BRAMBLE ENERGY

BEIS Net Zero Innovation Portfolio
Low Carbon Hydrogen Supply 2 Competition
Stream 1 Phase 1

HYS2159: Printed Circuit Board Electrolyser

Final Feasibility Report

5th October 2022

Executive Summary

Over several decades and billions of dollars of investment, the electronics industry has designed and optimised the manufacturing processes for printed circuit boards (PCBs). PCBs are now produced globally at a scale estimated to be c.20 billion m^2 PCBs per year using an optimised, precise and low-cost manufacturing process.

Bramble Energy is developing an electrolyser based on a PCB bipolar plate. Manufacturing electrolysers using PCBs as a platform offers significant cost reduction and manufacturing scale-up advantages compared to conventional electrolyser manufacturing techniques. Both cost reduction and manufacturing scale-up are crucial to deploying electrolysers at pace and at scale.

Within the Printed Circuit Board Electrolyser (PCBEL) project, Bramble Energy has undertaken an experimental development programme to prove the feasibility of printed circuit board (PCB) materials as a substitute for metallic bipolar plates within Anion Exchange Membrane (AEM) electrolyser stacks.

The experimental programme within the PCBEL project has included:

- The assessment of different catalyst, membrane and coating materials within an AEM electrolyser cell.
- The design, assembly and testing of 2x1 kW electrolyser stacks based on a 25cm^2 and 100cm^2 PCB cell design.
- Testing of a PCB electrolyser cell to 30 bar maximum pressure and operation to 10 bar pressure
- 1,000 hours cumulative testing of PCB materials within AEM electrolyser cell
- Simulation and modelling of cell design to support scale-up of a larger electrolyser system

This project has technically proven the feasibility of using PCB materials in AEM electrolyser cells and scaled and demonstrated this with 1 kW electrolyser stacks. The PCBEL design philosophy is to use PCB manufacturing routes to reduce production costs. The PCBEL will leverage the already established manufacturing facilities for PCBs from the electronics industry, with a typical PCB factory having capacity to produce 3 GW electrolyser modules per year. The PCBEL technology offers a low-cost, accelerated scale-up roadmap for AEM electrolysers. The PCBEL project strengthens the development base in the UK for AEM electrolysers, which will be crucial to producing green hydrogen at the cost and scale needed for the 2050 Net Zero pathway.

Following the feasibility project further development and testing is planned. Alongside the development of AEM membranes and catalysts, a particular focus to demonstrate the lifespan of these materials for commercial operation is required. In this report, a high-level plan is proposed for a follow-on project to further develop and demonstrate the technology and the UK supply chain for membranes, catalysts and electrolyser cells and stacks.

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Glossary

AEM	Anion Exchange Membrane
AST	Accelerated Stress Testing
BEIS	Department for Business, Energy and Industrial Strategy
BoP	Balance of Plant
CCM	Catalyst Coated Membrane
CFD	Computational Fluid Dynamics
CRM	Critical Raw Material
DI	De-ionised
HYS2	Low Carbon Hydrogen Supply 2 Competition
KOH	Potassium hydroxide
MEA	Membrane Electrode Assembly
PCB	Printed Circuit Board
PCBEL	Printed Circuit Board Electrolyser
PEM	Proton Exchange Membrane
PGM	Platinum Group Metal
QC	Quality Control
RES	Renewable Energy Sources
SS	Stainless Steel
TBC	To be Confirmed
TRL	Technology Readiness Level
WP	Work Package

1. Introduction

This report is the final report for the Printed Circuit Board Electrolyser (PCBEL) project. The PCBEL project is a 9-month feasibility project carried out by Bramble Energy from January to October 2022 and is funded by the Department for Business, Energy and Industrial Strategy (BEIS) through the £1bn Net Zero Innovation Portfolio's (NZIP's) Low Carbon Hydrogen Supply 2 competition Stream 1 Phase 1 programme (HYS2 Stream 1 Phase 1).

The PCBEL project's aim is to demonstrate the feasibility and potential for a printed circuit board (PCB) electrolyser based on anion exchange membrane (AEM) electrolyser technology. The PCBEL project builds on technology that Bramble has developed around proton exchange membrane (PEM) fuel cells. This leverages manufacturing processes from the PCB industry to reduce the cost and increase the scale of fuel cell / electrolyser production.

This final report provides an overview of the project, including technical aspects of the work completed and plans for further demonstration of the technology, the next steps and route-to-market.

2. Overview of the project

Prior to this project very little work had been undertaken to evaluate the feasibility of using printed circuit boards (PCBs) as a platform to design and manufacture electrolyser stacks. Bramble had previously completed a degree of experimental testing across PEM, alkaline and AEM electrolysis stacks, although minimal experimental work had been carried out on different AEM electrolyser cell designs, operating parameters and long-term testing of PCB materials.

For the first time, this project has conducted a range of experiments to prove the feasibility of PCB as a substitute for metallic bipolar plates within AEM electrolyser stacks. Should PCBs be proven successful as a material for AEM electrolysers there are considerable cost and scale-up advantages to manufacturing electrolysers by leveraging existing production processes already established and optimised over decades by the electronics industry.

Bramble's PCB electrolyser design includes an anion exchange membrane and catalysts enclosed within PCB plates, as illustrated by Figure 2.1 on the following page. The PCB will be designed with fluid flow channels which can be manufactured using existing PCB production processes, enabling for quick design iteration to test different flow field configurations.

Within this project Bramble has developed PCB electrolyser stack prototypes and designed the electrolysis system to be scaled-up and integrated with renewable energy sources, including wind turbine generators to generate zero carbon hydrogen.

The following objectives have successfully been completed as part of the feasibility project:

- Design and build 2 x 1 kW Anion Exchange Membrane (AEM) PCBEL prototype stacks.
- Demonstrate operation for >1,000 hours of a AEM PCBEL at 2 V.
- Demonstrate pressurised electrolyser operation at 10 bar.
- Computationally model the fluid flows in a 1 kW AEM PCBEL cell.
- Design a 500 kW electrolyser stack for phase 2 demonstration project.

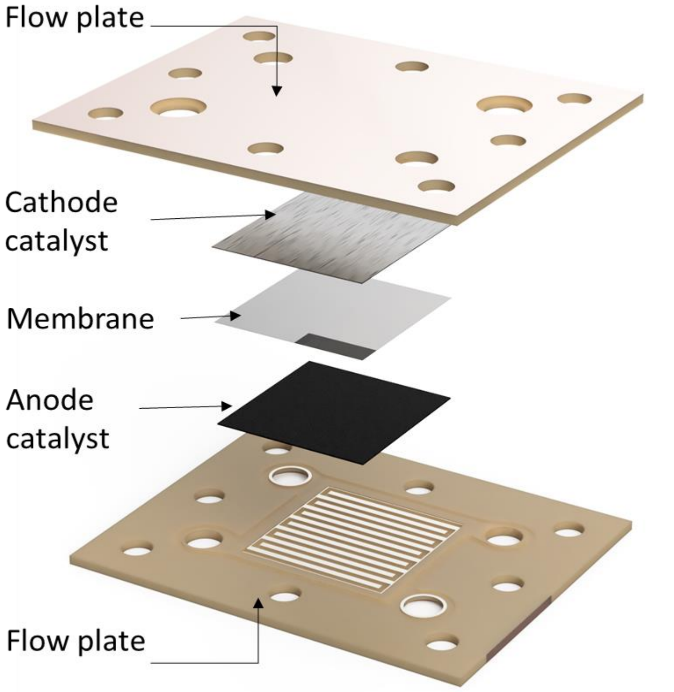

Figure 2.1: Exploded schematic of a PCBEL cell

These objectives were completed within the project, with further details in section 3. The PCBEL Phase 1 project included the following five technical work packages:

WP1 Long term testing: Included testing of different membranes and catalysts in the laboratory. This knowledge will determine the selection of materials for long-term tests. Further, the effectiveness of PCB corrosion coatings were examined.

WP2 Pressurised electrolyser operation: In WP2 Bramble completed testing of pressurised PCB electrolysers, this validated the performance of PCB materials under elevated pressures and informed the design of the electrolyser system.

WP3 Stack development: In WP3 Bramble designed, built and tested 2 x 1 kW PCB-based AEM electrolyser stacks for laboratory testing. The design of the stack was carried out in parallel to the testing of the AEM membrane, which was incorporated into the 1 kW stacks to compare performance between individual modules and the 'short stack'.

WP4 Modelling and design: Bramble performed computational fluid dynamics (CFD) modelling of AEM cell and stack designs to validate experimental testing in WP1 and WP3. This modelling tool was then used to simulate the design on a 500 kW PCB-based AEM electrolyser system.

WP5 Dissemination and commercialisation: Dissemination of project outputs was conducted by Bramble in WP5, alongside the development of a plan to commercialise the next stage of development towards the detailed design of the 500 kW PCBEL AEM system as pilot plant demonstrator.

