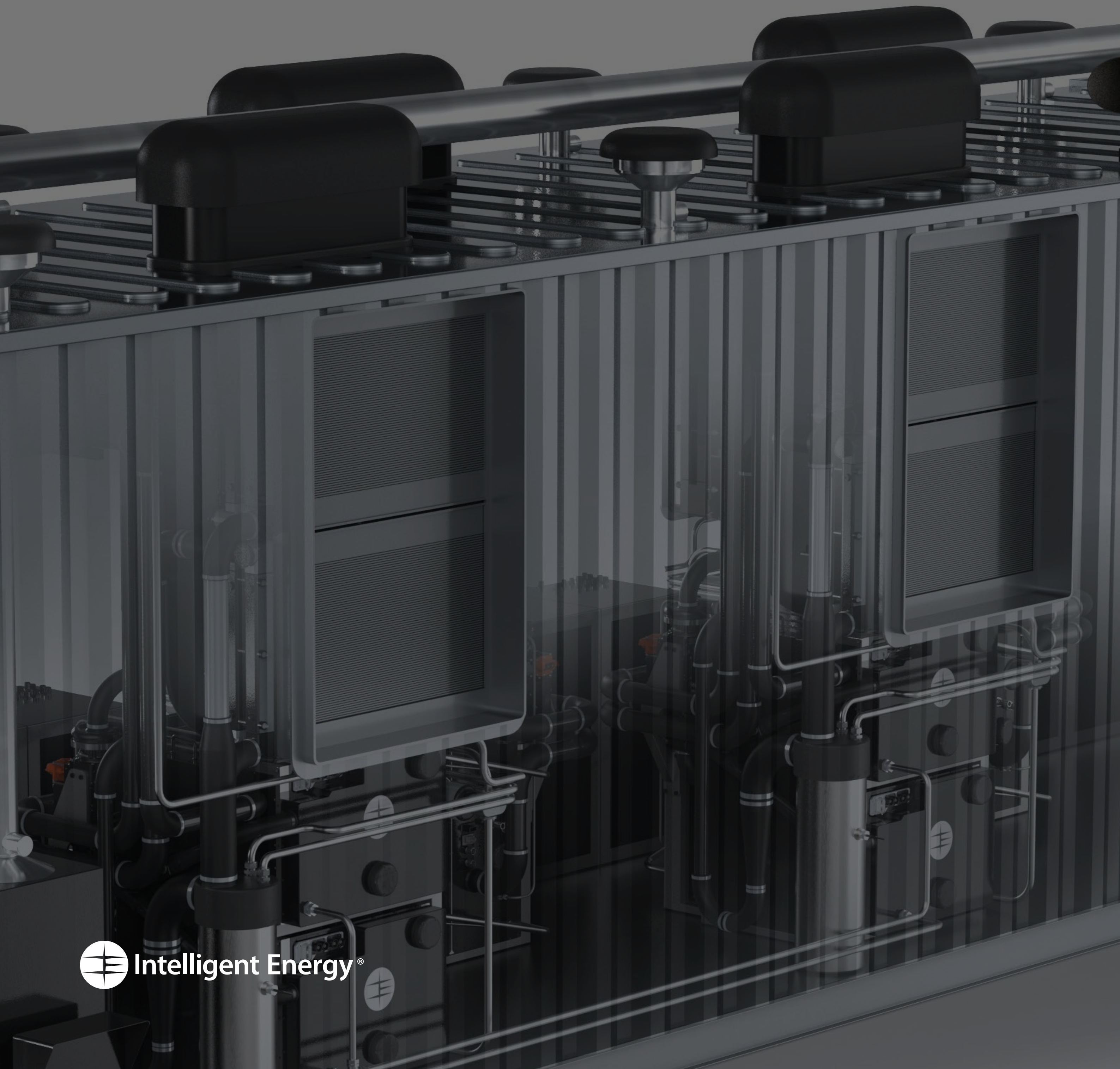
IE-GRID™

Maximising hydrogen fuel cell efficiency in stationary applications through novel thermal management techniques



Intelligent Energy®

1. Abstract

This white paper details the benefits of fuel cell use in stationary power applications and Intelligent Energy's evaporatively cooled architecture in particular. It highlights the potential thermal benefits offered by utilising the exhaust heat in Combined Heat and Power (CHP) systems.

MATLAB Simulink has been used to perform the data analysis, using dry air compression, thermodynamic and electrochemical equations such as those detailed in 'Fuel Cell Systems Explained'[1] and 'Temperature regulation in an evaporatively cooled proton exchange membrane fuel cell stack'[2].

These calculations have been supplemented with measured polarisation data from representative Intelligent Energy fuel cell stack technology and measured pressure drop data from a representative IE-DRIVE™ HD100 fuel cell system.

In all calculations of efficiency the lower heating value of hydrogen has been used, @ 33.3kWh/kg.

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[1] Dicks, A.L. & Rand, D.A.J. (2018) 'Fuel Cell Systems Explained', 3rd edition, Wiley, ISBN 978-1118613528

[2] Fly, A. & Thring, R.H. (2015) 'Temperature regulation in an evaporatively cooled proton exchange membrane fuel cell stack', International Journal of Hydrogen Energy Volume 40, Issue 35, pp. 11976-11982

2. Fuel cell overview

The function of a hydrogen fuel cell is to convert chemical energy to electrical energy through an electrochemical reaction between hydrogen and oxygen. The only by-products of this process are water vapour and waste heat.

Hydrogen fuel cells provide zero carbon emissions power at point of use. They can be used as a power source alternative to the traditional combustion engine or battery technologies for a range of applications including automotive, aerospace, stationary power, rail, marine and materials handling. There are various fuel cell technologies that are used across multiple market sectors and applications due to their performance characteristics, whether that be driven by mass, operating temperature, power density or fuel flexibility requirements.

	Proton Exchange Membrane	**Solid Oxide**	**Alkaline**	**Phosphoric Acid**
Electrolyte	Polymer membrane	Ceramic	Potassium hydroxide	Phosphoric acid
Anode catalyst	Pt	Ni + YSZ (ceramic)	Ni, Pt, Pd	Pt
Cathode catalyst	Pt	LSM (ceramic)	Pt, Pd, Ag, MnO_2	Pt
Typical fuels	Hydrogen	Natural gas, ethanol, biogas	Hydrogen, Ammonia	Hydrogen, Methanol
Typical operating temp	50-100°C	500-1000°C	40-75°C	150-200°C
Cell efficiency	50-60%	60%	60-70%	40-50%
Typical application power	1W to +1MW	10W to +1MW	500W to +200kW	100W to +400kW
Cell power density / Wcm^{-2}	2	1	1	0.3
Benefits	Quick start-up Transient response Small Lightweight	Fuel flexibility Efficiency	Quick start-up Efficiency Low cost Low temp operation	Operational stability Maturity Simple construction Impurity tolerance
Limitations	Hydrogen purity Humidity sensitivity Catalyst expense	Start-up time Transient response Expensive raw materials	Relatively large CO_2 sensitivity Liquid electrolyte management	Power densities Corrosive liquid & vapour Catalyst expense
Applications	Automotive Aerospace UAV MHE Portable power Stationary power	Stationary power Marine Combined Heat and Power	Military Stationary power	Stationary power Combined Heat and Power

Table 1 Fuel cell comparison

Proton Exchange Membrane (PEM) fuel cells have both high gravimetric and volumetric power densities, plus faster start-up and user load response times compared to other fuel cell technologies. These strong benefits allow for incorporation into a range of applications. Most obviously, the automotive sector utilises PEM fuel cells based on these fundamental characteristics and the adoption of PEM technology is well underway.

For stationary power applications, fuel cells not only provide reliable, clean power, but they can also remove the reliance on the existing power grid and therefore can be used as a sustainable microgrid case in many applications. The high-power density and scalability of the technology enables users to reach megawatt scale without the space constraints of other alternatives.

3. Stationary power application of fuel cells

CHP co-generation system architectures allow the capture and utilisation of the thermal power that is created as a by-product of an electricity generating reaction. By using this heat, CHP systems are a more efficient system configuration option.

Microgrids are energy independent systems that can be configured from one or more types of distributed energy. It is often common to find these microgrid systems in combination with renewable energy sources such as solar and wind, coupled with an appropriate energy storage technology e.g. batteries or hydrogen or both, thus generating a sustainable, green hub of power for users within a defined radius.

