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PERFORMANCE EFFICIENCY OF PEM ELECTROLYZER STACKS WITH NANO-COATED TITANIUM PTLs AND BIPOLAR PLATES

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The study presents an industrial-scale evaluation of two PEM electrolyser stacks incorporating Naco-engineered titanium coatings on porous transport layers (PTLs) and bipolar plates. Stack 0316/44 included both coated PTLs and coated bipolar plates, while Stack 0317/44 utilised only coated PTLs. Both stacks were conditioned for 40 hours at 15 bar and subsequently tested at current densities of 0.6 and 1.2 A cm^{-2}. At 150 A, the total voltages measured were 89.8 V for 0316/44 and 88.9 V for 0317/44, whereas at 300 A, they reached 99.3 V and 102.8 V, respectively. Gas purity remained within safe limits, with residual oxygen (O_2) in hydrogen (H_2) ranging from 14 ppm to 31 ppm and H_2 crossover remaining below 0.7 % across all tests. Integrated operation in the SIRIO 1000 system at 300 A produced the combined voltages of 106.0 V and 104.0 V for the two stacks. Average power consumption during joint operation was 5.75 kW/Nm^3, approximately 10–20 % higher than that of standard industrial stacks. The results confirm the stable operation and acceptable gas-separation performance of the coated components under high-pressure, high-current conditions, while also identifying efficiency gaps that require further optimisation. The study provides the first comparative industrial assessment of the coated PEM stack architectures and establishes a foundation for future durability and optimisation studies.

Keywords: *Bipolar plates, hydrogen crossover, PEM electrolysis, porous transport layers, stack performance, titanium coatings.*

1. INTRODUCTION

The rapid expansion of green hydrogen technologies has intensified global research efforts focused on improving the performance, durability, and cost efficiency of proton-exchange-membrane (PEM) water electrolysis systems [1]–[4]. PEM electrolysers remain one of the most promising technologies for high-purity hydrogen production due to their compact design, high current density operation, and fast dynamic response. Compared to conventional alkaline electrolysis, PEM electrolysers offer several intrinsic advantages, including high current density operation, rapid dynamic response, compact system design, and the ability to operate at elevated pressures. These characteristics make PEM technology especially attractive for coupling with intermittent renewable electricity sources such as wind and solar power [5]–[7].

In PEM electrolysis, water is electrochemically split into hydrogen and oxygen using a solid polymer electrolyte membrane that simultaneously serves as an ionic conductor and gas separator [8]–[10]. Protons are generated at the anode migrate through the membrane to the cathode, while electrons are transported through the external circuit. The solid-state nature of the electrolyte enables high gas purity and minimises cross-contamination between hydrogen and oxygen, which is essential for safe operation and downstream hydrogen utilisation.

Despite the advantages PEM provides, the widespread deployment of these electrolysers is currently constrained by high capital costs and durability challenges [3]. A significant fraction of these costs originates from the use of noble metal catalysts, titanium-based components, and complex stack architectures required to withstand corrosive operating conditions and high pressures. Porous transport layers and bipolar plates are exposed to aggressive anodic environments, where corrosion and contact resistance can negatively affect performance and long-term stability. Also, wide deployment of PEM is still constrained by material limitations, particularly those associated with degradation of catalysts, PTLs, and bipolar plates under harsh anodic operating conditions [11]–[14].

New advanced coatings and catalyst deposition strategies are therefore essential for achieving improved stack efficiency and longevity while keeping manufacturing costs under control [15]–[20]. Naco Technologies has proposed surface-engineered titanium PTLs and catalyst layers intended to enhance electrochemical performance without compromising structural integrity [21]. Yet, the behaviour of such newly coated components within complete PEM stack assemblies must be experimentally validated under industrially relevant operating conditions.

The present study investigates the performance of two PEM electrolyser stacks incorporating Nano-coated components. The first stack (SN 0316/44) contains both coated bipolar plates and titanium PTLs, whereas the second stack (SN 0317/44) incorporates only coated titanium PTLs.