3. Experimental results and conclusions

3.1 WP1 Long term testing

The primary goal of the PCBEL project was to assess the ability of PCB materials to be utilised in anion exchange membrane based electrolysers, which operate under mildly alkaline conditions. As discussed above, the project was divided into various work packages validating different areas of electrolyser operation.

Work package one focused on determining the suitability of various materials for use in alkaline electrolyser environments. This work package covered a number of core topics from understanding the commercially available AEM materials, the suitability of PCB materials and demonstrating longer term electrolyser cell operation.

Prototype structural electrolyser components were produced in house at Bramble; including stainless steel end plates that were produced to apply cell compression and allow gas/fluid connections, along with current collectors and seals. PCB plates were manufactured by a third party commercial PCB manufacturer, using standard PCB manufacturing techniques which could be translated to any PCB facility worldwide. Figure 3.1 shows an example of a prototype PCB electrolyser cell tested as part of this project.

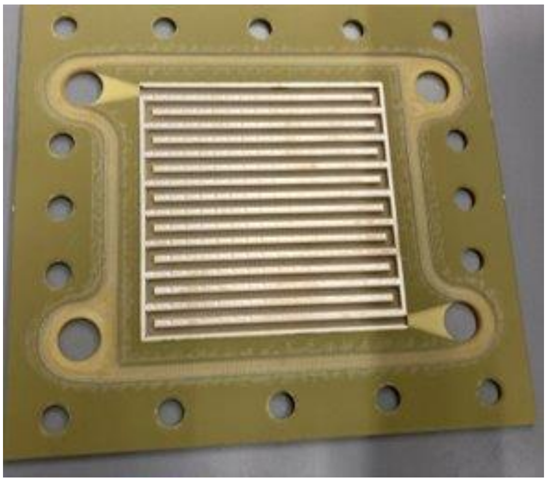

Figure 3.1: Example of a PCB based electrolyser plate

Electrolyser cells were assembled with commercially available membranes and catalyst materials. Using a bespoke test rig and a potentiostat the performance of different materials was characterised for PCB based AEM systems (see Figure 3.2). Overall, performance was found to be similar to the literature reports for equivalent materials such as that reported on the material suppliers websites and Lee et al., 2022[1]. Although, improvements in cell design are expected to allow optimal performance to be achieved.

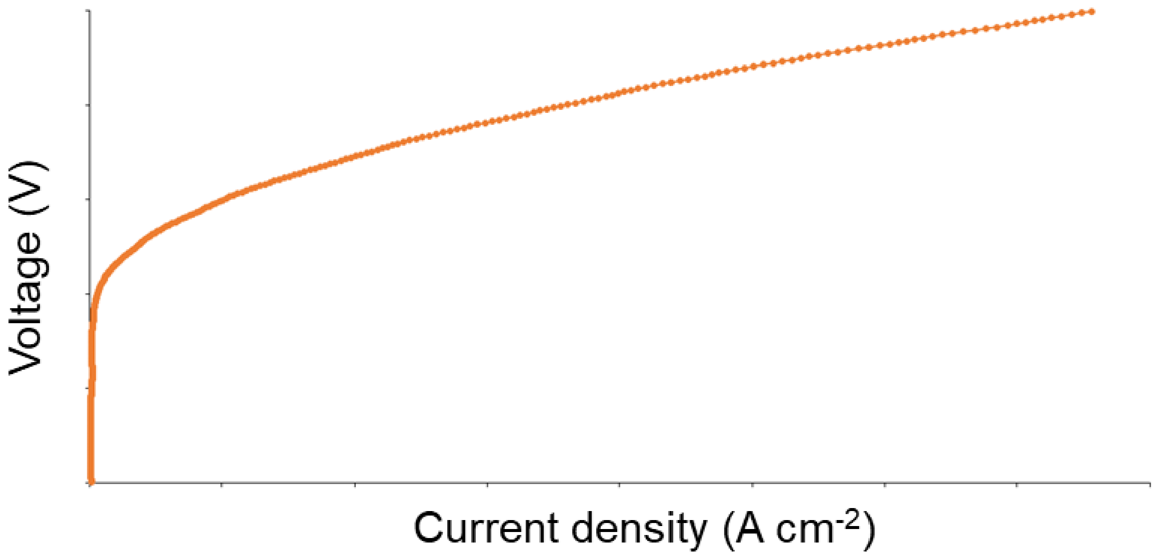

Figure 3.2: Example polar curve of PCB based AEM cell

Although the initial optimally performing materials proved difficult to purchase during the short span of the project, alternative AEM materials were identified and found to achieve the targeted performance. This highlighted the growth of the AEM supply chain, with a number of more established companies starting to provide state of the art materials. After the initial PCB and AEM material evaluation phase, a favoured membrane and catalyst materials were selected as a basis for further testing. Discussions with other material suppliers were continued and designs were made so as to allow "drop in" replacement for as many of the possible commercial materials as possible.

Alongside this work, corrosion testing was performed to understand the effect of coatings in alkaline electrolysis. Based on the Pourbaix diagram for copper (such as that in Celante et al, 2009[2]) and initial testing of corrosion of copper PCB samples, it was clear that a coating is required to protect the copper PCB from the chemical environment.

Nickel is widely used in alkaline environments and in alkaline electrolysers in particular. Additionally, Nickel based coatings on copper are widely used in PCB processes in facilities across the world. As such, Nickel based coatings were

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[1] Lee, S.A, Kim., J., Chang, K.C., Park, S.H., Jang, H.W., 2022; "Anion exchange membrane water electrolysis for sustainable large-scale hydrogen production", Carbon Neutralization; **https://doi.org/10.1002/cnl2.9**

[2] Celante, et al., 2009 Vinicius & Freitas, M.B.J.G. (2009). Electrodeposition of copper from spent Li-ion batteries by electrochemical quartz crystal microbalance and impedance spectroscopy techniques. Journal of Applied Electrochemistry.

evaluated for use in AEM type systems. Sample PCB tabs were prepared with Nickel based coatings (see Figure 3.3) produced via standard PCB type processes.

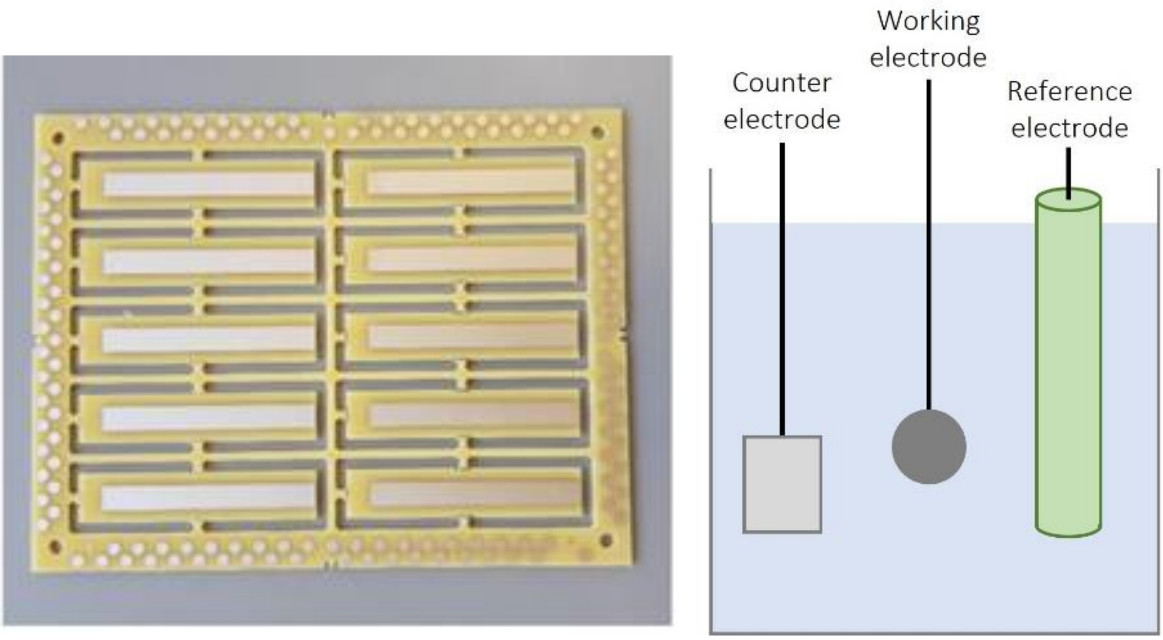


Figure 3.3: Ni coated PCB copper tabs (left); 3-electrode cell (right)

Corrosion testing was performed on these tabs using three electrode set ups in high concentration KOH at elevated temperatures. Potentials for corrosion testing were selected based on the operating position of the anode and cathode of AEM electrolysers. Conditions were selected to accelerate degradation of the coatings whilst aiming to replicate expected degradation processes and mechanisms. Low corrosion currents were observed for Nickel coated samples, indicating many of the Nickel based coatings are suitable for use in AEM electrolysers.

