BRAMBLE
ENERGY

System Architecture Advantages of the PCBFC™

2023

Contents

> “Bramble has simplified systems through stack design, manufacturing and material selection. Here’s how we developed not only the lowest cost fuel cell stack, but how we’ve empowered the lowest cost hydrogen fuel cell system* per kW.

(*low temperature, hydrogen, proton exchange membrane (PEM) fuel cell)

Dr Vidal Bharath

Chief Commercial Officer

Executive summary

Bramble's fuel cell technology, the PCBFC™, is a low-cost, scalable solution suitable for use in a range of sectors. The technology uses revolutionary materials and manufacturing methods common within the PCB industry, whilst at its core is a traditional low temperature hydrogen fuel cell. The PCBFC™ leverages the industrial maturity of the PCB industry, resulting in fuel cells that can be manufactured globally, at scale, today.

The PCBFC™ can also be manufactured into a multitude of form factors, servicing a variety of customers and use cases across several industries and sectors without requiring multiple bespoke factories. Crucially, Bramble Energy's PCBFC™ is an industry step change in cost. Bramble has recently published a white paper outlining the pathway to achieving a fuel cell stack cost of $60/kW.

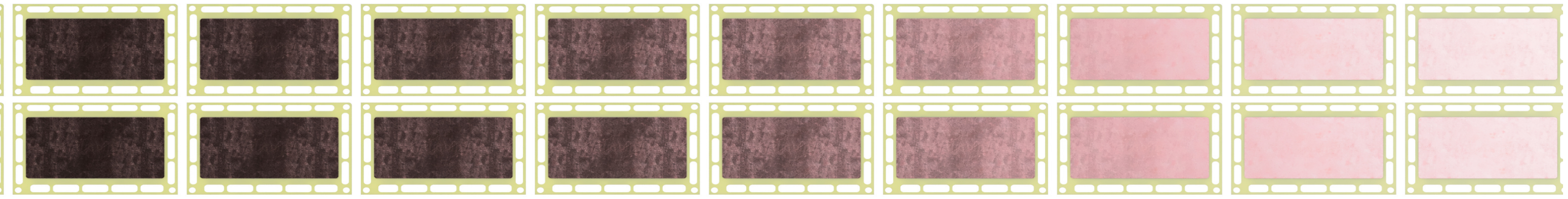
> “Bramble has designed fuel cell stacks that simplify system builds, component choices and integration. Using our low cost stack technology we've shown the pathway to the simplest, lowest cost system architecture.

However, Bramble's stack manufacturing capabilities don't just end with an improved stack technology that is low-cost, application specific and simplifies integration. In fact, at Bramble even though our core competencies aren't concentrated on system development (we leave this to the expert integrators, Tier 1 manufacturers, OEMs and product makers) we have been designing fuel cell stacks that simplify system builds, component choices and integration. Using our low-cost stack technology we've shown the pathway to the simplest, lowest cost system architecture.

At Bramble, our goal is to empower the hydrogen economy, whatever the application. Therefore, as far as we're concerned, there is little point in having the lowest cost fuel cell stack if the system to run it requires immense complexity and specifically made components that are expensive, bulky and heavy.

We've simplified systems through stack design, manufacturing and material selection. Here's how we developed not only the lowest cost fuel cell stack, but how we've empowered the lowest cost hydrogen fuel cell system* per kW.
(*low temperature, hydrogen, proton exchange membrane (PEM) fuel cell)

Core Stack Competencies Result in Significant System Savings



A fuel cell stack uses a membrane electrode assembly (MEA) to convert hydrogen and oxygen into power, emitting only heat and water. The stack enables this core electrochemical function, managing the supply of gases, hydration and coolant to the MEA to optimise the reaction. To ensure the stack operates effectively, a fuel cell system is required, often including components such as compressors, humidifiers, radiators, valves, pumps, batteries, etc. The system controls the supply of reactants to the fuel cell stack, as well as ensuring efficient heat removal and controlling start-up/shut-down procedures. A typical system is highly complex, adding significant weight, volume and cost to the installation.

