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# Evaluating the Effects of Clamping Force Variations on Performance and Current Distribution in PEM Electrolysis Cells

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## Abstract

This study presents an experimental investigation into the influence of varying clamping forces on the electrochemical performance and current density distribution in PEM water electrolysis cells. High-resolution segmented current measurement boards from DILICO engineering GmbH were employed in combination with a precisely adjustable single-cell setup provided by BalticFuelCells GmbH. The relationship between mechanical compression, contact resistance, and local current distribution was analyzed in detail through segmented in-situ current density measurements. The results demonstrate that a moderate increase in clamping force (1.2–1.4 MPa) leads to a significant improvement in cell performance. This is reflected in more homogeneous current distributions and reduced ohmic losses. For instance, at 1.2 MPa, a reduction in the standard deviation of current density by approximately 25% was observed. At the same time, polarization (UI) curves within this pressure range showed lower cell voltages for identical current densities. However, above 1.6 MPa, performance declined again, caused by excessive compression, mechanical deformation of the porous transport layers (PTLs) and localized membrane dehydration. The study identifies an optimal clamping force range that balances mechanical stability and electrochemical efficiency. The findings provide valuable design guidelines for the development of durable and efficient PEM electrolysis systems and emphasize the importance of mechanically optimized operating parameters.

## Introduction

Hydrogen is widely recognized as a promising alternative to fossil fuels due to its high energy density and its potential to enable carbon-neutral energy systems. It can be produced through renewable pathways and used in various sectors including transportation, power generation, and chemical processing, offering flexibility and deep decarbonization potential. Currently, most of the hydrogen is still produced from fossil sources such as natural gas via steam methane reforming, a process that emits considerable amounts of CO<sub>2</sub>. However, green hydrogen (produced from water electrolysis powered by renewable energy) represents a sustainable pathway that aligns with climate targets like those defined in the Paris Agreement [1]. Water electrolysis allows the decomposition of water into hydrogen and oxygen using electrical energy. Among the different technologies like alkaline, solid oxide, and proton exchange membrane (PEM) electrolysis with PEM offers superior dynamic response and higher current densities. When powered by renewable electricity, it provides a clean, scalable, and sustainable means of hydrogen production without emitting greenhouse gases [2,3], [9]. PEM electrolyzers are gaining traction due to their compact design, ability to operate at high pressures, and fast response to fluctuating power input. These characteristics make them especially suitable for integration with renewable energy systems and grid-balancing applications. Nonetheless, the high costs associated with noble metal catalysts (e.g., Iridium and Platinum) and the sensitivity of the components to operating conditions pose challenges for widespread commercial adoption. Recent research has focused on optimizing operating parameters such as temperature, pressure, and membrane thickness to improve system efficiency and durability [4]. An often overlooked, critical parameter in PEM water electrolysis systems is the clamping force (the mechanical pressure applied during assembly to compress the cell layers). This force significantly influences contact resistance, electrical conductivity, and the homogeneity of current distribution across the active area. Studies show that insufficient clamping leads to poor electrical contact between components (e.g., MEA, PTLs, and bipolar plates), which increases contact resistance and reduces performance. Conversely, excessive pressure can damage the porous transport layers and catalyst layers, resulting in mass transport limitations and long-term degradation. Advanced methods such as operando current mapping reveal that inhomogeneous mechanical pressure distribution causes localized hot spots and uneven current flow, which accelerates material fatigue and reduces system lifetime. Therefore, optimizing the clamping pressure is crucial to ensure efficient current distribution and reliable operation [5-8].

## 1. Scientific Approach

In this study, an experimental approach was employed to investigate the influence of varying clamping forces on the performance and current density distribution in a PEM electrolyser cell. In-situ current density measurements using segmented sensor boards enabled direct quantification of local effects caused by mechanical stress on the electrochemical performance of the cell.