Further to these Nickel based coatings, WP 1.2 also evaluated alternative coatings. These included other standard PCB coatings, along with coatings that were developed in-house that could be applied using standard PCB application processes. Generally, Nickel based coatings showed the best performance and work is on-going to fully understand the optimal materials for the lifetime of PCB based electrolysers.

Further testing of PCB based electrolyser cells was performed for extended periods of time, the aim of this was to confirm that the PCB did not degrade. Initial long-term testing was not found to be as reliable as predicted. Due to the harsh alkaline chemical environment coupled with the elevated temperature, a number of fittings, fixture and pumps showed relatively rapid and significant failures, which prevented consistent testing of the cell. However, these early issues were found to be a result of system and design issues rather than inherent PCB or AEM issues. As such, this proof of principle facilitated for further work on the project to continue.

From the results of the previous work package, along with design improvements from other work packages, additional long-term testing was conducted to further understand PCB based electrolysers. A more advanced cell design was used including flow disruptors to aid electrolyte and gas transport inside the cells.

Multiple extended tests of up to 500 hours were performed, evaluating the changes in performance over time. Different cell materials were evaluated including PCB components with nickel based coatings, it was found that although degradation was higher than hoped the majority of issues were the result of short-term reversible issues or failures of “off-the-shelf” equipment and / or materials selected due to lead times. Repeated testing of PCB materials strongly indicated it’s potential for extended PCB electrolyser operation.

Overall, the outcomes of WP1 provided a selection of commercial materials (membrane and catalysts) that are compatible with PCB AEM electrolysers whilst also showing that the PCB materials are suitable for use in electrolysers.

3.2 WP2 Pressurised electrolyser operation

Within work package two, work focused on ensuring that PCB based electrolysers can operate successfully at elevated pressures. Many commercial PEM and AEM electrolysers operate at up to 30 bar. As such, we focused on understanding the ability of PCB based electrolysers to withstand elevated pressures and the impact on PCB electrolyser performance. A number of academic research groups are investigating electrolyser operation at higher pressures, however for applications like automotive refuelling a target pressure of up to 1,000 bar is desirable which is outside the target of this project.

PCB based cells were assembled and hydraulically tested to failure, however it was found that 30 bar equipment limits were reached prior to failure of the PCB based cells. These initial tests were performed with equal pressures across the membrane, which is not Bramble’s preferred method for operation of the electrolyser at these output pressures, due to stresses on the membrane and impact on lifespan. Operating with differential pressure, gave some different results. Initially, failures were observed, including failure of the membrane. However, slight changes to the cell design provided support for the weak points allowing higher differential pressures across the membrane to be maintained.

After hydraulic testing proved the suitability of PCB based electrolysers to operate at elevated pressures, a test rig was designed and constructed that allowed electrolyser testing at elevated pressures. PCB based electrolysers were evaluated at different pressures to understand the impact of pressure on performance and ensure that hydraulic testing translated to operational stability.

Figure 3.4 displays an image and a schematic of a test rig set up for small cell testing of PCB electrolyser cells.

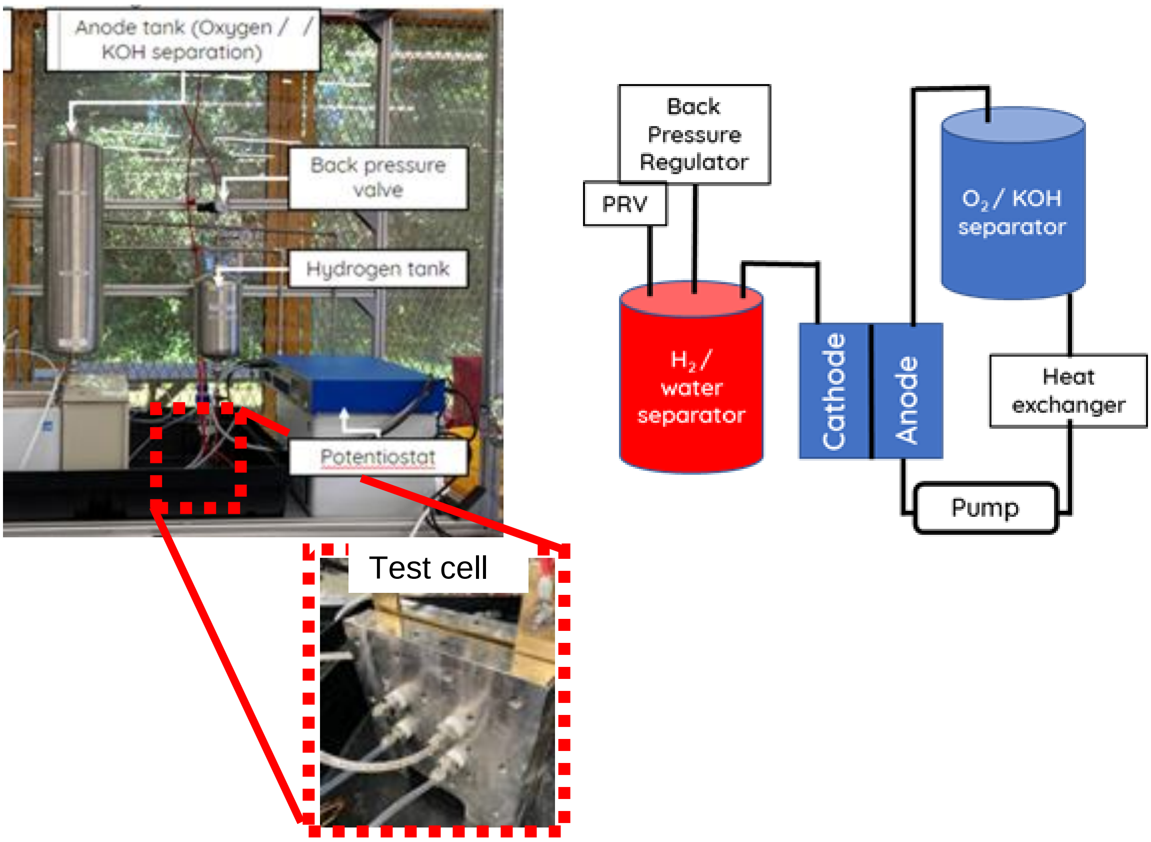


Figure 3.4: Test rig for pressurised operation

Figure 3.5 shows initial performance data from testing of a PCB based electrolyser after pressurisation with nitrogen gas.

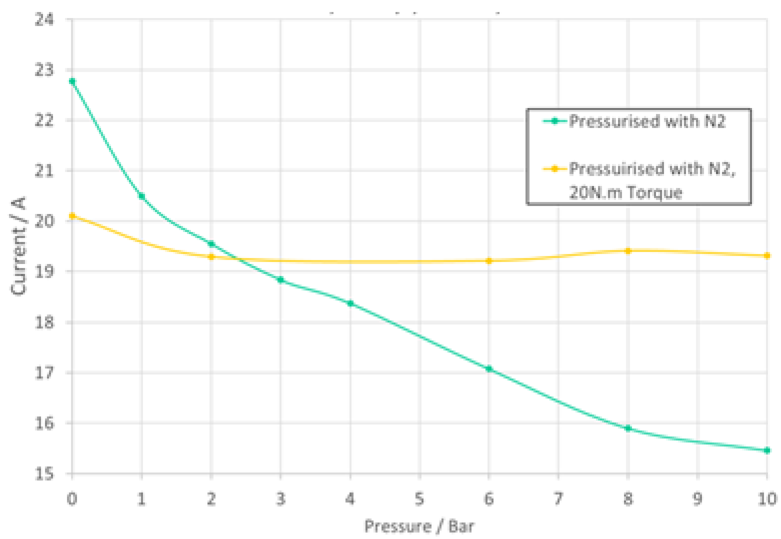


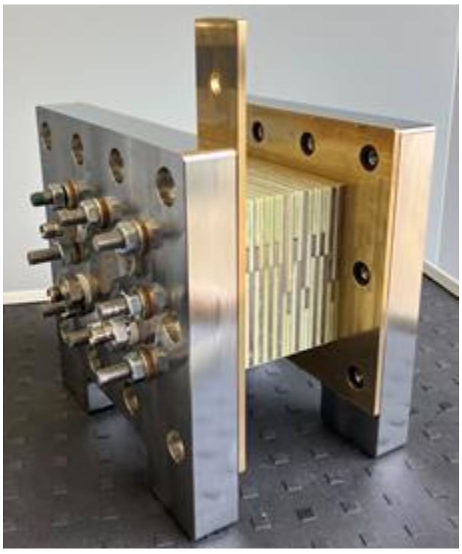
Figure 3.5: Effects on performance for a PCBEL at elevated pressure, with/without increased cell compression torque

Initially, it was found that a significant drop in performance was observed up to 10 bar. However, it was found that this was a result of mechanical loosening of the bolts holding the cell together. After increasing the bolt torque, performance was found to be very constant. Incorporation of suitable constant compression has thus been highlighted for future higher pressure operation. These results show that PCB based electrolysers can work at elevated pressure, and appear to work in a similar way to traditional electrolysers materials. Further work will be conducted to fully understand the operational limits of PCB materials.

