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PERSPECTIVE

# Reliable off-grid power supply utilizing green hydrogen

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## Abstract

Green hydrogen produced from wind, solar or hydro power is a suitable electricity storage medium. Hydrogen is typically employed as mid- to long-term energy storage, whereas batteries cover short-term energy storage. Green hydrogen can be produced by any available electrolyser technology [alkaline electrolysis cell (AEC), polymer electrolyte membrane (PEM), anion exchange membrane (AEM), solid oxide electrolysis cell (SOEC)] if the electrolysis is fed by renewable electricity. If the electrolysis operates under elevated pressure, the simplest way to store the gaseous hydrogen is to feed it directly into an ordinary pressure vessel without any external compression. The most efficient way to generate electricity from hydrogen is by utilizing a fuel cell. PEM fuel cells seem to be the most favourable way to do so. To increase the capacity factor of fuel cells and electrolysers, both functionalities can be integrated into one device by using the same stack. Within this article, different reversible technologies as well as their advantages and readiness levels are presented, and their potential limitations are also discussed.

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## Graphical Abstract

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

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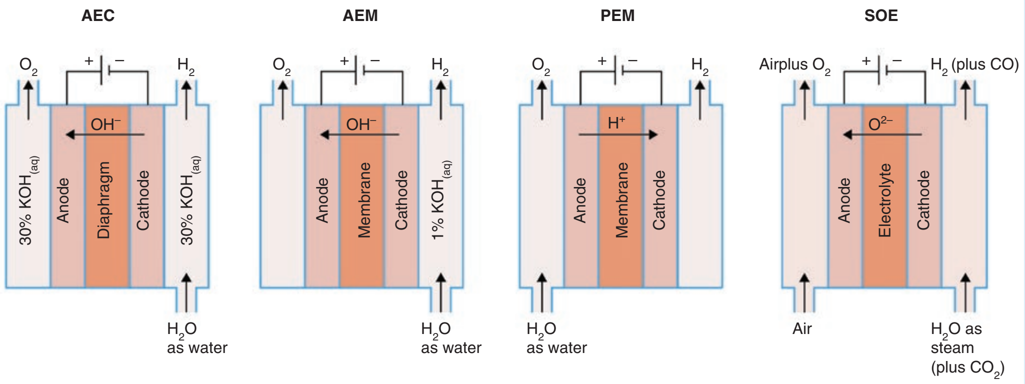
**Notes:**

- In the AEC, AEM and PEM, lye or water flow from the electrolyser cell with the oxygen and/or 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 (titanium for PEM) are used to stack adjacent cells in each electrolyser type.



| | **Alkaline Electrolysis Cell AEC** | **Anion Exchange Membrane/ Alkaline Electrolyte Membrane AEM** | **Polymer Electrolyte Membrane/ Proton Exchange Membrane PEM/PEMEC** | **Solid Oxide Electrolysis Cell SOE/SOEC** |
|---|---|---|---|---|
| Electrode material | – Cathode: Ni, Co or Fe<br>– Anode: Ni | – Cathode: Ni / Ni alloys<br>– Anode: Fe, Ni, Co oxides | – Cathode: Pt/Pd<br>– Anode: $IrO_2/RuO_2$ | – Cathode: Ni<br>– Anode: La/Sr/MnO (LSM) or La/Sr/Co/FeO (LSCF) |
| Electrolyte | Lye: 25–30% Potassium Hydroxide solution in water | Anion Exchange ionomer (e.g. AS-4) | Fluoropolymer ionomer (eg Nafion, a DuPont brand) | Zirconium Oxide with ~8% Yttrium Oxide |
| Energy source | 100% electrical power | 100% electrical power | 100% electrical power | ~25% heat from steam,<br>~75% electrical power |
| Current density | Up to 0.5 $A/cm^2$ | 0.2 – 1 $A/cm^2$ | Up to 3 $A/cm^2$ | Up to 0.5 $A/cm^2$ |
| Hydrogen or syngas product | Hydrogen | Hydrogen | Hydrogen | Hydrogen (or syngas if fed with steam and $CO_2$) |
| Gas outlet pressure | Up to 40 bar | Up to 35 bar $H_2$, 1 bar $0_2$ | Up to 40 bar | Close to atmospheric |
| Cell temperature | ~80 °C | ~60 °C | ~60 °C | ~750 to 850 °C |