As the microgrids operate independently from the grid, they support both remote use cases and applications that require constant power with no risk of intermittency (i.e. high availability). They can also provide benefits of both boosting and balancing the supply of grid network power, as shown in Figure 1.

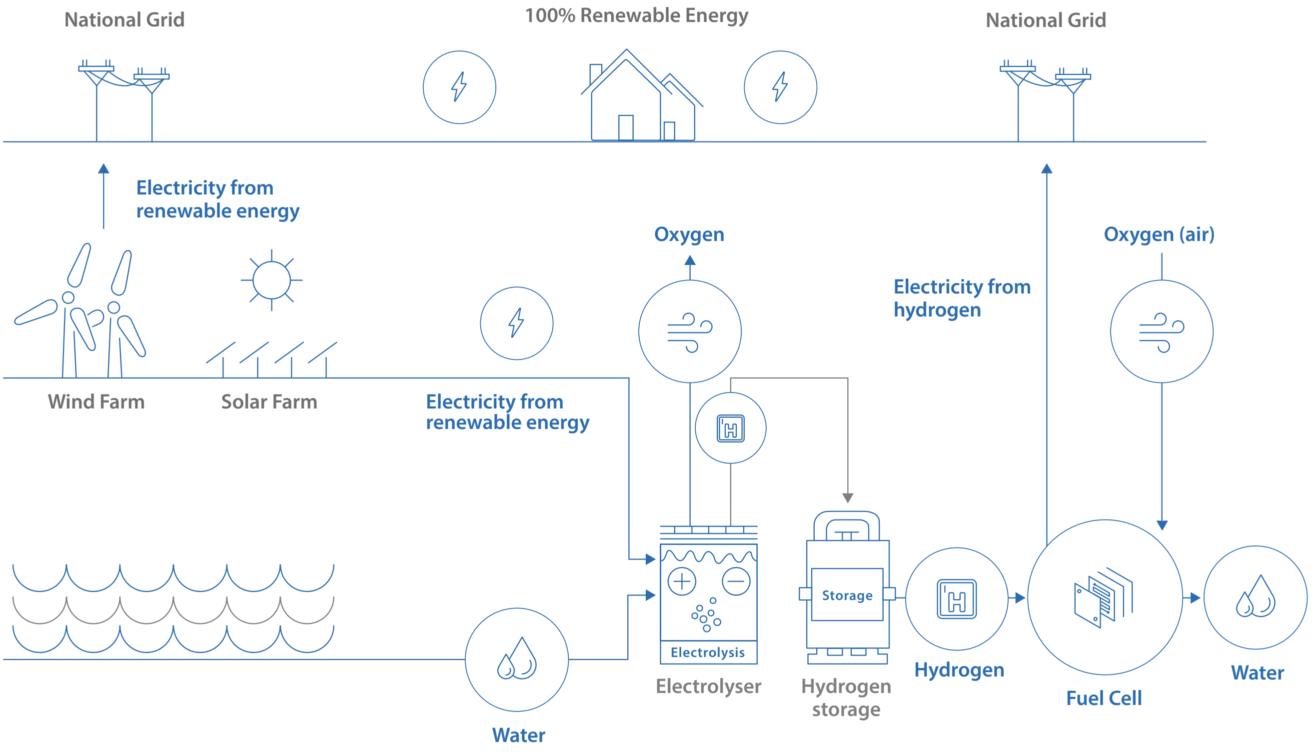

Figure 1 Typical microgrid

With PEM fuel cells being the preferred fuel cell technology of choice for the automotive sector, the opportunities to substantially reduce production cost and manufacture at scale are apparent. For example, the passenger vehicle market is a major volume opportunity with the California Fuel Cell Partnership targeting one million fuel cell electric vehicles by 2030[3]. Infrastructure needs to continually evolve to support increased volume uptakes and the associated manufacturing processes will positively impact costs and quality.

As a result, the cost of PEM technology will decrease and meet the cost targets for other applications such as stationary power. The latest PEM fuel cell system cost targets published by the US Department of Energy[4] and the UK Advanced Propulsion Centre[5] are $80/kW in 2030 and 2035 respectively.

It is expected that achieving cost reduction targets can also be realised through the implementation of national subsidies and grant mechanisms to facilitate supply chain growth and routes to volume production. For example, in the United States, the Regional Clean Hydrogen Hubs Program (H2Hubs) has been created with public funds of up to $7 billion from the US Department of Energy[6]. This initiative will be used to establish seven regional clean hydrogen hubs across the United States to form the foundation of a national clean hydrogen network that will contribute substantially to decarbonising multiple sectors of the economy. The hubs aim to put manufacturing and infrastructure in place to encourage economies of scale.

The US Inflation Reduction Act (IRA) is also supporting driving the reduction in the cost of hydrogen production, as this is obviously a key enabler in the scale-up and deployment of fuel cell technology.

The cost of hydrogen is one of the main influencers on the total cost of operations (TCO) in stationary power applications. The cost per kg is predicted to reduce over time as production costs reduce, primarily as the main production processes move from steam methane reformation to electrolysis from low-cost renewable electricity.

In 2021, the cost of hydrogen from renewable energy was around $5/kg[7] . The International Council on Clean Transportation (ICCT) estimates this cost to fall to $3.5/kg in the United States by 2030[8].

By 2050, PwC expects production costs of green hydrogen to be in the range of $1 to $1.62/kg in some parts of the Middle East, Africa, Russia, China, the US and Australia[9].

The price to the consumer will also include compression, transportation and dispensation, adding significantly to the production cost.

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[3] California Air Resources Board, https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf

[4] US DoE, U.S. National Clean Hydrogen Strategy and Roadmap (2023)

[5] Advanced Propulsion Centre UK, Fuel Cell Roadmap 2020 (2021)

[6] US DoE, https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving

[7] US DoE, https://www.energy.gov/eere/fuelcells/hydrogen-shot

[8] The International Council on Clean Transportation, https://theicct.org/the-price-of-green-hydrogen-estimate-future-production-costs-may24/#:~:text=The%20ICCT's%20central%20estimates%20of,compared%20with%20other%20published%20values

[9] PwC, https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

4. Fuel cell thermal management

The electrical power derived from the fuel cell also requires thermal energy to be dissipated. A higher electrical power output means more thermal energy to dissipate. With different fuel cell technologies and application cases comes different fuel cell system cooling requirements and configurations. There are three different methods of thermal management available for PEM fuel cells depending on the application and balance of plant requirements:

- Air cooling
- Liquid cooling
- Evaporative cooling

Air cooled fuel cells have the least complex associated system, where the air provided for the oxidant at the cathode is also the mechanism to remove the heat generated from the reaction. These systems tend to work well in the sub-kW to 20kW region. Above this, the air flow requirements become more demanding, particularly where packaging constraints become a major requirement.

Liquid cooled and evaporatively cooled systems have a significantly more complex system architecture than air cooled fuel cells, due to the nature of the coolant process. This precludes their use in low power applications as the balance of plant (mass, volume, cost) is disproportionate to the net electrical output. However, they are ideally suited to power outputs above 20kW .

The technology that allows the exploitation of higher stack power density and many benefits of heat management typically requires a slightly elevated air compressor loading due to the cathode design accepting both air & water, increasing the pressure ratio required and reducing overall system efficiency by up to 2%.

It is worth noting that assumptions have been made to generate the liquid cooled fuel cell values, primarily the use of consistent stack polarisation data. This enables like for like comparisons of the overall system performance.

