POWERING THE FUTURE

PEM Hydrogen Fuel Cell Powerhouse Sizing and Application Considerations

White paper by
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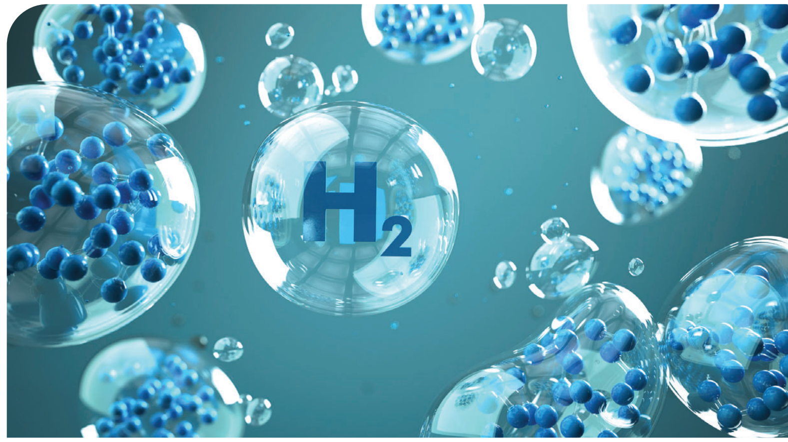
While traditional fossil fuel generators continue to play a significant role in ensuring energy resilience, there has been a notable surge in interest in alternative fuels such as hydrogen, particularly in stationary emergency and prime applications. For operators prioritizing on-site emission-free solutions, fuel cell technology emerges as a compelling choice. Engineered and constructed to meet rigorous international standards, fuel cells present a promising pathway toward sustainable power generation.

This paper constitutes the second installment of a three-part series on hydrogen technology. It provides a comprehensive exploration of Proton Exchange Membrane (PEM) hydrogen fuel cell technology. The paper delves into the intricate operational mechanisms of PEM fuel cells, addresses spatial considerations, hydrogen leak detection and control, derates, sizing considerations, and explores the codes and standards relevant to PEM fuel cells.

Fuel cell powerhouse benefits and applications:

As we venture into a new era of clean and efficient energy solutions, hydrogen fuel cell power systems are at the forefront of sustainable technology. The International Energy Agency (IEA) projects a rapid increase in global electricity demand over the next three years, driven by the accelerating transition to clean energy. Hydrogen fuel cells offer numerous benefits for diverse applications, revolutionizing our approach to energy generation and consumption.

These advanced systems are used in two main stationary applications: behind-the-meter (BTM) and front-of-the-meter (FTM). BTM applications deploy energy solutions on the customer's side of the meter, providing zero-emissions solutions for businesses. Examples include commercial and industrial facilities, electric vehicle (EV) charging stations, and hydrogen refueling stations. FTM applications involve large-scale integration within utility infrastructure, offering a zero-emission alternative to fossil fuel-based peaker plants and utility power plants.



From mission-critical operations to utility grid support, and from commercial and industrial sectors to EV charging stations, the advantages and potential applications of hydrogen fuel cell technology span various sectors. Their promise of a transformative impact on transportation, industry, and beyond is evident, heralding a future where sustainability and innovation seamlessly converge. Some of these benefits and applications are:

- Zero emissions, ensuring a clean environmental footprint.
- Swift system startup (seconds) for immediate use.
- Enhanced transient performance, augmented by integrated battery storage.
- Black start capability for reliable operation in emergency scenarios.
- Electrical efficiency spanning from 45% to 55%, maximizing energy utilization.
- Capacity firming support, bolstering grid stability.
- Seamless integration with renewable energy sources and microgrids.
- Versatile off-grid applications for remote power needs.
- Tailored solutions for data centers, ensuring uninterrupted operations.
- Efficient EV charging infrastructure for sustainable transportation.
- Reliable power supply for construction sites, fostering productivity.
- Flexible rental applications, catering to diverse energy requirements.

From a DC fuel cell to a PEM AC powerhouse:

The construction of a hydrogen AC powerhouse begins with the assembly of fuel cells, which are integrated with supplementary components to create fuel cell modules capable of generating specific DC kW outputs, such as 30 kW, 45 kW, and 150kW. These modules are organized into racks to optimize power density. Multiple racks, alongside an energy storage system, power conversion system, functional and safety control system, and cooling system, are then housed within an enclosure, resulting in the completion of the AC powerhouse. See image 1 and 2.

