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Use of membrane technology to enhance the integration of hydrogen into processing and manufacturing

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Abstract

Membranes are at the heart of the green hydrogen economy and are used at every stage along the infrastructure highway – from production of the gas to its end use. This article looks at the role membranes play in electrolysers, and carbon capture and storage, and how they can be used to produce hydrogen from feedstocks, such as biomass and bio-waste. It also illustrates their application in the production of green ammonia and the way in which this compound can be converted into ultra-pure hydrogen for a range of uses.

The structure of the future zero-carbon hydrogen (H_2) infrastructure chain is illustrated by the diagram in **Figure 1**.

Historically, H_2 has been a key constituent in the processing and manufacturing of several key industrial chemicals, including methanol (CH_3OH) and ammonia (NH_3), but it is predominantly used as an ingredient in hydrotreating operations during crude oil refining.

Whilst the use of H_2 in these already established areas will continue, the so-called "energy transition" – leading to the "hydrogen economy" – seeks to disrupt these conventional applications in favour of H_2 itself being used as a fuel.

As fossil fuels dwindle in importance over time, global leaders in the processing and manufacturing industry are searching for technologies that can help them achieve decarbonisation whilst, at the same time, enhance energy security.

Energy source

H_2 seems to be on track to becoming an energy source and its use is gathering notoriety. At the centre of this is membrane technology used in fuel cells, and H_2 manufacturing and processing.

H_2 – specifically green H_2 – has been a topic of interest for the renewable energy economy for a very long time.

H_2 remains one of the most abundantly available and commonly known elements in the world, and it will create a paradigm shift, with its significant contribution to the transition to clean energy.

H_2 is light, storable, energy-dense and at the point of use does not result in direct carbon emissions of greenhouse gases (GHGs).

Sectors such as crude oil refining and NH_3, CH_3OH and steel production have been using H_2 extensively. This gas will play a critical role in the transition to clean energy with the advancement of its applications in end-use sectors such as transportation (fuel cells), buildings (H_2 blending) and power generation.

Potential for unprecedented attention

The illustration in **Figure 2** shows the key technology trends impacting the H_2 industry and provides an overview of the progress of H_2 as a theme and its potential applications areas over the next three decades to 2050. It provides a detailed analysis of the H_2 value chain, participation of leading players and H_2 policies of key countries around the world.

H_2 technology is now harvesting the fruits of unprecedented political, environmental and business attention, with many strategies, policies and upcoming projects worldwide expanding swiftly. Globally, nations are striving to speed up the development of H_2 technology and implement it to resolve environmental concerns and strengthen energy security.

Formulating a remunerative and effective transition is an intricate issue, and the cost of H_2 production from renewable energy sources is currently not cost-effective. However, increasing focus on the components of the entire value chain is accelerating cost reduction in H_2 production, transmission, distribution, retail and end-applications. The time has now come to scale up zero-carbon technologies and precipitate cost reductions to enable H_2 technology to be used widely.

H_2 currently plays an insignificant role in the power-generating industry, and accounts for less than 0.2% of the total electricity generated.

But a shift is highly possible soon because mixing NH_3 and H_2 can decrease the effect of carbon in existing conventional power plants running on coal, H_2 gas turbines and combined-cycle gas turbines (CCGT).

Remote areas

In the long term, large-scale energy storage involving hydrogen (in the form of compressed gas, NH_3 or synthetic methane (CH_4)) will have a role to play in balancing seasonal discontinuities in electricity supply and demand from renewable energy sources.

H_2 also can be used to satisfy the power requirements of remote areas by using it in fuels cells to generate electricity and through electricity storage that comes as part of the integration of renewable energy sources (RES).

H_2-based fuel cells aim to ensure the daily and seasonal supply of electricity without relying on diesel generators, or any power generator based on fossil fuel, to enable remote areas to become energy self-sufficient whilst also significantly helping to meet climate change goals.