**Keywords:** green hydrogen; microgrid; stand-alone power system; SAPS; hydrogen storage; electrolysis; fuel cells; AEC; PEM; AEM; SOEC

## Introduction

Renewable electricity production, mainly from solar and wind, increased considerably in the last two decades worldwide. Due to the increased serial production of solar panels and wind turbines, the investment costs for these has plunged by >90%. In addition, innovative small-scale hydro turbines are gaining momentum. Start-ups like Smart Hydro, Suneco Hydro and Energy Systems & Designs offer turbines in the range of 2–10 kW. Some of them do not even need a weir or dam to work. These turbines compliment established players like Voith Hydro, which offers turbines with rated power capacities of 50 kW–1.2 MW. But electricity from solar, wind and hydro are subject to daily, weekly and seasonal fluctuations.

Off-grid electricity supplies in remote communities or mine sites, which have a decent electricity demand but are not connected to the main electricity grid due to their remoteness, were generally driven by diesel gensets in the past. The transportation costs of fuel to these remote locations are exorbitantly high. Hence, a combination of wind turbines, solar panels and potentially also small-scale hydropower might be economically viable to provide sustainable electricity supply for such remote off-grid applications.

Due to the different frequencies associated with the volatility of solar, wind and hydro electricity generation, different energy-storage technologies are necessary for different timescales. Battery-based electricity storage is typically only viable for several hours. In general, batteries are not appropriate to overcome extended periods of windless, 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 carrier with seasonal storage potential and can generate electricity on demand. Depending on the required storage size, different hydrogen storage are favourable.

## 1 Off-grid power supply based on hydrogen-storage solutions

### 1.1 Off-grid mine sites

In 2016, a behind-the-meter microgrid energy-storage system was implemented at the Raglan Nickel mine in northern Canada Fig. 1 [1]. Electricity for the mine is provided

**Fig. 1:** The wilderness of northern Canada where mining is common

Source: shutterstock.com.

by a wind turbine and power delivery is subject to fluctuations in the weather conditions. In order to compensate for that, the scheme uses a 350-kW rated HySTAT-60® alkaline electrolyser and a 200-kW rated HyPM® polymer electrolyte membrane (PEM) fuel cell, both from the Hydrogenic range. The hydrogen storage has a capacity of 4 $MWh_{H2}$ = 120 $kg_{H2}$. Three horizontal steel 'bullet' storage vessels operate at the electrolyser outlet pressure of 10 $bar_a$. Due to the relatively low output pressure from that type of electrolyser (10 $bar_a$), the working pressure difference—which defines the total hydrogen capacity—might be only 8 bar (10 – 2 = 8 bar). Therefore, the necessary storage volume for this amount of energy storage is very large, at 185 $m^3$.

## 1.2 Alpine refuge huts

Since 2015, an integrated off-grid energy-storage system designed by PowiDian has powered the alpine refuge at Col du Palet, in the French Alps. At its heart, a 2.5-kW Anion Exchange Membrane (AEM) electrolyser from Enapter produces ≤0.5 $Nm^3/h$ hydrogen at 30 $bar_a$ [2]. The hydrogen, which is mainly produced during the summer months from solar panels, is stored safely in a pressure vessel in a separate shed. During winter, when the solar panels are covered in snow, a 2.5-kW fuel cell delivers electricity from the hydrogen on demand. Due to the increased working pressure difference of ≥28 bar, the storage volume for the 5 kg hydrogen (= 166.6 $kWh_{H2}$) is only 2.2 $m^3$. This is considerably smaller than would be required if the electrolyser were to produce hydrogen at a lower pressure of 10 $bar_a$. The electricity output from the stored hydrogen is 90 kWh in total and corresponds to a fuel-cell efficiency of 54%.

