PALL APPLICATION DEVELOPMENT TEAM
**White Paper**

# Green Hydrogen Production: Separation and Purification Solutions

## Introduction

With most of the world's energy demand supplied by fossil fuel sources, the overall $CO_2$ emissions from fuel combustion currently surpasses 32.3 billion metric tons (1). These excessive emissions and other combustion pollutants have had a major impact on the ongoing climate change challenge. The effects of global warming and air pollution are becoming apparent in the various severe climate-related events now reported in many countries. Recently, there has been a remarkable shift to enable the renewable energy industry. At the end of 2019, the European Commission presented the European Green Deal outlining the new policies for achieving carbon neutrality by 2050 (2). Many countries have now joined this mission and are setting reduced emission goals by 2030. Even one of the world's largest oil exporters, Saudi Arabia, has initiated the construction of a carbon-free city as part of the NEOM project. In Asia, significant investments are being made by major oil refiners to advance the solar and wind energy infrastructure (3). In the USA, the renewable diesel industry is seeing a resurgence due to federal tax credits being issued (4).

In order to enable a transition from fossil fuels to renewable energy sources, hydrogen will play a key role. The advantage of hydrogen is that it is a clean fuel with no toxic emissions with the only by-product of its combustion being water vapor. Hydrogen can be used as an energy source and as an effective energy storage medium. It can be used in fuel cells for transportation, as a feedstock for refining and chemical processes, and for commercial/residential heat and power. When produced using renewable sources, also known as green hydrogen, it contributes to the decarbonization of these industries.

Hydrogen can be produced from various processes (Figure 1). Grey hydrogen is produced by steam reforming of natural gas and is currently the most common production method. Grey hydrogen is also the least expensive to produce at approximately $1.25-$3.5/kg (5). Blue hydrogen is produced in the same way as grey hydrogen, but a carbon capture step is added to eliminate the $CO_2$ emissions. Green hydrogen refers to the production of hydrogen by the electrolysis of water powered by renewable energy sources like wind, solar and/or hydropower.

