Power and efficiency of single and double membrane PEM fuel cells

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Abstract

Hydrogen-based proton exchange membrane fuel cells (PEMFCs) have risen to the forefront of the energy industry, with many deeming them capable of leading the takeover of hybrid and electric vehicles within the near future. We performed multiple tests to compare the power and current density and fuel efficiencies of PEMs with single and double membranes, oxygen gas and air at the cathode, and additionally contrasted them with a direct methanol fuel cell (DMFC). From our data, nonlinear regression determined the coefficients of polarization on a characteristic curve relating current density to efficiency, and power performance curves to analyze the effect of load resistance on power and efficiency. Most notably, the O_2-fueled cells had generally higher power density and efficiency than the air-fueled cell, which is consistent with the fact that more oxygen is present per amount of gas, as it's a pure composition.

1 Introduction

Proton exchange membrane (PEM) fuel cells have become increasingly popular as a clean, renewable energy source, especially in transportation as electric vehicles as a solution to the overwhelming majority of fossil fuel-driven vehicles. Continuous research and development are being poured into designing and optimizing PEM fuel cells because of their high efficiency, power, energy density, size, and refuel time. Costs tied to platinum group metal (PGM) catalysts for PEM fuel cells are the main thing separating them from widespread commercial use, despite the numerous advantages they hold.[1]

Direct methanol fuel cells (DMFCs) are an alternative fuel cell type that circumvent some of the cost issues that plague PEM fuel cells, but they are much less popular due to a limited scope of practical applications and a significantly lower overall power density. DMFCs cannot be operated at low temperatures, as the methanol must be combusted, and they are also not as efficient due to reaction kinetics and interactions with their catalysts, as a result of the presence of side reactions from membrane diffusion and the formation of carbon monoxide.[2]

PEM fuel cells operate by oxidizing hydrogen at the anode, sending the electrons through a wire outside of the fuel cell and allowing the protons to phase through a polymer membrane to the cathode, where they meet incoming oxygen atoms and along with the protons re-entering the cell, at which they react and form water, producing an electric current from the chemical energy released by the reaction. Load resistance is the primary variable which can affect the voltage, current, and therefore also the power and efficiency of the fuel cell. Generally, as load increases, overall power decreases, but the fuel conversion efficiency increases, especially at higher resistances as shown in the power performance curve for a given fuel cell.[3,4]

Numerous studies have been conducted in recent years in attempts to create better hydrogen-based PEM fuel cells aimed at improving not just efficiency and power density, but also optimizing for longevity, catalyst cost, and overall energy output by varying both membrane and catalyst material, along with different multi-cell designs like stacks, which increases the output voltage by lining several cells in series.[1,5,6]

2 Background

Proton exchange membrane (PEM) is an advancing electrochemical fuel technology. It has at its core the membrane, which conducts oxidized and reduced reagents as part of completing the electric circuit. The products of PEM fuel cell (PEMFC) that uses hydrogen and oxygen gas may be classified into energy output and water. The former includes electrical power and heat which are thermodynamically coupled. Hence this process complements PEM electrolysis where the opposite occurs.

Key challenges preventing broader adoption of this technology include thermodynamic and kinetic constraints. Thus far, it has been more common to use low temperature PEM (LT-PEM) that typically employs perfluorosulfonic acid as the membrane. This membrane integrates a hydrophilic phase, where water acts as the proton carrier. Hence, the membrane should remain hydrated for a lower overall resistance. This limits operating temperature above 100°C due to dehydration within the membrane.[7] Furthermore, temperatures below that are accompanied by volume expansion introduced by the phase change of water at normal atmospheric pressure. This adds further stress to an already constrained membrane.[8] These operating condition limitations arise since water is both a byproduct and an integral part of the electrolyte.

Of equal importance is the reaction kinetics at each of the electrodes. At the anode, the hydrogen oxidation reaction (HOR) occurs faster than the oxygen reduction reaction (ORR) at the cathode. To account for this difference, a Pt catalyst is often used to achieve higher exchange current density. This current density is further enhanced via alloying Pt with a transition metal.[9]

Here, we show how PEMFC electric potential E is affected by activation, ohmic resistance, and mass irreversibility. Leveraging their differing contributions to E over varying electric currents i, we uniquely calculate each of the coefficients specific to each irreversibility by applying nonlinear regression to experimental $E - i$ data. Furthermore, we derive the power performance curve $P - i$ to reveal the trade-off between power output and efficiency. This analysis

shows how high-current performance is severely limited by mass-transport losses, indicating a need for selecting operational parameters like the particular electrolyte and electrode coating for better energy delivery and storage.

