



## Research Article

## Dynamics Response of the Proton Exchange Membrane Fuel Cell Coupled with Electrolysis

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## A B S T R A C T

Fuel cells convert the chemical energy of reactants into electrical energy, with the Proton Exchange Membrane Fuel Cell (PEMFC) being a prominent example due to its simple structure, durability, and ease of operation. The power output of a PEMFC is influenced by the number of cells in the stack, provided there is an adequate supply of hydrogen. This experiment investigated how varying the number of cells affects the dynamic response of PEMFC output power, while maintaining a constant hydrogen flow rate produced by a 4-Volt DC electrolyzer. Stacks with 4, 7, and 10 cells were tested, each with resistance variations of 100, 150, 200, and 300 Ohms. Under Open Circuit Voltage conditions, the stack with 10 cells exhibited the highest maximum voltage. Conversely, the lowest power output was observed for the 4-cell stack. When loaded, the 7-cell stack generated higher output power as hydrogen was effectively utilized by all cells. However, the 10-cell stack produced lower power output than the 7-cell stack due to insufficient hydrogen supply. Thus, increasing the number of cells requires a corresponding increase in hydrogen supply. The findings of this experiment provide insights for future design considerations in fuel cell power systems.

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## 1. INTRODUCTION

The increase in world population and smart devices has rapidly increased the demand for electrical energy (Bedi & Toshniwal, 2019). Electricity from fossil fuels needs to be replaced with renewable energy due to its harmful impact on the environment (Kalair et al., 2021). The clean energy transition continues to be promoted by many countries. In the last few decades, many researchers have seen the potential of hydrogen as a fuel for its usage as a future clean energy solution due to the absence of carbon emissions (Brandon & Kurban, 2017). However, hydrogen is not considered an energy source because its formation as an element or molecule does not emerge directly in nature (Demirbas, 2017). Hydrogen, which is contained in water (H<sub>2</sub>O), is the most abundant compound in the world (Zhou et al., 2023). For this purpose, a device to convert substances into hydrogen is required.

A fuel cell is a device that helps convert hydrogen into electrical energy (Sazali et al., 2020). Through an electrochemical process between hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>), electricity is generated with waste products in the form of water and heat (Zhao et al., 2020). According to the type of electrolyte used, fuel cells are divided into several types, namely Polymer Electrolyte Fuel Cells (PEFC), Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Intermediate Temperature Solid

Oxide Fuel Cell (ITSOFC), Tubular Solid Oxide Fuel Cell (TSOFC) (Guangul et al., 2020).

One type of fuel cell that is widely developed is the Proton Exchange Membrane Fuel Cell (PEMFC), which is one part of the Polymer Electrolyte Fuel Cell (PEFC) due to its simple structure, easy operation, and good durability (Zhao et al., 2021). In PEMFC, hydrogen is converted into protons (H<sup>+</sup>) with mainly a platinum (Pt) catalyst at the anode, while oxygen becomes O<sub>2</sub><sup>-</sup> at the cathode (Ostroverkh et al., 2020). After reacting, hydrogen and oxygen will respond to H<sub>2</sub>O and heat. The hydrogen supplied to the PEMFC can be produced by the electrolysis process (Shaygan et al., 2019). Electrolysis is a chemical reaction technique to separate chemical molecules using an electrolyzer (Sankar & Jana, 2021).

Previous research states that the power generated by the fuel cell depends on the number of cells (Syampurwadi et al., 2017). However, to produce a larger power, it must be followed by designing the “balance of the plant”, such as the fuel storage tank, i.e., hydrogen. For example, heavier duty of the fuel cell electric vehicles will require a larger hydrogen storage.

Therefore, it is necessary to investigate the performance impact of fuel cells with limited hydrogen availability. In this experiment, a variation in the number of cells has been carried out to understand the correlation between the number of cells and the power generated by providing the constant hydrogen

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flow rate. Load variations are also given to analyze the electrical characteristics generated by the PEMFC.