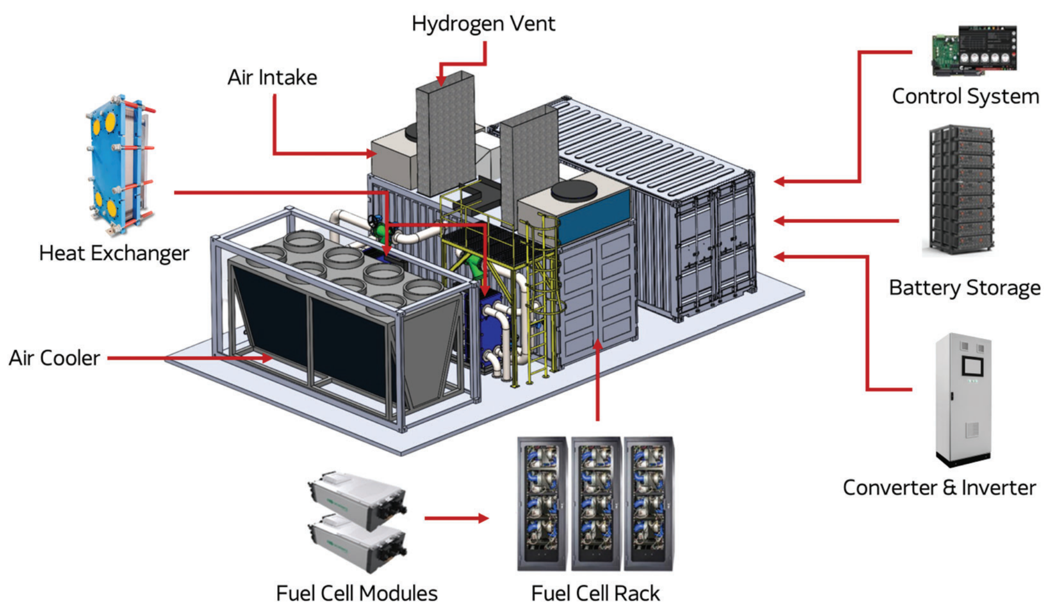


Image 1: Fuel Cell Powerhouse Elements

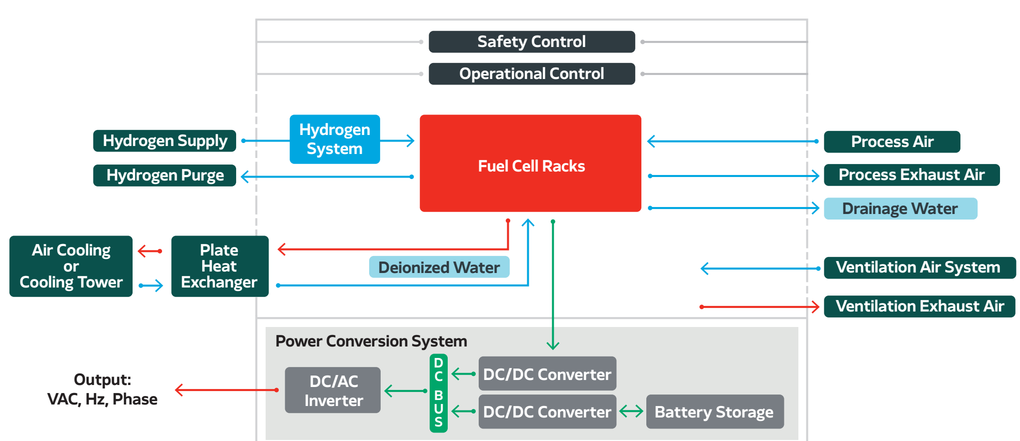


Image 2: Fuel Cell Powerhouse Functional Block Diagram

PEMFC

A Proton Exchange Membrane Fuel Cell (PEMFC) consists of several key components that work together to convert chemical energy into electrical energy. Here are the main components of a PEMFC (see images 3 and 4):