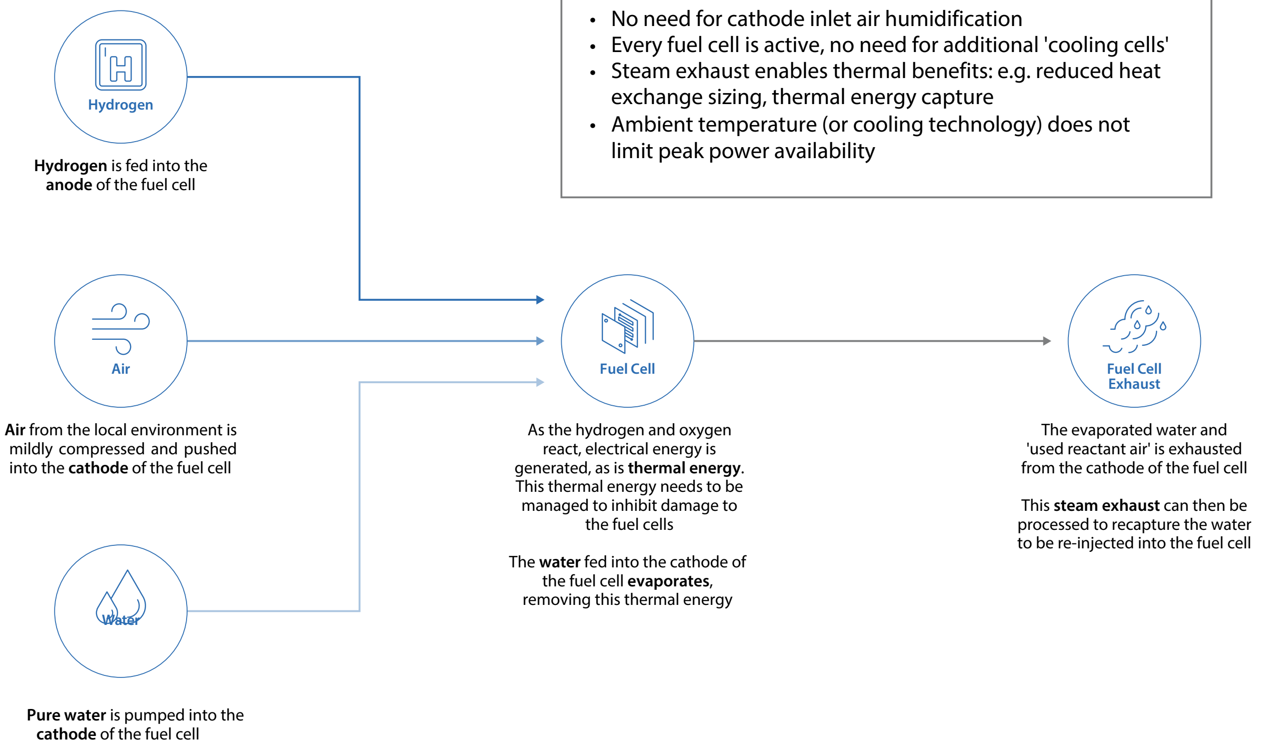
However, as evaporatively cooled fuel cell stacks do not require dedicated inter-plate cooling channels or humidifiers the efficiency deficit is offset by the increased power density and significantly reduced sized condenser versus heat exchanger, greatly improving the real world usability of the IE-DRIVE and IE-GRID system.

5. Evaporatively cooled fuel cell technology

Evaporatively cooled (EC) technology involves the injection of water directly into each active fuel cell. As this water evaporates, the thermal energy generated in the electrochemical reaction is absorbed during the water phase change. The evaporated water and oxygen depleted reactant air are exhausted from the cathode of the cells.

Key Benefits

- No need for cathode inlet air humidification
- Every fuel cell is active, no need for additional 'cooling cells'
- Steam exhaust enables thermal benefits: e.g. reduced heat exchange sizing, thermal energy capture
- Ambient temperature (or cooling technology) does not limit peak power availability



Hydrogen is fed into the **anode** of the fuel cell

Air from the local environment is mildly compressed and pushed into the **cathode** of the fuel cell

Pure water is pumped into the **cathode** of the fuel cell

As the hydrogen and oxygen react, electrical energy is generated, as is **thermal energy**. This thermal energy needs to be managed to inhibit damage to the fuel cells

The **water** fed into the cathode of the fuel cell **evaporates**, removing this thermal energy

The evaporated water and 'used reactant air' is exhausted from the cathode of the fuel cell

This **steam exhaust** can then be processed to recapture the water to be re-injected into the fuel cell

Figure 2 Evaporatively cooled fuel cell

Due to the cell cooling mechanism employed in evaporatively cooled fuel cells, the system balance of plant required with the fuel cell can be simpler than that used with a conventional liquid cooled (LC) fuel cell, a simplified schematic is shown in Figure 3. The core fluidic elements in an evaporatively cooled fuel cell system can be summarised as:

- **Evaporatively cooled fuel cell stack:** The heart of the system, converting chemical energy to electrical and thermal energy
- **Air compressor:** Providing the cathode of the fuel cell stack with air, to be used as the oxidant in the reaction

- **Hydrogen regulation:** Providing the anode of the fuel cell stack with the hydrogen fuel
- **Water tank and pump:** A buffer storage tank holding the water and a pump to supply water to the fuel cell stack and achieve evaporative cooling
- **Condenser and water separators:** A heat exchanger to condense steam in cathode air exhaust back to liquid and for it to be captured and returned back to the water tank for further fuel cell supply

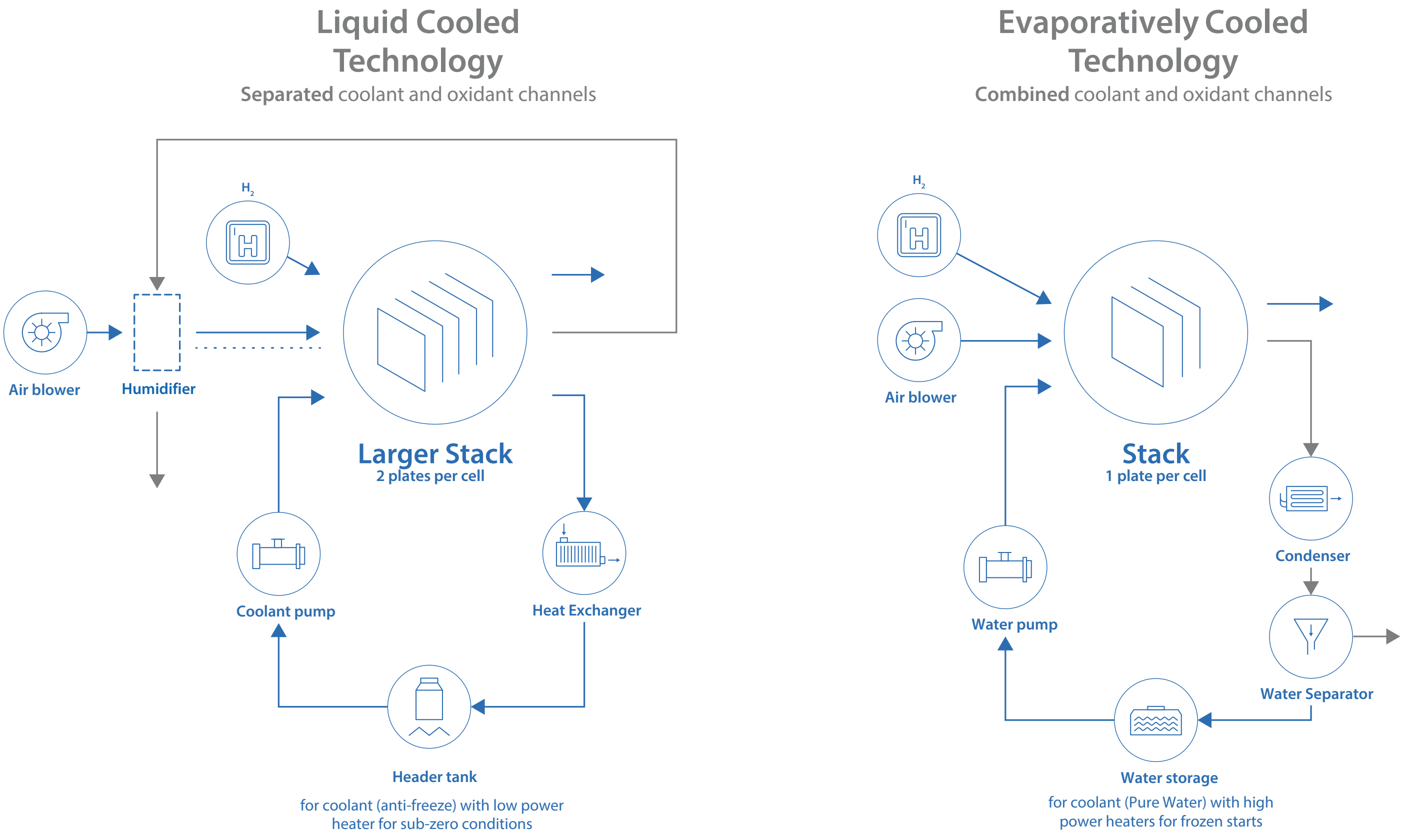


Figure 3 Comparison of evaporatively cooled and liquid cooled fuel cell technology

Figure 4 shows a basic architectural layout of the IE-GRID standard system architecture, with graphical focus just on the cathode fluidic elements (air and water). A glossary for identifying the key system components is shown for reference in Appendix 1.