## 2. LITERATURE STUDY

### 2.1. Fuel Cell

Fuel cells have gained interest recently because of their relatively high efficiency and environmental friendliness (Inci et al., 2021). They can be applied to electric vehicles or be used as a power plant, whether in small (milli Watt) or large capacity (mega Watt) (Das et al., 2017). A fuel cell comprises a negatively charged electrode (cathode), a positively charged electrode (anode), an electrolyte, and an external load. Each electrode is equipped with a catalyst to expedite the chemical reaction process. In a fuel cell, the electrodes facilitate the interaction between the reactants and the electrolyte (Hbilate et al., 2019). The electrolyte serves to prevent the direct combination of fuel (hydrogen) and oxidant molecules, thereby avoiding combustion within the cell (Benmouiza & Cheknane, 2018). The operational principle of a fuel cell closely resembles that of a battery; however, unlike a battery, hydrogen continuously flows through the cell until it reacts to form water (H<sub>2</sub>O), thus generating electricity. In essence, hydrogen flows into the cathode, where it releases positive ions and negatively charged electrons. The released protons migrate through the electrolyte (typically Platinum) to the anode, where oxygen is introduced. The electrons then travel to the external load and subsequently react with oxygen, resulting in the formation of water at the anode (Figure 1).

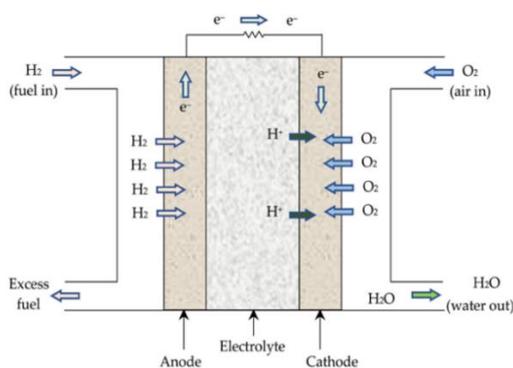
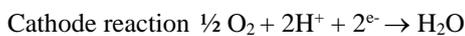


Figure 1. Fuel cell reaction (Ahmed et al., 2020).

The reaction occurring within the cell can be detailed as follows:



### 2.2. Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFC is a type of fuel cell that can directly convert hydrogen into electrical energy (Meloni et al., 2022). It uses an electrolyte that directly flows hydrogen ions (H<sup>+</sup>) from the anode to the cathode. PEMFC can work at 60-80°C temperatures because the electrolyte material only works at low temperatures (Rosli et al., 2017). The electrical power density of PEMFC is superior to that of other fuel cells, ranging from 300 to 940 mW/cm<sup>2</sup> (Peng et al., 2017). Additionally, PEMFCs offer advantages in ease of start-up and operation, making them well-suited for motorized vehicles and as an efficient energy source (Gong et al., 2020). The reaction in a PEMFC theoretically occurs isothermally and reversibly (Ghasemi et al., 2017).

### 2.3. Electrolysis Process

Electrolysis is a technology that splits water into hydrogen and oxygen (Brauns & Turek, 2020). A direct current (DC) is applied across two electrodes, causing a change in charge (Ding, 2022). At the cathode, water molecules are dissociated; hydrogen atoms lose electrons, while oxygen atoms gain electrons. The oxygen atoms transform into O<sub>2</sub> and receive additional electrons, while hydrogen atoms become H<sup>+</sup> ions. The negatively charged cathode attracts hydrogen ions, which gain electrons and revert to neutral hydrogen atoms. These atoms then combine to form H<sub>2</sub> gas. Meanwhile, the negatively charged oxygen ions move towards the positively charged anode, where they release their electrons and become neutral oxygen atoms. These oxygen atoms then react with O<sub>2</sub> to form bubbles that rise upwards (Guo et al., 2019).

## 3. METHOD

### 3.1. Methodology

This experiment utilizes a PEMFC-type fuel cell. Each cell has a power of 200 mW. Hydrogen is used as fuel in this case. Hydrogen is produced through an electrolyzer with a power specification of 15 W. A schematic of the test equipment components is shown in Figure 2.