## 1.3 Off-grid consumer applications

Different hydrogen-storage technology is applied at the recently launched LAVO system [3] that is targeted at consumer markets. It integrates one 5-kW PEM fuel cell and two 2.5-kW AEM electrolysers with a predicted stack lifetime of ~30 000 hours. With an assumed annual utilization of 3000 hours, that would result in stack replacement after 10 years of operation. The electrolyser produces hydrogen at a pressure of 35 bar for storage on a newly designed metal hydride system that can store ≤2.4 kg of hydrogen, which corresponds to 40 kWh of electricity assuming a fuel-cell efficiency of 50%.

## 1.4 Can external hydrogen compression be favourable?

As an alternative to using a pressure vessel to store hydrogen at the electrolyser output pressure, the use of high-pressure compressed-gas hydrogen storage can be favourable for applications where space for the compressor is available and portability is not a priority. An example might be the injection of hydrogen into the natural-gas pipeline grid for admixing with methane. A maximum pressure of 100 bar is typically employed in transmission pipelines for natural gas. Usual outlet pressures of alkaline and PEM electrolysers are

~30 bar. To achieve the required injection pressure, hydrogen compression is required. As the pressure ratio from 30 to 100 bar is only 3.33 (100/30 = 3.33), a single-stage piston compressor could be utilized. Nevertheless, even a single compression unit for hydrogen adds considerable CAPEX to the whole project. OPEX is also impacted due to the requirement for the maintenance of moving parts and the compressor-motor power demand.

Ahluwalia *et al.* [4] recently analysed different hydrogen-storage technologies. For the compressed-gas storage in steel tubes, he found a minimum CAPEX of 516 $/kg$_{H2}$. For his analysis, he found the optimum with coated steel pipes (inner diameter of 585 mm) and a working pressure difference of 92 bar (100 – 8 = 92 bar$_a$). External compression is necessary in order to achieve such a high working pressure difference, which adds additional CAPEX and OPEX. On the other hand, when reducing the working pressure difference, also the relative storage capacity decreases proportionally, while the specific CAPEX increases accordingly. The results of this simple analysis are shown in Table 1 and the usage of an identical steel tube was assumed, for the sake of simplicity. With a more sophisticated optimization, the break-even point at which external hydrogen compression with a higher working pressure difference is more viable than the installation of more steel tubes with a lower working pressure difference can be determined. If at the same time the maximum total pressure decreases, the pipeline wall thickness can be reduced, which might reduce CAPEX furthermore. As fuel cells operate at ambient pressure, industry standard pressure regulators are utilized in all cases, as this is already done nowadays when compressed hydrogen is shipped in bottles at 200 bar.

### 1.5 Remote communities

Currently, Horizon Power is replacing its aging diesel-wind power-supply system in the remote community of Denham, Western Australia [5], with a solar-hydrogen-based utility. Hybrid Systems Australia was awarded the contract to build a solar farm with a rated capacity of 704 kW [6]. During the day, excess electricity is stored as hydrogen that is produced on a 348-kW electrolyser. During times of low wind and no sun, a 100-kW fuel cell supplies electricity from the compressed hydrogen storage. Annually, 13 000 kg of hydrogen will be produced. This corresponds to a hydrogen production of 1185 kWh$_{H2}$/day = 35.6 kg$_{H2}$/day, and results in a capacity factor for the electrolyser of only 21.8%.

Besides the volatility of wind and solar power, the electrolyser does not operate when the fuel cell is in use and vice versa. As an alternative scheme to overcome this low-capacity factor, unitized regenerative fuel cells (URFCs) could be used to 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 could potentially achieve a much higher capacity factor.

## 2 Reversible fuel-cell technologies for off-grid applications

### 2.1 Reversible PEM-based systems

In the 1990s, NASA conducted [7], for its extraterrestrial space activities, extended research into URFCs, particularly for energy storage. These were based on the PEM technology. URFCs based on PEM or AEM may be an option for energy storage on future Mars missions (Fig. 2) in outer-space applications where payload is everything and stack lifetime is not as important.

Later, at the beginning of the 2000s, Proton Energy, now Proton OnSite, a subsidiary of NEL, offered their reversible product UNIGEN [8]. Despite these initial product launches and various ongoing research projects, no commercial reversible PEM-based products are available for use at scale today.

