



Hydrogen storage, electrolyzers and fuel cells: Cost-effective power management and microgrids

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Renewable electricity production, mainly from solar and wind, increased considerably in the last two decades worldwide. Electricity from solar, wind, and hydro are subject to daily, weekly, and seasonal fluctuations.

The higher the penetration of renewables into the electricity grid, the more challenging it is to match supply and demand.

Pumped hydro is the classical way to overcome daily fluctuations. Nowadays, there is also an increase in large-scale battery storage projects. Nevertheless, the energy storage profile of these technologies is not appropriate to overcome extended periods of sunless 'dark-doldrums' that persist in many locations over the course of a year.

On the other hand, green hydrogen can be a clean energy vector with seasonal storage potential and can generate electricity demand. Due to the high volatility of solar and wind power, electrolyzers are not utilised to their full extent in times of dark-doldrums. Unitised regenerative fuel cells (URFC) can operate either in fuel cell mode to produce electricity from hydrogen or in electrolysis mode to produce hydrogen from electricity. Due to this flexibility, a URFC can achieve a high utilisation, or capacity factor, which can improve project economics.

Reversible SOC-based systems: high-potential URFC candidates

A solid oxide cell (SOC) can operate both in fuel cell and electrolyser mode. There are three main types of cell: anode-supported (ASC); metal-supported cells (MSC); and electrolyte-supported cells (ESC). Each has distinct specifications for power density,

and operating temperature.

Since an oxygen ion-conducting electrolyte is utilised, fuels like natural gas, methanol, and ammonia can also be used in the fuel cell (SOFC) mode as alternatives to hydrogen.

In the early 2010s, Versa Power Systems, now a subsidiary of FuelCell Energy, conducted research into reversible solid oxide fuel cells (RSOFCs). Their focus was on degradation mechanisms, with ultra-high current densities of ASCs in both modes with hydrogen fuel. Recently, FuelCell Energy received another \$3m research grant to develop RSOFCs.

Sunfire successfully demonstrated its reversible solid oxide cell (RSOC) technology within the EU-funded GrInHy project from 2019. Its RSOC had three operating modes:

- Electrolyser: 150 kW_(AC) input with 40Nm³/h hydrogen output
- Fuel cell: Hydrogen fuel with 30 kW_(AC) output
- Fuel cell: Natural gas fuel with 25 kW_(AC) output

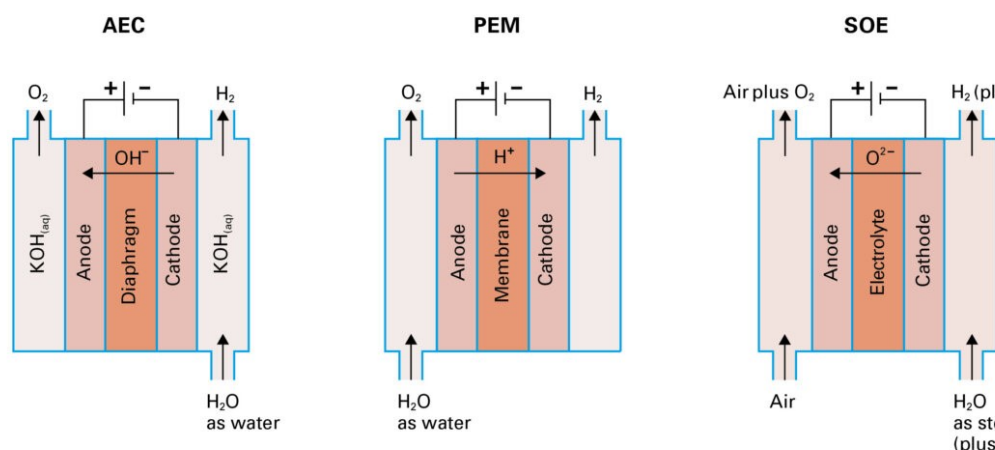
Electrolysers: AEC, PEM and SOE for hydrogen (and syngas) production

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Notes:

- In the AEC and PEM, lye or water flow from the electrolyser cell with the oxygen and hydrogen gases. These liquids are mixed and recirculated to the electrolyser.
- Air is used to purge the SOE anode to avoid oxygen accumulation which may present a hazard at the high operating temperature.
- Bipolar plates made of stainless steel are used to stack adjacent cells in each electrolyser type.