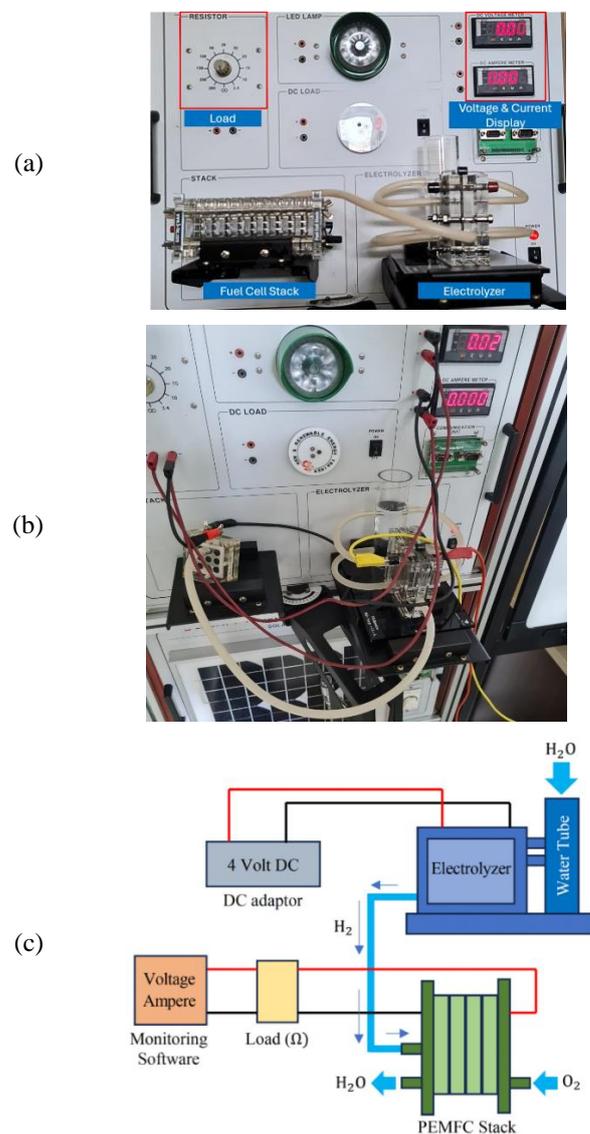


Figure 2. PEMFC experiment set-up; (a) main components of the apparatus; (b) experimental set-up; (c) schematic diagram of the experimental set-up.

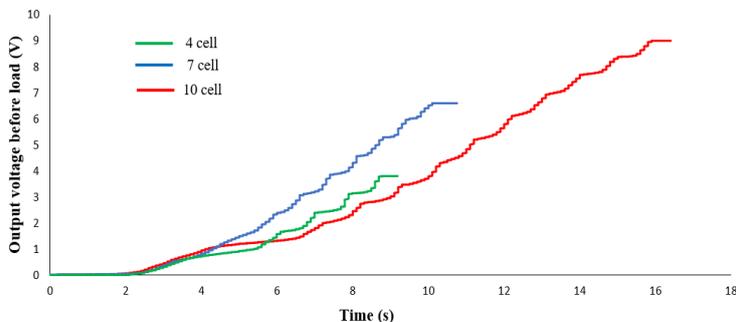
Intuitively, increasing the number of cells in a PEMFC stack should also increase the area available for hydrogen and oxygen to react, thus enhancing the electricity generated. This experiment evaluates PEMFCs with 4, 7, and 10 cells. The hydrogen flow rate is maintained constant by applying a voltage of 4 Volts to the electrolyzer. Each cell has a reactant area of 9 cm<sup>2</sup>, so the total reactant areas for stacks of 4, 7, and 10 cells are 36 cm<sup>2</sup>, 63 cm<sup>2</sup>, and 90 cm<sup>2</sup>, respectively. The type of PEMFC is consistent throughout the experiment. Load variations include resistances of 100 Ohms, 150 Ohms, 200 Ohms, and 300 Ohms, applied after reaching the maximum Open Circuit Voltage (OCV).

The first stage of the experiment involved setting up the device as shown in Figure 2. Electrolysis was conducted with a 4-Volt input to the electrolyzer. The initial tests were performed on a 4-cell stack, applying different resistances after reaching the maximum voltage. Voltage and current data were recorded using data logger software. The experiment was then repeated with 7-cell and 10-cell stacks. The hydrogen flow rate was kept constant throughout, and oxygen was supplied from atmospheric airflow, assumed to be at standard conditions (STP) (Sucipta et al., 2023).