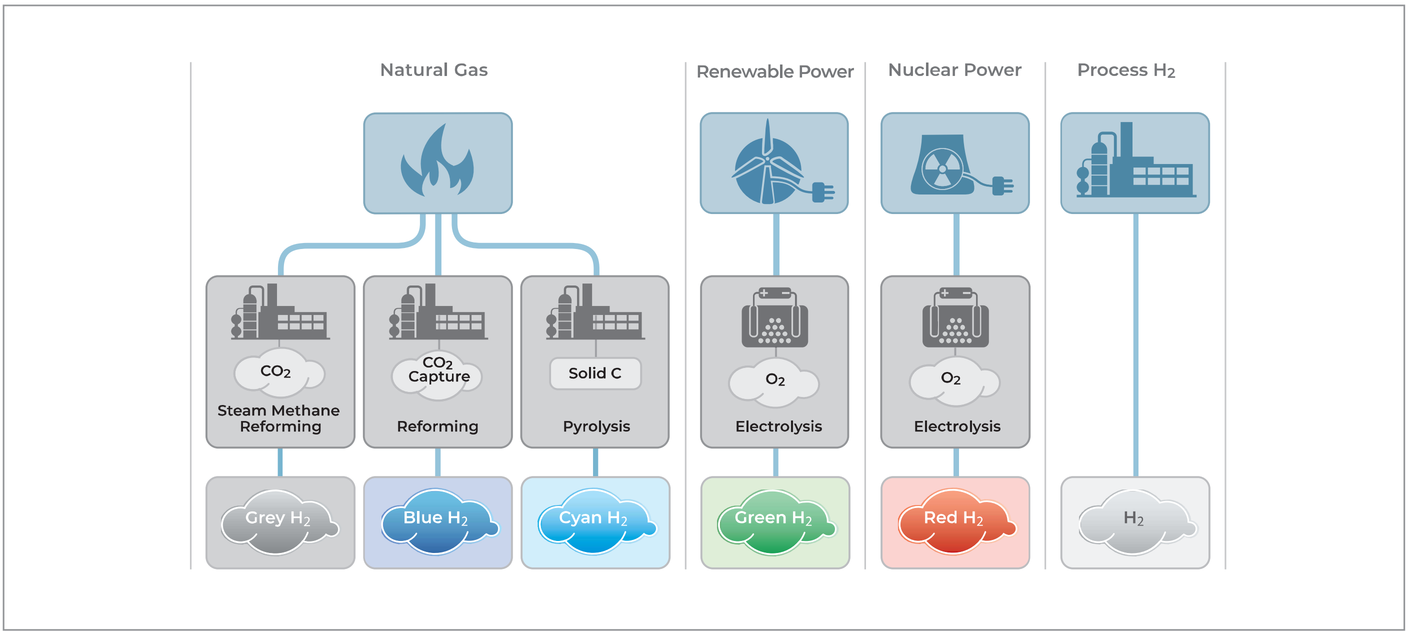


*Figure 1:* Hydrogen production processes

Although it provides no carbon emissions it is also currently the most expensive production method ranging from \$2.5 to \$7.25/kg (6).

The current global demand for hydrogen is >70 million tons per year (7). The majority being used for refining and chemical processes such as ammonia production. The Hydrogen Council estimates that by 2050 the demand will increase to 500 million tons per year. To meet this increase in demand combined with the net-zero emission goals, the production of green hydrogen must be greatly expanded. In the paper by G. Kakoulaki, it was found that in all European countries analyzed, the total electricity potential exceeds the total electricity demand including the demand required to power electrolysis for green hydrogen production. Therefore, it shows the transformation from grey to green hydrogen to be technically possible but significant challenges remain for commercialization and scale-up. The high capital cost of electrolyzers coupled with stringent gas purity specifications suggest that further process optimization is required.

Liquid/gas separations, along with solids removal, are crucial to the success of the green hydrogen production process. The choice of separation equipment is influenced by factors such as quality needed, flow rate, solid and liquid contamination. Economics also plays a significant role considering initial capital costs, operating costs, waste disposal costs, and maintenance. It is important to conduct a thorough process review to fully understand which type and where to integrate the separation technology.
As a leader in separation and purification technology, Pall Corporation (Pall) is fully committed to contributing to the advancement of green hydrogen production. With a large and diverse portfolio of products covering a wide range of markets and with technical experts and manufacturing locations present across the globe, Pall can develop the separation solutions required. This article describes the separation steps in the green hydrogen production process as well as the technologies that can be applied to each. Lastly, several case studies are presented in which Pall products are currently being applied to green and blue hydrogen production.

## Green Hydrogen Production

Green hydrogen is produced by the electrolysis of water powered by renewable electricity sources such as solar and wind. Electrolysis involves the dissociation of the water molecule in an electric field. Hydrogen is produced at the cathode and oxygen at the anode with an electrolyte present in between the electrodes. There are three types of electrolyzers. The alkaline (AEL), the polymer electrolyte membrane (PEM), and the solid oxide (SOEC) electrolyzers (Figure 2). The AEL, using liquid potassium hydroxide as the electrolyte, is the most common and widely used in industrial applications. The PEM uses a solid polymer electrolyte, and its use is rapidly growing to overcome some of the drawbacks of the AEL. The SOEC, using a solid ion-conducting ceramic electrolyte, is the least developed technology and not yet widely commercialized.
Regardless of the electrolysis technology used, the hydrogen and oxygen streams produced need to be further processed to remove solid, liquid, and gaseous contaminants to meet the gas purity specifications. For example, for fuel cell vehicles the maximum concentration of oxygen and water in the hydrogen allowed is 5 ppm each. After alkaline electrolysis, concentrations in the range of 2000-6000 ppm of oxygen and >2000 ppm of water in the hydrogen are reported in commercial systems (7).