Based on these results an investigation of alternative methods for operating electrolysers at elevated pressures was investigated. Briefly, it was found that a number of different techniques are utilised for operating at higher pressures and reducing differential pressures. From the observed methods, none seemed preferable for PCB based electrolysers compared to alternative (metallic) bipolar plate materials. As such, it was concluded that the differential pressurisation approach was most likely the ideal route for PCB based AEM electrolysers particularly for shorter term exploitation.

3.3 WP3 Stack development

Work package three took the results of work packages one and two and incorporated these results into electrolyser short stacks using two different cell designs. Initial testing was performed to optimise the performance of the electrolyser single cells, this involved evaluating the operation conditions (temperature, KOH concentration, etc) on the performance of a single cell. Multiple cell stacks were then built and tested up to the > 1 kW target, this was performed for 25 and 100 cm^2 active area cells. Figure 3.6 shows the two different 1 kW electrolyser short stacks built and tested within this project.



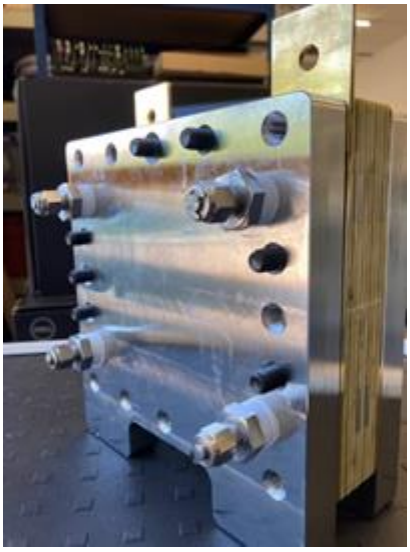


Figure 3.6: Image of 1 kW stacks with 25 and 100 cm^2 PCBEL cells, left and right respectively

Generally, the variation in cell performance was low, although some cells showed poorer performance which was found to be mainly due to a resistance issue. The purpose of testing stacks with two different cell sizes (25 cm^2 and 100 cm^2) was to understand the impact of stacking and larger active areas, as both approaches will be needed when scaling-up. The smaller active area stack (25 cm^2) allowed a higher number of cells whilst maintaining the total power at a level that could be readily tested with our current equipment.

Both short stacks (25 cm^2 and 100 cm^2) were found to perform in a similar way to the single cells, although operation at higher pressures will require improvement in the stack compression methods. The longer stacks need further optimisation to ensure consistent performance. Whilst these relatively small area short stacks are useful for building an understanding of performance, the limited hydrogen production per cell would necessitate stacks to have a large number of cells. As such, future designs will focus on electrolysers with larger cell areas and increasing stack sizes.

3.4 WP4 Modelling and design

Alongside the experimental work to validate PCB based electrolysers, work package four was focused on using computational modelling to improve and optimise the cell and stack designs. Computational fluid dynamics (CFD) was utilised to examine the water and gas transport properties through cells with different designs and dimensions, with an early example shown in Figure 3.7(a). Subsequently, this was extended into modelling of stacks, also shown in Figure 3.7(b).

Modelling of single cells showed that optimising the flow path from a square pattern to one which has more rounding features, gave better flow distribution with less areas for gas to get trapped. Alternate designs with different flow distribution methods were also investigated for future design iterations. Combining results from the experimental tests with modelling of single cells allowed designs for larger cells and stacks to be produced. The modelling was used to ensure that there was suitable distribution of water through a large stack at the required flow rates and that the pressure drops would be suitable for available pumps. This large stack modelling was used for designing components for the larger 100+ kW electrolyser systems. A bespoke modelling tool was developed that allowed for pressure drops, flow distribution and other parameters to be understood without the direct need for development and testing.

Figure 3.7 (a): CFD modelling of single cell

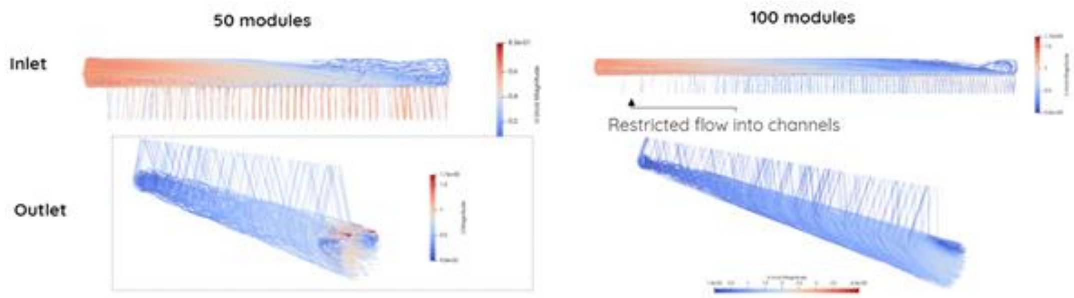


Figure 3.7 (b): CFD modelling of PCB AEM electrolyser stack

Figure 3.7: CFD modelling of single cell and stack of PCB AEM electrolyser

Finally, alongside this experimental work, WP 4.2 focused on the system requirements of a larger electrolyser system. Based on the experimental result of the short stack and modelling data for larger stacks, system components were specified from available options. Figure 3.8 shows a schematic of the system with key components. Suppliers for all critical components have been established, with requirements on both sides discussed and plans for full system compatibility outlined. The system design utilises one pump and one cooler for multiple stacks (e.g. 4 stacks of 125 kW). This simplifies the balance of plant (BoP) and can reduce cost by 10-15% (e.g. single bespoke BoP vs 4 times the same BoP).

The PCBEL electrolyser stack operation has been proven at 10 bar, however, based on state-of-the-art commercial electrolyser systems a target of 30-35 bar looks to be optimal. From the experimental results completed so far, there is no suggestion this would not be possible for PCBEL electrolyser. We expect the demonstration system to operate at a temperature 50 - 60°C, typical for AEM electrolysers.

Further work for complete validation of the system is still required, however, from this project the feasibility of a PCB based AEM electrolyser stack has been demonstrated at small scale. The potential of this technology has been proven, overcoming a number of areas of potential issues. Whilst substantial experimental and system development work is required for an operational electrolyser system, the initial hurdles have been overcome, the technology has been de-risked and areas to focus on further development and scale-up have been highlighted.

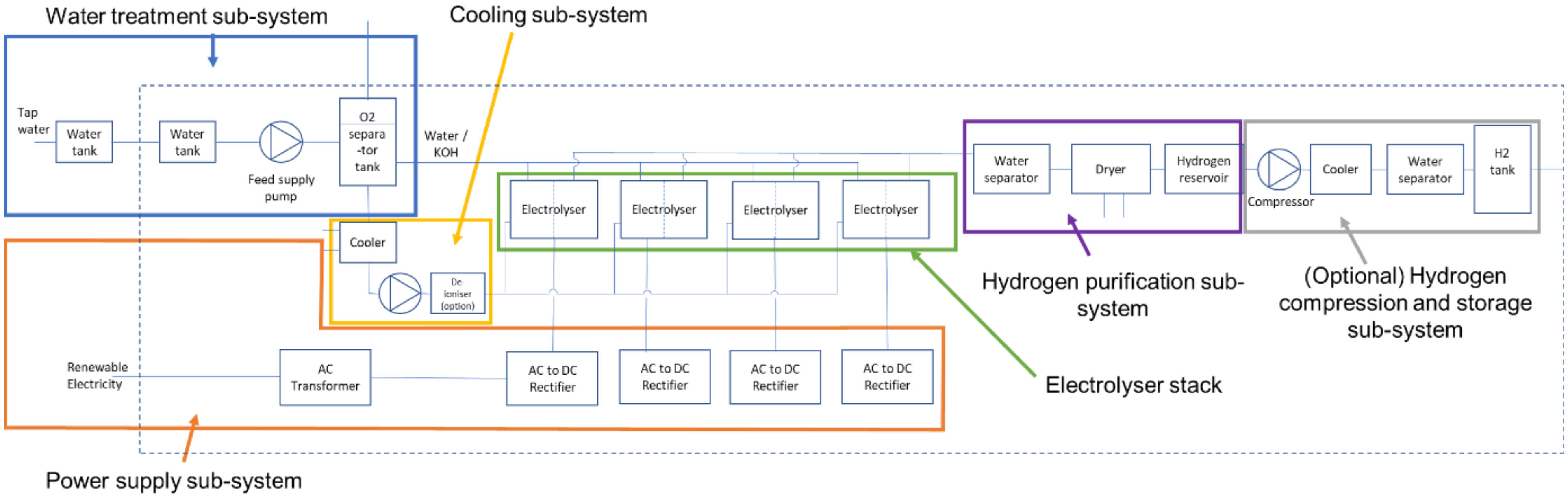


Figure 3.8: Schematic of a PCB based AEM electrolyser system

4. Description of the demonstration project

The phase 1 project presented in sections 2 and 3 has proven the feasibility of the printed circuit board electrolyser. The next stage is to further develop and scale-up the technology for a demonstration in a real-world environment. The demonstration project outlined here is a plan for a follow-on to the feasibility project and is focused on the wider development of the AEM electrolyser technology, which is important to develop the technology and accelerate the deployment of a commercial system.