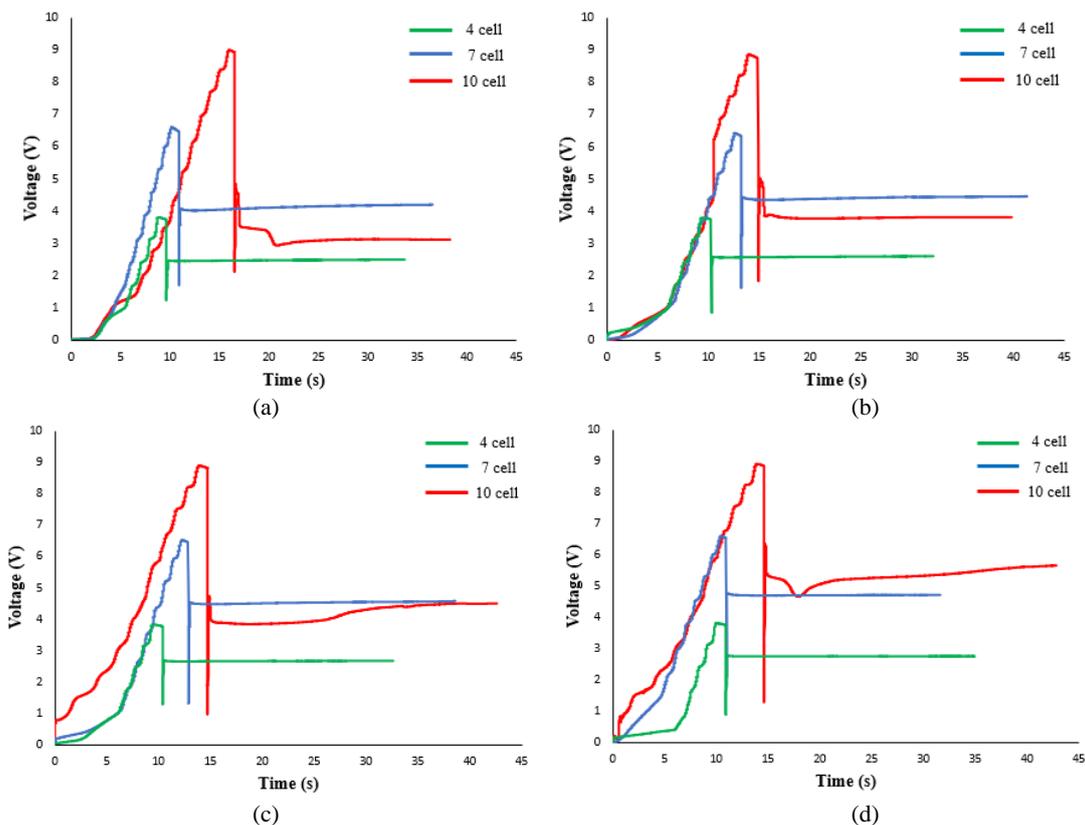
**4. RESULTS AND DISCUSSION**

The results from the PEMFC output voltage experiments for stacks with 4, 7, and 10 cells are presented. The maximum Open Circuit Voltage (OCV) observed before applying any load is depicted in Figure 3. The maximum voltages recorded are 3.78 V for the 4-cell stack, 6.61 V for the 7-cell stack, and 9.0 V for the 10-cell stack. Across all variations, the maximum voltage achieved remains relatively consistent regardless of resistance.

The time required for each stack to reach its maximum voltage varies with the number of cells. The 10-cell stack, despite producing the highest OCV, takes the longest time to reach its maximum voltage, approximately 16.5 seconds. The 7-cell stack reaches its maximum voltage faster than the 10-cell stack, while the 4-cell stack reaches its maximum voltage in the shortest time, around 9.6 seconds. This indicates a direct proportional relationship between the time required to reach maximum voltage and the magnitude of the OCV. In Figure 3, all cell variations begin generating voltage after 2 seconds. The 4-cell and 10-cell stacks show a relatively small voltage increase gradient between the 4th and 6th seconds. In contrast, the 7-cell stack exhibits a relatively constant increase in voltage from the start, reaching its maximum more steadily.