	Alkaline Electrolysis Cell AEC	Polymer Electrolyte Membrane/Proton Exchange Membrane – PEM/PEMEC	Solid Oxide Electrolysis Cell SOE/SOEC
Electrode material	– Cathode: Ni, Co or Fe – Anode: Ni	– Cathode: Pt/Pd – Anode: IrO ₂ /RuO ₂	– Cathode: Ni – Anode: La/Sr/MnO (LSM) or La/Sr/Co/FeO (LSCF)
Electrolyte	Lye: 25-30% Potassium Hydroxide solution in water	Fluoropolymer ionomer (eg Nafion, a DuPont brand)	Zirconium Oxide with ~8% Yttrium (YSZ)
Energy source	100% electrical power	100% electrical power	~25% heat from steam, ~75% electrical power
Current density	Up to 0.5 A/cm ²	Up to 3 A/cm ²	Up to 0.5 A/cm ²
Hydrogen or syngas product	Hydrogen	Hydrogen	Hydrogen (or syngas if fed with steam and CO ₂)
Gas outlet pressure	Up to 40 bar	Up to 40 bar	Close to atmospheric
Cell temperature	~80 °C	~60 °C	~750 to 850 °C

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Reversible AEM-based systems: demonstration project shows potential

The Anion Exchange Membrane (AEM) system uses a solid electrolyte. It combines the advantages of the PEM and alkaline cells, utilising membranes that avoid precious metal loading.

In the last decade, Giner received several grants from the US DOE to perform research into AEM systems. Results published in 2020 show a good performance within the first 2,000 operating hours. Long-term degradation and lifetime expectation must now be assessed to demonstrate this technology can be applied reliably at scale.



Regenerative fuel cells could enable Mars missions in the future.

Reversible PEM-based systems: not yet commercialised

In the 1990s, NASA conducted extended research into URFC's and energy storage to enable extra-terrestrial space activities. They were based on the Polymer Electrolyte Membrane (PEM) technology.

For outer-space applications where payload is everything and stack lifetime not as relevant, URFC's based on PEM or AEM might be viable for energy storage on potential future Mars missions.

For a short period in the early 2000's, Proton Energy, now Proton OnSite – a subsidiary of NEL, offered its reversible product. However, despite ongoing research projects, no commercial reversible PEM-based products are available for use at scale today.

Project parameters drive the best-fit technology

There are several challenges for integrated reversible PEM and AEM-based systems, which the RSOFC does not suffer from.

The reversible AEM or PEM system must handle humidified gas streams in the fuel cell mode, but liquid water will be in contact with the membrane in the electrolysis mode. Each mode must therefore consider two-phase flow optimisation. The pressure differential in fuel cell mode is low, at 0.3 bar but very high in electrolyser mode – up to 30 bar. This places high sealing loads on the equipment.

On the other hand, RSOFC systems operate at atmospheric pressure. Therefore, hydrogen generally needs to be compressed before entering the electrolyser. A hydrogen compressor may require maintenance every 4,000 to 8,000 hours. Compressor operation is especially challenging if the power is to be derived from an intermittent variable renewable energy source, because the compressor prevents stable operation. This constraint makes RSOFC systems unsuitable for off-grid applications.

Limitations of reversible systems

The spread in operating voltage is challenging for power electronics in URFC systems. The operating voltage in electrolyser mode is twice as much as in fuel cell mode meaning that the area-specific current densities are doubled. This results in 4-6 times higher

input (AC) of the electrolyser than power output (AC) in fuel cell mode. The implication is that the ratio of electrolyser input to fuel cell output power cannot be chosen freely – they are inextricably linked by this ratio.

PEM fuel cells, in particular for mobility applications, are optimised for a fast start up and a high power output. Their expected lifetime is about 10,000 hours. On the other hand, an electrolyser stack would be expected to have a lifetime of at least 60,000 hours to be economically viable. There is a wide gulf between the requirement versus performance.



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A PEM or AEM based reversible system could potentially be used for off-grid energy storage applications. The benefit would be that when hydrogen storage is incorporated, the system could have a higher energy storage capacity than currently available battery technologies. In this application, due to the maximum stack lifetime, multiple stack replacements would be necessary over the lifetime of 20 years (175,200 hours) of operation which is the typical lifetime expectation for an infrastructure project.

When considering the cost of frequent stack replacements, the economic benefit of an URFC compared to a similar system with separate devices (an electrolyser and a fuel cell), becomes questionable. The economics of integrating the electrolyser and a fuel cell are also compromised because different balance of plant (BoP) components, for example power electronics or gas cleaning units, which are necessary for each operating mode.



Independent fuel cells and electrolyzers with hydrogen storage offer flexibility

Separate fuel cell and electrolyser units can add flexibility when integrated into one system or product because each element is optimised according to the system requirements.

This is the design concept of the recently launched LAVO system. It is targeted at consumer markets and integrated one 5 kW fuel cell and two 2.5 kW AEM electrolyzers with a predicted stack lifetime of about 30,000 hours. That would result in a stack replacement after 10 years of operation, with an assumed annual utilisation of 3,000 hours.

The electrolyser produces hydrogen at a pressure of 35 bar for storage on a newly designed metal hydride system that stores 1 kWh of electricity. That corresponds to 2.4 kg of hydrogen, assuming a fuel cell efficiency of 50%.