4.1 Demonstration project work streams

As opposed to simply scaling-up the AEM electrolyser stack, the development of a commercial AEM electrolyser system requires further development across the membranes, catalysts, cell and stack design. The demonstration project has been divided into separate work packages, as outlined below. These could all be standalone development programmes or projects in their own right, and these are all crucial in establishing AEM technology. Figure 4.1 provides a high-level timeline overview of these technology workstreams and how they integrate together to deliver the demonstration electrolyser system.

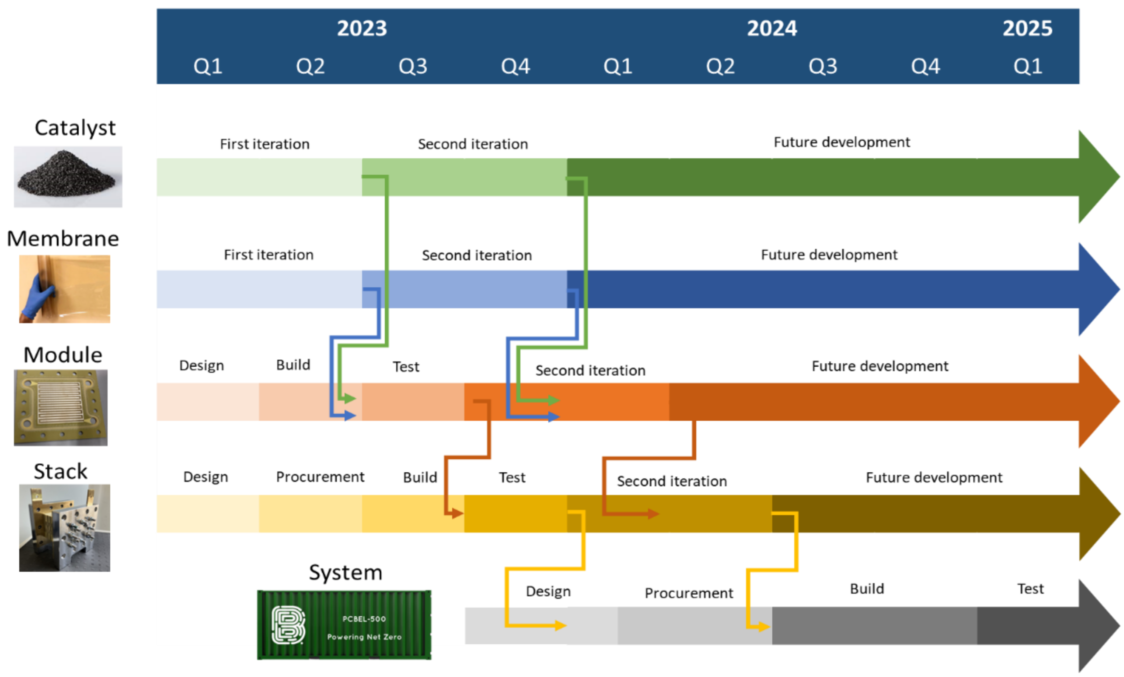


Figure 4.1: Overview of HYS2 Phase 2 technology roadmaps across different electrolyser components, all of which are critical for a commercially viable AEM electrolyser

This proposed project also focuses on a strategic development of the UK AEM supply chain, with a demonstration focused on providing a test bed from the Phase 2 project and platform for larger electrolyser stacks and systems to be manufactured in the UK. This collaborative approach with the supply chain will enable Bramble to progress its electrolyser technology from TRL 4 through successive demonstration steps to a higher power rated stack, supported by performance and durability developments from the electrolyser materials. This will be showcased in a prototype demonstration in a relevant environment (TRL 7), which will be used as a test bed beyond the demonstration project to trial different control strategies and AEM electrolyser materials, accelerating commercialisation of UK-based AEM electrolyser development.

Demonstration of a higher TRL will involve investigation into the following areas:

4.1.1. Membranes

The development of membranes is key to the performance and commercial readiness of AEM electrolysers. The overall goal of this work stream is to develop membranes which will maintain performance (high electrical resistance, low ionic resistance) at lower concentration of alkaline solution (potassium hydroxide, KOH) and ultimately de-ionised (DI) water. Current AEM electrolyser systems are estimated to have lifespan of c.11,000 hours as opposed to c.80,000 hours for alkaline electrolysers[3]. Therefore, ensuring membranes are mechanically, thermally and chemically stable for commercial lifespans of electrolyser (target >30,000 hours or 0.3%/1,000 hours) is of critical importance to the commercial viability of AEM electrolysers.

Performance characterisation and accelerated stress testing (AST) with thermal cycling and long-term testing of single cell experiments will need to be conducted to assess the membranes and catalysts with >10,000 hours of testing planned.

4.1.2. Electrocatalysts

The aim of the electrocatalysts work package is to develop PGM (Platinum Group Metal)-free catalysts, these can also be defined as Critical Raw Material (CRM)-free materials, with a target from the Clean Hydrogen Partnership of 0.4 mg/W for AEM by 2024 as opposed to PEM which is currently c.2.5 mg/W and has target of 1.25 mg/W by 2024[4].

Anode catalysts assessed will based on Ni-Fe materials, and cathode catalysts based on Ni, Ni-Cu, NiCuMo and NiMo. The performance and durability of these catalyst materials will be analysed at different loading rates in comparison with Pt/C reference electrode. In addition to the catalyst material the manufacturing method will also be optimised to apply these catalysts to the membrane, for the manufacture of the catalyst coated membrane (CCM). This manufacturing process will be designed to protect the membrane, which has a temperature / humidity sensitivity.

[3] Lifespan based on 10% reduction in electrolyser efficiency, with alkaline electrolyser based on 0.125%/1,000 hours and AEM electrolyser based on 0.9%/1,000 hours from Clean Hydrogen Partnership Strategic Research and Innovation Agenda, 2021, https://www.clean-hydrogen.europa.eu/system/files/2022-02/Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf

[4] Clean Hydrogen Partnership Strategic Research and Innovation Agenda, 2021, https://www.clean-hydrogen.europa.eu/system/files/2022-02/Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf

4.1.3. Electrolyser cell development

The single cell design will be developed based on printed circuit board (PCB) module with Ni electroplating and produced using conventional PCB manufacturing processes. The performance of the cell will be assessed against conventional stainless steel and Ni coated bipolar plates. The module design will be developed, supported by simulations using computational fluid dynamics (CFD) analysis and the 100cm^2 design from feasibility project will be scaled up to 500 cm^2 and 1,200 cm^2 active areas.

The cell design will review the product gas removal during operation of larger cell areas. This will optimise the cell design to avoid the formation of gas entrapments and the ensuing crossover of gas through the separator and pressure drop. This analysis will also specify the requirements for the pumps needed in the electrolyser system.

Another advantage of the printed circuit board approach is the ability to separate conductive components within the electrolyser cell. This is unique to the Bramble approach using PCBs, and allows for multiple electrodes to be incorporated within a single cell. This has the advantage that membranes within a cell can be linked in series to operate at a higher voltage. The benefit of this is that the design of the power electronics can be simplified with the electrolyser operating at a higher voltage (and lower current), with lower cost power electronics and improved efficiency with power conversion. The design of the higher voltage electrolyser cell will be supported with electrolyser system requirements for direct connection to wind turbine and electricity grid.

4.1.4. Electrolyser stack development

Electrolyser stacks will be developed to demonstrate an electrolyser stack with capacity to produce c.12 kg H_2/day based on the 500 cm^2 cell design. This electrolyser stack design will be scalable to c.60 kg H_2/day, based on the same electrolyser cell design with multiple cells per stack. Multiple electrolyser stacks could then be included in a system, for instance 4 stacks would provide c.240 kg H_2/day.

A longer-term scale-up of the electrolyser stack will be a c.1,200 cm^2 cell with 125 cells per stack, with a 300 kW stack design.

Both c.1,200 cm^2 and c.500 cm^2 cell designs will be demonstrated as short-stacks within the demonstration project. These will be tested at Bramble's electrolyser testing facility and incorporated into the electrolyser test bed system which will be the standalone system demonstration and electrolyser test bed developed through the project.