1. **Anode:** The anode is where hydrogen fuel is supplied to the fuel cell. It is typically made of a porous material coated with a catalyst, often platinum, to facilitate the electrochemical oxidation of hydrogen molecules into protons (H+) and electrons (e-).
2. **Cathode:** The cathode is where oxygen from the air is supplied to the fuel cell. Similar to the anode, the cathode is also porous and coated with a catalyst, usually platinum, to facilitate the electrochemical reduction of oxygen molecules by combining with electrons and protons to form water.
3. **Proton Exchange Membrane (PEM):** The PEM is a solid polymer electrolyte membrane that separates the anode and cathode compartments of the fuel cell. It selectively allows protons to pass through while blocking electrons, facilitating the migration of protons from the anode to the cathode while preventing the mixing of fuel and oxidizer gases.
4. **Bipolar Plates (BPP):** Bipolar plates are conductive plates that serve as current collectors, distributing electrical current generated by multiple cells in a fuel cell stack. They also provide channels for the flow of reactant gases (hydrogen and oxygen) to the respective electrode surfaces and facilitate the removal of water produced during the electrochemical reaction.
5. **Gas Diffusion Layers (GDLs):** Gas diffusion layers are porous materials placed between the electrodes and the bipolar plates. They help distribute the reactant gases evenly across the electrode surfaces and provide pathways for the removal of water produced during the electrochemical reaction.
6. **End Plates and Seals:** End plates enclose the fuel cell stack and provide structural support, while seals prevent gas leakage between the different compartments of the fuel cell.

These components work together in a PEMFC to facilitate the electrochemical reactions that produce electricity, with hydrogen fuel and oxygen from the air as inputs, and water and electrical energy as outputs.

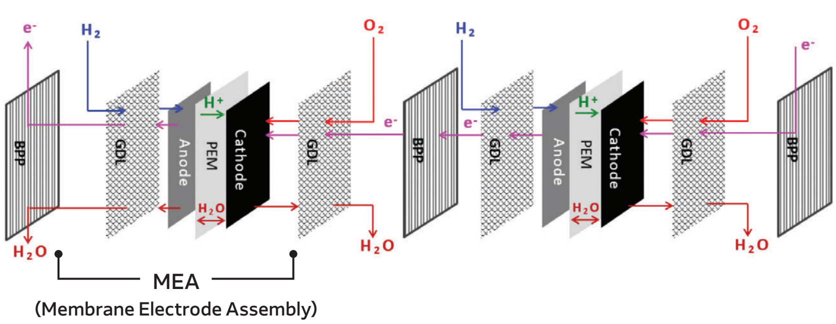


Image 3: Components of a Fuel Cell

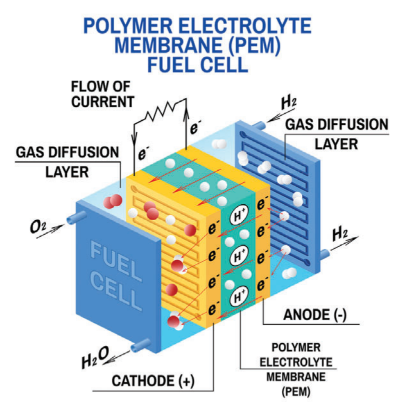


Image 4: PEM Fuel Cell

FUEL CELL MODULE

The various components outlined in the preceding section, coupled with an operational and safety electronic control unit, are combined to create a larger, scalable power-generating system known as a fuel cell module. See image 5 for an example of the Accelera by Cummins 45kW fuel cell module.

It's imperative to recognize that a fuel cell operates primarily as a current source rather than a voltage source. Typically, a single fuel cell maintains a voltage of around 0.6 to 0.8 volts, although this voltage diminishes over time with usage. Consequently, to sustain the requisite power output demanded by the load, the current must increase proportionally as the fuel cell ages. To achieve a higher DC output voltage, fuel cells are often stacked in series, a concept to be elaborated upon in the second installment of this paper series. In this specific example (Image 5) the module specifications are:

- Operating current: 0 to 450A DC
- Operating voltage: 88 to 180V DC
- Peak efficiency: 60%
- Response time from off to rated power: ≤ 30 seconds
- Response time from minimum to rated power: ≤ 5 seconds
- Response time from rated to minimum power: ≤ 1 second

