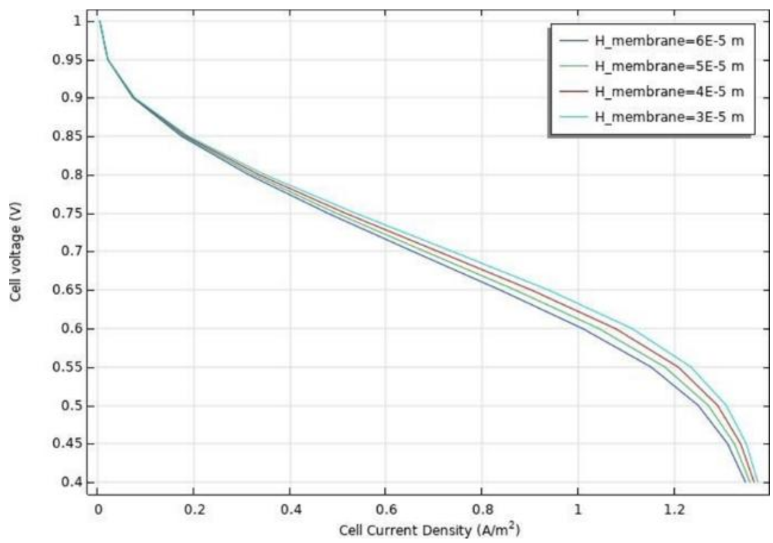

Figure 4. Polarization curves comparison of PEMFC at different membrane thickness.

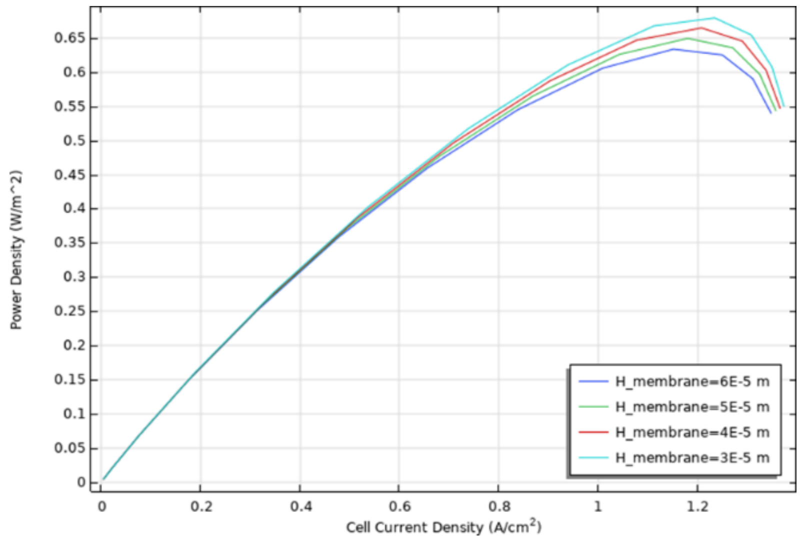

Figure 5. Power curves comparison of PEMFC at different membrane thickness

From the curves in Figure 6 and Figure 7, it can be observed that increasing the applied pressure has a positive impact on the performance of the PEMFC. Higher pressures result in improved reactant transport and enhanced mass transfer within the fuel cell. This leads to higher cell potential and increased power output as shown in Figure 7. The polarization curves demonstrate an upward shift as the applied pressure increases, indicating improved fuel cell performance. Besides, the power curves clearly show an increase in the maximum power density as the pressure is raised. This suggests that higher operating pressures promote more efficient power generation in the PEMFC. The observed trend highlights the significance of pressure control in optimizing the performance of fuel cell systems.