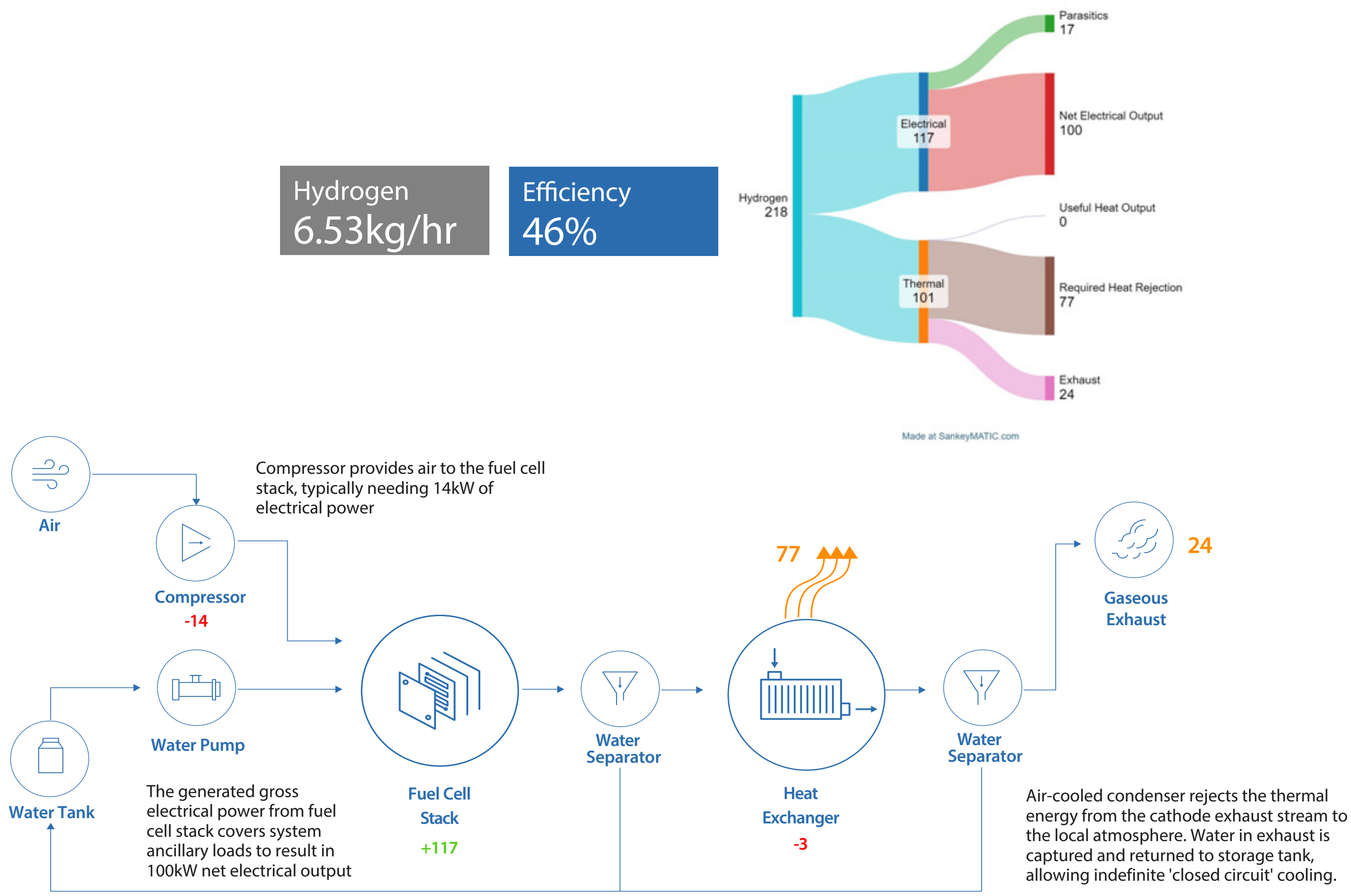
This standard configuration utilises the IE-DRIVE HD100 system, the highlighted numbers are:

- Electrical power consumption i.e. parasitic loss represented by a negative number (red text)
- Electrical power generation represented by a positive number (green text)
- Thermal power generated (amber text)

To support comparisons with alternative configurations, the simulations have been set to meet a modelled 100kW electrical net output.

In the standard system, shown in Figure 4, the fuel cell stack is producing a gross electrical output of 117kW which is used to power the compressor (consuming 14kW) and the condensing heat exchanger fans (consuming 3kW), resulting in a 100kW net electrical output.

The fuel cell also produces 101kW of thermal power, 77kW of which needs to be rejected to condense the required amount of steam to liquid, for injection back into the fuel cell stack to ensure continuous operation without the cell overheating, and the balance of 24kW is ejected out of the exhaust. The resultant system efficiency of 46% is a simple calculation of system useful output power divided by the hydrogen consumed.



Compressor provides air to the fuel cell stack, typically needing 14kW of electrical power

The generated gross electrical power from fuel cell stack covers system ancillary loads to result in 100kW net electrical output

Air-cooled condenser rejects the thermal energy from the cathode exhaust stream to the local atmosphere. Water in exhaust is captured and returned to storage tank, allowing indefinite 'closed circuit' cooling.

NB: Values shown are in kW

Figure 4 IE-GRID standard (100kW)

Benefits associated with evaporatively cooled fuel cell design include:

- Each individual fuel cell is fully humidified via the injection of liquid water, eliminating the need for a large external humidifier or more complex cell component design to allow for intercell humidification.
- Power density (in terms of both kW/kg and kW/L) can be increased at the fuel cell stack level through the removal of 'cooling cells'. Every cell is active in terms of electrical power generation, and all plates are true bipolar plates.
- The condensing heat exchanger frontal area can be 27% less[10] than that of a conventional liquid cooled system at an equivalent electrical power rating.
- Better durability during transient loads can be achieved as a lower thermal inertia is present and direct water injection yields better immediate and dynamic hydration.

Two unique benefits of evaporatively cooled architecture will be explored further in this document:

- Independence from ambient temperature
- Provision of a higher grade of heat

Intelligent Energy has 400 patents around its EC technology.

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[10] Fly, A. & Thring, R.H. (2016) 'A comparison of evaporative and liquid cooling methods for fuel cell vehicles', International Journal of Hydrogen Energy Volume 41, Issue 32, pp. 14217-14229

6. Independence from ambient temperature

Conventional liquid cooled fuel cells use a recirculated liquid coolant (e.g. glycol) to remove the thermal energy generated by the electrochemical reaction. Prior to the coolant re-entering the fuel cell, this liquid needs to be cooled to an acceptable temperature as the returning coolant temperature is a limitation on the fuel cell available electrical power.

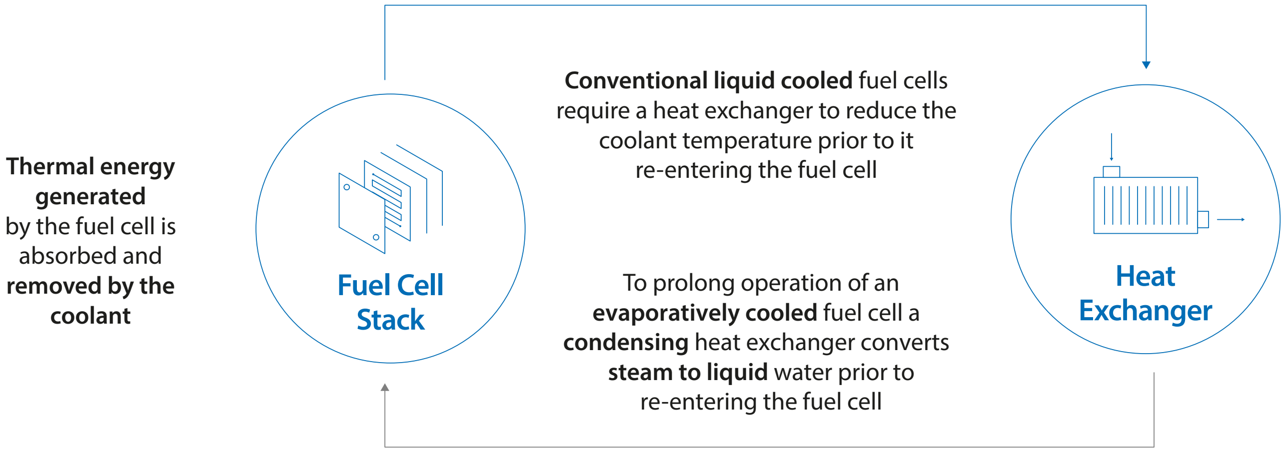


Figure 5 Fuel cell management loop

Evaporatively cooled fuel cells only require the water coolant to be liquid at any temperature (i.e. not vapour). This de-links the available fuel cell electrical power output from the coolant temperature. For automotive applications, this allows for peak electrical powers to be obtained which are far higher than standard operational or "rated" electrical powers. Also, for stationary power applications it can allow for the removal of the heat exchanger entirely by incorporating a minor 'top-up' flow of water.