Oxygen is removed from the hydrogen by catalytic recombination in a process called deoxygenation. To remove water several steps are required including cooling, liquid/gas phase separation, and drying. Solid contaminants can originate from process piping and equipment such as pumps and compressors and after the drying step. Solids can also be present in the incoming water feed as well as in the electrolyte (in AEL systems only). After final purification, the oxygen is released to the atmosphere and the hydrogen is sent to storage. Hydrogen can be stored in tanks, salt caverns, or as a chemical if converted to liquid ammonia by the Haber-Bosch Synthesis. Figure 3 shows a typical schematic of a hydrogen production process using an AEL electrolyzer with subsequent purification steps and outlines the equipment required.

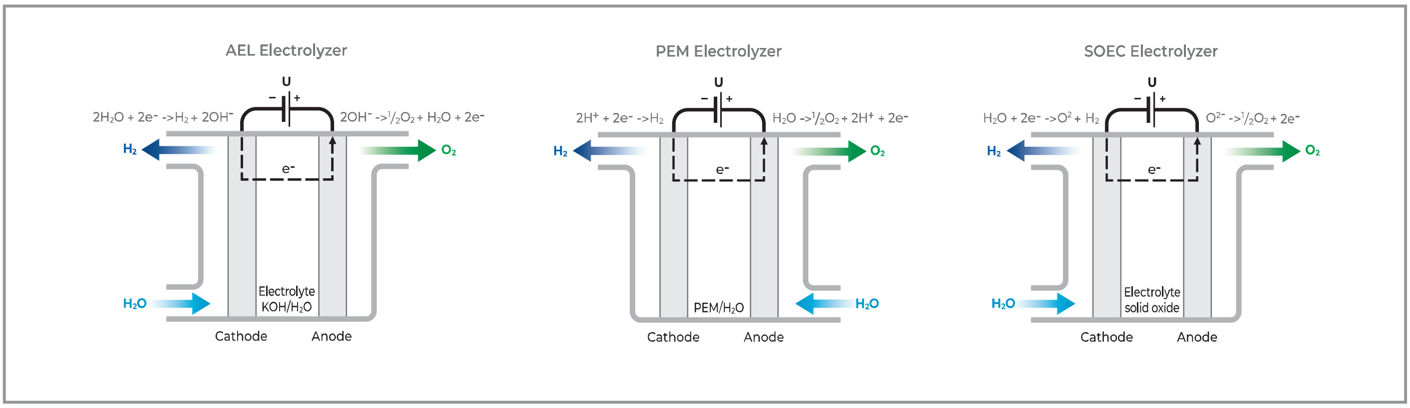
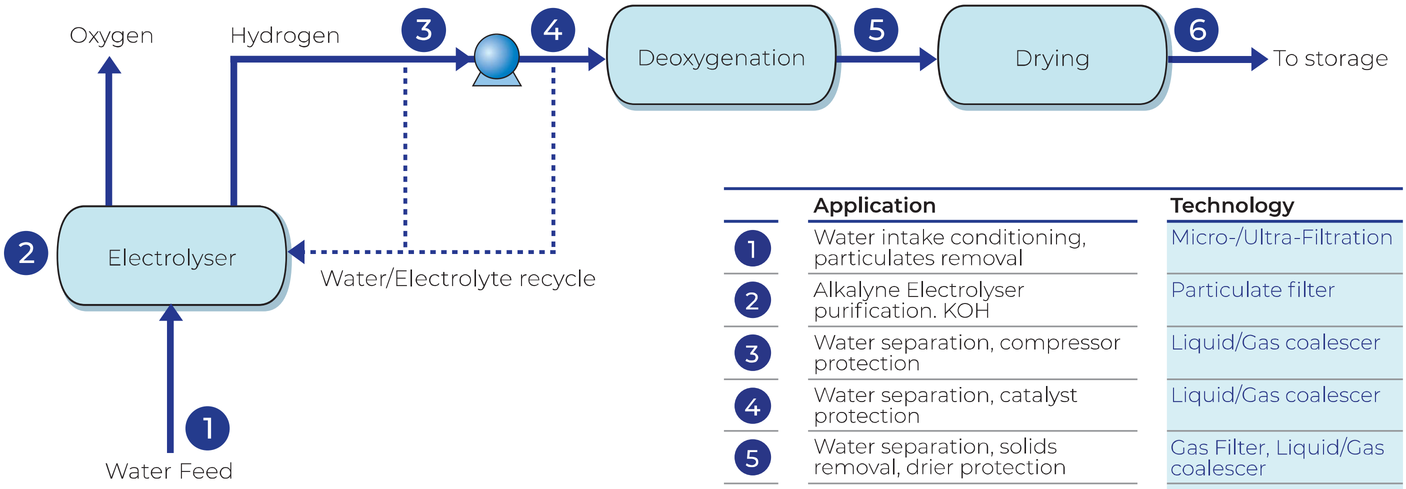