## 2. Experimental Set-Up and Cell Specifications

To investigate the impact of varying clamping forces on the performance and current distribution of PEM electrolyser cells, the DILICO HCTS-50 Flexible High Pressure AEM/PEM Electrolyser Test Bench from DILICO engineering GmbH. The HCTS-50 is a modular test bench designed for the characterization of PEM electrolysis cells under realistic operating conditions. It enables reproducible investigations of single cells or short stacks at operating pressures up to 8 bar (optionally 50 bar). It also supports the analysis of

degradation processes, material behaviour, and operational strategies. The system is equipped with automated media and temperature control and features an in-situ current density and temperature sensing system (DILICO CURR TEMP), allowing spatially resolved characterization of cell performance across the membrane surface.

For in-situ analysis of the PEM electrolyser cell, a sensor board DILICO CURR TEMP 64 baltic qCf FC50/125 is positioned behind the monopolar plate on the cathode side within the cell fixture. The Measurement board (with 64 Segments) enables spatially resolved measurements of current density and temperature. PT100 sensors capture local temperature distributions with high precision. The current density is determined by using low resistance shunt resistors, based on the voltage drop caused by the cell current. Data enables conclusions about inhomogeneities due to uneven compression, aging, or gas distribution. Thermoelectric correlations become apparent with the simultaneous measurement of these two variables. This allows for the recording of dynamic conditions under real operational scenarios. It supports the understanding of localized degradation mechanisms and helps optimize operating strategies. This measurement technique is particularly suitable for detailed investigations at the single-cell level presented in this work.

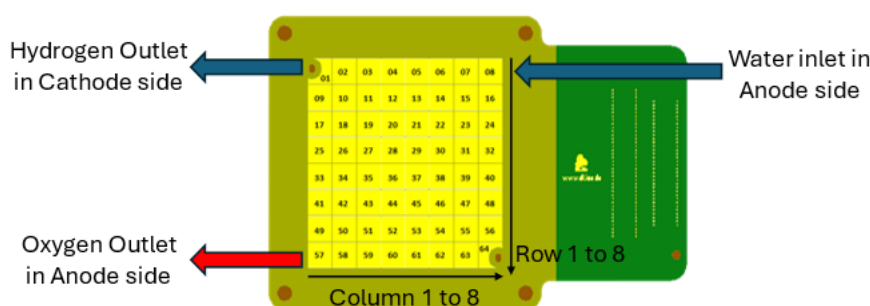


Figure 1: Segment numbering and alignment of the media inlet and outlet interfaces.

Test procedures are controlled via a LabVIEW-based user interface, which enables customizable measurement protocols and integrated safety functions. The cell mounting is based on the baltic quickCONNECT fixture FC25/125, which is optimized for rapid component exchange. In this study, the cell was equipped with Quintec CCM-E25-N117 membrane electrode assemblies (MEAs), featuring a Nafion™ 117 membrane. The cathode catalyst loading was 1.0 mg/cm<sup>2</sup> Pt on advanced carbon support, while the anode comprised 2.0 mg/cm<sup>2</sup> Ir. The PTL on the anode side used is a Thermally Platinized High Porosity Titanium Fiber Felt with a porosity of approximately 70-73 % and a thickness of 0.2-0.3 mm. On the cathode side, Toray Paper 060-TGP-H-060, a carbon fiber composite paper with a total thickness of 0.19 mm, is employed.



Figure 2: Function principle of the quick Connect Fixture cell frame and pressure transmission from the pneumatic cylinder to the cell area.

In this study, the quickCONNECT fixture qCf FC25/125 LC 8 bar was installed and operated within the test stand. According to the manufacturer's datasheet, optimal operation is achieved at a clamping pressure of approximately 1 to 2 N/mm<sup>2</sup>. The monopolar plate of the

test cell consists of a graphite flow field and the datasheet specifies that the applied pressure should not exceed 2.5 N/mm<sup>2</sup>. The cell features a square active area of 25 cm<sup>2</sup> and the piston used has a diameter of 125 mm.



Figure 3: Complete setup of DILICO CURR TEMP in the DILICO HCTS-50 test bench from DILICO engineering GmbH.