Image 5: 45kW Fuel Cell Module

FUEL CELL RACK

Image 6: Example of a 120kW DC Fuel Cell Rack

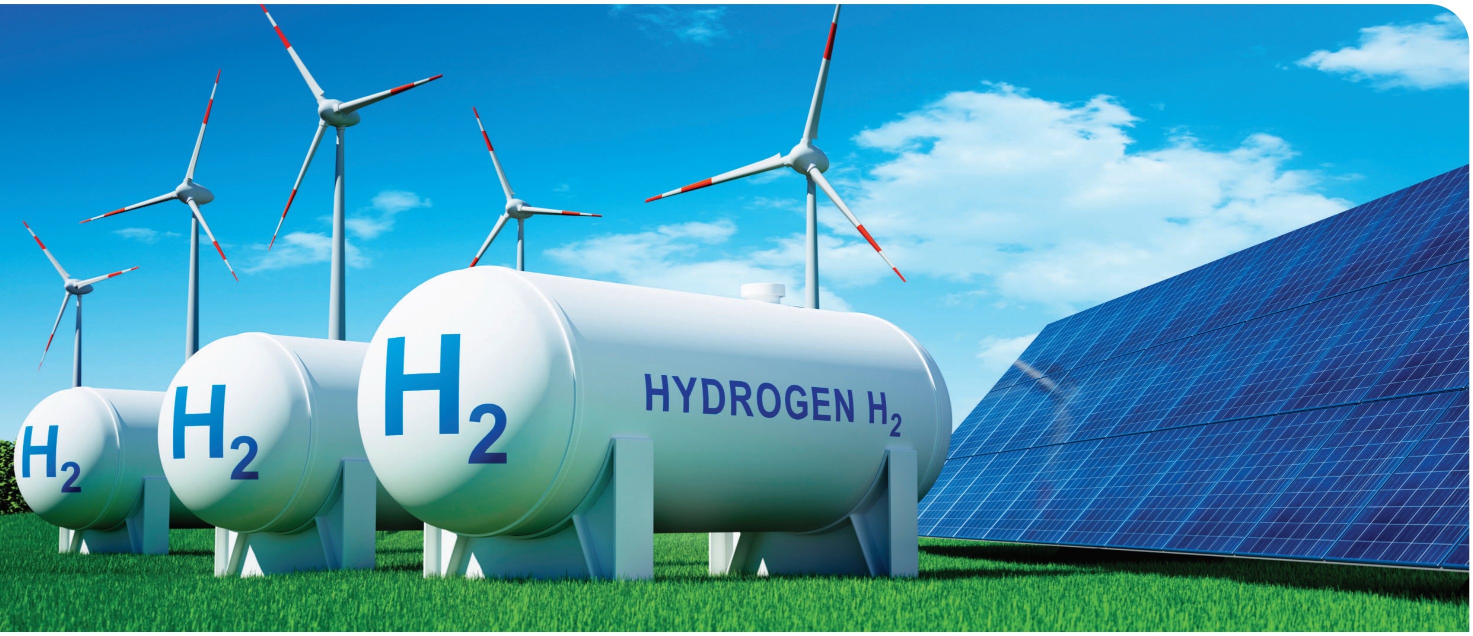
In specific scenarios, a single fuel cell module may fall short of meeting the required power needs. Consequently, multiple fuel cell modules can be consolidated into a rack, complemented by fuel, air, and water management systems, coolant pumps, as well as control hardware and software. This approach significantly augments power density, ensuring adequate power output for the intended application. For instance, this particular fuel cell rack can accommodate up to four modules, delivering a combined 120 kW of DC power. See image 6.

ENERGY STORAGE:

A fuel cell power system often incorporates an energy storage system, such as Lithium Titanate Oxide (LTO) or Lithium Iron Phosphate (LFP), to serve multiple functions. Primarily, the energy storage provides rapid bursts of power during block-loading of the fuel cell, significantly enhancing the system's transient response. Additionally, it enables black start capability and offers instant power, particularly after extended periods of downtime when the powerhouse may need up to 5 minutes to cycle through safety protocols before starting.

LTO batteries are frequently utilized due to their high discharge rate, typically ranging from 6C to 10C. This capability enables them to deliver strong bursts of power swiftly, ensuring an instantaneous transient and ample power to handle various load steps. This high discharge advantage translates to a smaller footprint for energy storage compared to LFP systems.

Selecting the appropriate energy storage technology for the powerhouse system depends on the specific requirements of the application.