Both stacks were subjected to a standardised testing procedure, including leak checks, operation in a dedicated test electrolyser, and subsequent integration into a full-scale SIRIO 1000 electrolyser system [22]. Individual cell voltages, total stack voltages, gas purity, and hydrogen cross-over behaviour were measured at multiple current densities ranging from 0.6 to 1.2 A cm^{-2}. Initial single-stack evaluations were performed after 40 hours of conditioning at 15 bar, followed by joint operation of both stacks within the commercial electrolyser environment for an additional 20 hours under 200–300 A load conditions. A summary comparison of the key performance indicators for both stack configurations is provided in Table 1.

Table 1. A Summary Comparison of the Key Performance Indicators for Stacks 0316/44 and 0317/44

Parameter	Unit	Stack 0316/44	Stack 0317/44
Number of cells	–	44	44
Conditioning time	h	40	40
Total voltage at 150 A	V	89.8	88.9
Average cell voltage at 150 A	V	~2.04	~2.02
Voltage range at 150 A	V	1.93–2.34	1.86–2.10
Total voltage at 300 A	V	99.3	102.8
Average cell voltage at 300 A	V	~2.26	~2.34
Voltage range at 300 A	V	2.09–2.44	2.11–2.37
O_2 in H_2 at 150 A	ppm	31	14
H_2 in O_2 at 150 A	%	0.69	0.64
O_2 in H_2 at 300 A	ppm	25	21
H_2 in O_2 at 300 A	%	0.75	0.70
Voltage at 300 A (system)	V	106.0	104.0

Performance differences between the two configurations were clearly observed. For example, at 150 A and approximately 50 °C, Stack 0316/44 reached a total voltage of 89.8 V, while Stack 0317/44 operated at 88.9 V. At higher current density (300 A), the total voltages increased to 99.3 V and 102.8 V for stacks 0316/44 and 0317/44, respectively, indicating some variation in electrode kinetics and ohmic resistance between the two coated designs.

A subsequent operation inside the SIRIO 1000 system at 300 A and 57 °C resulted in combined stack voltages of 106.0 V for 0316/44 and 104.0 V for 0317/44, while average power consumption reached 5.75 kW Nm^{-3}, around 10–20 % higher than standard PEM stacks produced by the testing organisation. Gas purity analyses revealed residual O_2 concentrations in H_2 between 14 ppm and 31 ppm and H_2 crossover in O_2 consistently below 0.7 %, aligning with standard system behaviour. These observations highlight that, while the coated components functioned reliably under high-pressure operation, further optimisation might be required to fully match or exceed the efficiency of established industrial stack designs.

The hypothesis of the study is that the application of Naco-engineered coatings on titanium PTLs and bipolar plates will improve or maintain stack performance, particularly voltage efficiency, gas purity, and hydrogen crossover, relative to standard titanium-based components, without introducing operational instabilities at high pressure and high current density.

This study seeks to answer the following research questions:

1. How do the coated PTLs and bipolar plates influence cell-level and stack-level voltages at current densities of 0.6–1.2 A cm^{-2}?
2. Do the coated components affect gas purity, particularly residual O_2 in H_2 and H_2 crossover into O_2, under 15-bar operating conditions?
3. Are there measurable performance differences between stacks containing both coated PTLs and bipolar plates (0316/44) and stacks containing only coated PTLs (0317/44)?
4. How does the performance of coated stacks compare to that of standard industrial PEM stacks during joint operation in the SIRIO 1000 electrolyser?
5. Are the observed performance characteristics stable after extended conditioning and increased operational load?

The methodology applied in this study followed a structured industrial testing protocol designed to assess the performance of PEM electrolyser stacks incorporating Nano-coated titanium components under realistic operating conditions. Both stacks underwent comprehensive internal and external leak validation before being connected to the dedicated test electrolyser. Each stack was then operated individually for 40 hours of conditioning at 15 bar, after which performance measurements were taken at current levels of 150 A and 300 A, corresponding to current densities of 0.6 and 1.2 A cm^{-2}. During these tests, cell-resolved voltages for all 44 cells in each stack were recorded, along with total stack voltage, temperature, and pressure.