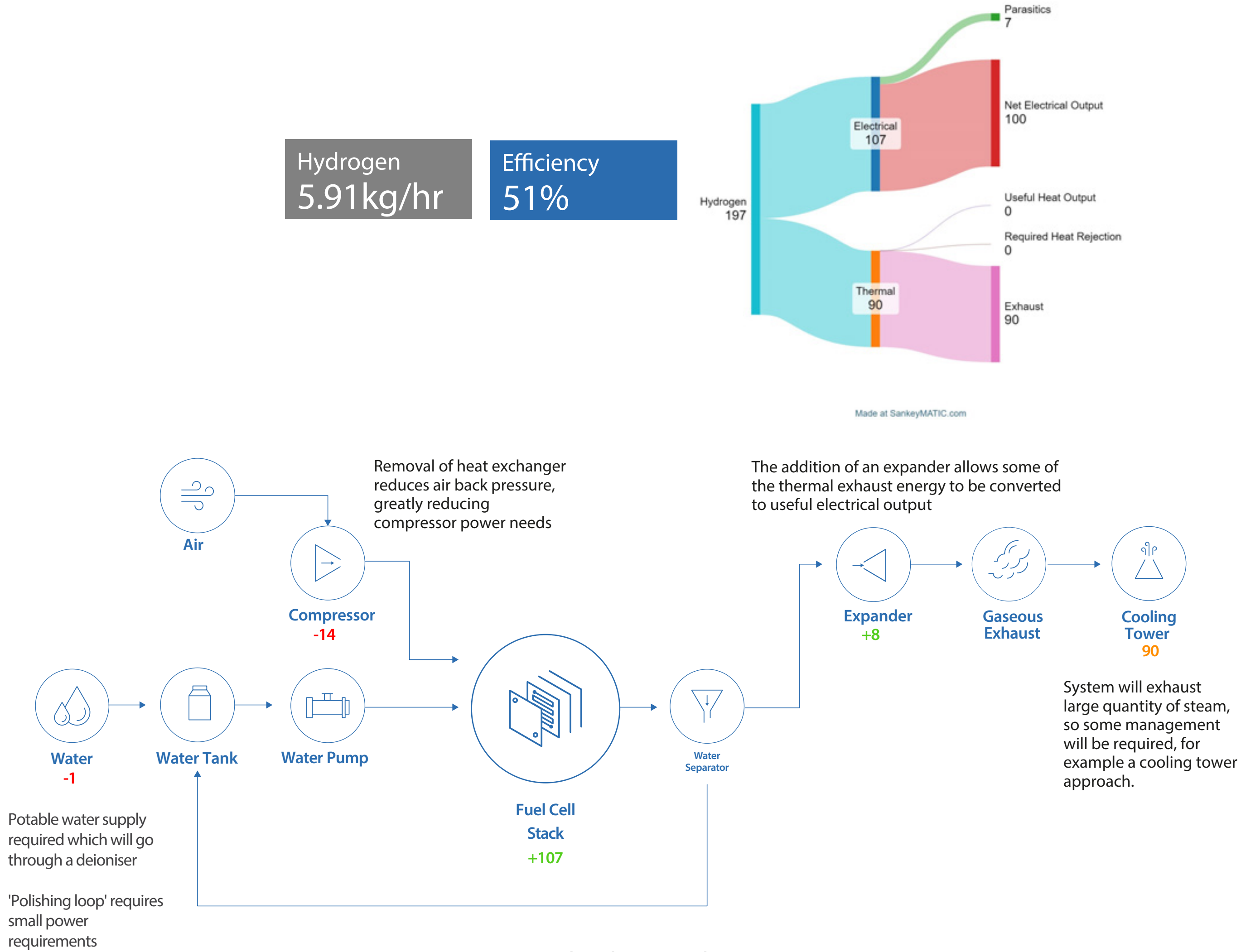
Removal of the heat exchanger

As previously stated, as long as the fuel cell is supplied with water at the required flow rate, the exhausted thermal power may be dissipated away from the fuel cell stack and system, thus removing the heat exchanger from the fuel cell system circuit. To achieve this, an amount of water must be provided to the fuel cell system for the cooling, as shown in Figure 2, for example at approximately 125kg/hr (2L/min) for 100kW net electrical output.

The simplest form of condensing heat exchanger is an air-cooled design, and simply operates by passing air over the heat exchanger (the cold side) to absorb heat from the fuel cell exhaust stream (the hot side). Thus, the temperature of the air (ambient) plays a major role in the performance of the heat exchanger; removal of the need for this heat exchanger provides an independence from the ambient temperature.

Removing the fuel cell reliance on a heat exchanger yields the benefits of independence from the ambient conditions, but also a significant uplift in system efficiency. The air compressor that supplies air for the fuel cell reaction no longer has to overcome the back pressure restriction of the heat exchanger onto the fuel cell cathode. As the air compressor is the largest parasitic load on the fuel cell system supplying oxygen for the cathode reaction, then any reduction in power consumed by the compressor greatly improves overall fuel cell system efficiency and operating cost due to lower hydrogen consumption.

Furthermore, due to the nature of the evaporatively cooled fuel cell "exhausting" all the thermal energy produced during the reaction, via heated air and steam, there is the potential for recovery of energy. This can be realised via a turbo-expander, effectively reducing the electrical demand of the compressor by ~40%.



Removal of heat exchanger reduces air back pressure, greatly reducing compressor power needs

The addition of an expander allows some of the thermal exhaust energy to be converted to useful electrical output

System will exhaust large quantity of steam, so some management will be required, for example a cooling tower approach.