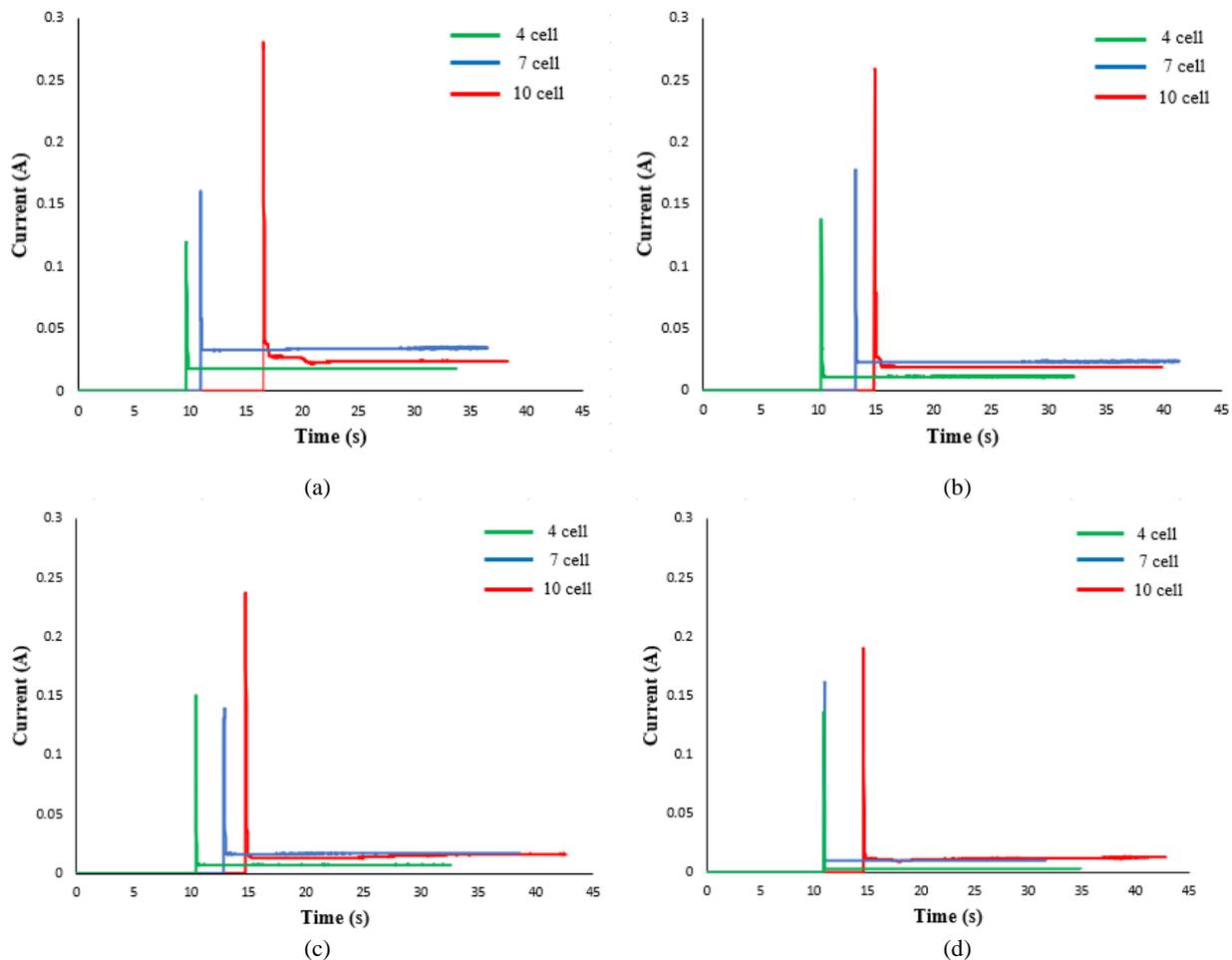
**Figure 3.** Maximum voltage of each PEMFC stack before given load.



**Figure 4.** Graph cell stack output voltage when given resistance: (a) 100 Ohm; (b) 150 Ohm; (c) 200 Ohm; and (d) 300 Ohm.

The maximum voltage observed in a PEMFC cannot serve as the sole reference for its practical performance. It is crucial to evaluate the fuel cell's behavior under load conditions. Experiments were conducted with four different load variations to analyze this. Figure 4 illustrates the dynamic response of the output voltage from the moment hydrogen is supplied to the point when a load is applied. Initially, the voltage rises until it reaches a maximum or steady state. Once the maximum Open Circuit Voltage (OCV) is achieved, applying a load causes a voltage drop, which recovers relatively quickly to a new stable

level. For the 10-cell stack, the maximum voltage achieved is 9 V. After applying a 100 Ohm load, the voltage drops to 2.13 V but eventually stabilizes at 2.49 V. For the 4-cell stack, the voltages under 100, 150, 200, and 300 Ohm resistances are 2.49 V, 2.59 V, 2.67 V, and 2.77 V, respectively. In the 7-cell stack, the voltages are 4.03 V, 4.36 V, 4.48 V, and 4.72 V, respectively. For the 10-cell stack with resistances of 100, 150, and 200 Ohms, the voltages are 3.11 V, 3.81 V, and 4.50 V, respectively.