Gas purity analyses were performed to quantify residual oxygen in the hydrogen stream and hydrogen crossover into the oxygen stream. Following the single-stack evaluations, both stacks were installed in the SIRIO 1000 commercial electrolyser and operated jointly, first at 200 A and then at 300 A, allowing assessment of integrated system performance and overall energy consumption, expressed as power per normalized cubic meter of hydrogen.

Despite the rigor of this methodology, several limitations constrain the scope and generalizability of the findings. The study includes only two stacks, each with a distinct coating configuration, limiting the statistical robustness of comparative conclusions. The total operating time, 40 hours of conditioning plus 20 hours of joint operation, captures short-term behaviour but does not reflect long-term degradation, corrosion effects, or durability trends commonly observed in PEM electrolysers over hundreds or thousands of hours. Furthermore, all measurements were conducted at a single pressure level (15 bar), leaving unexplored potential variations in performance at lower or higher operating pressures. The absence of a simultaneously tested uncoated reference stack restricts the ability to establish a precise baseline for performance comparison. Additionally, diagnostic depth was limited; techniques such as electrochemical impedance spectroscopy, accelerated stress testing, and post-mortem materials analysis were not included, thereby limiting insight into failure mechanisms and the microstructural effects of the coatings. These methodological constraints define the boundaries within which the research results should be interpreted.

The scientific input of this study lies in the first documented industrial-scale performance evaluation of PEM electrolyser stacks incorporating Naco-engineered titanium PTL and bipolar-plate coatings, tested at high pressure (15 bar), high current density (up to 1.2 A cm^{-2}), and in a commercial electrolyser platform (SIRIO 1000). The study provides the first comparative analysis between two coated stack architectures, one including both PTL and bipolar-plate coatings, and one incorporating only PTL coatings, allowing insights into the contribution of each component type to overall stack efficiency. Moreover, the report demonstrates that gas purity and hydrogen crossover remain within standard operational ranges, an important validation for the safe use of advanced coated components. These findings contribute valuable empirical data to the ongoing development of corrosion-resistant, high-performance materials for next-generation PEM electrolysers.

2. METHODOLOGY

The methodology used in this study follows a structured industrial testing procedure aimed at evaluating the electrochemical performance, gas purity characteristics, and operational behaviour of two PEM electrolyser stacks incorporating coated titanium components of Naco Technologies. The experimental workflow was designed to ensure that both intrinsic stack performance and system-level behaviour could be assessed under controlled and industrially relevant conditions. Before the operation, both stacks underwent comprehensive internal and external leak validation using standard pressure-retention and sealing verification procedures commonly employed in high-pressure PEM electrolyser manufacturing. Only after confirming the absence of internal leaks and external losses were the stacks considered suitable for electrochemical evaluation. Following this preliminary qualification step, each stack was mounted independently on a dedicated test electrolyser platform equipped with temperature, pressure, flow, and current control systems, enabling stable regulation of operating conditions throughout the experiment.

Each stack was conditioned for a continuous period of 40 hours at 15 bar, allowing catalysts, PTLs, and coated components to reach steady-state wetting, ionic conduction, and thermal equilibrium. After conditioning, performance measurements were conducted at two controlled load levels: 150 A, corresponding to a current density of 0.6 A cm^{-2}, and 300 A, corresponding to 1.2 A cm^{-2}. Stack temperature was regulated between approximately 49 °C and 64 °C, depending on the specific test configuration. During these tests, voltage readings were collected for all 44 cells in each stack with high-resolution multichannel acquisition equipment, providing detailed voltage maps that enabled identification of cell-to-cell variability, potential local activation losses, and any voltage deviations indicative of irregular gas distribution or coating-related effects.

Total stack voltages were recorded simultaneously to assess overall efficiency under each operating condition. Alongside electrochemical measurements, gas purity analyses were conducted to quantify residual oxygen concentration in the hydrogen stream and hydrogen crossover into the oxygen stream. Gas sampling was performed at stable load conditions, with measurements taken using dedicated analysers designed for trace gas detection at high pressure. These data were used to evaluate whether the advanced coated components influenced gas separation behaviour or contributed to elevated crossover levels.