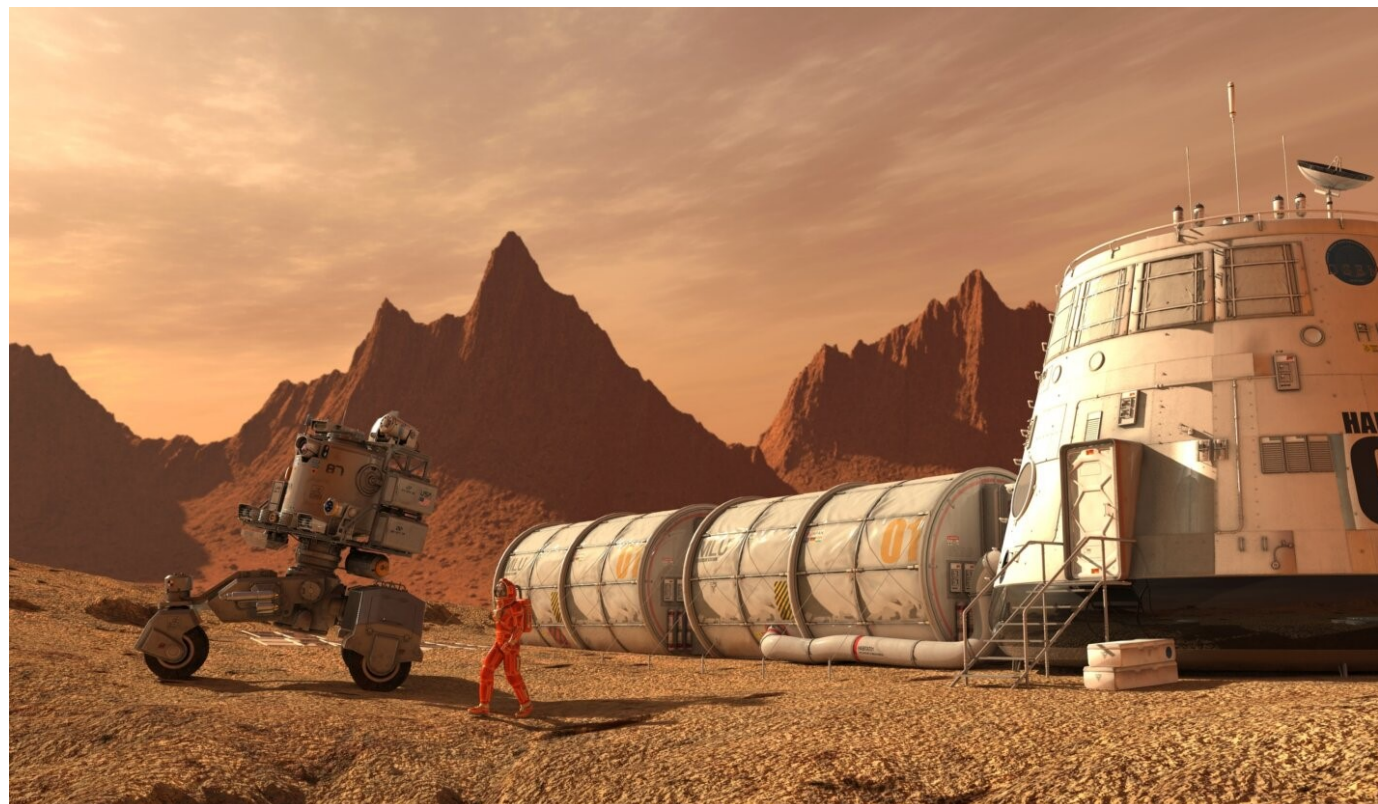
Using a pressure vessel to store hydrogen at the electrolyser output pressure of 35 bar, compressed gas hydrogen storage could be unfavourable for applications where space and portability are not the priority. To achieve the same capacity at this pressure, the cylinder volume would need to be eight times more than a metal hydride storage system.

The hydrogen purity requirements for pressurised hydrogen storage are less stringent than for metal hydride storage. PowiDi has chosen to incorporate compressed hydrogen storage into their integrated off-grid power system.

In 2016, a behind-the-meter microgrid energy storage system with a separate electrolyser and fuel cell was implemented at the Nickel mine close to Nunavik, Quebec (*pictured below*) in northern Canada. Electricity for the mine is provided by a wind turbine power generation is subject to fluctuations in the weather conditions.



The Raglan mine scheme uses a 350 kW-rated HySTAT-60® alkaline electrolyser and a 200 kW rated HyPM® PEM fuel cell, both in the Hydrogenics range. The ratio of electrolyser and fuel cell power is 1.75:1. If a reversible system had been selected that ratio would need to be closer to 4:1. Hydrogen storage is integrated into the scheme with 4 MWh of capacity using three horizontal steel storage vessels which operate at the electrolyser outlet pressure.



Rendering of a potential future Mars base enabled by regenerative fuel cells

The future of regenerative fuel cells

For many applications, separate electrolyser and fuel cell units are more likely to fit the application rather than integrating both functions into one unit because in the single reversible unit there is a fixed ratio of the electrolyser and the fuel cell capacities.

A single reversible unit might save some capex on day one, but long-term system performance is generally much more important than initial capex. The use of a separate electrolyser and fuel cell in a scheme means the size of each component can be independently optimised. Also, the fuel cell and electrolyser technologies can be chosen separately to maximise the overall system performance according to the local requirements.

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