Applications using a fuel cell will often utilise a battery as a key part of the electrical architecture[1]. The battery pack can be used in two distinct ways, influencing the fuel cell control strategy and fuel cell sizing. These layouts can be summarised as follows:

- The battery acts as the main source of power for the electric motor to move the vehicle which, in turn, is recharged by a fuel cell system. In this configuration, the fuel cell system is called a “range extender” and the fuel cell is sized to low/medium power and operates at a single optimised efficiency. The battery pack is sized to allow for medium to high power output with a sufficiently large energy storage capacity[1].
- Design decisions on system efficiency and response time means the battery acts as a transient and additional power source to the fuel cell. The fuel cell response time is in the order of several seconds or even minutes depending on the stack and system sizing and performance. In this configuration, the fuel cell system is called a “prime mover” and is typically sized to enable high power outputs. The battery is kept small both in terms of power and energy[1]. A passenger car with a 100 kW+ fuel cell system and 2 kWh battery pack is an example of this configuration[1].

In addition to balancing the battery and fuel cell stack size for the application, the system designer must also consider the size of the hydrogen fuel tank. This will vary not only depending on the available space, but also on the required range of the vehicle. The range of a given vehicle can be improved by increasing the amount of hydrogen stored within the tank, either by increasing the tank size for a given pressure, or increasing the pressure of the hydrogen. Heavy duty applications with significant range requirements may use multiple liquid hydrogen tanks as an energy-dense fuel supply[2].

Bramble's differentiator and ability to simplify system architectures stems from one core fundamental factor: dielectric material sets. The PCB materials are inherently dielectric – they're designed to have areas of conductivity and non-conductivity within the same plane; it's what makes typical PCB electronics boards work. Bramble Energy's PCB based fuel cells are not only manufacturable at any PCB factory worldwide, they also use the same materials and processes used for standard PCB manufacture.

In the PCBFC™ electrical conductivity is achieved via copper layers whilst reactant and coolant pathways and structural integrity is achieved using machined FR4 (a glass-reinforced epoxy resin laminate). This separation translates into a unique cell and stack design with features that cannot be achieved in metallic or graphitic fuel cells (Figure 1).

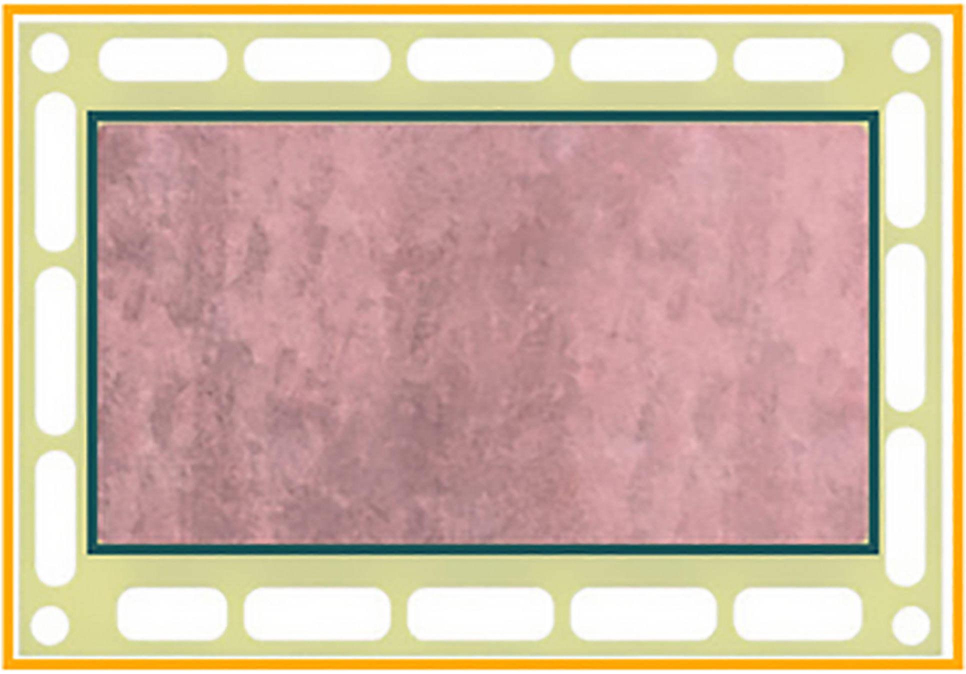


Figure 1. Diagram of a single PCBFC™ module showing the conductive copper surfaces outlined in green and non-conductive FR4 outlined in yellow.