POWER CONVERSION SYSTEM:

The voltage of a single PEM fuel cell typically hovers around 0.7VDC. However, when multiple cells are linked in series to form a fuel cell module, the resultant output voltage typically ranges, for example, from 90 to 180 VDC. As most applications necessitate an AC output voltage, various power electronics components—such as a DC-DC converter, DC bus, DC-AC inverter, and isolation transformer —are integrated to yield the desired voltage and frequency tailored to the installation region. Also, a circuit breaker is incorporated at the final stage of the power conversion system of the fuel cell power system, ensuring electrical protection and safe distribution of the output power.

OPERATIONAL AND SAFETY CONTROL SYSTEMS:

The control system plays a pivotal role in ensuring the optimal performance and safety of the PEM powerhouse. Recognizing its critical importance, the control system is meticulously structured into multiple layers, each serving distinct functions. These layers are intricately designed to facilitate seamless coordination and communication among various subsystems, enabling precise monitoring and control of essential parameters. By adopting a multi-layered approach, the control system enhances operational reliability and safety, mitigating risks and ensuring uninterrupted power generation.

COOLING SYSTEM:

The hydrogen cooling system stands as a vital component in the seamless operation of a fuel cell. Given the intricate electrochemical processes at play within the fuel cell, precise chemistry is imperative for optimal performance. The presence of ions in the water coolant poses a significant risk, potentially leading to damage to both the cathodes and anodes. To mitigate this risk, deionized water (DI H_2O or 50% ethylene glycol/DI H_2O) is employed to circulate through the fuel cell modules, ensuring purity and preventing harmful ion contamination. This purified water is then directed to a plate heat exchanger, where it undergoes thermal exchange, before connecting to either an air cooler or a cooling tower. By employing this sophisticated cooling mechanism, the hydrogen cooling system effectively maintains the necessary operating temperatures within the fuel cell, safeguarding its integrity, efficiency, and longevity.

Codes and standards:

Safety is of utmost importance especially when it comes to hydrogen fuel systems, numerous international codes and standards have been established to ensure the safe design and operation of stationary fuel cell power systems. Below are some of the standards that a hydrogen fuel cell powerhouse must adhere to:

- IEC 62282-3-100 Ed. 2.0 b:2019 fuel cell technologies - Part 3-100: stationary fuel cell power systems (Which also covers CSA/ANSI FC1)
- CSA/ANSI FC1
- ASME B31.12:2019 hydrogen piping and pipelines
- ASME B31.3:2022 process piping
- IEC 60204-1:2016 (ED. 6.0) electrical equipment of machines
- ISO 13850 safety of machinery - emergency stop function - principles for design
- ISO 13849-1:2015 (Cat. 4, PL e) Safety of machinery Safety-related parts of control systems Part 1: General principles for design and EN 61508:2010 (SIL 3)
- IEC 60079.10.1:2022 explosive atmospheres – Part 10-1: classification of areas – explosive gas atmospheres

By implementing appropriate safety measures and adhering to stringent standards, hydrogen fuel cell powerhouses can achieve a hazardous area classification of Zone 2 NE or be classified as non-hazardous.

Two additional codes and standards are integral to the implementation and advancement of hydrogen technology. These standards play a crucial role in ensuring the effective installation and operation of hydrogen-related systems and infrastructure:

- NFPA 2: Hydrogen Technologies Code. It provides requirements for the safe storage, handling, production, and use of hydrogen in various applications, including fuel cell systems.
- NFPA 853: Standard for the Installation of Stationary Fuel Cell Power Systems. This standard provides guidelines for the installation, operation, and maintenance of stationary fuel cell power systems to ensure their safe and effective deployment.
- ISO TR 15916: Basic Considerations for the Safety of Hydrogen Systems
- OSHA 1910.103: Hydrogen
- CGA G-5: Hydrogen

ISO 8528

ISO 8528 stands as a cornerstone among familiar standards, offering comprehensive guidelines and specifications for the design, testing, and performance of reciprocating internal combustion engine-driven alternating current (AC) generators. Among its provisions, ISO 8528-1 delineates crucial power ratings such as Emergency Standby Power (ESP), Prime Power (PRP), Limited-Time Running Power (LTP), and Continuous Power (COP). Additionally, ISO 8528-5 sets forth transient performance classes and acceptable limits.