After startup, the test bench was brought into operation and the test cell was heated to 70 °C. This temperature was kept constant throughout the experiments using a thermostat. Two different measurement methods were applied to investigate the influences of contact pressure and cell internal pressure on PEMWE single Cell. In all test procedures, efforts were made to keep other parameters constant to ensure better comparability of the data, as listed in the following table:

Table 1: Constant parameters across all three measurement procedures

Description	Value
Thermostat Temperature	70 °C
DI-Water Temperature	70 °C
Cell Temperature	70 °C
DI-water flow rate	15 to 20 ml/min
Voltage (CV)	2.2 V
Current ramp	0.5 A/s

#### Method 1– Constant Cell Pressure, Manual Adjustment of Cylinder Pressure:

In this method, the internal cell pressure (H<sub>2</sub> and O<sub>2</sub>) was kept constant at 1 bar ( $P_{\text{cell}}$  in formula 1), while the cylinder pressure was manually adjusted using a pressure gauge to achieve different mechanical contact pressures. The corresponding target values are shown in Table 2. Overall, the resulting clamping force can be calculated using the following equation:

$$F_A = p_{\text{cylinder}} \cdot A_{\text{cylinder}} - p_{\text{cell}} \cdot A_{\text{active}} \quad (1)$$

In each measurement step, the cylinder pressure was initially adjusted using the manometer and then fine-tuned to the desired decimal precision via the test stand's software-based sensor control. To precondition the membrane before the experiment, the test stand was preheated to an initial clamping force of 1 N/mm<sup>2</sup> for 1800 seconds at the beginning of each step. The system was then automated (scripting) such that, during each step, it performed three cycles of current sweeps from 5 A to 50 A and back over 300 seconds, with a current density change rate of 0.5 A/s. This procedure enabled the recording of reliable current-

voltage (UI) characteristics based on averaged data. After each ramp-up to 50 A, a ramp-down to 5 A was carried out. All other parameters remained as specified in Table 1. It should also be emphasized that the cylinder pressures were rounded, as the manometer does not allow for fine adjustment to two decimal places.

Table 2: Software-controlled cell pressure and manual cylinder adjustment

Step	Cylinder Pressure [bar]	Cell Pressure (H <sub>2</sub> and O <sub>2</sub> ) [bar]	Contact Pressure [N/mm <sup>2</sup> ]
1	2.4	1	1
2	2.8	1	1.2
3	3.2	1	1.4
4	3.6	1	1.6
5	4.0	1	1.8
6	4.4	1	2

### Method 2 – Constant Cylinder Pressure, Variable Cell Pressure:

In the second method, the cylinder pressure was fixed at 4.5 bar, a value that allows the internal cell pressure to reach close to its maximum, approximately 8 bar. The internal cell pressure was then varied via the software until the same effective contact pressure as in the first method was achieved. To ensure better comparability between both test conditions, the system was initially operated at a clamping force of 1 N/mm<sup>2</sup> for 1800 seconds, allowing the membrane to be humidified and properly conditioned before the actual test. The target values for this setup are summarized in Table 3. In this case, the cell pressures are rounded like the cylinder pressure in Table 2. Following this, the system was automated using scripting to perform, in each step, three cycles of current sweeps from 5 A to 50 A and back over 300 seconds, with a current density ramp rate of 0.5 A/s, enabling the acquisition of reliable and repeatable current-voltage characteristics.

Table 3: Achieved contact pressures via variable cell pressure at fixed cylinder load

Step	Cylinder Pressure [bar]	Cell Pressure (H <sub>2</sub> and O <sub>2</sub> ) [bar]	Contact Pressure [N/mm <sup>2</sup> ]
1	4.5	7.8	1
2	4.5	6.5	1.2
3	4.5	5.2	1.4
4	4.5	3.9	1.6
5	4.5	2.6	1.8
6	4.5	1.3	2

Although both the methods were designed to achieve identical mechanical contact pressures, they differ in the way this pressure is applied and controlled. The objective of this study was to investigate whether these differing in-situ adjustment strategies lead to observable deviations in the resulting current density distributions and polarization curves, or whether their influence remains negligible.