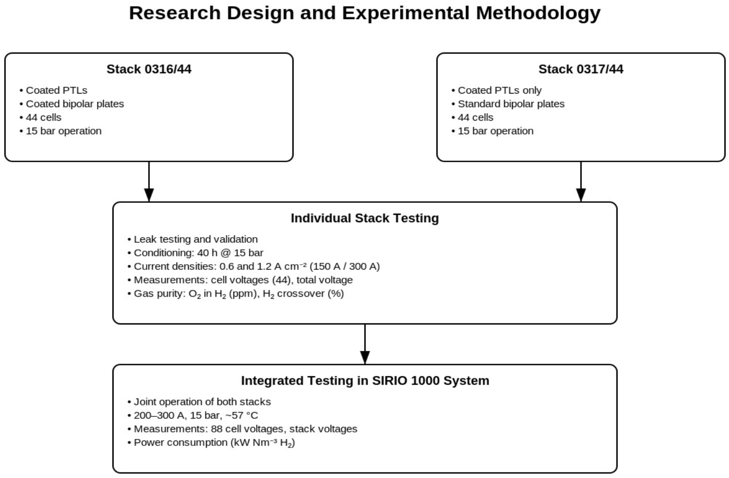

Fig. 1. Research design of the study.

After completion of the individual stack tests, both stacks were integrated into the SIRIO 1000 electrolyser system, replacing standard production stacks. Electrical, hydraulic, and gas-handling connections were performed according to the manufacturer's procedures to ensure full compatibility with system-level instrumentation. The combined system was then operated for an additional 20 hours at 200 A to stabilise joint operation and to allow both stacks to equilibrate under shared flow, temperature, and pressure conditions. Following this stabilisation phase, the current was increased to 300 A, corresponding again to 1.2 A cm^{-2}, and system-wide measurements were collected. These included individual cell voltages for all 88 cells combined, total stack voltages for each stack operating in series, and hydrogen production rate. Power consumption was calculated in kilowatts per normalized cubic meter of hydrogen to allow comparison with standard industrial benchmarks. The applied operating conditions of the test matrix are summarised in Table 2.

Table 2. Applied Operating Conditions of the Test Matrix

Test stage	Stack ID	Coating	Pressure (bar)	Current (A)	Current density (A cm^{-2})	Temperature (°C)	Test duration
Conditioning	0316/44	Coated PTLs / coated BPs	15	–	–	~50	40 h
Conditioning	0317/44	Coated PTLs only	15	–	–	~49	40 h
Single-stack test	0316/44	Coated PTLs / coated BPs	15	150	0.6	~50	Steady-state
Single-stack test	0316/44	Coated PTLs / coated BPs	15	300	1.2	~64	Steady-state
Single-stack test	0317/44	Coated PTLs only	15	150	0.6	~49	Steady-state
Single-stack test	0317/44	Coated PTLs only	15	300	1.2	~63	Steady-state
Integrated operation	Both	Mixed	15	200–300	0.8–1.2	~57	20 h

Throughout all phases of the experiment, operating conditions, including pressure, temperature, flow rates, and current, were maintained within strict tolerances to minimise variation and ensure that performance differences could be attributed primarily to the material configurations under investigation. No additional diagnostic techniques, such as impedance spectroscopy, degradation rate analysis, or post-mortem component examination, were included in the testing sequence, as the objective of this methodology was to characterise short-term operational performance rather than long-term durability or failure mechanisms. Data acquisition, storage, and processing were carried out according to the laboratory's certified procedures, ensuring traceability, repeatability, and compliance with internal quality standards for PEM electrolyser evaluation.

3. RESULTS

The results obtained from the experimental evaluation of the two PEM electrolyser stacks provide a comprehensive overview of the electrochemical behaviour, cell-to-cell uniformity, total stack voltage characteristics, and gas purity performance of the coated titanium components under industrially relevant pressure and current conditions. For Stack 0316/44 (see Table 3), which incorporated both coated bipolar plates and titanium PTLs, initial testing at 150 A and 50 °C yielded a total stack voltage of 89.8 V, corresponding to an average cell voltage slightly above 2.0 V. Individual cell voltages ranged from approximately 1.93 V to 2.34 V, with most cells clustering near the 2.05–2.15 V range, indicating generally stable operation with moderate cell-to-cell variability.