Potable water supply required which will go through a deioniser

'Polishing loop' requires small power requirements

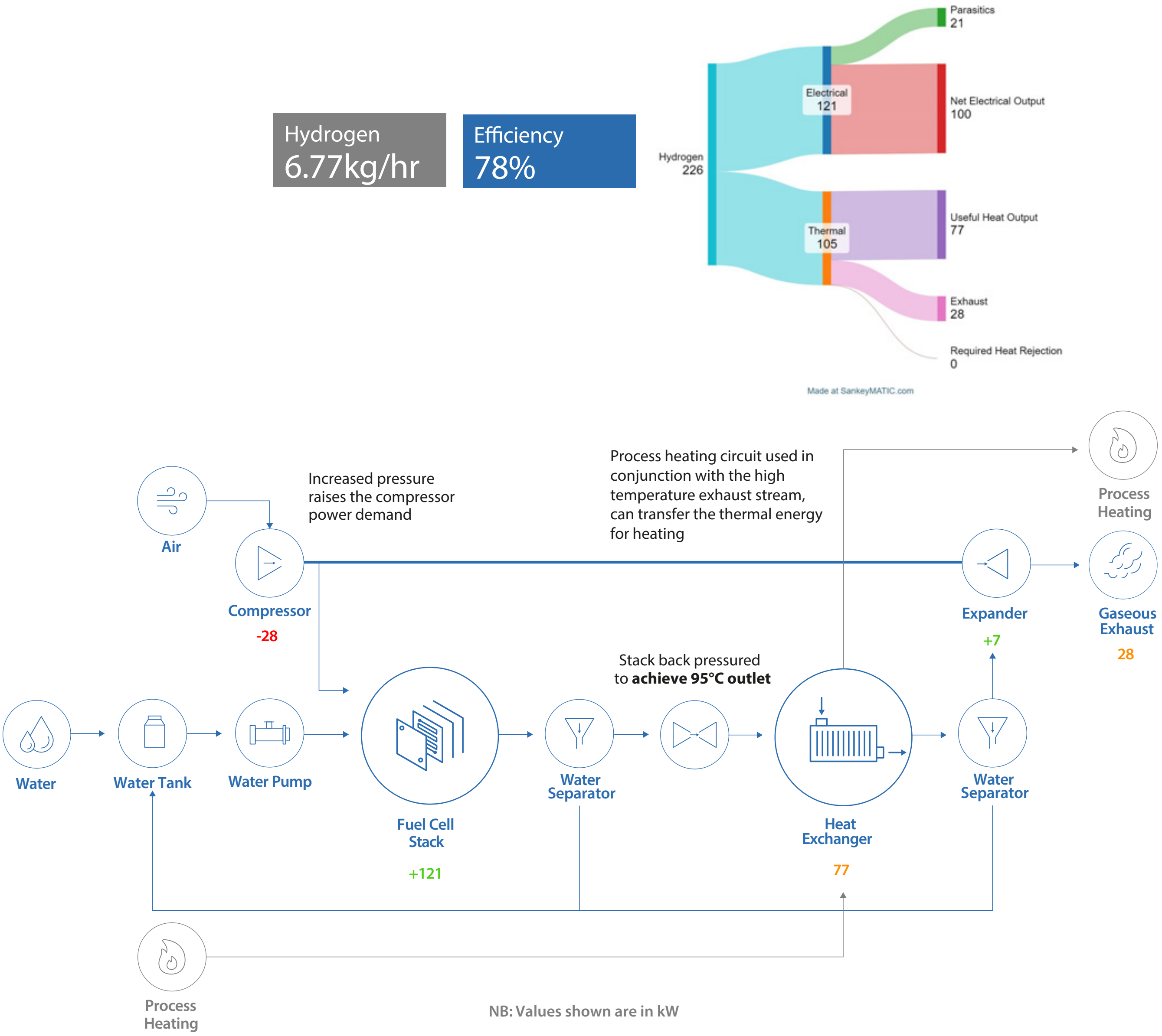
NB: Values shown are in kW

Figure 6 IE-GRID removal of condenser (100kW)

7. Provision of a higher grade of heat

The cell temperature of PEM fuel cells is typically 75°C (±10°C), making the waste heat from the reaction low-grade, meaning it is more difficult to re-use efficiently due to the low temperature differential to the process heating requirement. For reference, high-grade heat that is obtained from the combustion of fossil fuels can be typically >400°C. To enable the use of PEM fuel cell waste heat, the temperature must be raised to meet the process heat demands.

An approach to raising the cell temperature is to increase the back pressure of the cathode. A limitation to this approach includes increased pressure demands on the cathode air compressor, and fuel cell material temperature considerations. The increased compressor power demand is again partially offset by a turbo-expander recovering energy. The use of the waste temperature for process heating is now considered additional useful output energy, and therefore adds significantly to the overall system efficiency, as shown in Figure 7.



NB: Values shown are in kW

Figure 7 IE-GRID cathode back pressure (100kW)

A second option is possible due to the nature of the evaporatively cooled fuel cell raising the exhaust temperature. The steam content of the exhaust may be passed through a further stage of compression, in turn raising the temperature of the exhaust gases without affecting the cell temperature or impacting the cell material selection. This gives the application access to the thermal energy generated by the fuel cell reaction at a far more usable temperature of ≥100°C. With this higher hot-side temperature to the heat exchanger, it can transfer substantial energy to heating circuits as shown in Figure 8.

As this is achieved through a further stage of compression, and therefore increased parasitic loading, hydrogen consumption will be increased. However, as the typically “inefficient” heat losses are being reclaimed, the overall system efficiency increases.

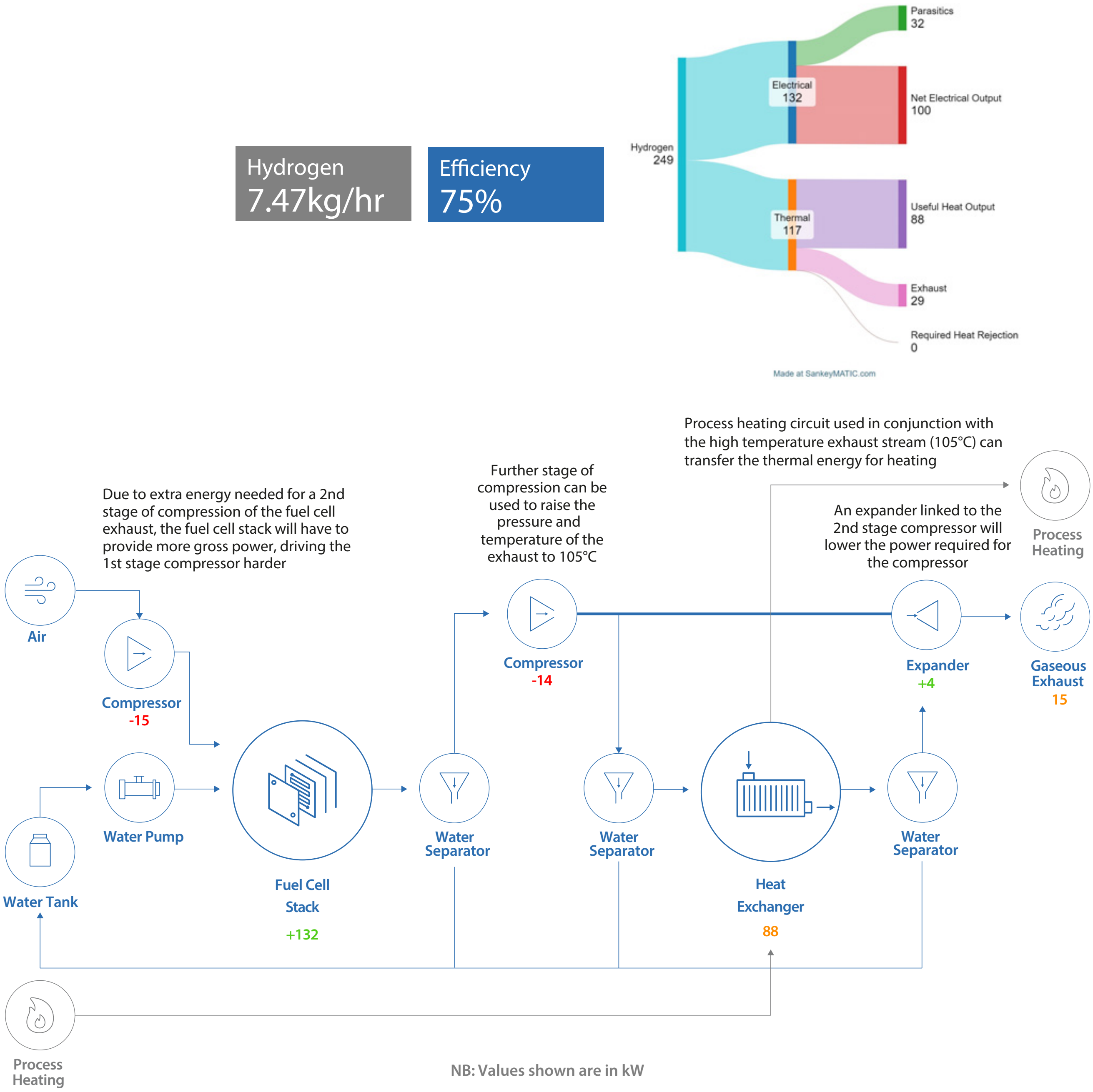


Figure 8 IE-GRID exhaust compression (100kW)

8. Modularity of IE-GRID

There is significant global demand for containerised fuel cell-based solutions for use as backup power systems, for grid balancing or as permanent power sources, with over 550MW of stationary fuel cells already installed in the United States providing clean, distributed power[11].

A key benefit of fuel cell technology and Intelligent Energy's PEM fuel cell products is scalability through modular design. In particular, IE-GRID™ is based on the commercially-available IE-DRIVE HD100 product (Figure 9) utilising two core systems in a suitable configuration for power generation to form a 200kW module (Figure 10). This can enable Intelligent Energy to supply to a wide range of industries, matching power to demand requirements up to megawatt scale with containerised solutions and subsequent deployable scaling of the containers as required. The use of PEM fuel cells in the heavy duty commercial vehicle segment has driven particular characteristics such as prolonged continuous high-power operation, which is highly applicable to stationary power applications.