## 3. Results

### Influence of Clamping Pressure on the Spatial Current Density Profile

After the measurements were taken, the data was evaluated and visualized. To improve the understanding of segment assignment and media flow orientation, an image of the sensor surface is in the experimental set-up provided (see Figure 1). The results, which revealed significant differences between the two measurement methods, are shown below.



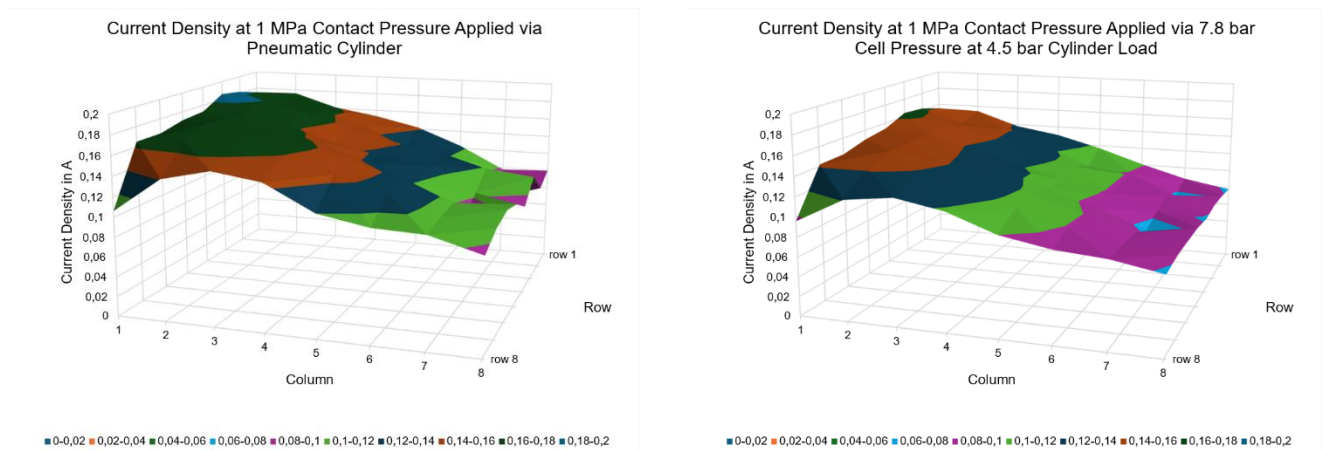


Figure 4: Current density profiles at 1 MPa using method 1 (Left) and Method 2 (Right).