**Figure 5.** Graph cell stack output current when given resistance: (a) 100 Ohm; (b) 150 Ohm; (c) 200 Ohm; and (d) 300 Ohm.

The graph in Figure 5 illustrates the output current observed after a load is applied. Theoretically, applying a load causes the voltage to drop while the current increases. Figure 5(a) provides details with 10 cells. Initially, without a load, the current in the PEMFC is 0 A. However, upon applying a 100-ohm load, the current experiences a sharp spike, reaching 0.24 A. This initial spike occurs because the load requires a substantial amount of current. After this spike, the current decreases and stabilizes at 0.1 A. As the load increases, the current produced by the cell also increases. In a stack of 4 cells with resistances of 100, 150, 200, and 300 ohms, the currents are 0.018 A, 0.012 A, 0.007 A, and 0.003 A, respectively. For a stack of 7 cells, the currents are 0.035 A, 0.023 A, 0.017 A, and 0.01 A, respectively. In the 10-cell stack, the currents are 0.024 A, 0.019 A, 0.016 A, and 0.012 A, respectively.

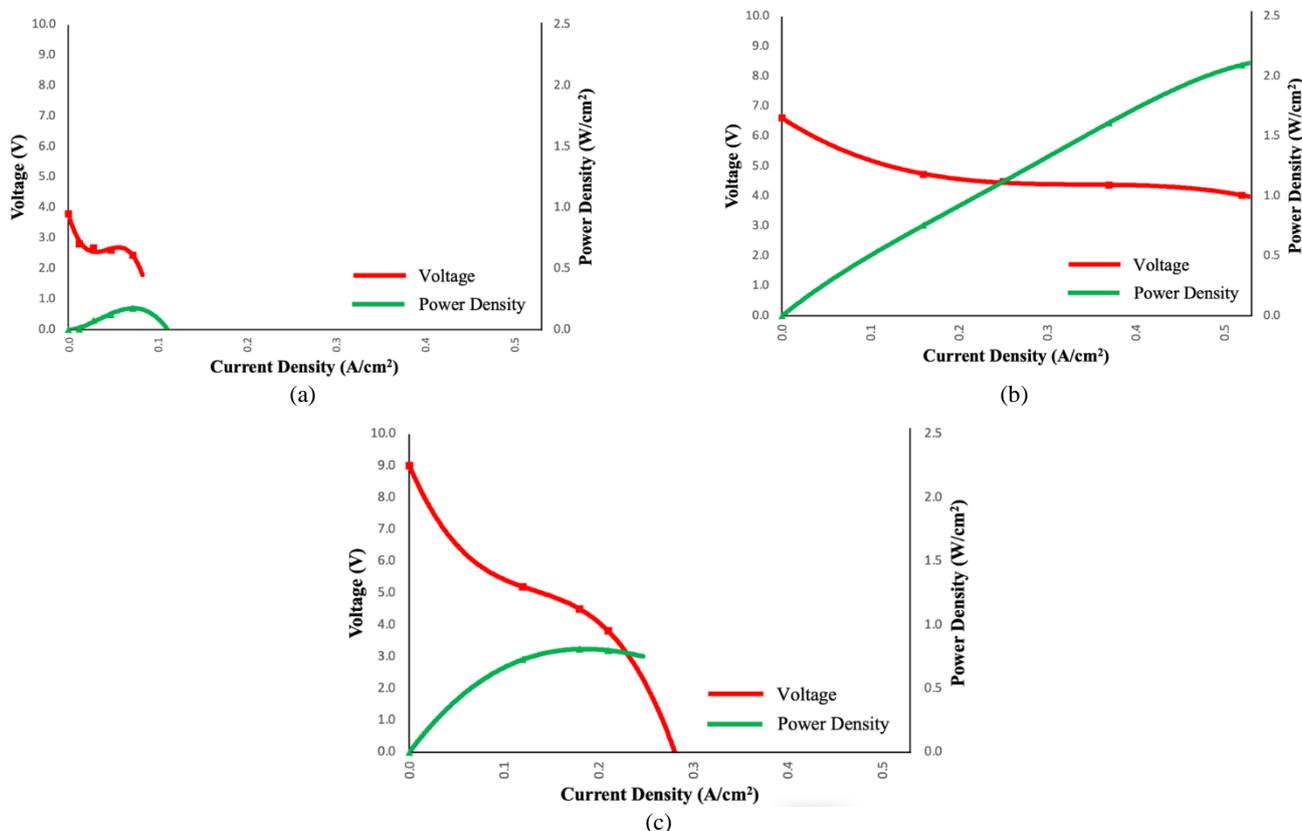
Increasing the load enhances the power generated by the fuel cell. For loads of 100, 150, and 200 ohms, the output power