Table 3. Test Results for Stack 0316/44 at 150 A and 50 °C

Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)
1	2.05	12	2.16	23	2.08	34	2.2
2	2.05	13	2.12	24	2.02	35	2.03
3	2.34	14	2.08	25	2.05	36	2.12
4	2.01	15	2.1	26	1.99	37	2.04
5	2.04	16	2.04	27	2.03	38	2.01
6	2.03	17	2.15	28	2.09	39	2.16
7	2.19	18	2.09	29	2.11	40	2.14
8	2.05	19	2.06	30	1.93	41	2.1
9	2.03	20	1.96	31	2.12	42	2.04
10	2.06	21	2.06	32	1.97	43	2.07
11	1.99	22	2.02	33	2.04	44	2.04

The distribution of voltages did not display extreme outliers. However, a few cells demonstrated elevated activation behaviour than the majority, suggesting minor differences in local catalyst activity or gas transport within the coated structure. Gas purity measurements conducted during this test indicated residual oxygen levels of 31 ppm in the hydrogen stream and hydrogen crossover reaching 0.69 % in the oxygen stream.

At the higher load of 300 A and 64 °C, Stack 0316/44 (see Table 4) exhibited an increase in total voltage to 99.3 V, consistent with the expected rise in ohmic and kinetic losses at elevated current density.

Table 4. Test Results for Stack 0316/44 at 300 A and 64 °C

Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)
1	2.27	12	2.31	23	2.18	34	2.28
2	2.28	13	2.28	24	2.23	35	2.23
3	2.44	14	2.3	25	2.22	36	2.3
4	2.25	15	2.25	26	2.18	37	2.21
5	2.25	16	2.34	27	2.19	38	2.15
6	2.31	17	2.34	28	2.26	39	2.27
7	2.22	18	2.26	29	2.29	40	2.26
8	2.2	19	2.18	30	2.09	41	2.23
9	2.28	20	2.33	31	2.26	42	2.22
10	2.18	21	2.26	32	2.1	43	2.23
11	2.32	22	2.34	33	2.22	44	2.22

Cell voltages ranged from roughly 2.09 V to 2.44 V, with a tighter cluster of values near 2.25–2.32 V. The uniformity across the 44 cells remained consistent with the lower-current test, with a few cells again presenting higher voltages that could indicate localized limitations in mass transport or slight variations in coating uniformity. Gas purity values improved marginally with increasing load, with residual oxygen in hydrogen decreasing to 25 ppm and hydrogen crossover registering at 0.75 %, a value consistent with stable membrane behaviour under high-pressure differential conditions.

Stack 0317/44, which incorporated only coated titanium PTLs, demonstrated comparable but distinct performance characteristics. At 150 A and 49 °C (see Table 5), this stack achieved a total voltage of 88.9 V, slightly lower than that of Stack 0316/44 under similar conditions. Individual cell voltages ranged from approximately 1.86 V to 2.10 V, with most readings concentrated between 1.95 and 2.06 V.

Table 5. Test Results for Stack 0317/44 at 150 A and 49 °C

Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)
1	2.09	12	2.0	23	1.91	34	2.04
2	2.06	13	2.0	24	2.03	35	1.98
3	2.1	14	1.95	25	1.99	36	2.09
4	2.1	15	2.03	26	2.03	37	1.96
5	1.98	16	1.96	27	2.05	38	1.86
6	1.98	17	1.99	28	2.09	39	1.97
7	2.04	18	2.02	29	1.95	40	1.99
8	1.97	19	2.06	30	2.06	41	1.97
9	2.06	20	2.06	31	2.1	42	2.0
10	1.99	21	1.92	32	2.03	43	2.03
11	2.01	22	1.93	33	2.02	44	2.07

This distribution exhibited somewhat lower overall values and tighter clustering than the first stack, suggesting that the configuration incorporating only coated PTLs displayed marginally reduced resistive and activation losses. Gas analysis during this stage revealed 14 ppm residual oxygen in hydrogen and 0.64 % hydrogen crossover, both indicative of effective membrane integrity and proper gas-separation function under 15-bar pressure.