Figure 9 IE-DRIVE HD100

This 200kW building block in turn can be scaled, using common system balance of plant components to achieve higher power outputs as required by the application, such as 400kW installed within a standard 10' shipping container (Figure 11), and 1MW within a standard 30' shipping container (Figure 12).

The scaling can be done simply, with straight repeats of the 200kW building block allowing for flexibility in output power configuration. Each 200kW unit, although part of a larger overall system, can produce variable load as demanded and work independently of other units allowing for redundancy in the cases of maintenance. The system can be modified to achieve further efficiency gains and cost improvements (CAPEX and OPEX) through selection of appropriately sized components, with a common fluid management system being used for multiple 200kW units, e.g. twin-screw compressors capable of efficiently providing a constant high quantity of reactant air.

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[11] Fuel Cell & Hydrogen Energy Association, https://www.fchea.org/stationary

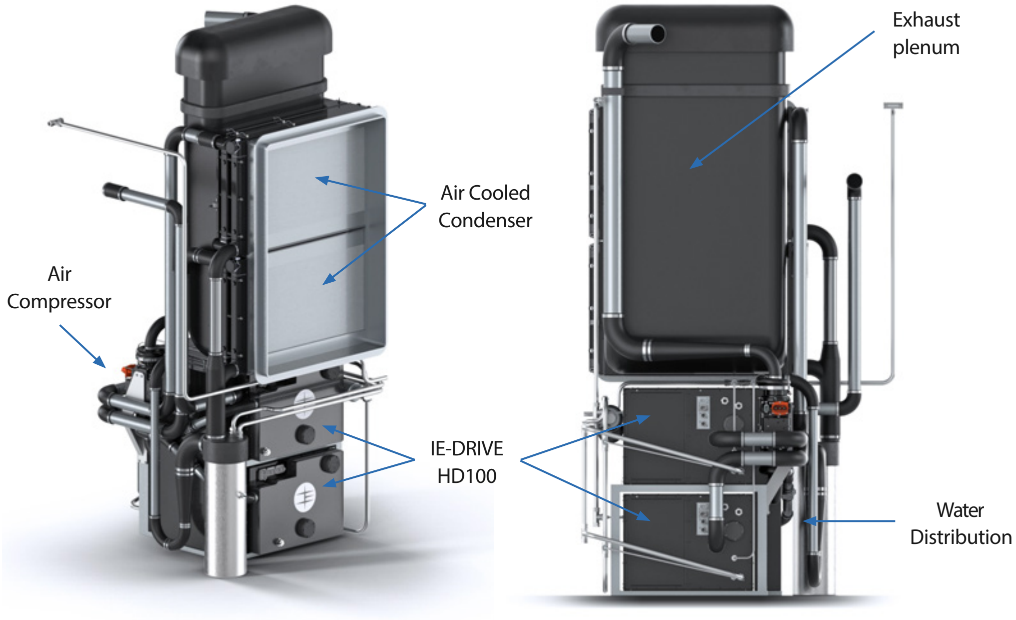

Figure 10 IE-GRID 200kW building block

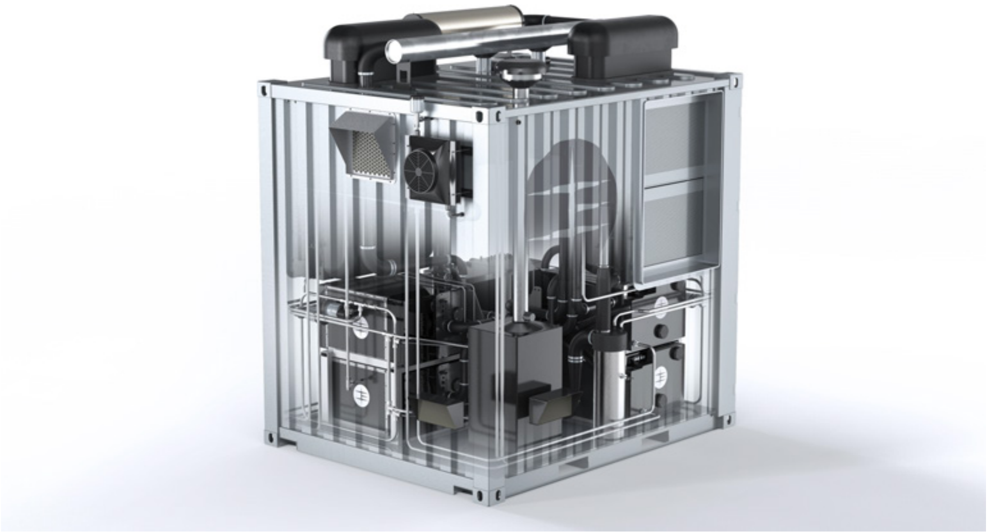

Figure 11 IE-GRID 400kW 10’ container concept

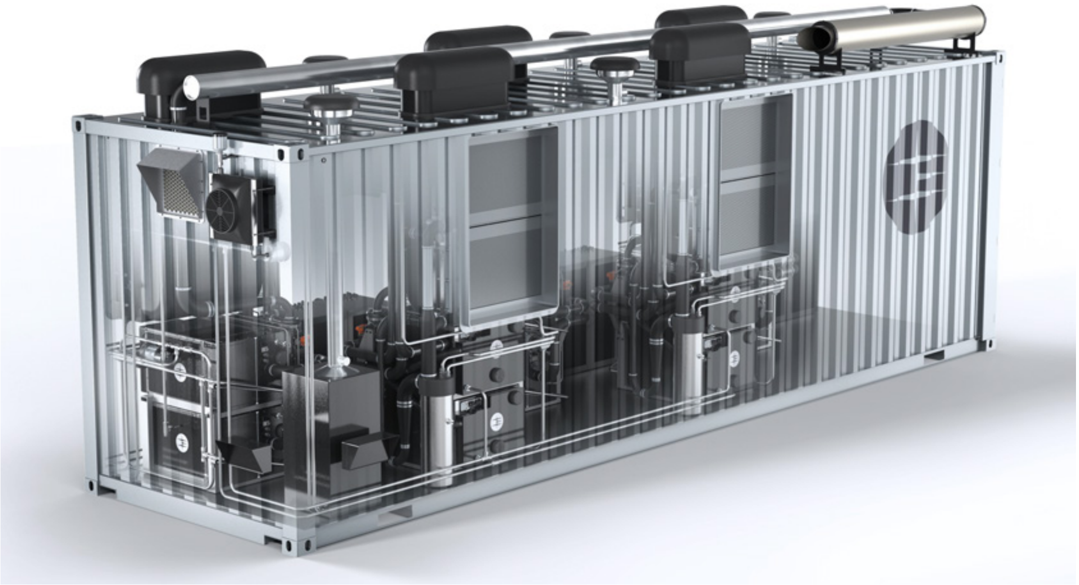

Figure 12 IE-GRID 1MW 30’ container concept

9. Conclusion

There is a clear need for scalable, responsive and reliable energy sources for stationary power applications. Fuel cells play a key role in achieving the decarbonisation of the sector while meeting these needs.