4.1.5. Electrolyser system development

The electrolyser system is proposed to be developed as a standalone electrolyser to be installed at a demonstration site to act as a test bed and system demonstrator for AEM electrolysers. The electrolyser system will be installed in a 40' shipping container and connected to the grid / renewable energy generation source and water supply. The electrolyser system will include power electronics, water treatment, hydrogen purification, compression and storage. The electrolyser system will be sized to accommodate multiple and larger stacks for future testing.

The electrolyser stack will be manufactured by Bramble and Bramble's suppliers, assembled and tested at Bramble's facilities in Crawley. The electrolyser, either through a direct connection (or simulated connection) to an onshore wind turbine, will demonstrate the close coupling of power electronics between wind turbine generators and electrolysers. This will reduce the power conversion requirement and improve power conversion efficiency / save cost on the rectifier / transformer that is required for a grid connected electrolyser.

4.2 Enabling the hydrogen economy

The demonstration project supports the development of next generation AEM electrolysers, which will be developed using PGM-free catalysts and water plus electricity as input. The Bramble AEM electrolyser will be developed alongside UK-based supply chain, supporting the development and commercialisation of AEM membrane and catalysts.

Currently only smaller AEM units (<2.4 kW) for niche applications have been commercialised. Larger electrolyser systems designed for large-scale roll-out need to prove lifespan and durability of AEM materials. The low-cost stack manufacturing using Bramble's electrolyser technology as a platform for AEM will accelerate commercialisation of AEM electrolysers. The manufacturing approach from Bramble utilises a low-cost method to make bipolar plates, which will be utilised in the electrolyser stack.

The novel approach of manufacturing electrolyser cells using manufacturing processes from the electronics industry accelerates the manufacturing readiness of the Bramble electrolyser technology. The electrolyser is designed around the high precision, automated and high volume manufacturing already established by the PCB industry. The automated stack assembly process Bramble is currently developing for fuel cell stacks will also be applied to electrolysers, providing a fully automated electrolyser assembly and disassembly line. This will also support local manufacture of electrolysers, reducing transportation costs and emissions associated with importing electrolysers.

The automated electrolyser stack assembly process can also be applied to electrolyser stack disassembly and refurbishment. This enables Bramble, at comparatively low-cost to other electrolyser manufacturers, to replace membranes within a used electrolyser stack and repurpose the stack. This improves the cost of replacing electrolyser stacks within a system and the overall levelized cost of hydrogen across the electrolyser system lifespan.

The electrolyser system will be designed with integration with renewable energy sources (RES) as part of the core to the electrolyser cell design. This will reduce the power conversion requirements when connecting the electrolyser to the grid or directly to wind turbine generators. There is specific opportunity for wind plus hydrogen solutions, particularly in the UK with the large-scale production and plans to accelerate offshore wind generation. The variability of wind energy, where high pressure periods can last a few days also suits hydrogen as an energy storage medium over other electrochemical (i.e. battery options) which are suited to short-term storage. Wind energy is well suited to electrolysis and hydrogen production, where load factors are relatively high, amortising the depreciation of capital cost of electrolyser installation over more kWh input electricity and kg of output hydrogen.

5. Design of demonstration

As outlined in section 4, the proposed project will include a development roadmap for membranes, catalysts, cell and stack design to commercialise an AEM electrolyser system. The development of all these aspects are important for the further development of AEM electrolyser technology. The UK has a strong technology base across this supply chain, although currently has no commercial offerings in the nascent AEM electrolyser market. The demonstration project seeks to address this through collaboration between membrane, catalyst and stack suppliers and providing a platform to demonstrate AEM electrolyser technology and accelerate its commercialisation.

The electrolyser system demonstrated at the end of the project will be established as a working electrolyser system test bed. The system will be designed to support multiple and larger electrolyser stacks and provide the system and instrumentation to install, operate and gather high granularity performance data that would otherwise be required for a commercial system. The electrolyser system test bed will also include the ability to operate at variable power inputs to simulate direct connection to renewable energy generation assets. This is all with the aim to maximise the learnings of the electrolyser membrane, catalysts and stack under a real-world environment. The system will also allow side-by-side comparison of electrolyser stacks running under different operating conditions, or with different membranes or catalysts.

The core function of the demonstration facility is to enable acceleration of not only electrolyser stacks, but also catalysts and membranes to the market and will be an asset to the UK's electrolyser development capabilities. The demonstration system layout is shown in Figure 5.1. This system will be the foundation for a commercial system, which Bramble aim to commercialise with partners following the demonstration project. The commercial system is expected to be designed with two electrolyser stacks for 240 kg H_2/day production capacity and 500 kW power demand (system efficiency 50 kWh/kg H_2). The commercial electrolyser system will be designed alongside the demonstration test bed.

The electrolyser stack testing will focus on operating controls for the electrolyser to maximise lifespan of the electrolyser stack, which is currently critical for AEM electrolysers. Stack testing of c.500 cm^2 and c.1,200 cm^2 cells will be carried out in the electrolyser test bed.

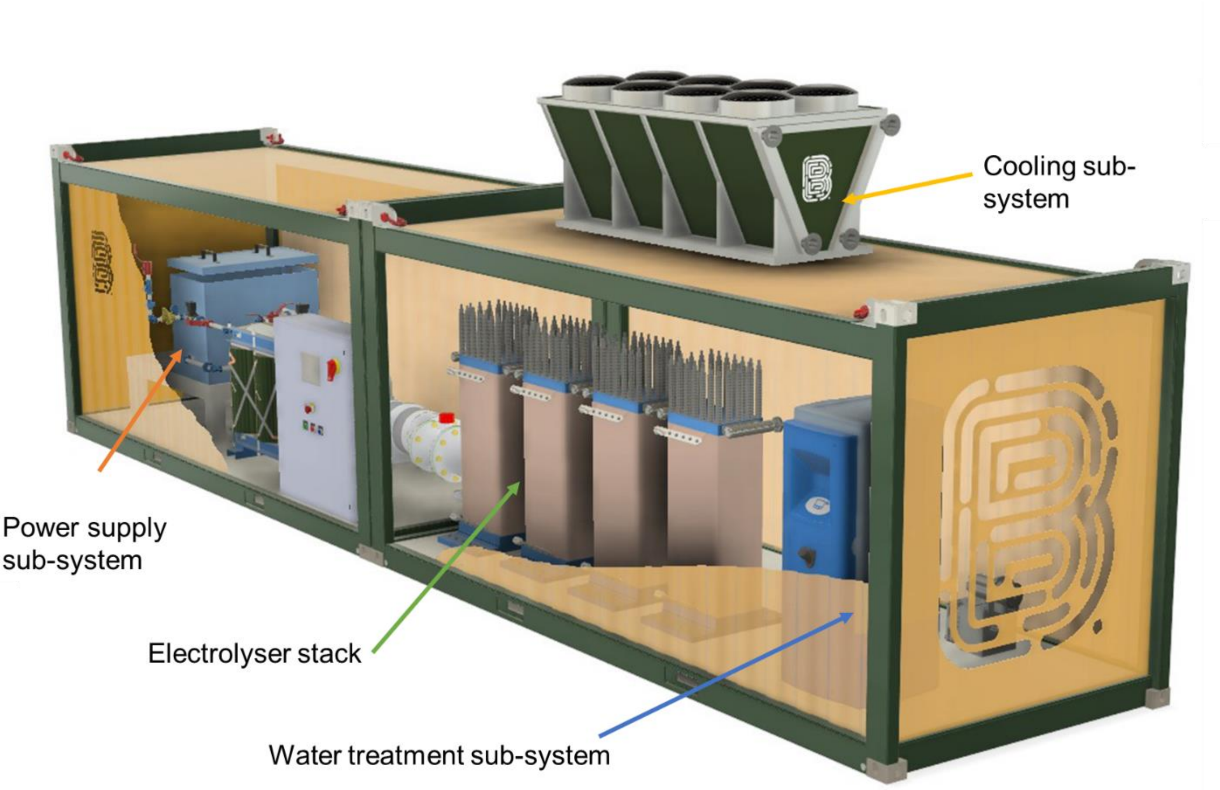


Figure 5.1: Proposed layout of Bramble's electrolyser system for demonstration phase

Within the HYS2 Phase 2 proposed project the demonstration system will allow testing of:

1. Electrolyser stack demonstration
2. Electrolyser system variable power input demonstration to mirror generation from offshore and onshore wind farms.
3. Electrolyser stack with high voltage configuration to simplify the power conversion process and improve overall integration with renewable generation assets.

6. Rollout potential

The rollout potential for the PCB-based AEM electrolyser is two-fold;

i. Scale-up capacity is available using existing manufacturing techniques and materials from the printed circuit board industry

ii. The use of critical raw materials-free catalysts (CRM-free) unlike PEM electrolysers, will avoid raw material price spikes and supply bottlenecks in the future.