At 300 A and 63 °C, Stack 0317/44 (see Table 6) reached a total voltage of 102.8 V, which was slightly higher than Stack 0316/44 under equivalent conditions. Individual cell voltages ranged from 2.11 V to 2.37 V, with a clear majority falling within the interval of 2.20–2.33 V.

Table 6. Test results for Stack 0317/44 at 300 A and 63 °C

Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)	Cell No.	Cell Voltage (V)
1	2.34	12	2.34	23	2.35	34	2.21
2	2.25	13	2.33	24	2.35	35	2.21
3	2.25	14	2.22	25	2.31	36	2.36
4	2.38	15	2.24	26	2.25	37	2.37
5	2.28	16	2.29	27	2.18	38	2.11
6	2.24	17	2.33	28	2.33	39	2.26
7	2.26	18	2.31	29	2.33	40	2.22
8	2.19	19	2.35	30	2.26	41	2.2
9	2.28	20	2.32	31	2.26	42	2.18
10	2.36	21	2.18	32	2.35	43	2.16
11	2.26	22	2.24	33	2.28	44	2.17

The increased spread at this current density suggested a rise in cell-to-cell performance divergence, potentially reflecting localized kinetic limitations or progressive uneven utilisation of coated PTLs under high load. Gas purity measurements indicated 21 ppm residual oxygen in the hydrogen stream and 0.70 % hydrogen in the oxygen stream, values comparable to those measured in the first stack and well within acceptable operational boundaries.

Following independent testing, both stacks were integrated into the SIRIO 1000 electrolyser system and evaluated together under identical conditions. After 20 hours of co-operation at 200 A, the current was increased to 300 A while maintaining a system temperature of 57 °C. Under this integrated configuration, Stack 0316/44 exhibited a total voltage of 106.0 V, with cell voltages ranging from approximately 2.25 V to 2.52 V. The distribution revealed several cells trending above 2.45 V, indicating increased activation or mass transport stresses under shared system operation compared to isolated testing. Stack 0317/44, under the same conditions, showed a total voltage of 104.0 V, with most cell voltages falling between 2.29 V and 2.49 V. While generally comparable to its partner stack, a subset of cells displayed elevated values above 2.45 V, suggesting similar patterns of stress distribution within the combined electrolyser configuration.

During this joint operation, the average power consumption of the two-stack system was calculated as 5.75 kW per normalized cubic meter of hydrogen, representing a 10–20 % increase relative to the manufacturer's standard PEM stacks operated under similar load and pressure conditions. Despite the elevated power consumption, gas purity and crossover remained stable. As seen in Fig. 2, measurements consistently show hydrogen-in-oxygen crossover below 0.7 % across all tested current densities and a pressure of 15 bar. Graphical data confirmed that crossover values followed predictable trends with no anomalous behaviour attributable to the coated components.

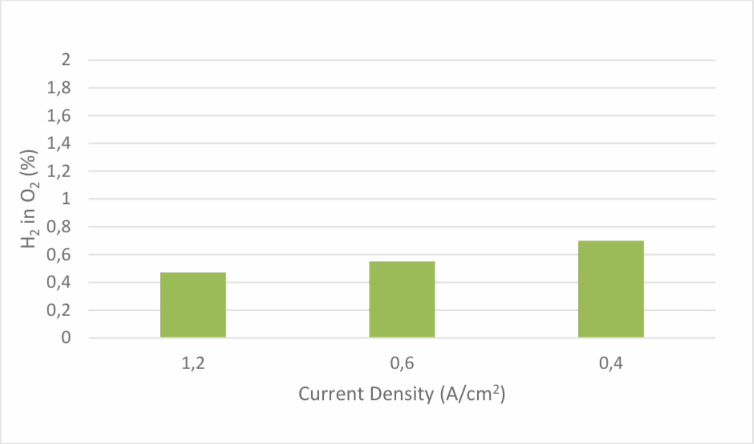

Fig. 2. Hydrogen-in-oxygen crossover across all tested current densities (15 bar).