*Figure 2:* Types of electrolyzers



| | Application | Technology |
|---|---|---|
| ① | Water intake conditioning, particulates removal | Micro-/Ultra-Filtration |
| ② | Alkalyne Electrolyser purification. KOH | Particulate filter |
| ③ | Water separation, compressor protection | Liquid/Gas coalescer |
| ④ | Water separation, catalyst protection | Liquid/Gas coalescer |
| ⑤ | Water separation, solids removal, drier protection | Gas Filter, Liquid/Gas coalescer |
| ⑥ | Solids removal, product quality | Gas Filter |

*Figure 3:* Typical separation applications in hydrogen production using an AEL electrolyzer

## Removal of Liquid Contaminants

As seen in Figure 3, the first step after hydrolysis is liquid/gas phase separation. The liquid/gas mixture flows from the electrolysis cell to the liquid/gas separator. This separation can be accomplished by cooling followed by gravity separators, mist eliminators pads, filter vane separators, and/or more recently liquid/gas coalescers. Cooling the gas presents a major cost of production and can be as high as 5% of the total system cost (8). Gravity separators or knock-out drums use gravitational force to enact the separation. These systems require very large housings with low gas velocities and are used when the droplets are very large in size (> 300 microns). Mist eliminator pads, consisting of fibers or knitted meshes, can remove droplets down to 10 microns but the vessel containing them is also relatively large because they must be operated at low velocities to prevent liquid re-entrainment. Filter vane separators use a series of baffles or plates within a vessel. They can typically operate at higher gas velocities than mist eliminators and are similar in efficiency removing droplets down to 10 microns. In liquid/gas coalescers the gas flows through a very fine pack of bound fibrous material with a wrap on the outer surface to promote liquid drainage. When properly designed and sized, drainage of the coalesced droplets from the fibrous pack allows gas velocities much higher than in the case of mist eliminator pads and vane separators with no liquid re-entrainment or increase in pressure drop across the assembly. Liquid/gas coalescers can remove much finer droplets down to 0.1 micron when using the high efficiency versions (9). Figure 4 shows a schematic of a Pall liquid/gas high efficiency coalescer system.