The PCB-based AEM electrolyser solution would be scaled, initially by leveraging existing PCB manufacturing capacity in the UK to manufacture PCB electrolyser modules. The electrolyser stack would then be assembled at Bramble Energy's manufacturing facilities using automated process developed from fuel cell stack manufacturing (Bramble are currently investigating this for automotive fuel cell stacks). Figure provides an overview of the planned electrolyser stack scale-up from HYS2 Stream 1 Phase 1 through to the HYS2 Stream 1 Phase 2 project and future scale-up sizing of the electrolyser stack.

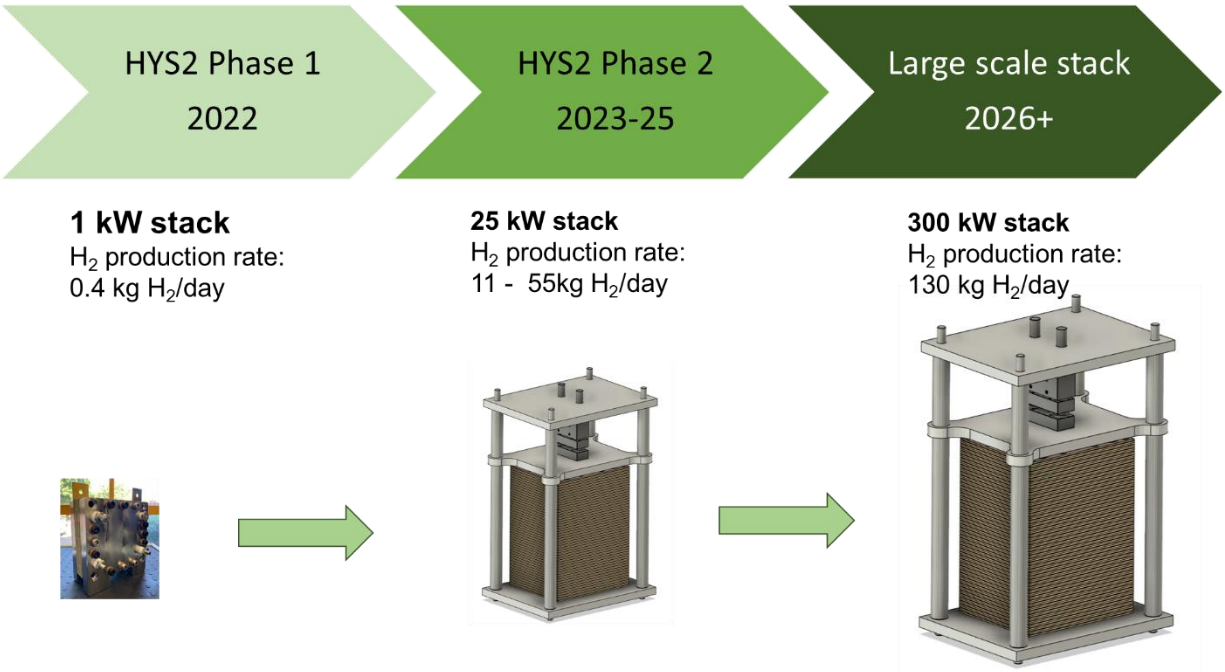


Figure 6.1: Scale-up plan for Bramble's AEM electrolyser from HYS2 Phase 1 (demonstrated 2022) to HYS2 Phase 2 (demonstrated 2023 -25) to large-scale stack (planned for 2026+).

There are c.60 PCB manufacturers in the UK, most of which have moved from large-scale production to specialist prototype PCB development. There exists capacity in the UK and knowledge in supply chain and with regards to automation and manufacturing scale-up to develop competitive electrolyser PCB manufacturing in the UK. A typical PCB factory would be able to produce enough PCB modules for 3 GW electrolyser capacity per year. Bramble is currently investigating automated stack manufacturing for fuel cell PCBs, which would share the same automation process as electrolyser stacks (different module sizing and geometries). This would use the same processes as fuel cells, including the same quality control (QC) procedures; visual inspection, electrical check, leak checks, seal application and stack assembly before final QC of the stack.

6.1 Material supply chain

In comparison to PEM electrolysis, AEM has the advantage of not requiring noble-metals, and uses titanium-free components, with PEM electrolysers typically using titanium and platinum coatings on bipolar plates. AEM electrolysers therefore have a much lower bill of materials cost to PEM electrolysers and one which is more similar to alkaline electrolysers. There is also considerably reduced risk in relation to raw-material shortages or escalating raw material costs. AEM electrolysers have the ability to operate at similar conditions of PEM electrolyser (high pressure output, higher power density, fast response times and fresh water input).

The main material inputs into the PCB-based electrolyser will be the pre-preg materials used in PCBs, which are made up of a glass reinforced resin such as FR-4. Global production capacity of glass fibre for PCB manufacturing is estimated to be over 500,000 tonnes/year[5]. The global market for glass fibre materials is estimated over 12 million tonnes, with applications for wind turbine blades, automotive and aviation sectors. There is therefore a large availability for the raw materials required for the PCB-based approach and there are steps within the PCB industry to utilise recyclable materials.

This is in contrast to some materials used in PEM electrolysers, which require rare metals, such as Iridium. PEM electrolysers typically require between 1 – 2.5 g/kW Iridium, which has limited global production and is particularly sensitive to volatile price spikes (e.g. Iridium price increased almost x3 over 2 months in 2021[6]). The global production capacity of Iridium is also estimated as 7 – 7.5 tonnes/year, which would provide enough for 10-12 GW electrolysers/year globally, this is expected to be a bottleneck for PEM electrolyser production in the next decade[7].

The PCB approach to manufacturing electrolysers allows for accelerated scale-up in production capacity. The technology and material requirement of AEM electrolysers provides a low-risk to future electrolyser material supply. Both of these aspects would support UK companies to capture the emerging AEM electrolyser market and supply chain.

6.2 Market size

During the PCBEL project, the UK Government and European Commission have strengthened their commitment and targets for low-carbon hydrogen production / usage for 2030. The UK Government has increased low-carbon hydrogen production capacity ambition from 5 to 10 GW by 2030, with at least 5 GW of this from electrolysis production. Based on this ambition, the UK low-carbon hydrogen production is estimated as 2 million tonnes H_2/year. Europe has a target for a demand of 20 million tonnes of low-carbon hydrogen per year (which includes hydrogen import and 65 GW electrolysis production capacity by 2030)[8]. Prior to the updated strategies for low-carbon hydrogen from the UK and Europe, Goldman

[5] Composites World, 2014; https://www.compositesworld.com/articles/printed-circuit-boards-a-mobile-market
[6] Reuters, 2021, Tight supply and hydrogen hopes drive iridium up 160%; https://www.reuters.com/article/us-precious-iridium-idUSKBN2AC1DG
[7] International Renewable Energy Agency, 2022, Innovation Trends in Electrolysers for Hydrogen Production; https://www.irena.org/publications/2022/May/Innovation-Trends-in-Electrolysers-for-Hydrogen-Production
[8] European Commission, 2022, European Commission staff working document, Implementing the repower EU action plan: investment needs, hydrogen accelerator and achieving the bio-methane targets; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2022%3A230%3AFIN&qid=1653033922121

Sachs estimated global commitment to hydrogen production as 130 GW by 2030[9]. To limit global warming to 1.5°C, Boston Consulting Group has forecast a need for 565 million tonnes of low-carbon hydrogen per year by 2050[10].

The electrolyser market is estimated to be $10 billion per year from 2030, growing to $100 billion per year from 2040[9]. Considering constraints in material supply, particularly concerning Iridium for PEM electrolysers and the current market maturity of alkaline electrolysers, and with established PCB manufacturing in China, there is a significant potential for the UK and Europe to develop a supply chain for AEM electrolysis. The PCBEL electrolyser accelerates the much needed scale-up of electrolyser manufacturing capacity by leveraging established manufacturing routes from the electronics industry and accelerates cost reduction and supply chain scale-up.

7. Benefits and barriers

The main benefits and barriers of the technical approach and demonstration are highlighted below:

7.1 Benefits

+ **PCB scale-up potential:** The platform to manufacture electrolysers using already established manufacturing process is a key advantage, as this enables scale-up to meet the growing demand for electrolysis. A standard PCB factory has capacity to manufacture c. 3 GW electrolyser modules per year. There are PCB factories already operating at high volume, with high precision and quality control processes in place all over the world. The PCB electrolyser is designed for manufacturing at scale, therefore ramping up manufacturing is simplified compared to all other electrolyser technologies which require £100's millions of investment into production facilities and establishing new manufacturing processes.
+ **Low-cost PCB platform:** Leveraging the already established manufacturing processes from the PCB industry also has cost saving advantages for the manufacture of the electrolyser stack. This cost saving is from the manufacturing efficiencies already established through the PCB manufacturing process, as well as bill of materials savings due to the lower cost of the composite materials that are used in the electrolyser. As a result of this, Bramble's electrolyser cost targets for 2025 are below the Clean

[9] Goldman Sachs, 2022, Carbonomics: The clean hydrogen revolution; https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf
[10] Boston Consulting Group, 2022, How to Meet the Coming Demand for Hydrogen; https://www.bcg.com/publications/2022/how-to-meet-future-low-carbon-hydrogen-demand

Hydrogen Partnership's 2030 cost target for AEM electrolysers of €300/kW (£260/kW)[11].