Unlike other fuel cell manufacturers, Bramble is able to leverage this material set and apply it to the construction of the fuel cell. The ability to customise the core module design to customers and applications also gives rise to a number of advantages including:

- Customisable voltage-current map;
- Non-conductive coolant channels and;
- Non-conductive external surface.

These advantages allow for customisable fuel cell stacks for the end user or system integrator allowing greater flexibility, with the option to simplify the overall system, resulting in cost reductions and weight / volume savings. To understand how these factors can result in significantly less complex, lower cost systems, let's explore it further.

High Voltage PCBFC™ Stacks

Fuel cells are typically used in conjunction with a battery as a key part of a hybrid powertrain's electrical architecture. The size of the battery, the fuel cell and the hydrogen tanks are all decisions that are made based on the end application and its desired characteristics and capabilities. When a fuel cell is used in a hybridised application, it provides the energy to a vehicle's powertrain whilst the battery is used to provide the power.

If we consider the case where a 100 kW fuel cell is operated as a prime mover, for example in a passenger car, a typical fuel cell stack operates at 200 V – 400 V. Electric powertrains are continually evolving and gaining improved efficiency through innovative designs and electrical configurations. One such advancement is the increase in the voltage level of the vehicle architecture. Today we see many battery packs operating at > 400 V across mobility and stationary sectors, with significant advantages seen by those operating at > 800 V[3]. The use of high (> 800 V) voltage electrical architectures allows for the use of significantly lower currents; enabling reductions in cable size. The use of lower currents means there is less copper required for conduction through the vehicle and therefore the system build can be carried out with thinner cables that save significant weight and thus improve overall system efficiency and cost. Furthermore, electrical system integrations become materially easier to deal with when handling thinner, more flexible cabling as both mass and bending radii are reduced.

We now need to consider the case where longer range is needed in applications that require large quantities of energy – consider moving heavy vehicles long distances such as haulage, busses etc. In these cases, range extension of the battery pack in a hybrid architecture is required. A hybrid power train necessitates taking the fuel cell architecture and integrating it seamlessly with the battery architecture to provide the end user with an electrified driving experience with the convenience of replacing the energy (hydrogen in this case) at the same speed as refuelling petrol or diesel.

Marrying these architectures together is often tricky as you must take a fuel cell voltage and current profile and convert it using a DC-DC converter to be compatible with the battery chemistry's charging requirements.

All fuel cells are made up of individual cells stacked together (referred to as a stack) and information on fuel cell construction can be found from many sources. Each cell in an automotive stack will typically operate at 0.6 V, and the number of cells you have, the higher the overall stack voltage. For example, if we consider a typical graphite or metal plate fuel cell operating at c. 100 kW, it may have c. 300 - 400 cells, each providing i.e. 0.6 V and, therefore, has an operating voltage of c. 180 V – 240 V (typically this range can be wider). When we combine this into a hybrid powertrain with a battery pack at 400 V or 800 V, we must install a DC-DC boost converter to increase the fuel cell output voltage to the necessary voltage required to charge the battery pack.

The DC-DC converter can be considered as a step-up transformer with electronics to ensure stable output voltages. DC-DC converters are customised, expensive and heavy components that are large and can be difficult to fit within the confines of the vehicle architecture. The DC-DC can be less electrically efficient in the boost configuration than in its opposite mode where it steps the voltage down from a higher input to a lower output voltage.

In designing the PCBFC™ stack, we have considered these factors and determined a means by which to increase the overall stack voltage whilst providing the same power output for a given stack. This advantage is inherent within our design and PCB materials set and whilst still in line with our aggressive cost reduction pathway.

The dielectric materials used within the PCBFC™ allow segmentation of the MEA within a single plane (or as we refer to it a module), increasing the voltage across that plane.