However, in the realm of hydrogen fuel cell powerhouses, a notable gap exists as there are currently no international standards governing their ratings or transient response. Despite this, some manufacturers of hydrogen fuel cell powerhouses have embraced aspects of the ratings and terminology outlined in ISO 8528. This adoption is often driven by the familiarity of consultant specifying engineers and designers with ISO 8528, despite its original focus on internal combustion engine-driven generators.

It is crucial to emphasize that ISO 8528 should not be used to size hydrogen fuel cell powerhouses. Applying these ISO ratings and performance characteristics to hydrogen fuel cell systems can be misleading and potentially disadvantageous. ISO 8528 should only serve as a rough guide when applied to hydrogen fuel cell powerhouses, as the ratings, performance characteristics, and size of diesel generator sets and hydrogen fuel cell powerhouses are not directly interchangeable.

HYDROGEN LEAK DETECTION AND CONTROL:

Hydrogen fuel cell systems require multiple layers of protective subsystems to effectively manage the hazards associated with hydrogen leaks. These subsystems encompass:

- Pressure regulators, which reduce hydrogen line pressure before entry into confined spaces.
- Double block and bleed systems, comprising two fail-closed electrically actuated solenoid valves and a manual ball valve. This setup enables the safe venting of hydrogen gas through vent lines designed in accordance with CGA G-5.5 standards.
- Pressure relief valves, facilitate the safe release of hydrogen gas in case of rack line overpressure.
- Pressure transmitters for monitoring line pressure, fail-close solenoid valves within 50 milliseconds in response to abnormal pressure conditions.
- Air inlet-mounted flow switches, which ensure the system operates only with adequate airflow. This feature guarantees sufficient ventilation, thereby diluting potential gas leaks and minimizing risks associated with flammable gases.
- A hydrogen sensor is positioned at the system's highest point. Upon detecting hydrogen, the solenoid valves shut within 50 milliseconds, and the system transitions into its fault state, operating exclusively the ventilation and safety subsystems.

HYDROGEN-CARRYING COMPONENTS:

The hydrogen-carrying components within the fuel cell system possess the following characteristics:

- They operate at hydrogen pressures below 10 bar, ensuring limited pressure levels.
- They maintain sufficient airflow to dilute any potential gas leaks, thereby minimizing the risks associated with flammable gas leakage.

With the implementation of appropriate safety measures, these systems can achieve a hazardous area classification of Zone 2 NE or be classified as non-hazardous.

COOLING FLUID LEAK DETECTION AND CONTROL:

The fuel cell system should employ protective sub-systems to manage the risks linked with potential cooling fluid leaks. These sub-systems comprise a flood sensor positioned at the system's lowest point to detect any leaked cooling fluid and halt system operation before the cooling fluid can reach any electrical components.

TEMPERATURE MONITOR AND CONTROL:

The fuel cell system must incorporate protective subsystems to manage the hazards associated with heat generation and adverse ambient temperatures. These subsystems encompass:

- A temperature transmitter for monitoring system temperature. This transmitter facilitates the regulation of ventilation and heat-generating subsystems. Should abnormal temperature conditions arise, the system will transition into a fault state, operating solely on ventilation and safety subsystems.
- A temperature switch is designed to trigger a system shutdown upon reaching a maximum temperature threshold. This action prompts the system to enter a fault state, operating exclusively on ventilation and safety subsystems.
- A temperature transmitter for monitoring cooling fluid temperature. This transmitter enables control over the fuel cell cooling system. In instances of abnormal temperature conditions, the system will transition into a fault state, functioning solely on ventilation and safety subsystems.

In summary, the standards underscore the importance of preventing hydrogen fires by addressing both the prevention and mitigation of hydrogen leaks. This objective can be accomplished through adequate system ventilation, the installation of sensors, and the incorporation of safety shut-off valves.

Cummins PEM hydrogen fuel cell powerhouse systems meet and exceed all the listed standards and safety requirements.

Fuel supply, process air quality and fuel consumption:

When designing a system integrating a hydrogen fuel cell powerhouse, it's essential to start by thoroughly understanding the sourcing and storage of hydrogen. Hydrogen gas quantities are typically measured in kilograms, in contrast to diesel, which is measured in gallons.