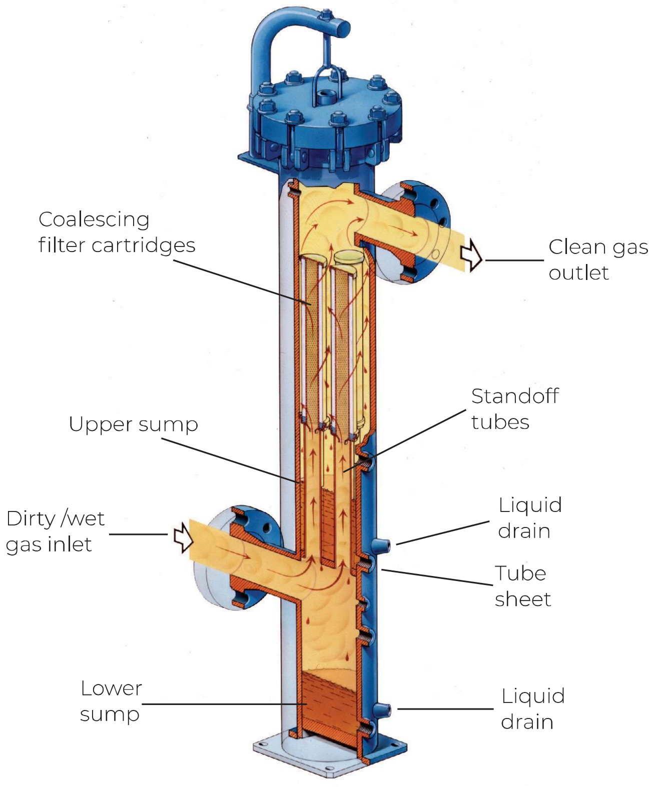


*Figure 4:* Pall liquid/gas high efficiency coalescer system

After the liquid/gas phase separation, the gas is compressed where additional liquid droplets may condense out along with compressor oil droplets that can contaminate the gas. The water and oil droplets must be removed to prevent fouling of the catalyst used in the deoxygenation step. Since the droplets are now much finer, high efficiency coalescers should be used after compression. The water and electrolyte separated flow back to the electrolyzer to be re-used. Next, the gas flows to the deoxygenation step where the oxygen component is removed. During this step, water is produced which then will need to be removed. A high efficiency liquid/gas coalescer can be used followed by a dryer to remove the remaining moisture. These final step driers are typically adsorbent based including Temperature Swing Adsorption (TSA) and Pressure Swing Adsorption (PSA) units.

Pall Corporation can offer a range of liquid/gas coalescers to meet removal efficiency, flow, temperature, pressure, and material compatibility requirements. Pall's SepraSol™, SepraSol™ Plus, Medallion™ and Coreless liquid/gas coalescer product lines can be applied to the separations mentioned above.

## Case Studies

### Liquid/Gas Separation in AEL

Pall Corporation has recently completed a retrofit of a mist eliminator with Pall Coreless liquid/ gas coalescers to remove a water/KOH mixture from the hydrogen gas produced using an AEL electrolyzer. The coalescers provided similar separation efficiency and differential pressure as the mist eliminator. However, the coalescers were made of a fully compatible material as the traditional glass fiber materials used in mist eliminators are not compatible. Testing will continue to determine the lifetime of the cartridges and evaluate the operating costs. After 1 year in operation, further optimization on separation efficiency can be completed. Testing the coalescers on the oxygen stream will also move forward this year.

### Liquid/Gas Separation After Compression

As mentioned above, after the hydrogen is compressed, additional liquids and compressor oil droplets can also be present in the gas stream. These must be removed to prevent fouling of the catalyst used in the deoxygenation step. Pall Corporation has extensive experience providing solutions for gas clean-up after the compressor. The SepraSol™ and SepraSol™ Plus coalescers are used widely in the industry to remove any solids and liquids after compression.

## Removal of Solid Contaminants

Solid contaminants must be removed from the incoming water feed (mostly in PEM systems) as well as the liquid electrolyte (in AEL systems). Solid contaminants can also originate from oxidation in process piping and equipment such as pumps and compressors. Lastly, adsorbent fines from the final driers can get released and contaminate the gas.

To remove solid contaminants, regenerable and disposable gas filters in different micron ratings (absolute) can be employed throughout the process. An absolute micron rating is defined by the National Fluid Power Association (NFPA) as: "The diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. It is an indication of the largest opening in the filter element". In contrast, many filter manufactures rely on nominal ratings. A nominal rating is defined by the NFPA as: "An arbitrary micron value assigned by the filter manufacturer, based upon removal of some percentage of all particles of a given size or larger. It is rarely well defined and not reproducible". Due to the wide variability in nominal ratings, nominal filters are not recommended for green hydrogen production.

For PEM systems, ultra-pure water is required and must be filtered using a reverse-osmosis system. Within the water treatment system, very fine filters are typically employed upstream (5 microns absolute) to protect the RO system and downstream (1 micron absolute) to capture any fines that may have been released. The final filters for the system can be as fine as 0.02 microns absolute. Also, removal of ions such as iron and calcium has become important for feed water quality in PEM systems. Pall Corporation's UltiKleen™ and IonKleen™ (for ion removal) product families can provide a range of ultra-fine filters for use in RO systems in different materials and configurations.