### 2.2 Reversible AEM-based systems

The AEM technology uses a solid electrolyte. It combines the advantages of the PEM and alkaline cells by utilizing 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 recently show a good performance within the first 2000 operating hours [9]. Long-term degradation and lifetime expectation still need to be assessed to demonstrate that this technology can be applied reliably at scale.

### 2.3 A high-potential candidate—solid-oxide cells (SOCs)

A SOC can operate in both fuel-cell and electrolyser modes. There are three main types of cell: anode-supported cells (ASCs), metal-supported cells and electrolyte-supported cells. Each has distinct specifications for power density, lifetime and operating temperature. Since an oxygen-ion-conducting electrolyte is utilized, alternative fuels like natural gas, methanol and ammonia can also be used directly in the fuel-cell (SOFC) mode.

**Table 1.** Effect of hydrogen storage pressure on CAPEX cost and storage capacity

| **Working pressure difference** | bar | 92 | 52 | 22 | 8 |
|---|---|---|---|---|---|
| **Specific CAPEX** | $/kg$_{H2}$ | 516 | 913 | 2158 | 5934 |
| **Relative storage capacity** | % | 100 | 56.52 | 23.91 | 8.70 |

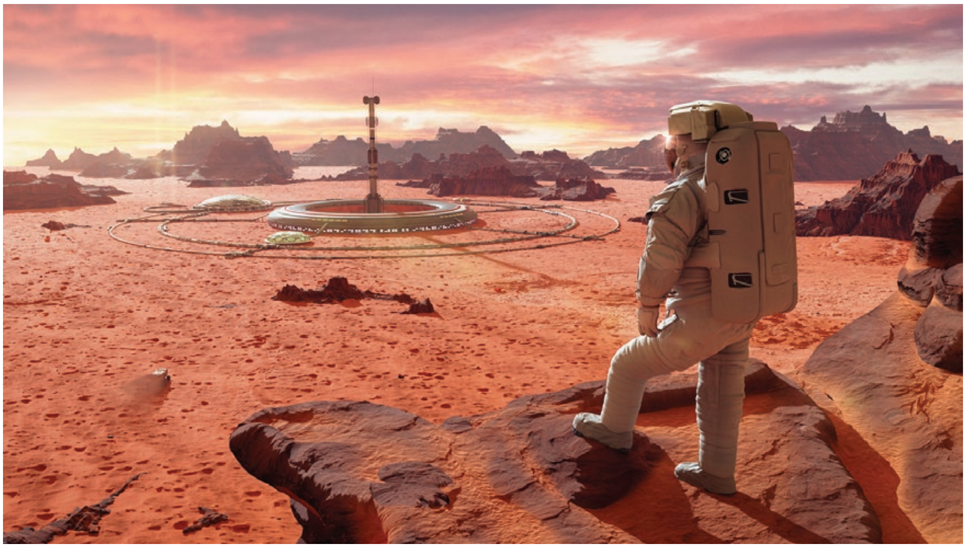


**Fig. 2:** Rendering of a potential Mars station where URFCs have been considered

Source: shutterstock.com.

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 as fuel [10]. Recently, FuelCell Energy received another 3-million-dollar research grant to further develop RSOFCs.

Sunfire demonstrated their reversible solid-oxide cell (RSOC) technology within the EU-funded GrInHy project from 2016 to 2019. Their RSOC had several operation modes [11]:

- electrolyser: 150-kW$_{(AC)}$ input with 40-Nm$^3$/h hydrogen output;
- fuel cell: hydrogen fuel with 30-kW$_{(AC)}$ output;
- fuel cell: natural-gas fuel with 25 kW$_{(AC)}$ output.

There are several challenges for integrated reversible PEM- and AEM-based systems, which the RSOC 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 optimization. The pressure differential in the fuel-cell mode is low, at 0.3 bar, but very high in electrolyser mode, at ≤30 bar [9]. This places high sealing loads on the equipment.