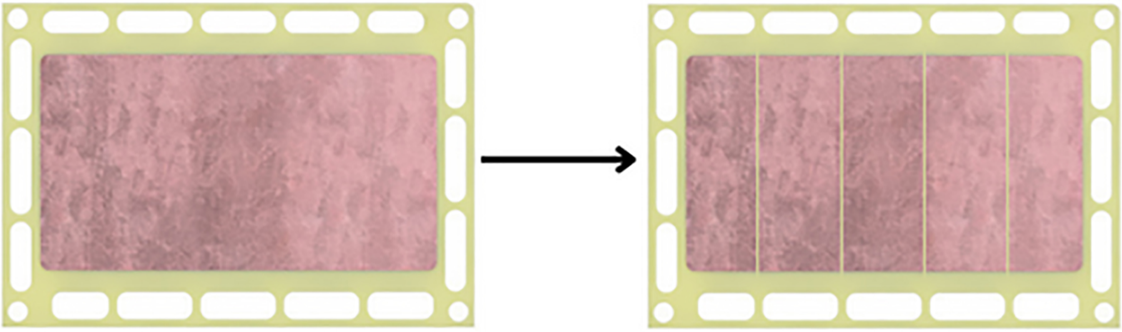


Figure 2. Diagram showing the use of segmented MEAs within a PCBFC™ module to increase the voltage across a single plane.

To demonstrate this, if we consider Figure 2 above, the PCBFC™ allows for the installation of an MEA divided into five distinct segments; the voltage of this module is therefore increased from 0.6 V to 3 V, whilst providing a similar power output. When we assemble the modules into a stack (as shown in Figure 6) it results in a fuel cell with a voltage profile five times greater than would be expected from its metallic or graphitic plate counterparts.

If we consider our earlier example of a typical 100 kW stack comprised of c. 350 plates operating at c. 210 V, we can now compare a 100 kW PCBFC™ comprised of c. 350 plates which would operate at c. 1050V. This is shown in Table 1, which shows how MEA segmentation can be used to produce stacks with powers 30 to 100 kW at ~1000 V output. Fuel cell stacks that run at customer specified voltages allow several advantages through marrying the fuel cell operating voltage with that of the battery pack including:

1. Simplified buck DC-DC converters reduce cost and increase electrical system efficiency.
2. The use of off-the-shelf, lower cost system components.
3. Lower system mass and volume and improved integration with thinner cables and reduced DC-DC component size.
4. Total stack output power can be scaled whilst maintaining a constant stack voltage. This simplifies integration of the fuel cell with existing system architectures at predetermined voltages (cf. with examples in Table 1).

Table 1. PCBFC™ stack power variation at a high voltage output target of c. 1000 V

Exemplary PCBFC™ Stack	**30 kW Stack**	**60 kW Stack**	**100 kW Stack**
Total Active Area*	220 cm²		
Segmented MEA Zones	17	8	5
Voltage at 0.6 V per cell	1050 V	1013 V	1050 V
Number of Modules	103	211	350

** The given active area is one possible example to illustrate power variation capabilities using PCBFC™ technology.*

In some cases, we can go one step further. Based on operating parameters, it is possible through module design to remove the DC-DC converter all together in an architecture in which a load management device can take the fuel cell voltage and put it across the battery directly.

In this mode of operation, whilst there is less control on the charging circuit, the fuel cell power follows the battery pack curve; ultimately further reducing the system mass, volume, cost and complexity.

The above advantages are made possible using the PCBFC™ technology as the dielectric structure of the fuel cell allows for subdivision of electrical zones within a single fuel cell module and creates the possibility to tune current and voltage output of the cell independent of active area and cell count. A single module would consist of sub-cells that can be connected in a variety of configurations to tailor the electric output to the specific needs of the application.

PCBFC™ stack – removal of coolant deioniser in the cooling circuit

To ensure optimum operation of a low temperature PEM fuel cell stack, it needs to be operated at c.80°C (this can vary depending on MEA). As a rule of thumb a system can operate at 50% - 65% efficiency, the resulting heat must therefore be dissipated by the system.

With potentially large quantities of heat to be removed from a fuel cell system it is important to have an efficient cooling circuit. Unlike an internal combustion engine (ICE), heat removal is significantly lower at the tail pipe for a fuel cell system and, thus, the cooling system typically operates at relatively lower temperatures. A typical schematic for a fuel cell cooling circuit is shown in Figure 3 and is comprised of coolant hoses, an electric coolant pump, an electrical coolant valve or thermostat, a coolant heater (to quickly heat the stack in cold conditions), a radiator and a header tank. The exact component arrangement will vary depending on the application.