Some of the standards for hydrogen fuel are listed below:

- ISO 14687-2019: Minimum quality characteristics of hydrogen fuel
- SAE J2719: Hydrogen fuel quality standard for commercial PEM fuel cells
- Fuel purity: 99.97% or better
- Feed pressure (head pressure): 8-12 bar(g)
- Fuel temperature range: -25°C to 46°C

The quality of the process air that enters the fuel cell is vital for its proper function and longevity. It must adhere to specific criteria regarding chemical composition, including substances like ammonia, benzene, sulfur, nitrogen, carbon monoxide, carbon dioxide, and other elements, as specified by the manufacturer. To ensure compliance, chemical and particulate filters are necessary, aiming to limit particulate size to less than 10 microns and keep particulate concentration to < 5ppm for optimal performance.

Typically, 1 kilogram of H_2 yields approximately 15 to 17 kilowatt-hours (kWh) of electricity. To put it differently, for a 1-megawatt (MW) system to operate for one hour, approximately 63 to 66 kilograms of hydrogen is consumed.

Since 1kg of hydrogen occupies 11.1 Nm^3 [Nm^3 = Normal Cubic Meter at 0 °C (273.15 °K) and one atmospheric pressure (1.013 bara)], therefore, storing hydrogen at atmospheric pressure is impractical due to its low density. As a result, hydrogen must be compressed to higher pressures, such as 500 bar or 700 bar, or liquefied to achieve practical storage densities.

Fuel Cell rating, sizing, efficiency, and derates:

Fuel cells degrade over time due to catalyst and membrane deterioration, corrosion of metallic components, fuel contamination, and thermal cycling. These factors compromise efficiency and performance, necessitating careful management for a prolonged lifespan. Two terms are coined to gauge the performance and efficiency of the fuel cells: "Beginning of Life" (BOL) and "End of Life" (EOL). However, the term "End of Life" can be misleading, as it suggests that the fuel has reached the end of its lifespan when, in fact, the fuel cell continues to operate during this phase. At EOL, the electrical efficiency of the fuel cell stack decreases by a few percentages compared to BOL. The efficiency reduction is approximately 10% from BOL which pertains solely to the fuel cell stack, not the entire system. Consequently, more fuel, hydrogen, is consumed, and additional heat is rejected. However, it is imperative for the manufacturer account for this additional heat rejection during the initial design of the entire system. As the fuel cell's output voltage decreases with age, the current then must increase to meet the required output power demand.

When evaluating the efficiency of a hydrogen fuel cell powerhouse system concerning the applied load, the efficiency fluctuates by less than 5% across the spectrum from 20% to 70% loading. Additionally, there's an extra 5% reduction in efficiency within the ranges of less than 20% and greater than 70% loading. This remarkable consistency underscores the efficiency of fuel cell systems even when operating at very low loads. In contrast, diesel generator sets exhibit a distinct pattern, showcasing optimal efficiency around 60% loading but demonstrating significant inefficiency within the 20% to 30% loading range.

Another critical factor influencing the performance and efficiency of a hydrogen fuel cell powerhouse is the operating conditions, including temperature and altitude. Altitude derating for a powerhouse begins above 500 meters, with a reduction in performance of approximately 4% per 305 meters of elevation.

The typical operating temperature range for a fuel cell powerhouse is from -25°C to 46°C. Manufacturers typically provide derating curves to illustrate the impact of temperature on system performance. Temperature derating typically starts above 40°C, with an approximate reduction of up to 5% of power per 1°C increase up to 49°C. Sites experiencing temperatures 50°C and above require special consideration to ensure optimal performance and longevity of the system.

When determining the net AC kW size of a hydrogen fuel cell powerhouse system, the manufacturer must factor in several key elements, including the BOL, EOL conditions, fuel cell stack degradation, number of run hours per year, peak loads and the balance of plant loads in the powerhouse. This consideration ensures an accurate estimation of the net output power. For instance, a fuel cell powerhouse with a net AC output of 1.0 MW may require a DC rating of around 1.6 or possibly 2.0 MW to accommodate factors such as EOL effects, balance of plant parasitics, load profile variations, and annual operational hours.