3 Theory

The cell's potential across the electrodes E is reduced by activation, ohmic, and mass transport losses. Where PEMFC electric potential is empirically modeled by

$$E = E_0 - b \log i - Ri - m \exp(ni) \tag{1}$$

as a function of current density i.[4] This accounts for each of these potential-reducing factors. The exponential term ($-m \exp(ni)$) represents oxygen diffusion limitation, which critically influences E at higher current densities. The total cell resistance R one the other hand is linearly related to E. While sluggish ORR kinetics is accounted for by the logarithmic term and becomes less significant with increasing i. These losses sum up, and the difference is then calculated by comparison with the open-circuit voltage E_0. The coefficients E_0, b, R, m, and n are determined by non-linear regression fitted to $E - i$ data. Each coefficient contributes distinctly to E depending on i (i.e., E is most sensitive to transport losses). Hence, data may be leveraged to isolate each coefficient by considering different current densities.

The power performance curve (PPC) serves to optimize PEMFC sizing to satisfy some specified external load. The maximum power occurs at a load resistance equal to the internal resistance, which in turn reduces PEMFC efficiency. Hence, optimizing both efficiency and power output simultaneously is not possible.[3] A similar logic is followed to reduce the absolute error between calculated and experimental characteristic equation by dividing overall curve to segments and approximating each by a Bézier curve.[10] The PPC is derived following equation (1) to define power

$$P = E \cdot I \tag{2}$$

as function of current. Whereby mass-transport losses at higher currents $i > i_{\max}$ cause the power output P to drop significantly while efficiency increases. The efficiency

$$\eta = \frac{iV}{iV_0} \tag{3}$$

where v_0 is the PEMFC measured voltage at zero resistance load, and $i_{\max}$ is where $\frac{dP}{di}$ equals zero.

Using outlined methods, a comparison is then made between hydrogen and oxygen gas, hydrogen gas and air, and 3% methanol. In addition to comparing single and double membrane fuel cells for the first two cases.

4 Methods

An electrolyzer attached to two storage tanks at two different points (high and low) was powered to generate hydrogen and oxygen gas from deionized water resting in the tanks. The two tanks storing the gases were connected to a small PEM fuel cell via rubber piping and a valve, allowing gases to potentially enter the top portion of the fuel cell. Additional piping and valves were connected to the bottom (exit) channels of the fuel cell for H_2 vs O_2 fuel cells. For H_2 vs air fuel cells, a cap was removed such that air could flow into the fuel cell on the cathode side; the O_2 storage tank was left unconnected from the fuel cell.

The system was first degassed to remove any unwanted substances by running the electrolyzer with valves closed to fill the tanks with gas, and then opening all valves to let the gases escape. This was repeated three times for each individual fuel cell used. Next, wires were attached to an ammeter such that the flow of electrons began from the positive fuel cell terminal, went through the decade resistance box and the ammeter, and ended at the negative fuel cell

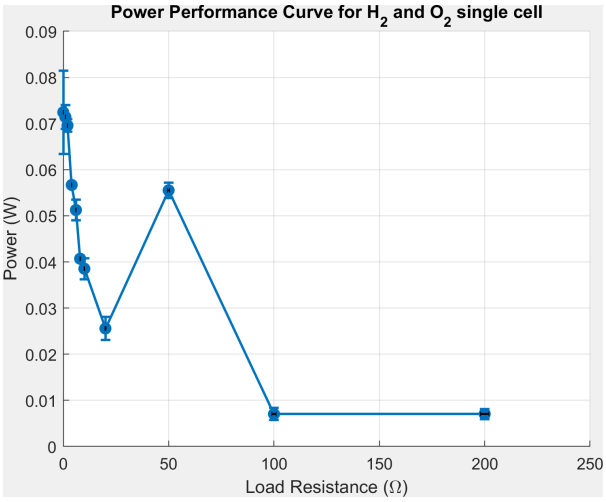
terminal. The voltmeter was connected to the positive and negative fuel cell terminals only.