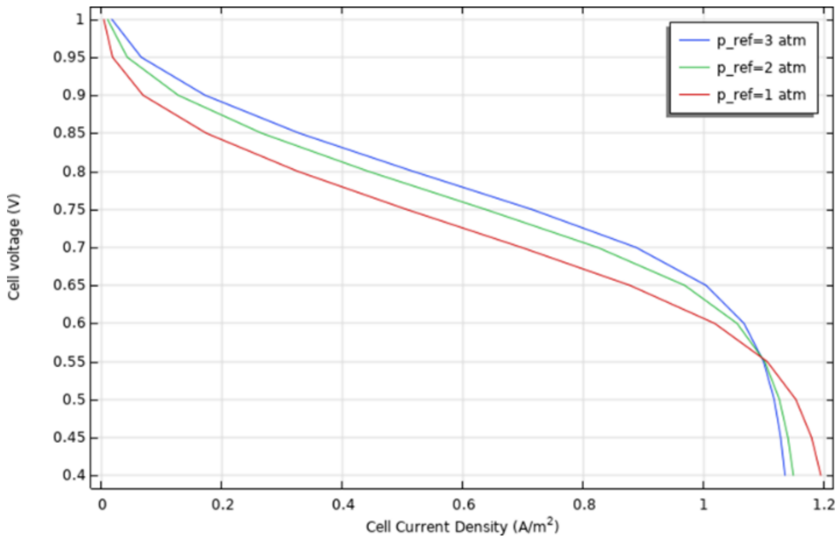

Figure 6. Polarization curves comparison of PEMFC at different reference pressure

ISSN 2180-1053 e-ISSN 2289-8123 Vol.18 No.1

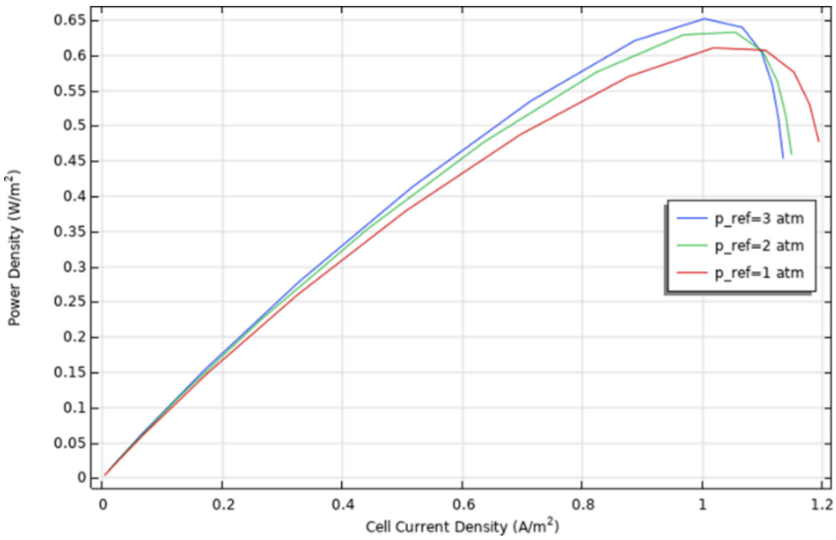

Figure 7. Power curves comparison of PEMFC at different reference pressure

3.2 Cost of PEMFC

The cost analysis of a 1-kW PEMFC system, based on Battelle's 2017 [6] study, highlights how material, labor, machine, scrap, and tooling costs contribute to overall manufacturing expenses. As shown in Tables 4 and 5, increasing production volume leads to reduced unit costs, particularly in materials and labor, demonstrating the impact of economies of scale and improved cost efficiency in high-volume manufacturing.

Table 4: PEM Stack Manufacturing Cost Summary for 1-kW system [Battelle Memorial Institute].

Category	1kW			
	100	1000	10000	50000
Material	$1516.70	$597.43	$313.45	$236.50
Labor	$145.49	$123.66	$121.44	$121.24
Machine	$1394.09	$227.51	$88.52	$77.54
Scrap	$115.45	$27.82	$13.49	$11.20
Tooling	$759.14	$75.91	$17.41	$13.61
Part Total	$3930.86	$1052.35	$554.32	$460.09

Table 5: PEM Assembly Cost Summary for 1-kW system [Battelle Memorial Institute].