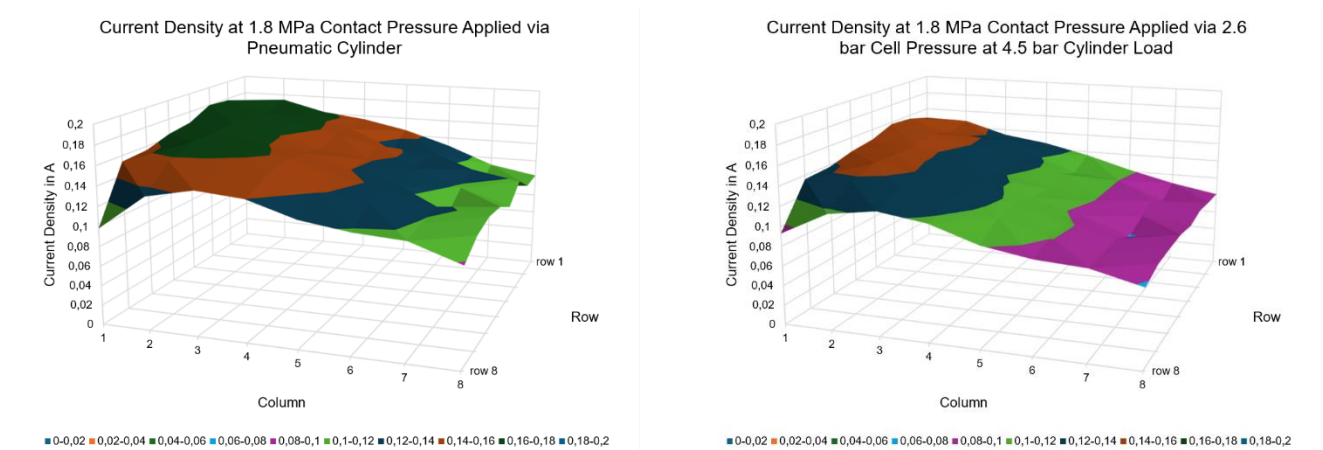


Figure 5: Current density profiles at 1.8 MPa using method 1 (Left) and Method 2 (Right).

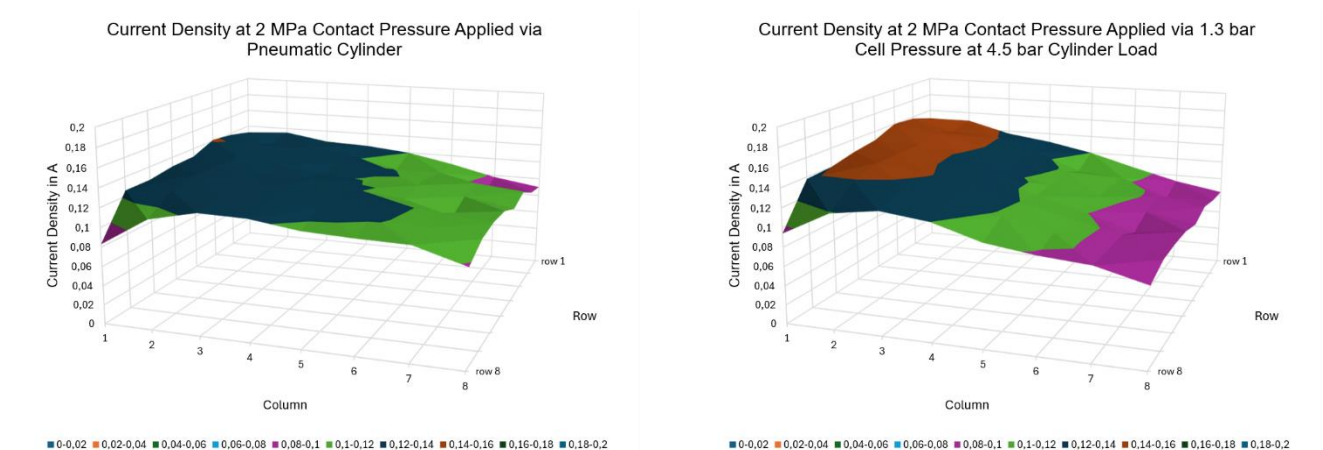


Figure 6: Current density profiles at 2 MPa using method 1 (Left) and Method 2 (Right).

Figures 4 to 6 and Tables 4 and 5 show how the two measurement methods respond to changes in clamping pressure, applied in units of N/mm<sup>2</sup>. Both methods reveal that the mechanical pressure strongly affects the current distribution across the active area, but each method highlights different aspects of behaviours.

In the first measurement method, as shown in Figure 6 on the left, increasing contact pressure leads to a visibly more uniform current distribution. This is confirmed by the declining relative standard deviation values in Table 4, which indicate improved homogeneity.

In the second measurement method, as shown on the right side of Figures 4 to 6, the current density profile becomes gradually more homogeneous with increasing clamping pressure on the cell. The distribution flattens, indicating a reduction in spatial variation across the measured zones. This suggests that higher contact pressure improves both mechanical and electrical contact between the cell components, resulting in a more uniform current flow across the active area.

Both measurement methods demonstrate that increasing clamping pressure enhances the uniformity of current distribution across the active area. However, the first method reflects this effect with greater clarity and spatial precision, making it more obvious where and how the distribution improves in response to mechanical compression.