of the 10-cell stack is lower than that of the 7-cell stack, as the power generated by the 10-cell stack is less. However, with a 300-ohm load, the voltage and current of the 10-cell stack surpass those of the 7-cell stack, resulting in higher power generation. The lower power of the 10-cell stack is attributed to the constant hydrogen supply, which cannot react with all cells. This observation aligns with the previous research by (Golmarz et al., 2018), which noted that  $O_2$  and  $H_2$  consumption increases from the inlet to the outlet, a characteristic of PEMFCs. The 4-cell stack produces low power due to its small cell area, which cannot react with the supplied hydrogen, leading to hydrogen returning to the outlet. Syampurwadi's previous study found that increasing the number of cells boosts the generated voltage. However, Syampurwadi also observed that increasing the number of cells also increased the hydrogen flow rate. Thus, this experiment demonstrates that with a constant hydrogen supply, increasing the number of cells results in a non-

proportional relationship between the number of cells and the power generated.

To understand the characteristics of the electricity generated, it is essential to examine the graph depicting the relationship between current density, voltage, and power density, as shown in Figure 6. The graph indicates that as the current density (current per cell area in a stack) increases, the relative output

voltage decreases, though this relationship is not constant under load conditions. Increasing the applied load results in a decrease in the generated current. Conversely, power density increases as current density rises or as the load decreases. However, the power density graph shows a turning point when the voltage and current generated by the cell reach their maximum values.



**Figure 6.** Relationship graph of current density with voltage and power density at cell variation: (a) 4 cells; (b) 7 cells; and (c) 10 cells.

In Figures 6(a) and 6(b), increasing the number of cells enhances the power density produced. This improvement occurs because the total cell area available for reacting with hydrogen increases. However, in the case of a stack with 10 cells, the resulting current density and power density are lower. This is due to the constant hydrogen flow rate, which leads to an insufficient hydrogen supply for all cells. In contrast, a 4-cell stack, despite receiving more hydrogen, has a smaller reactive area, resulting in lower current density. The current density is low when the voltage is high due to reduced oxygen consumption. These observations are supported by previous research findings (Sadeghi et al., 2019).

## 5. CONCLUSIONS

The increase in human population has led to a higher demand for electricity. To address the harmful environmental impacts of fossil power generation, renewable energy sources must be utilized. Hydrogen presents a promising solution for clean energy due to its abundance in water. To produce electricity from hydrogen, a conversion device such as a fuel cell is necessary. Fuel cells are considered promising for the future because of their relatively high efficiency and zero emissions. Among the various types, the Proton Exchange Membrane Fuel Cell (PEMFC) is widely developed due to its simple structure, ease of operation, and good durability.

The performance of a PEMFC is influenced by the number of cells in a stack. Experimental results indicate that in a 4-cell stack with a constant hydrogen supply, the hydrogen is not fully utilized due to the small surface area of each cell, leading to excess hydrogen being expelled. Conversely, in a 10-cell stack, the hydrogen supplied is insufficient to adequately support all cells, as the supply is distributed equally among more cells. Consequently, the power generated is not maximized. In contrast, a 7-cell stack can produce higher output power than a 10-cell stack because the hydrogen supply can be more evenly distributed among the fewer cells. Therefore, it is essential to balance the ratio between the hydrogen supply and the number of cells. Increasing the number of cells without a corresponding increase in hydrogen supply results in inefficient PEMFC power generation. For optimal performance, the number of cells must be increased in conjunction with an increased hydrogen supply.

## 6. ACKNOWLEDGEMENT

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