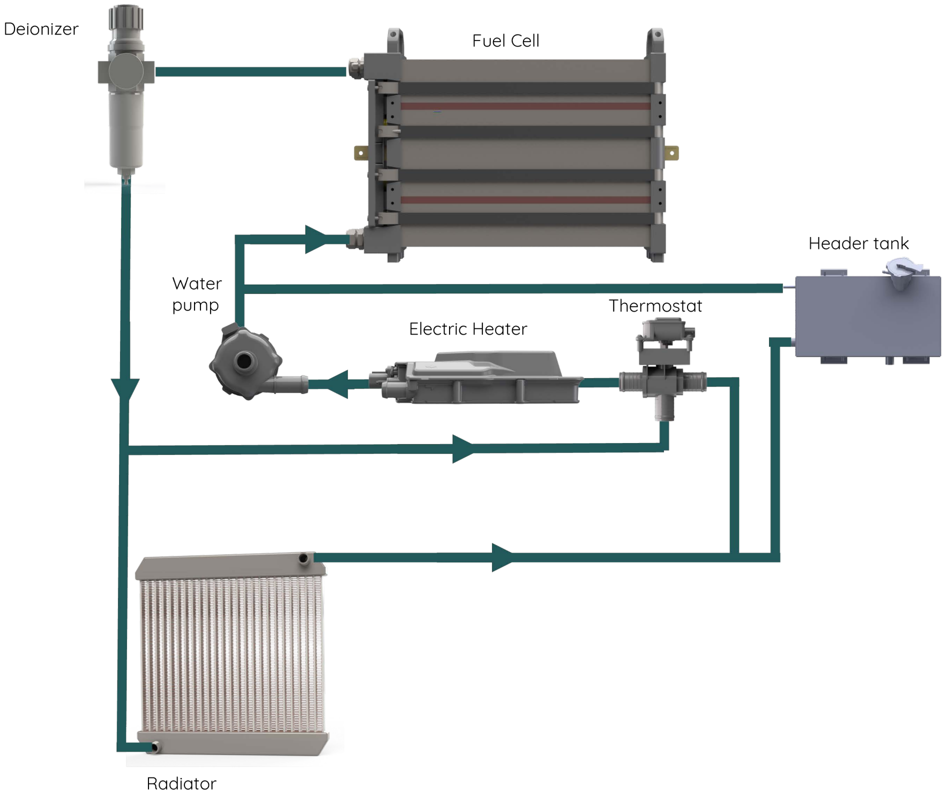


Figure 3. Fuel Cell cooling circuit.

Conventional metallic or graphitic fuel cell stacks have complex cooling circuits that require deionised water as the coolant medium. This is because the plates that make up the stack (bipolar plates) in these constructions are electrically conductive. Therefore, to avoid short circuiting the stack through the cooling fluid it is common practice to use low electrical conductivity coolant. Deionised water is therefore often the medium of choice for these systems. In typical fuel cell operation, a deioniser is placed in line with the coolant flow which is constantly monitored through a conductivity sensor to ensure safe operation. The deioniser will typically need to be serviced and replaced and the maintenance schedule can be expensive and result in downtime and increased user cost.

In the case of PCBFC™ stacks, however, the FR4 material which the coolant channels are constructed from are electrically insulative. The entirety of the coolant pathway is constructed from the non-conductive FR4 material and is isolated from the electrically conducting copper surfaces and pathways. This negates the requirement for deionised cooling water and the in-line deioniser and sensors required to maintain it. The PCBFC™ can be cooled with a water glycol mix and can drop into existing hybrid cooling architectures.

Removal of the deionised water loop and deioniser results in simplification of the wider fuel cell system, as heat exchangers and radiators exclusively used for the coolant circuit can also be removed. The resulting simplified system has a lower operation power draw, mass, volume and cost. Reduced components numbers directly correspond to lower maintenance and CAPEX costs for the system.

Non-conductive External PCBFC™ Stack Surfaces

In a conventional fuel cell stack the bipolar plates consist of electrically conductive material and are electrically separated by the membrane. It is therefore crucial to not short circuit a stack at its external surface by making a cell-to-cell connection. This requires additional safety considerations during stack integration, resulting in more complex system design considerations, increased overall cost, mass and volume.