Category	1kW			
	100	1000	10000	50000
Material	$0.00	$0.00	$0.00	$0.00
Labor	$130.93	$104.58	$101.94	$101.71
Total Cost	$130.93	$104.58	$101.94	$101.71

The cost analysis of the PEM system's Balance of Plant (BOP),highlights how increased production volume lowers unit costs and identifies high-cost subassemblies like fuel processing. Recognizing these cost drivers helps target areas for cost reduction and resource optimization. Table 6 and Figure 8 further illustrate the trend of decreasing unit costs with higher production volumes, supporting improved financial feasibility and commercial viability of hydrogen fuel cell technology.

Table 6: Overall fuel cell system cost summary for 1-kW system [B].

Category	1kW			
	100	1000	10000	50000
Component Cost	$3930.86	$1052.35	$554.32	$460.09
BOP	$13,149	$9,988	$8,565	$7,951
System Assembly	$130.93	$104.58	$101.94	$101.71
Total Cost	$17210.79	$11144.93	$9221.26	$8512.8

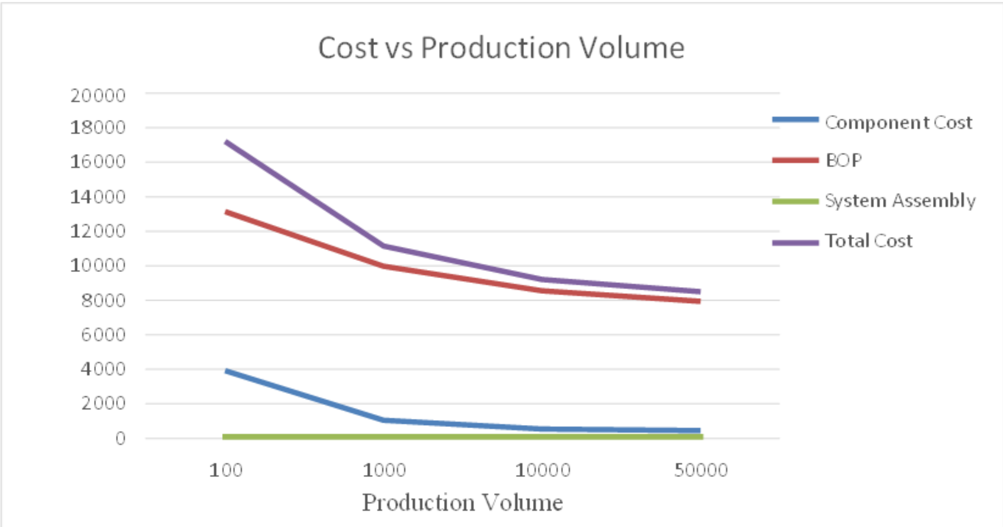

Figure 8. Cost vs production volume charts.

3.3 Comparative Total Cost of Ownership

This Comparative Total Cost of Ownership (TCO) analysis builds upon Hemant Kumar et al. [7] comprehensive TCO analysis of Fuel Cell Electric Vehicles (FCEVs), Battery Electric Vehicles (BEVs), and Internal Combustion Engine Vehicles (ICEVs). The study focuses on mid-size vehicles, specifically the Chevrolet Malibu (ICEV), Tesla Model 3 (BEV), and Toyota Mirai (FCEV). The analysis examines various cost components over an 11-year ownership period to determine the overall financial implications of each vehicle type.

Table 7 indicates that BEVs incur the lowest annual fuel costs (USD 491), compared with ICEVs (USD 1,231) and FCEVs (USD 2,083). Maintenance, repair, and tire costs are highest for ICEVs (USD 1,434), while BEVs and FCEVs are comparable (USD 1,119). Insurance costs are slightly lower for BEVs and FCEVs, and BEVs also benefit from reduced licence, registration, and tax expenses.