+ **Simplified power conversion:** The PCB approach combines insulating glass fibre with conductive Copper/ Nickel. This is unique to electrolyser design, where conventional electrolyser cells are manufactured using conductive metals. This allows Bramble to include multiple conductive areas within a cell, which could then be connected in series to increase the voltage and reduce the current requirement. This has potential advantages with the power supply specification for an electrolyser system, with an opportunity to save on capital cost of power supply equipment as well as efficiency improvement in the power conversion.
+ **CRM-free materials:** This benefit is across AEM electrolysers, however this has the potential to be accelerated through the PCB-AEM platform. The development of AEM catalysts is still on-going and although there is the ability for AEM electrolyser to operate without CRM materials, the performance improvement is currently generally worth the additional cost of including CRMs within the electrolyser design. This will unlikely be the case in the near future, with development on-going to remove CRMs from AEM catalysts.
+ **De-ionised (DI) water input:** Similar to the development of CRM-free materials above there is a possibility to operate the AEM electrolyser with just DI water. There is currently a performance benefit or operating at mildly alkaline conditions, which is worth the inclusion of alkaline solution in the system. Operation of AEM electrolysers with DI water has been proven and is a viable approach. Further improvements to membranes are on-going which promise to remove the need for alkaline in the near future.
+ **Performance comparable to PEM:** As shown in Table 1 below AEM electrolysers can operate at similar current densities to PEM (although generally slightly lower). The design of AEM electrolysers could also be suited to responding quickly to power inputs, similar to PEM. This makes the AEM electrolyser a suitable candidate electrolyser technology to coupling with renewable generation sources and responding to variable power demands.

[11] Clean Hydrogen Partnership Strategic Research and Innovation Agenda, 2021, https://www.clean-hydrogen.europa.eu/system/files/2022-02/Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf

Table 1: Comparison of operating parameters of low-temperature electrolyser technologies

		PEM	Alkaline	AEM
Anode		Iridium	Ni / Co / Fe	Ni-Fe
Cathode		Platinum	Ni	Ni, Ni-Cu, NiCuMo and NiMo
Voltage	**V**	1.75 – 2.2	1.8 – 2.4	2
Current density	**A/cm^2**	0.6 – 2.0	0.2 – 0.4	1
Pressure	**bar**	10 - 30	1 - 30	1 - 30
Input water / Electrolyte		DI Water / Proton exchange membrane	NaOH or KOH (20 – 40 % weight)	DI water / DI water, NaOH or KOH (<1 mol or <4% weight)
Separator plates		Titanium	SS	PCB / Ni / SS

7.2 Barriers

- **Lifespan of membranes:** One of the main drawbacks of AEM electrolysers is the limited lifespan of membranes. This is measured as the degradation rate of membranes, with current AEM electrolysers estimated to have lifespan of c.11,000 hours as opposed to c.80,000 hours for alkaline electrolysers[12]. Therefore, ensuring membranes are mechanically, thermally and chemically stable for commercial lifespans of electrolyser (target >30,000 hours or 0.3%/1,000 hours) is of critical importance to AEM electrolysers.
- **Not proven at scale:** There are commercially available AEM electrolysers, which are manufactured in 2.4 kW units and have generally been used in lower volume, niche applications. For AEM electrolysers to make an impact on CO_2 emissions and demonstrate the reduction in hydrogen cost, AEM electrolysers need to be scaled-up. This has yet to be demonstrated and will need to be over the next few years.
- **Performance risk of membranes and catalysts for AEM:** AEM electrolysers have the potential for comparable performance to PEM electrolysers, however with CRM-free materials and lower costs. For this to be

[12] Lifespan based on 10% reduction in electrolyser efficiency, with alkaline electrolyser based on 0.125%/1,000 hours and AEM electrolyser based on 0.9%/1,000 hours from Clean Hydrogen Partnership Strategic Research and Innovation Agenda, 2021, https://www.clean-hydrogen.europa.eu/system/files/2022-02/Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf

realised further development and performance improvement of membranes and catalysts are needed. There is therefore a development risk related to the on-going development of AEM catalysts and membranes.

8. Costed development plan

A high-level breakdown of the development plan for HYS2 Stream 1 Phase 2 is shown below in Table 2. This has proportioned cost between the main technology pathways for catalysts, membrane, cell, stack and system development. The total budget for this from January 2023 – February 2025 is estimated as £6 million excluding VAT (TBC).

Table 2: Summary of high-level estimates for costed development plan for HYS2 Phase 2

Workstreams	Total Cost	Engineering Design	Materials & Equipment
Catalyst development	£700,000	£350,000	£350,000
Membrane development	£700,000	£350,000	£350,000
Cell development	£1,250,000	£650,000	£600,000
Stack development	£1,400,000	£800,000	£600,000
System development	£1,950,000	£750,000	£1,200,000
Total (excluding VAT)	**£6,000,000**	**£2,900,000**	**£3,100,000**

9. Route to market assessment

The resulting demonstration of the phase 2 project will develop a one-off system test bed demonstration unit but also develop the supply chain for AEM electrolysers in the UK. The electrolyser system will be demonstrated at TRL 7 by 2025. From 2025 onwards Bramble plan for the commercial deployment, with demonstration of PCB electrolyser matching performance of commercial electrolysers. Large-scale manufacturing will be developed throughout 2025 – 27 for full commercial scale deployment from 2027/28 onwards, this will entail a Bramble PCB manufacturing plant, possibly in conjunction with an existing PCB manufacturer and a Bramble assembly and testing plant, alongside established Bramble electrolyser R&D facilities.

Bramble are targeting a route to market for PCB electrolyser technology which will be focused on deploying technology in conjunction with renewable energy build-out. The development of PCB electrolysers will be demonstrated to be coupled closely with renewable energy developers / technology providers, where benefits of co-location of electrolysers with renewables has benefits in terms of; single installation costs, simplified power electronics and coupling with renewable generators (reduces CAPEX for rectifiers / transformers and the efficiency losses of power electronic conversion).

The Phase 2 project will work in conjunction with a renewable energy operator to ensure the electrolyser meets their requirements. They could also be an early customer for the deployment of the PCB electrolyser system.

10. Dissemination

Dissemination activities from the project include announcement through social media channels and on Bramble's website. A white paper and webinar are currently being prepared which will provide an overview of the project and commercial opportunities for AEM electrolysers. The release of the webinar and white paper will be co-ordinated to maximise reach and impact (e.g. during European Hydrogen Week at the end of October), a draft of this will be shared with BEIS before the end of the project.

11. Conclusions

The PCBEL HYS2 Stream 1 Phase 1 project has successfully demonstrated the feasibility of an AEM electrolyser using manufacturing techniques from the PCB industry. The PCB electrolyser utilises membranes and catalysts from AEM electrolysers. Bramble has demonstrated the technology works up to 10 bar with PCB based AEM electrolyser and within a electrolyser stack with >1 kW power demand.

Experimental work has progressed the AEM technology using Bramble's PCB approach. From this feasibility testing there were no indications that PCB based electrolysers had any significant issues compared to non-PCB electrolysers.

Overall, approximately 1,000 hours of testing was performed with most degradation being of third party materials or system components (pumps, fittings, seals, etc). These areas will be further developed within the proposed Phase 2 project.

Additionally, at elevated pressures PCB based cells show good promise for use up to at least 10 bar. Based on the initial differential pressure issues, future anode and cathode designs may need modification for operation at higher differential pressures to prevent cross leaks occurring. Performance losses were observed at elevated pressures, attributed to cell expansion. Additional research into cell compression methodologies will be conducted for future electrolyser stack development.

Electrolyser stacks were designed and constructed, optimal materials and conditions were selected from a cost, performance and availability point of view. Performance of these materials translated well into stacks, with operating conditions also translating well from 25 cm^2 to 100 cm^2 cells and stacks. This is promising for future increases in cell and/or stack sizes

Overall, the performance of PCBEL stacks showed good agreement with single cell performance and literature reports for AEM performance, again showing promise for increasing sizes of PCBEL stacks for large multi kW systems

The long-term performance of the AEM electrolyser needs to be further validated and approaches to improve the lifespan of the electrolyser will be further explored to develop the technology in the proposed Phase 2 project. This will be in conjunction with partners to support development of membranes and catalysts for AEM electrolysers. The PCB approach has advantage with low-cost manufacturing and scalability to address the demands for green hydrogen and reduce the production cost. The proposed Phase 2 project will demonstrate AEM electrolysers can be scaled-up for commercial operation and develop the AEM supply chain in the UK.