When the current was reduced back to 150 A while maintaining 57 °C, both stacks showed expected decreases in total voltage, with Stack 0316/44 measuring 90 V and Stack 0317/44 measuring 89 V. Individual cell voltages exhibited narrower distributions compared to the 300 A test, indicating improved uniformity and reduced electrochemical stress at lower load. Gas purity remained within the same operational envelope, and no sudden deviations or instabilities were observed during the transition between load levels.

The results demonstrate that both coated-stack configurations operate reliably under high-pressure, industrially relevant conditions, with stable gas purity and acceptable levels of voltage uniformity. Differences between the two stacks were observable in total voltage, cell voltage distribution, and minor variations in gas purity, yet both configurations maintained performance consistent with expectations for PEM electrolyser systems operating at 0.6–1.2 A cm^{-2}. The data indicate that while the coated components function effectively, system-wide power efficiency requires optimisation to fully align with the performance of established industrial stacks.

4. CONCLUSIONS

1. Both PEM stacks incorporating Nano-coated titanium components demonstrated stable operation under industrially relevant conditions, including 15-bar pressure and current densities up to 1.2 A cm^{-2}.
2. Stack 0316/44 (coated PTLs + coated bipolar plates) and Stack 0317/44 (coated PTLs only) both passed internal and external leak tests, confirming the mechanical integrity of the coated components.

3. At 150 A, both stacks showed comparable performance, with total voltages of 89.8 V for 0316/44 and 88.9 V for 0317/44, indicating that the presence or absence of coated bipolar plates did not significantly alter low-current efficiency.
4. At 300 A, the two stacks exhibited distinct behaviour, with Stack 0316/44 reaching 99.3 V and Stack 0317/44 reaching 102.8 V, implying differences in ohmic resistance or kinetic losses between the two coating configurations.
5. Cell-to-cell voltage distributions remained within acceptable ranges for all tests, although some cells showed slightly elevated voltages, suggesting localized variations in coating performance or gas transport.
6. Gas purity measurements remained within safe and expected limits, with residual O_2 in H_2 between 14–31 ppm and H_2 in O_2 consistently below 0.7 %, indicating that the coated components did not negatively impact gas separation or membrane integrity.
7. During integrated operation within the SIRIO 1000 electrolyser system, both stacks functioned reliably, producing stable voltages of 106.0 V (0316/44) and 104.0 V (0317/44) at 300 A.
8. Average power consumption of 5.75 kW/Nm³ was observed during joint operation, representing a 10–20 % increase compared to the manufacturer's standard industrial PEM stacks.
9. The elevated power consumption suggests that the coated component configurations require further optimisation to reach or surpass the efficiency of established commercial stack designs.
10. Hydrogen crossover behaviour remained stable and predictable across all current densities, with no abnormal increases detected that could compromise operational safety.
11. Lower current operation (150 A inside the SIRIO 1000) produced improved cell-voltage uniformity, confirming that electrochemical stresses at higher loads contributed to performance divergence.
12. The study validated that Nano-coated PTLs and bipolar plates could operate safely under high-pressure, high-current PEM electrolyser conditions, supporting their feasibility for industrial systems.
13. However, the performance differences between the two stacks indicate that the coating configuration, whether applied only to PTLs or to both PTLs and bipolar plates, significantly affects overall efficiency.
14. Short-term testing confirmed functional reliability, but long-term durability remained unknown, as the study covered only 40 hours of individual testing and 20 hours of integrated system operation.
15. Further investigations are required to evaluate coating stability, degradation rates, and lifetime performance, particularly under prolonged dynamic or stress-cycling scenarios.
16. The results contribute valuable empirical data for the development of advanced corrosion-resistant coatings in PEM electrolyser stacks, illustrating their strengths while identifying areas for improvement.

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