In terms of total cost of ownership (TCO) that includes purchase price, one-time repairs, recycling, fuel, and service costs, BEVs are the most expensive. ICEVs have the lowest TCO

(USD 83,564), followed by BEVs and FCEVs (USD 117,462). The cost per mile is USD 0.51 for ICEVs, USD 0.64 for BEVs, and USD 0.71 for FCEVs, representing a 26% and 41% cost premium over ICEVs, respectively. Although ICEVs currently offer the lowest ownership costs, these results depend on assumptions regarding fuel prices, maintenance, and incentives. Importantly, FCEVs provide long-term advantages: zero harmful emissions, rapid refueling, and suitability for long-distance travel. With continued improvements in fuel cell technology and infrastructure, FCEVs are expected to achieve greater competitiveness and support sustainable transport transitions.

Table 7: Comparative Total Cost of Ownership Analysis.

	Units	ICEV	BEV	FCEV
Annual Operating Costs				
Estimated Fuel (based on mpg)	$/year	1,231	491	2,083
Maintenance, repair and tires	$/year	1,434	1,119	1,119
Full-coverage insurance	$/year	1,245	1227	2,076
License, registration, taxes	$/year	730	74	74
Finance Charge	$/year	684	826	826
Total Services	$/year	4,093	3246	4,095
Annual Costs				
Fuel	$/year	1,231	491	2,083
Services	$/year	4,093	3,246	4,095
Total Cost of Ownership (TCO)				
Vehicle Manufacturer SuggestedRetail Price (MSRP)	$	25,000	49,000	49,500
One Time Repair (Battery Replacement)	$	0	13500	0
Recycle Cost (Battery, Fuel Cell)	$	0	13,50	0
Fuel	$	13,541	5,404	22917
Services	$	45,023	35,706	45,045
Total Cost of Ownership $, TCO (for 11 years)	$	83,564	104,960	117,462
CPM $/mile	$/mile	0.51	0.64	0.71
Markup above ICEV		1	1.26	1.41

4.0 CONCLUSION

This study provides insights into the performance, economic feasibility, and optimization strategies of Proton Exchange Membrane Fuel Cell (PEMFC) systems. Simulation results validate the accuracy of the developed model, demonstrating a peak power output of 21.74 W and a maximum power density of 0.69 W/m^2. Performance is notably enhanced by utilizing thinner membranes and operating under higher pressures. The cost analysis underscores the potential for economies of scale, with unit costs decreasing significantly at higher production volumes—strengthening the financial viability of both PEMFCs and Fuel Cell Electric Vehicles (FCEVs). Overall, the findings support the advancement of PEMFC technology as a clean and efficient energy solution. To further improve sustainability, the study recommends continued research into low-carbon hydrogen production methods for PEMFC applications.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to International Islamic University Malaysia for providing the facilities and support necessary to carry out this study. The authors acknowledge the use of COMSOL™ Multiphysics software for simulation purposes.

REFERENCES

[1] Deloitte China, "Fueling the future of mobility: Hydrogen and fuel cell solutions for transportation", *Financial Advisory*, vol. 1, 2019.

[2] J. Zhang et al., "Techno-economic assessment of various hydrogen production methods – A review", *Renewable and Sustainable Energy Reviews*, 11(July), 124175, 2017.

[3] R. Yukesh Kannah et al., "Techno-economic assessment of various hydrogen production methods – A review", *Bioresource Technology*, vol. 319, 124175, 2021.

[4] L. Fan, Z. Tu, and S. H Chan, "Recent development of hydrogen and fuel cell technologies: A review", *Energy Reports*, vol. 7, pp. 8421–8446, 2021.

[5] M. Jourdani, H. Mounir, and A. Marjani, "Three-dimensional PEM fuel cells modeling using COMSOL multiphysics", *International Journal of Multiphysics*, vol.11, no.4, 427–442, 2017.

[6] Battelle Memorial Institute, "Manufacturing cost analysis of 1 kW and 5 kW proton exchange membrane fuel cell systems for primary and backup power applications", *U.S. Department of Energy*, 2017.

[7] B. Hemant Kumar, A. Hemant Kumar, and A. S. Joan Rubin, "Hydrogen Powered Cars and Trucks: Is there a role for them in the electrified U.S. future?", 2022.