Next, after the electrolyzer was run to create gases within the storage tanks, the valves connecting the storage tanks to the fuel cell were opened (while leaving the valves connected to the atmosphere closed), generating current and voltage within the fuel cell. Those values and their uncertainties (standard deviation of a fluctuating dataset) were measured and recorded using the ammeter and voltmeter after a short stabilization period for each trial, beginning with an initial value at $R = 0$. A wide range of resistances were used to better estimate the trends of load resistance's effect on power and efficiency in fuel cells of both different reactants and membranes.

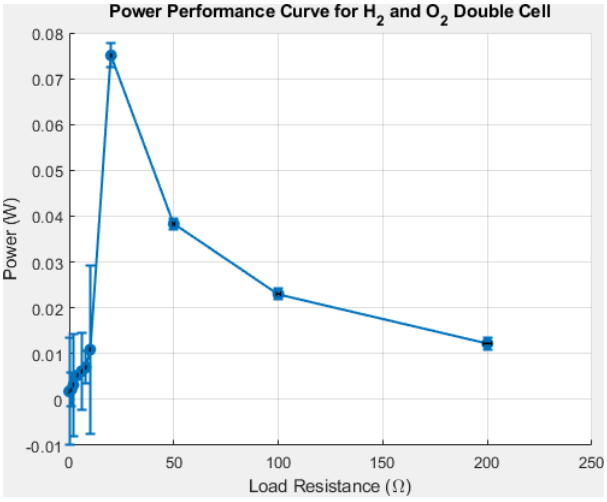
5 Results

This experiment examines the impact of different fuel cells and their power output given different load resistance. Overall, the data shows an expected rise in power to a maximum at a certain load and a decrease in power after increasing the load.

Since air contains 21% O_2, it was used as an oxidizer to react with the H_2 produced from the electrolysis of water.

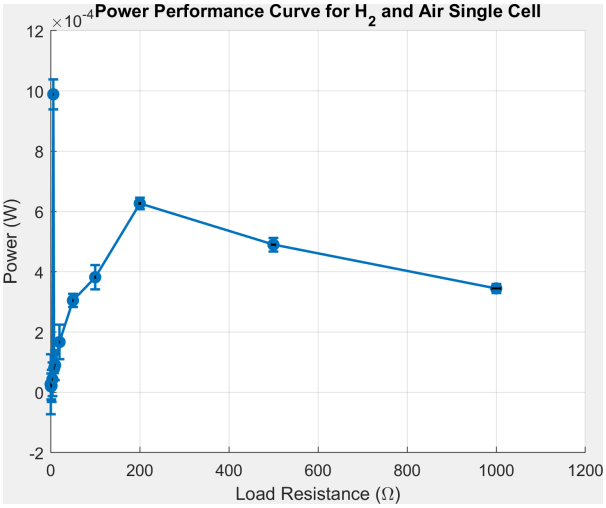


(a) **Figure 1a**. Power performance curve for H_2 and O_2 single cell. The curve shows a maximum value at a certain load, and the data points closer to $x = 0$ have high vertical uncertainty, suggesting low precision data sets.

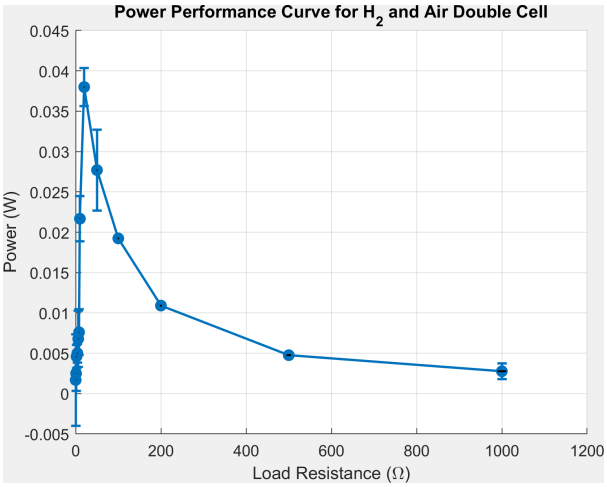


(b) **Figure 1b**. Power performance curve for H_2 and O_2 double cell. The curve shows an expected increase in maximum power from Figure 1a at a smaller load value. There is relatively high vertical error for smaller load values.