Table 4: Values from segmented current density distribution under the first measurement method

Contact Pressure [N/mm <sup>2</sup> ]	Max [mA]	Min [mA]	Spread [mA]	Mean [mA]	Standard deviation [mA]
1	186	75.2	110	140	28.9
1.2	154	72	82.4	120	21.5
1.4	155	68.8	86.4	116	23.8
1.6	156	77.6	78.4	119	21.7
1.8	180	97.6	82.4	141	23.3
2	141	83.2	57.6	120	12.9

Table 5: Values from segmented current density distribution under the second measurement method

Contact Pressure [N/mm <sup>2</sup> ]	Max [mA]	Min [mA]	Spread [mA]	Mean [mA]	Standard deviation [mA]
1	164	75.2	88.8	116	27
1.2	161	74.4	86.4	114	26.2
1.4	158	74.4	84	113	25.5
1.6	158	76	81.6	113	24.7
1.8	158	78.4	79.2	115	23.7
2	160	80.8	79.2	119	23

## Influence of the clamping pressure on the polarization curve

As shown in Figure 7, the performance of a PEM electrolyser single cell was investigated under varying clamping pressures ranging from 1.0 MPa to 2.0 MPa. The resulting polarization curves revealed a non-linear relationship between applied mechanical pressure and cell efficiency. From 1.0 MPa to 1.4 MPa, a clear improvement in electrochemical performance was observed. This enhancement is primarily attributed to better interfacial contact between the cell components, namely the membrane, catalyst layers, porous transport layers (PTLs) and bipolar plates. A tighter mechanical interconnection reduces contact resistance and leads to a more uniform current distribution across the active area, ultimately decreasing voltage losses and increasing efficiency.

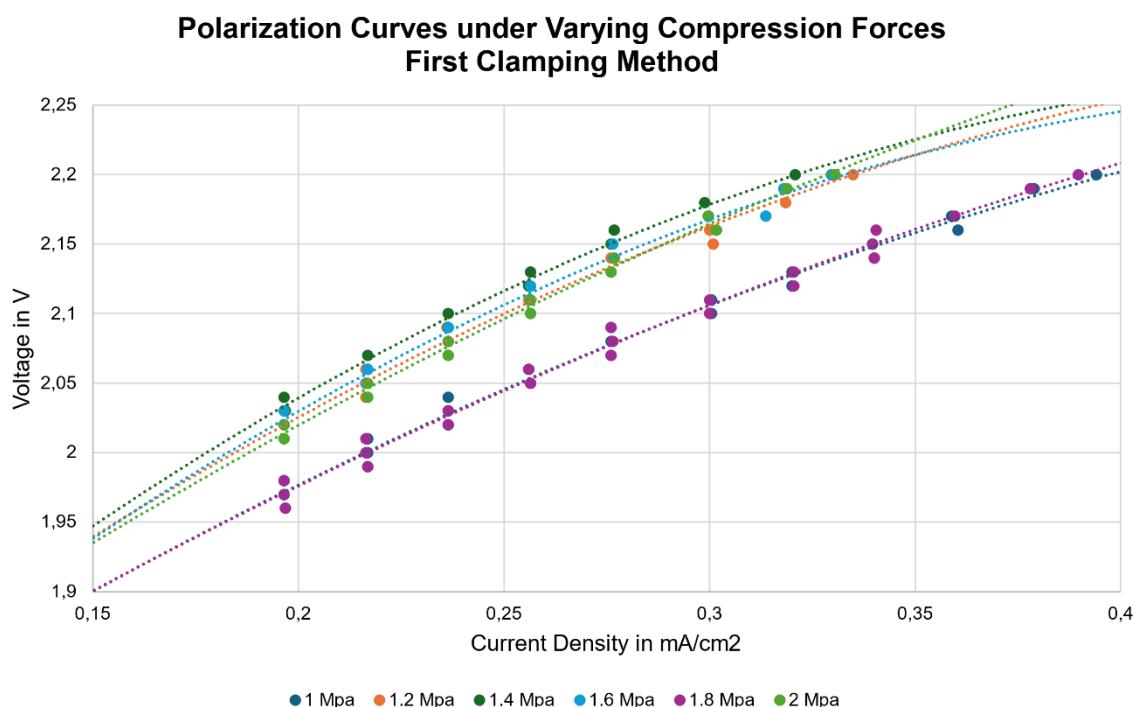


Figure 7: Polarization curve by varying the cylinder pressure under the first measurement method.