PEM fuel cells show clear advantages over alternate fuel cells. They offer:

- **A compact footprint and flexible modularity**
  This allows for specific power demands and duty cycles to be met with the correctly sized unit, and portability of the genset to be allowed for
- **Economies of scale directly leveraged from automotive volumes**
  PEM fuel cells will benefit from decreased manufacturing costs and increasing quality through the high volumes driven by the automotive sector, which the stationary sector can exploit
- **A rapid start up time and response**
  In combination with micro-grids, the fuel cell can switch in and out when required, enabling non-reliable forms of renewable energy to be utilised and clean power availability to be maintained

Configuration	IE modification	Useful heat available?	Hydrogen Consumption [kg/hr]	System Efficiency [%]	Cost [$/kWh]	
					$12/kg H_2 Typical target H_2 cost	$7/kg H_2[12]
IE-GRID Standard	n/a	No, temp too low	6.5	46	0.78	0.46
IE-GRID Removal of Condenser	Expander Vented exhaust	No, exhaust vented	5.9	51	0.71	0.41
IE-GRID Cathode Back Pressure	Back pressure on stack Liquid cooled heat exchanger Vented exhaust	Yes, 80kW 95°C	6.8	78	0.46	0.27
IE-GRID Exhaust Compression	Compressor post stack Liquid cooled heat exchanger	Yes, 90kW 105°C	7.5	75	0.48	0.28
Typical Conventional Liquid Cooled Fuel Cell	n/a	No, temp too low	6.4	Up to 2% difference	0.77	0.45

Table 2 Summary of IE-GRID configurations (data per 100kW)

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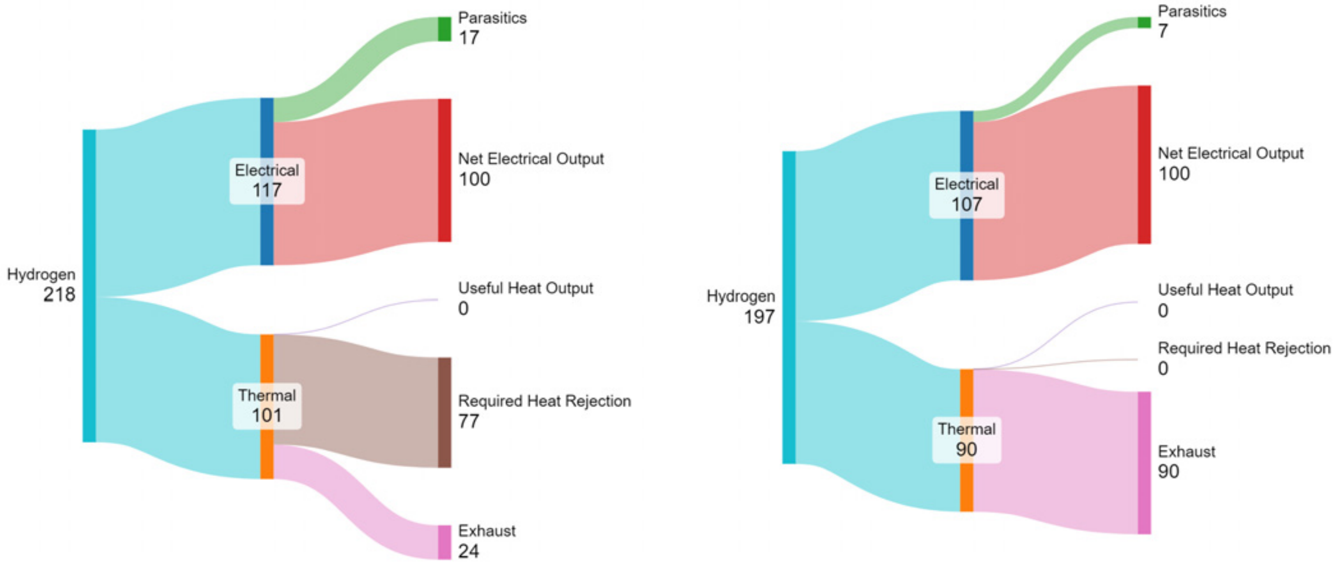
[12] US DoE, Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan (2024)

All fuel cell systems can be optimised to meet the most efficient operating point and component selection, such as sizing the fuel cell stack. However, Intelligent Energy's IE-GRID product can offer a significant differentiator, in terms of the unique evaporatively cooled fuel cell exhaust, that sets it apart from conventional liquid cooled PEM fuel cells, as summarised in Table 2.

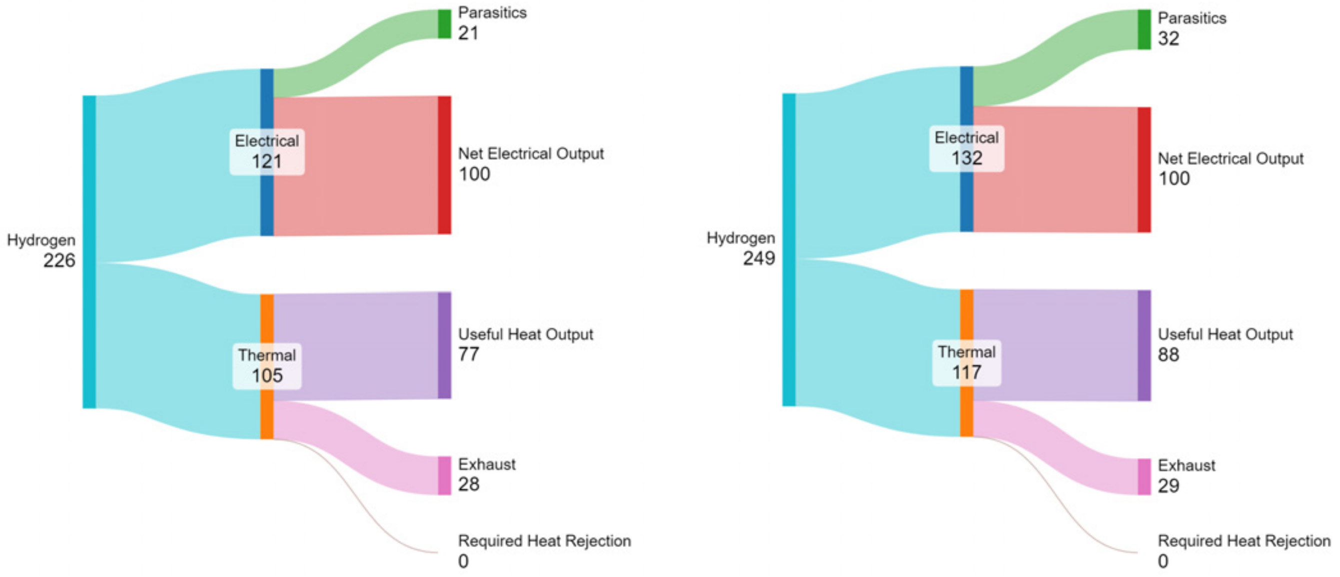
- **A higher-grade heat is achievable**
  IE-GRID offers a more attainable CHP system, dramatically increasing efficiency of hydrogen conversion to useable energy (electrical and thermal). A 1MW electrical genset could provide up to 800kW of thermal power for an additional cost of 4kg/hr of hydrogen (compared to a conventional liquid cooled fuel cell providing only electricity), saving $150,000 annually over additional gas costs (assumed $0.05/kWh).
- **Independence of ambient conditions**
  The removal of the need to condition the fuel cell coolant allows IE-GRID to be used in a wide range of ambient conditions without power limitations, with significant improvements in efficiency. For a 1MW genset, IE-GRID hydrogen consumption can consume 5kg/hr less than the equivalent conventional liquid cooled fuel cell system, saving in excess of $300,000 per year.

10. Appendix



IE-GRID standard

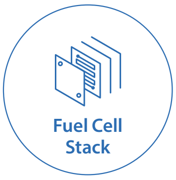
IE-GRID removal of condenser



IE-GRID cathode back pressure

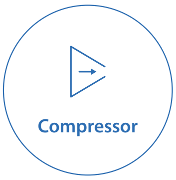
IE-GRID exhaust compression

Figure 13 Energy balance (units kW)



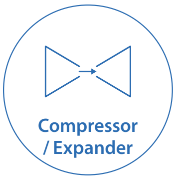
Fuel Cell Stack

A device that converts chemical energy to electrical and thermal energy, by combining hydrogen and oxygen (from air)



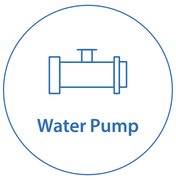
Compressor

A device that supplies air flow to a fuel cell stack to be used as the oxygen supply in the fuel cell reaction



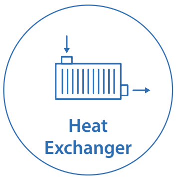
Compressor/Expander

As compressor (above), however with an expander that acts like a turbocharger, driven by exhaust gases to reclaim energy



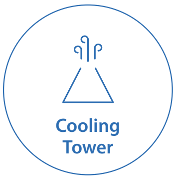
Water Pump

A device to move water from a storage tank to the fuel cell stack to provide cooling of the fuel cell reaction



Heat Exchanger

A device used to condense water vapour in the fuel cell exhaust to liquid water. Typically uses air flow act as the coolant



Cooling Tower

As the heat exchanger above, however using evaporation to cool

Water Separator

A device to remove liquid water from the gaseous exhaust stream and return it to the water tank

Water Tank

A buffer tank for the water used to cool the fuel cell stack

Figure 14 Glossary for schematics

IE-GRID™

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