Figure 1: Comparison of power performance for single and double membrane fuel cells using H_2 and O_2.



(a) **Figure 2a**. Power performance curve for H_2 and air single cell. As expected, the curve shows a maximum increase at around 200 Ω. The figure has relatively low vertical error with negligible horizontal error.



(b) **Figure 2b**. Power performance curve for H_2 and air double cell. The curve peaked at a smaller load with a higher peak than Figure 2a. A higher vertical error shows that the data is not precise.

Figure 2: Comparison of power performance for single and double membrane fuel cells using H_2 and air as reactants.

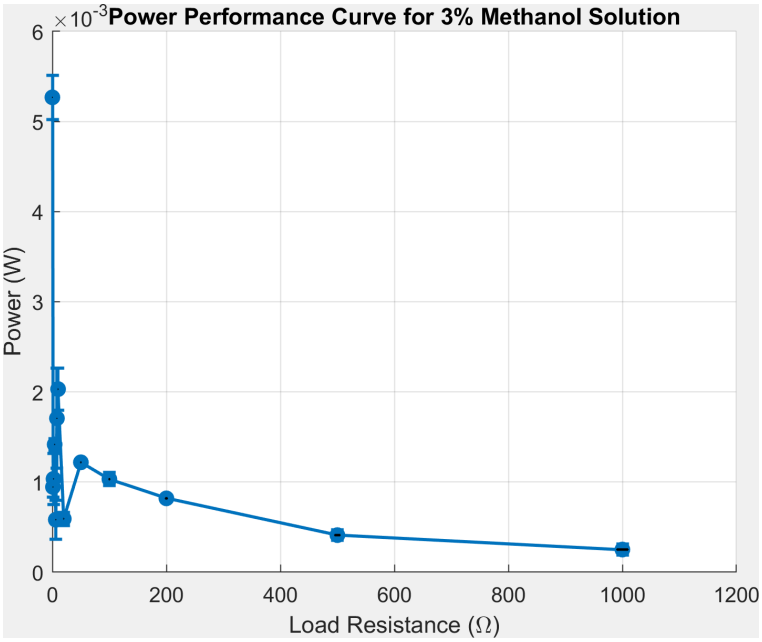


Figure 3: Power performance curve for 3% methanol solution. This curve shows a small peak at a smaller load than the previous figures. There is also an outlier at $x = 0$. This curve has relatively high vertical error, especially at lower values.

A 3% methanol solution was introduced, where methanol is oxidized and oxygen gas is reduced as inputted into the cell from the air.

6 Discussion

The figures in results section all show the expected shape of a power performance curve (PPC), showing a maximum peak power at a certain load. The PPC for H_2 and O_2 fuel cell shown in Fig. 1a has the highest peak compared to PPC for H_2 and air shown in Fig. 2a and PPC for 3% methanol shown in Fig. 3. This is as expected since air is only 21% O_2 and electrolysis of methanol solution produces even less oxygen as the methanol is prioritized over water in electrolysis so more of methanol electrolysis products are produced than H_2 and O_2 from water.

On top of using a single membrane for the fuel cells, double membranes were also used to determine if increasing the surface area for more equilibrium to occur will affect the maximum power. Fig. 1a shows a maximum power of $55.5mW$ at a load resistance of 50Ω. This is smaller

than the peak for Fig. 1b at $75.1mW$ at a load resistance of 20Ω. This is expected as more membranes in a cell means more area for equillubrium, which means more power output produced. This is also shown when comparing Fig. 2a and Fig. 2b, where Fig. 2a has a smaller maximum power of $0.627mW$ compared to the double membrane in Fig. 2b with a maximum power of $38.0mW$.

When comparing all the different types of cells, a clear trend emerged. The purer the fuel used in the PEM fuel cell, the higher the power output and adding more membranes will also increase the maximum power output. Since H_2 and O_2 double membrane fuel cell has the highest purity and membranes, it will have the highest maximum power.

This experiment has a lot of sources of error which in evident from the fact that the vertical errors on the figures are relatively high especially on the smaller load values. This is expected due to slow ORR kinetics as shown by the logarithmic term in equation 1. There is also a break in trend on H_2 and air single cell, which is predicted to have a higher maximum power than 3%methanol. There was an attempt to minimize hysteresis by randomizing the independent variable but the same random string of numbers were used on all the fuel cells. This is a small source of error as hysteresis was not observed.