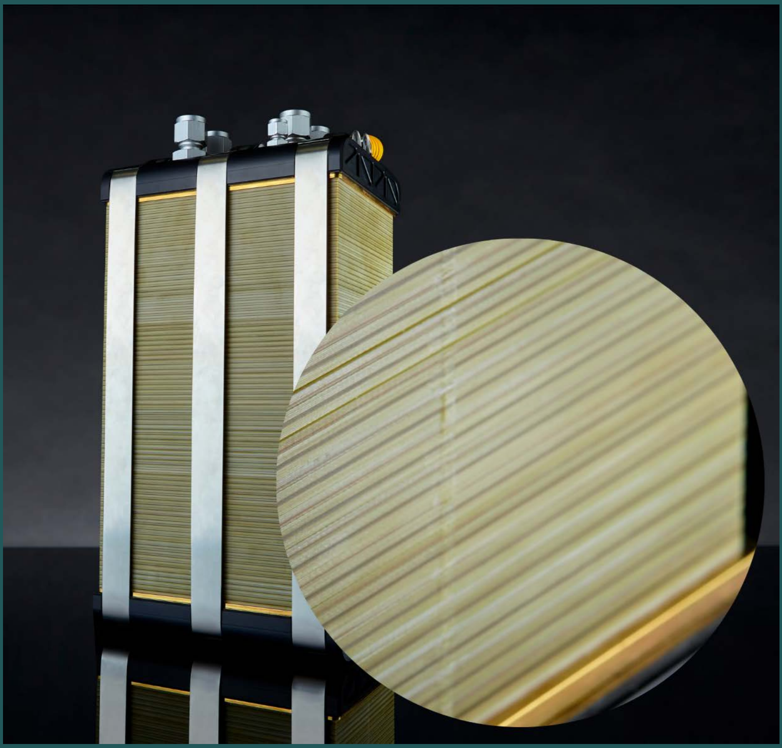


Figure 4. Close up on the PCBFC™ stack surface exhibiting only FR4 material.

Utilising dielectric PCB materials, the PCBFC™ stack is designed to have only the non-conductive FR4 material exposed at the outer surface as shown in Figure 4. This design has also meant that in complex systems where cell-by-cell voltage monitoring (CVM) is required, it is a simple process without risk of short circuiting, offering the user or integrator an inherent safety advantage.

Bramble's technology is designed for scalability whilst also providing a unique solution for each individual customer. By reducing the risk of short circuiting, unlike our competitors, Bramble's fuel cells can be packaged closely together without risk to the stack or user. This in turn can improve the power density and safety of large installations comprising multiple fuel cell stacks.