However, from 1.4 MPa to 1.8 MPa, the trend changes noticeably. The polarization curve begins to align with the initial measurement at 1.0 MPa, indicating that the earlier performance gains have possibly decreased. This behaviour can be explained by the emergence of over compression effects. Excessive clamping pressure can deform delicate layers within the cell, particularly the porous transport layers and catalyst-coated membrane, leading to restricted mass transport, uneven gas diffusion and potential dehydration of the membrane. These mechanical distortions can increase internal resistance, limit proton conductivity, and reduce the overall effectiveness of the electrochemical reactions.

Interestingly, at 2.0 MPa, the polarization curve trends upward again, aligning closely with the performance observed at 1.2 MPa. While this partial recovery in performance may seem unexpected, it might be caused by improved sealing of the cell or redistribution of mechanical stress, which could reestablish better contact conditions in certain areas of the cell. Alternatively, microstructural adjustments at this pressure may counteract some of the earlier compression that induced limitations. However, such effects should be interpreted with caution, as they could also result from temporary relaxation or local inconsistencies in the cell architecture.

Significantly, the divergence between the polarization trendlines becomes more pronounced beyond a current density of 0.35 A/cm<sup>2</sup>. This suggests that higher electrochemical loads amplify the impact of mechanical compression particularly in terms of mass transport resistance and ohmic losses. At low current densities, the influence of clamping pressure is less dominant, but as the system operates under more demanding conditions, structural and transport-related limitations become increasingly relevant.

In the second measurement approach, as shown in Figure 8, a clear nonlinear relationship is observed between the clamping pressure and the polarization behaviour of the PEM electrolyser single cell, like the results from the first method. As the clamping pressure increases from 1.0 MPa to 1.4 MPa, the polarization trendline improves, indicating reduced



overpotentials and enhanced electrochemical performance. This improvement is most likely due to better contact between cell components, which reduces interfacial resistance and enhances current homogeneity across the active area. However, as the pressure increases from 1.4 MPa to 1.6 MPa, the trendline stagnates particularly in the current density range between 0.2 and 0.3 A/cm<sup>2</sup>. At 1.8 MPa, the curve nearly overlaps with the initial value at 1.0 MPa, indicating a partial loss of cell performance, likely caused by the onset of over compression effects such as the deformation of porous transport layers or impaired gas transport.

Significantly, at 2.0 MPa, the polarization trendline drops further and lies clearly below the one recorded at 1.0 MPa. This decline in performance points to severe over compression, which may lead to increased mass transport limitations and internal resistances due to structural stress or membrane dehydration. Additionally, beyond a current density of approximately 0.35 A/cm<sup>2</sup>, the trendlines begin to converge, indicating that at higher electrochemical loads, the differences between clamping pressure conditions become less pronounced. This suggests that the dominating factors affecting performance at these current densities may shift away from mechanical compression effects and toward other limitations such as membrane conductivity, gas transport, or reaction kinetics. It emphasizes the complex interplay between mechanical and electrochemical influences and the need for careful pressure optimization across different operating ranges.