A larger source of error is the inconsistency in data collection. It was noticed that the voltage and current values would rise or fall (though in opposite directions) depending on selected load resistance. These values would continuously change in one direction for each of the respective measurement due the irreversibilities mentioned earlier. The data was collected

Table 1: Maximum power output for different fuel cells. A purer fuel and more membranes tend to produce more maximum power.

Type of Cell	Maximum Power (mW)
H_2 vs O_2 single cell	55.5
H_2 vs O_2 double cell	75.1
H_2 vs air single cell	0.627
H_2 vs air double cell	38
3% methanol	2.03

by taking the average value and standard deviation after 100 samples were taken. However, at times, the voltage and current values would still not stabilize by the time 100 samples were taken. At first, the data was strictly averaged over 100 samples but halfway into the experiment, the data were recorded after it seemed to have stabilized, which may or may not take 100 samples. This means that if the data was taken before it was stabilized, there will be a higher standard deviation and error, which is shown in Fig. 1a, Fig. 1b and Fig. 2b where they have relatively high vertical errors, which shows low precision in the data sets.

It was also noticed that the voltage and current values would fluctuate and barely stabilize at lower load resistance values, which caused the shape of the graph to be inconsistent with what it is supposed to look like on lower load values. There should only be one peak and no spike so any load values below 10Ω were ignored.

The errors discussed above uncovered a deeper mistake, which is poor data planning. The independent values for data collection were arbitrarily set at 0Ω, 1Ω, 2Ω, 4Ω, 6Ω, 8Ω, 10Ω, 20Ω, 50Ω, 100Ω, 200Ω, 500Ω, 1000Ω to see the shape of the graph at a wider range of load values. However, all the peaks occurred at load values above 10Ω but the independent variables were most precise between $0 - 10\Omega$, which means that there is only one data point at the peak with barely any points around it.

The mistake was not switching to a more precise data set for independent variable and switching to a linear scale for the x-axis when it was known that all peaks occurs above 10Ω. This means that the actual peak is not known due to the lack of datasets in between the peaks. As a more extreme example, Fig. 2a has a peak power at 200Ω but the data points before and after it is at 100Ω and 500Ω, so it is unknown weather the peak is really at 200Ω or somewhere in between 100Ω and 500Ω. A smaller range of independent variable should have been used around the value where a peak is expected.

7 Conclusions

From the range of power performance curves, two main trends stand out: both the overall power across the range of load resistances $0 < R \leq 200\Omega$ and the peak power density in the single membrane fuel cells were found to be consistently higher than that of the double membrane cells, as shown in Tab. 1. In particular, Fig. 1b, which most resembles the power performance curve example found in [3], the maximum power density reaches 75.1 mW after a fast rise, and quickly dissipates afterwards as load resistance increase. Additionally, the H_2 vs O_2 cells had higher overall power and maximum power density than the H_2 vs air fuel cells, as noted in Tab. 1. Furthermore, the 3% methanol fuel cell's power performance curve plotted in Fig. 3 had a significantly lower maximum power than the PEM fuel cells aside from the H_2 vs air single cell, which is likely an outlier due to faulty equipment and poorly run trials.

Overall, the graphs shown in Fig. 1a, Fig. 1b, Fig. 2a, Fig. 2b, and Fig. 3 are generally unreliable and have major uncertainties attached to them, and don't accurately match previously generated power performance curves those depicted in [3]. However, the overall shapes do reflect the predicted behavior of the power performance curves, with a singular peak at low load resistance followed by an exponential decline.

Further testing should be done to evaluate the efficiencies of the fuel cells to more accurately determine the advantages of single vs double membranes. While it is clear that O_2 is a much better reactant than air at the cathode, it's inherently more expensive as air can be taken straight from the atmosphere rather than requiring a separate reaction to first take place. Illustrating the extent to which O_2 is superior and comparing it's cost efficiency could provide an avenue to discovering cheaper fuel cell designs. Additionally, different concentrations of methanol should be tested against these fuel cells to determine how they compare to . A final potential avenue of further research could be to test different catalysts, as the fuel cells in this experiment all used a common catalyst. More tests like those done in [1] could produce a superior catalyst for both O_2 and air based fuel cells.