When determining the appropriate net AC kW size for a hydrogen fuel cell powerhouse, several crucial factors come into play, significantly impacting its design, DC kW capacity, physical dimensions, and overall cost. Among these influential factors are:

- Total system power demand
- Minimum and maximum load requirements
- Hours of operation at peak and minimum loads
- Annual operational hours
- Load profile characteristics
- Black start capability necessity
- Site ambient conditions and altitude restrictions
- Cooling system specifications

When evaluating hydrogen power systems from different manufacturers, it's crucial to ensure a fair comparison by focusing on the installed DC kW. This metric directly impacts the system's ability to meet the specified requirements and operational demands outlined above. Depending on the specific application and operational parameters, a higher installed DC capacity may be necessary to adequately fulfill the listed criteria. Therefore, comparing systems based on their installed DC kW provides a more accurate assessment of their suitability and performance capabilities which ultimately impacts the physical size and cost of the system. Image 7 shows an example of a 1MW AC hydrogen powerhouse with 1.6MW DC fuel Cells and 200kWh LTO energy storage. In this instance, the system comprises roughly three 20-foot ISO containers housing PEM fuel racks, power conversion electronics, energy storage units, isolation transformers, cooling systems, and plate heat exchangers.

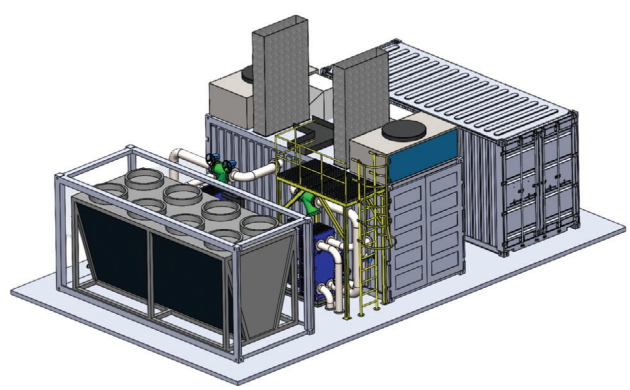


Image 7: Example of a 1MW AC (1.6MW DC) PEM Powerhouse

Image 8: Example of a 40kW (45kW DC) PEM Generator Set

Summary:

Traditional fossil fuel generators, while significant for energy resilience, are being increasingly challenged by the need for cleaner alternatives. Hydrogen fuel cell technology emerges as a promising solution, especially for stationary applications where emission-free power is prioritized.

KEY POINTS:

- Hydrogen fuel cell technology offers zero emissions and swift startup, making it suitable for various applications including emergency power, grid support, and electric vehicle charging.
- The construction of hydrogen AC powerhouses involves assembling fuel cell modules into racks, along with supplementary components for power conversion, energy storage, and safety.
- Proton Exchange Membrane Fuel Cells (PEMFCs) consist of anode, cathode, PEM, bipolar plates, gas diffusion layers, and end plates, working together to convert chemical energy into electrical energy.
- Fuel cell modules and racks are scalable to meet power demands, with integrated energy storage systems ensuring rapid bursts of power during block-loading and black start capability.
- Safety measures, including adherence to international standards and the incorporation of hydrogen leak detection and control subsystems, are paramount in the design and operation of fuel cell power systems.
- Factors such as fuel supply, process air quality, fuel consumption, and system efficiency, as well as derating considerations due to temperature and altitude, are crucial for designing and sizing hydrogen fuel cell powerhouses.
- Evaluating a fuel cell power system based on installed DC kW and considering the BOP parasitics, and stack degradation provides a fair comparison and ensures suitability for specific applications, impacting physical size and cost.

Overall, PEM hydrogen fuel cell technology presents a promising pathway toward sustainable energy solutions in stationary applications, offering reliability, efficiency, and environmental benefits.

About the author

Hassan Obeid is a Global Technical Sales Leader – New Energy Solutions at Cummins Inc., focusing on technical vision, business strategy, and solving a wide range of complex problems. Hassan has been with Cummins since 2007 in various roles, including global technical advising, power systems design engineering, project engineering, and applications engineering. He has designed power systems involving switchgear, controls, paralleling, BESS, PEM hydrogen fuel cells, transfer switches, generator sets, DERs, microgrids, and digital solutions. Additionally, Hassan has developed and conducted technical power seminars on several topics and products, including BESS, PEM hydrogen fuel cells, paralleling, grounding, power systems, and controls. He holds a bachelor's degree in Computer Science and a master's degree in Electrical Engineering from Minnesota State University, Mankato.

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