For electrolyte filtration in AEL systems absolute filters in the range of 5-10 microns can be used. For example, Pall Corporation's Ultipleat® High Flow 10-micron filters can be used to filter a 30% KOH/water solution at 80°C. In addition, gas particle filters can be used downstream of the final driers to remove any carryover dust. However, the cleanliness requirements have not been well defined yet for these applications.

Pall Corporation can provide absolute, disposable filters in a wide range of micron ratings, materials of construction, and configurations to match any specific need.

## Case Study

### Blue Hydrogen

As the production of green hydrogen is optimized, the production of hydrogen using fossil fuels can be improved by capturing and storing the $CO_2$ produced. This type of hydrogen is termed blue hydrogen. Recently, an electricity provider has initiated operations of a pilot plant producing blue hydrogen by gasifying coal and capturing and storing the $CO_2$ produced. The hydrogen is then liquified and shipped to a neighboring country. Pall Corporation's metal blow back technology was tested with success at this pilot plant to remove char from the gaseous stream after gasification. Pall's PSS® Series filter elements (see Figure 5) made of iron aluminide were able to meet the extreme material and temperature resistance that the application required. Pall continues to work with the client as the production process progresses through the scale up.

*Figure 5:* Pall PSS Series filter elements in pilot housing

## Hydrogen Storage

After the hydrogen is produced, it can be stored compressed in tanks, in salt caverns, or as a chemical by conversion to ammonia using the Haber-Bosch Synthesis. As previously mentioned, after compression, the gas can become contaminated with fine solids and compressor oil. Further contamination can occur during storage in tanks as well as in the salt caverns. Pall gas filters and liquid/gas coalescers can be employed to reduce the contaminants to reach the quality specifications required for the end use (e.g. fuel cells). In addition, Pall has extensive experience with separation applications in the production of ammonia with over 200 filter and coalescer installations in ammonia plants worldwide.

## Conclusions and On-going Work

As the shift to renewable energy continues to grow, hydrogen plays a key role as a clean energy source and storage medium. To meet the new hydrogen demands, green hydrogen production must be greatly increased. However, the production process still faces challenges in commercialization and scale up. The high cost of electrolyzers and stringent purity standards make green hydrogen the most expensive way to make hydrogen. Liquid, gaseous, and solid contaminants must all be removed from the hydrogen produced to meet the purity standards required.

As a leader in separation and purification technology, Pall Corporation is committed to help advance the production of green hydrogen. Pall Corporation can offer a wide range of separation and purification solutions to meet any specific need. Pall will continue to work towards developing solutions for this highly evolving market to help assist making green hydrogen more economical and sustainable.

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## References

1. Norazlianie, S., “Emerging technologies by hydrogen: A review,” *International Journal of Hydrogen Energy* (2020)
2. Kakoulaki, G., Kougias, I., et.al., “Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables,” *Energy Conversion and Management* (2021)
3. Energy Industries Council, “Moving the Needle Towards Net-Zero Carbon Emission Within the ASEAN Region,” March 31, 2021
4. Bryan, T., “Renewable Diesel’s Rising Tide,” *Biodiesel Magazine; January 12, 2021*
5. Dagdougui, H., Sacile, R., et.al., “Hydrogen Infrastructure for Energy Applications” (2018)
6. Ball, M. and Weeda, M., “Compendium of Hydrogen Energy” (2016)
7. Ligen, Y., Vrubel, H., and Girault, H., “Energy efficient hydrogen drying and purification for fuel cell vehicles,” *International Journal of Hydrogen Energy* (2020)
8. Centro Nacional de Experimentación de Tecnologías de Hidrógeno y Pilas de Combustible (April 2021)
9. Wines, T. and Brown, R., “Recent Developments in Liquid/Gas Separation Technology” presented at the Laurance Reid Gas Conditioning Conference; Norman, Oklahoma; February 28, 1994

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