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(10) Louzazni, M.; Al-Dahidi, S.; Mussetta, M. Fuel Cell Characteristic Curve Approximation Using the Bezier Curve Technique. *Sustainability* **2020**, *12*.

Appendix

1. Proton Exchange (PEM) Fuel Cells with Platinum Group Metal (PGM)-Free Cathode

    - Author(s): L. Du, G. Zhang, and S. Sun
    - Year published: 2021
    - Journal name: Automotive Innovation
    - 1-3 major accomplishments of this paper:
        (a) Determined the different stabilities of PGM-free catalysts in H_2/air PEM fuel cells.
        (b) Demonstrates a shorter activation time for a hybrid catalyst layer (PtCo/Co-N-C) than the commercial Pt/C catalyst layer while maintaining similar stability, while also showing higher performance than both Pt/C and Fe-N-C catalyst layers.

2. The power performance curve for engineering analysis of fuel cells

    - Author(s): J.B. Benziger et. al
    - Year published: 2006
    - Journal name: Journal of Power Sources
    - 1-3 major accomplishments of this paper:
        (a) Determined the power performance curve (PPC) of a single fuel cell, dependent on load resistance versus power and fuel conversion efficiency
        (b) Concluded that external load driven is the critical variable that affects power and efficiency of a fuel cell, and that maximum power density and fuel efficiency are mutually exclusive.

3. Modeling of Proton Exchange Membrane Fuel Cell Performance with an Empirical Equation

- Author(s): J. Kim, S.M. Lee and S. Srinivasan
- Year published: 1995
- Journal name: Journal of the Electrochemical Society
- 1-3 major accomplishments of this paper:
  (a) Developed a model using an empirical equation relating current density and cell potential of a PEM fuel cell that closely resembles experimental data at various cathode conditions.
  (b) Determined electrode kinetic and mass-transport parameters using this model for certain PEM fuel cells

4. Fatigue-Resistant Polymer Electrolyte Membranes for Fuel Cells

- Author(s): M. Kim et al.
- Year published: 2023
- Journal name: Advanced Materials
- 1-3 major accomplishments of this paper:
  (a) Determined that a Nafion-PFPE membrane in fuel cells reduce maximum power density by 20%, but increase fatigue threshold by 175% and cell lifetime by 70% than that of a purely Nafion (a plastic electrolyte) membrane fuel cell.

5. Optimizing hydrogen utilization in Fuel Cell Hybrid Vehicles: Modeling fuel cell systems and managing energy between batteries and fuel cells

- Author(s): H.S. Lim et al.
- Year published: 2025
- Journal name: International Journal of Hydrogen Energy
- 1-3 major accomplishments of this paper:

(a) Used hydrogen-based PEM fuel cells in a stack to improve efficiency in vehicles; specifically, it was found that 24% less hydrogen consumption was necessary in low-load conditions and 10% less in high-load conditions.

6. Determination of methanol concentration for DMFC systems by fuel cell-based sensor

   - Author(s): S. Celik, N. Cuhadar, and M. Yagiz
   - Year published: 2025
   - Journal name: Fuel Cells
   - 1-3 major accomplishments of this paper:

     (a) Determined that high temperature and low methanol concentrations are mandatory conditions for best DMFC sensor performance due to a drop in stability after a 2M concentration.

7. Polymer membranes for high temperature proton exchange membrane fuel cell: Recent advances and challenges

   - Author(s): S. Bose et al.
   - Year published: 2011
   - Journal name: Progress in Polymer Science
   - 1-3 major accomplishments of this paper:

     (a) Experimentally contrast high temperature PEM and low temperature PEM.

     (b) Potential applications of HT-PEMFCs in higher power generation

8. Effect of sub-freezing temperatures on a PEM fuel cell performance, startup and fuel cell components

   - Author(s): Q. Yan et al.
   - Year published: 1988

- Journal name: Journal of the Electrochemical Society
- 1-3 major accomplishments of this paper:
  (a) Comparison of ORR on Pt-Cr alloys with Pt0.65Cr0.35 and Pt0.2Cr0.8

9. Fuel Cell Characteristic Curve Approximation Using the Bezier Curve Technique

- Author(s): M. Louzazni, S. Al-Dahidi, and M. Mussetta
- Year published: 2020
- Journal name: Sustainability
- 1-3 major accomplishments of this paper:
  (a) Approximated non-linear behavior of fuel cell characteristic curves