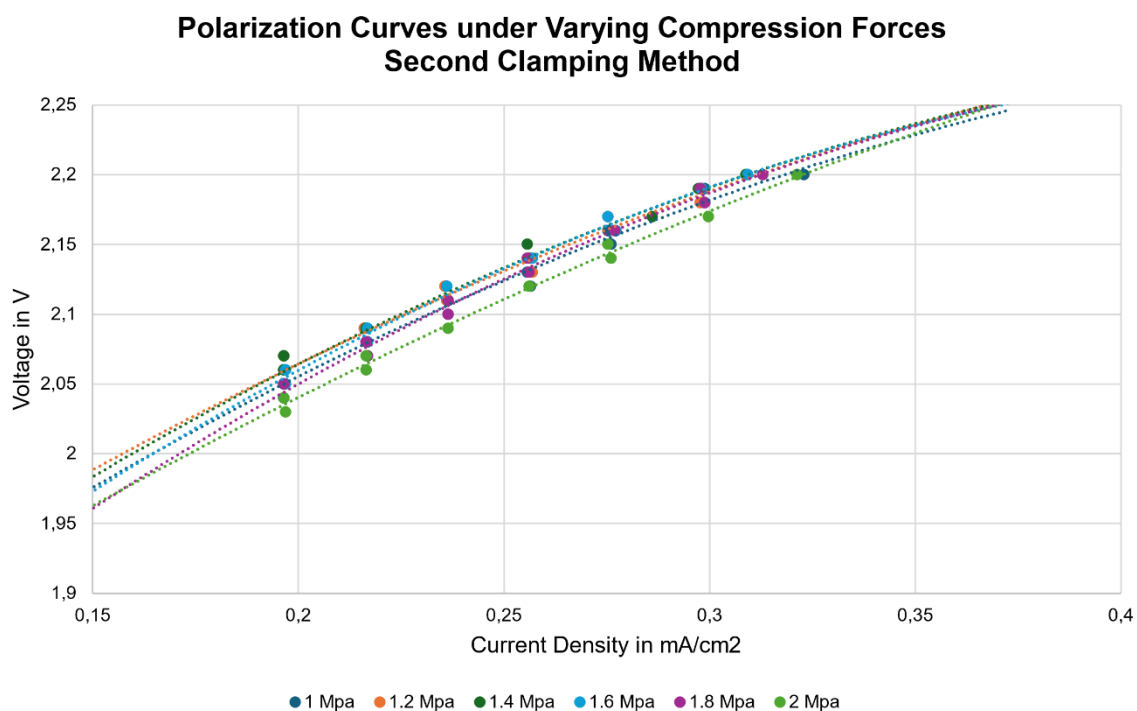


Figure 8: Polarization curve by varying the cylinder pressure under the second measurement method.

## Conclusion and Perspectives

Clamping pressure is more than a structural requirement in PEM electrolysis. It is a performance-determining variable with system-level implications. This study demonstrates that the electrochemical response of a single PEM cell is strongly dependent on how mechanical pressure is applied and distributed. Across two distinct measurement methodologies, the influence of clamping force on current distribution and polarization behaviour exhibited consistent trends, yet with significant method-specific deviations. These deviations suggest that the mechanical-electrochemical coupling is not only nonlinear but also context-dependent. Crucially, the findings show that there is no universally optimal clamping pressure. What improves performance under one configuration may impair it under another. In method 1, moderate compression led to improved uniformity and reduced overpotential, with partial performance recovery even at higher pressures. In contrast, method 2 revealed continuous performance degradation beyond the mid-pressure range, likely due to differences in internal pressure balancing and membrane constraint dynamics. This variability highlights clamping pressure must be considered a system-specific optimization parameter rather than a fixed design value. Factors such as fixture rigidity, membrane swelling behaviour, gas diffusion layer morphology, and internal pressure regimes all play a role in how the cell responds mechanically and electrochemically. Therefore, a globally valid pressure target is neither practical nor scientifically justified. Future work must integrate operando diagnostics, advanced modeling, and long-term stability analysis to map clamping effects not just spatially, but also temporally and in stack-relevant configurations. As PEM electrolysers scale toward industrial relevance, understanding and controlling mechanical-electrochemical interfaces (e.g., via electrochemical impedance spectroscopy) will be key to maximizing both performance and durability.

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