On the other hand, RSOC systems operate at ambient pressure. Therefore, hydrogen generally needs to be compressed after the electrolyser. A hydrogen compressor may require maintenance every 4000–8000 hours. Compressor operation is especially challenging if the power is to be derived from variable renewable energy because the compressor prefers a stable operation. This constraint makes the RSOC systems less suitable for off-grid applications.

## 3 Limitations of reversible systems

The spread in the operating voltage is challenging for power electronics in reversible systems. The operating voltage in the electrolyser mode is twice as high as in the fuel-cell mode, which means that the area-specific current densities are doubled, while internal resistance remains roughly the same. This results in a four to six times higher power input (AC) of the electrolyser than the power output (AC) in the fuel-cell mode. The implication is that the ratio of the electrolyser input power to the fuel-cell output power cannot be chosen freely—they are linked by this fixed ratio.

Putting some numbers around this point can clarify the case. A 10-kW$_{(DC)}$ electrolyser stack would only operate as a 2.5-kW$_{(DC)}$ fuel-cell stack. When coupled to a photovoltaic (PV) array with an assumed capacity factor of 20%, 28.8 kWh of hydrogen can be produced per day (10 kW × 24 hours × 0.2 × 0.6 = 28.8). In this calculation, 60% efficiency has been assumed, meaning that 48 kWh$_{(DC)}$ of electricity input has been used to feed the electrolyser. An additional 5 kWh are necessary for the supply of the BoP (Balance of Plant), increasing the actual power input to 11 kW$_{(AC)}$ [12]. The BoP includes pumps, valves, a control system and heaters—all of which consume power in addition to the electrolyser stack itself.

When operating as a fuel cell, the same unit could run for 6.9 hours at 2.5-kW$_{(DC)}$ output (28.8 kWh × 0.6/2.5 kW$_{(DC)}$). This calculation assumes that the fuel cell is operating at full load and 60% efficiency. Over that time duration, the fuel cell would produce 17.25 kWh$_{(DC)}$ of electricity from the stored hydrogen. Due to the BoP demand and other energy-conversion losses, only 15.2 kWh$_{(AC)}$ are usable and can be fed into the grid, reducing the effective output power to 2.2 kW$_{(AC)}$. This power output is five times smaller than the electrolyser power input of 11 kW$_{(AC)}$. The overall efficiency results in 31.6% due an output of 15.2 $\mathrm{kWh}_{(AC)}$ in relation to 48 $\mathrm{kWh}_{(DC)}$ of input. If the electrolyser would be fed with AC electricity from the grid, additional losses from the rectifier would need to be taken into account. The combined capacity factor is 48.75%, whereas the combined utilization factor is 74.5 %. This assumes an average daily operation of 11 hours in electrolyser mode—mainly in part load—plus the 6.9 hours of full-load fuel-cell operation.

Depending on the geographic location, the capacity factor of the PV panels would vary and that in turn influences the required fuel-cell operation time. If the above parameters fit the location and application, then the reversible unit may be suitable. If the above operating profile does not fit the local requirements, then separate electrolyser and fuel-cell components may be preferred. In that case, each of those units can be freely adapted to be optimized to the requirements of the local climate and the power-demand pattern.

PEM fuel cells, for mobility applications, are optimized for a fast start-up and a high power output. Their expected lifetime is ~10 000 hours. On the other hand, an electrolyser stack is expected to have a lifetime of ≥60 000 hours to be able to be economically viable.

A PEM- or AEM-based reversible system could potentially be used for an off-grid energy-storage application. 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, several replacements would be necessary over the course of 20 years (175 200 hours) of operation, which is the typical lifetime expectation for an infrastructure project.

When considering the cost of multiple stack replacements, the economic benefit of an URFC compared to a similar system based on separate devices (an electrolyser and a fuel cell) become questionable. The economics of integrating the electrolyser and a fuel cell are also compromised because of the different BoP components, such as power electronics or gas-cleaning units, are necessary for each operating mode.

## 4 Summary

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 unit, there is a fixed ratio of the electrolyser and the fuel-cell capacities.

A single unit might save some CAPEX on day one, but long-term system performance is generally much more important than initial CAPEX and, when using separate systems, the two operating functions can be independently optimized to maximize the overall system performance according to the local requirements.

## Conflict of Interest

None declared

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