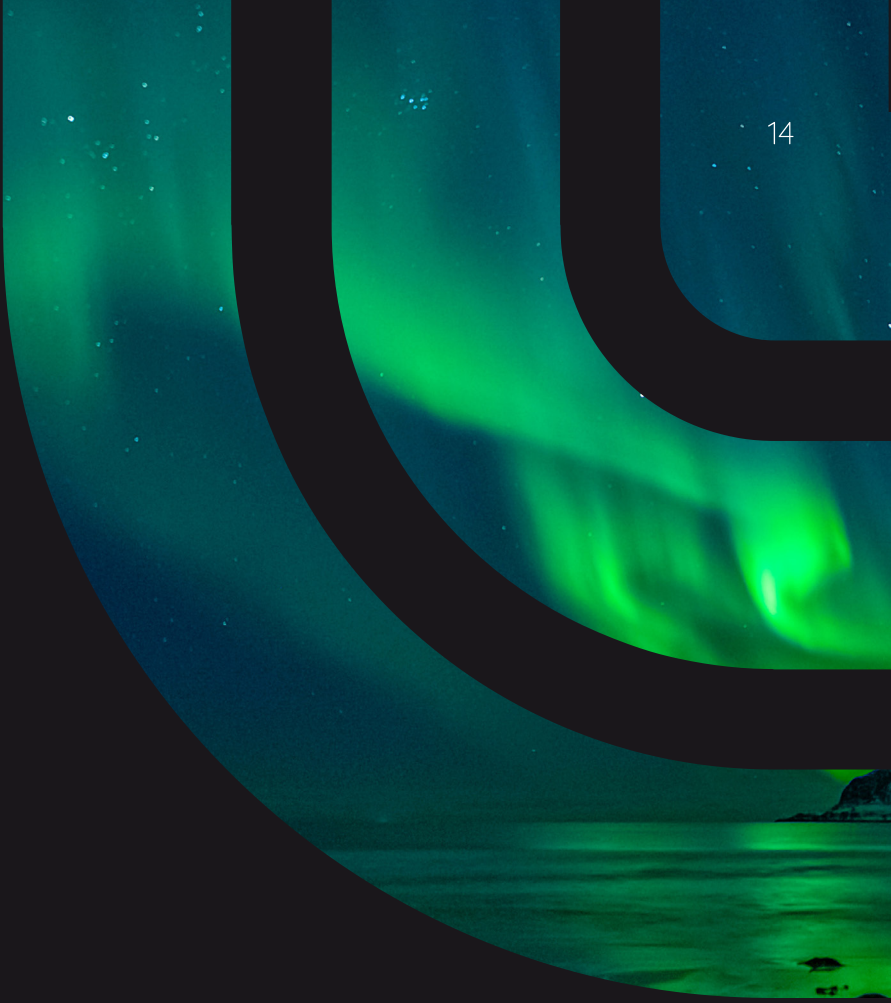
Delivering The Benefits

Bramble's fuel cell technology, the PCBFC™ offers a unique way to manufacture fuel cells using the same core PEM electrochemistry as incumbent metallic or graphitic technology. The PCB manufacturing route enables rapid scaling of customer driven fuel cell technology and is the lowest cost fuel cell stack technology[4].

In developing the PCBFC™ stack technology, Bramble has solved fundamental system architecture issues with no additional impact on the already industry leading cost pathway. These advantages stem from the dielectric materials used in the construction of the PCBFC™ and impact directly the system's electrical efficiency, packaging envelope and cost.
The effective use of materials and their properties within the PCBFC™ results in a clear separation between conductive and non-conductive routes within the fuel cell module. This allows for the following system benefits:

- Reduction in size or removal of the power conversion unit as current and voltage output of the stack can be customised to meet the application or readily available off-the-shelf component specifications .
- Removal of the deioniser and the complex deionised cooling loop as coolant channels are not in electrical contact with the stack. Coolant stream can be replaced with typical ICE water glycol mix coolants.
- Removal of surface protection of the stack as the outer surface is non-conductive and thus allows for tighter packaging envelopes as we link stacks together for larger power installations.

At Bramble, our core competencies are in PCBFC™ stack development; however the benefits of our stack have been designed to be felt throughout the integration. After all, we're here to empower the hydrogen economy, and a low-cost stack means little without a low-cost system to run it.



About Bramble Energy

Bramble Energy is powering Net Zero, solving key challenges in the production of hydrogen fuel cells including lead times, up-front investment, manufacturing cost and scalability.

We are fast becoming the leading hydrogen fuel cell provider for a cleaner and more sustainable world. Our fuel cell stacks come in any size, any shape, and are completely scalable to your energy requirements. From mobility to construction to industrial use cases, our customisable designs enable it all.

Through revolutionary fuel cell design and manufacturing techniques, we have developed the unique printed circuit board (PCB) fuel cell – the PCBFC™. A patent protected fuel cell that can be manufactured in almost all printed circuit board (PCB) factories worldwide.

We also manufacture modular electrolysers to produce clean, green hydrogen. Our solution focuses on two key pillars, making our hydrogen production reliable and affordable; with this we intend to empower the global uptake of the hydrogen economy and ultimately an energy secure world dominated by truly renewable energy regardless of geographical constraint.

We're ready to bring the lowest cost fuel to market with our PCB-X™. Platform technology unlocking a diverse range of use cases and breaking down traditional barriers to fuel cell production.

For more information about us and our ambition visit www.brambleenergy.com.

References

1. Petronilla Fragiacomo, et al. (2022). Hydrogen-Fuel Cell Hybrid Powertrain: Conceptual Layouts and Current Applications.*Machines*, 1121. https://www.mdpi.com/2075-1702/10/12/1121
2. R.K. Ahluwalia, et al. (2023). Liquid hydrogen storage system for heavy duty trucks: Configuration, performance, cost, and safety. *International Journal of Hydrogen Energy,* 13308-13323. https://www.sciencedirect.com/science/article/abs/pii/S0360319922058700)
3. Johnson, E. (2019, July 31st). Introduction to Electric Vehicle Battery Systems. All About Circuits: https://www.allaboutcircuits.com/technical-articles/introduction-to-electric-vehicle-battery-systems/
4. Bramble Energy *PCBFC™: The Pathway to the Lowest Cost Fuel Cell* https://www.brambleenergy.com/resources/whitepapers/discover-the-pathway-to-the-lowest-cost-fuel-cell/

Contact us

Bramble Energy

www.brambleenergy.com
getintouch@brambleenergy.com

2023