H_2 economy

The longing for the H_2 economy is rooted in the fact that this gas is a clean-burning fuel and abundantly available. It can work in tandem with renewable energy derived from solar, wind and other sources, and it can take on the role of an energy carrier for renewable energy when deployed for electrification purposes.

RES, such as wind and solar power, are expected to be a building block for the realisation of a green H_2 economy.

Electrolysers

Electrolysers are key to attaining a zero-carbon society. There are three main types of electrolysers and these are distinguished by the type of membrane that each one uses.

The features of these technologies are summarised by **Figure 3**. From left to right it shows alkaline electrolyte (AEL), acidic, using a polymer electrolyte membrane (PEM) and solid oxide electrolyser cells (SOEC), respectively.

These electrolysers function in slightly different ways depending on the electrolyte membrane material involved:

- Both alkaline and PEM electrolysers can deliver H_2 on site and on demand; pressurised H_2 without a compressor; and 99.999% pure, dry and carbon-free H_2.
- SOECs operate at a much higher temperature (> 700°C) than alkaline and PEM electrolysers (up to 80°C) and have the potential to become much more efficient than PEMs and alkaline electrolysers.

Electrolysers are stepping up swiftly – scaling up from megawatt (MW) to gigawatt (GW) power ratings – as technology continues to evolve and progress.

According to the International Renewable Energy Agency (IRENA), the cost of electrolysers has dropped by 60% since 2010, reaching today's level of $840/kW, and could drop another 40% and 80% in short-term and long-term scenarios, respectively.[1]

Attaining these cost reductions depends on continued innovation to enhance electrolyser performance, and standardisation and increasing manufacturing capacity, along with increased output quantity at reduced per unit total cost of production (economies of scale). This has the potential to bring down the cost of green H_2 to less than $2/kg – a breakthrough for cost competitiveness – and a 40% decrease in electrolyser cost, that is, $336/kW by 2030, with over 100 GW of capacity deployed.

IHI Engineering Australia Pty Ltd (IEA), a subsidiary of Japan's IHI Corp that operates in the power-generating sector, estimates that by 2030 renewable H_2 (green H_2) will become the cheapest option for clean H_2 supply for numerous greenfield uses.[2]

Major participants operating across the electrolyser market space include, Air Liquide, Next Hydrogen, Plug Power, McPhy Energy, ITM Power, Asahi Kasei Corp, Idroenergy, Cockerill Jingli Hydrogen, Nel ASA, Tianjin Mainland Hydrogen Equipment, Kobelco Eco-solutions, Erredue, Green Hydrogen, Areva H2Gen, Acta (Enapter), Sunfire, Cummins, Air Products, Siemens Energy, Linde and Suzhou Green Hydrogen Energy.

There has been an increase in the number of new market entrants, such as HyNet and H2PRO, that focus on widespread availability of electrolyser capacity and technology. In addition, Energy leader Iberdrola and partner Ingeteam have established the company Iberlyzer, which is dedicated to electrolyser technology.

Electrolysers are, therefore, expected to play a pivotal role in shaping application areas such as manufacturing, industrial H_2 production, power-to-X strategy management and power-grid normalisation.

Green ammonia production

Figure 4 shows how membrane technology can facilitate green NH_3 production to replace the Haber–Bosch production route.

H_2 is viewed as a viable energy source for aviation, but is often ruled out because of cost, the public's perception of safety and an underdeveloped infrastructure. Furthermore, most current production methods rely on fossil fuels, thus negating the carbon-neutral potential of H_2.

The idea of using NH_3 as a carrier for H_2 delivery has gained popularity in recent years because NH_3 is much easier to liquify than H_2 and, therefore, is easier to store and transport. In addition, NH_3 can be cracked to produce H_2, again at the point of use.

Through funding from the Net Zero Technology Centre (NZTC) we are currently studying the materials requirements for an electrochemical NH_3 synthesis process. The study will specifically address high-flux, cost-effective nitrogen capture from air and integrate it with H_2 in a catalytic membrane reactor to synthesise NH_3.

Air separation

To produce green NH_3, the energy required in the air separation unit (ASU) must also come from renewable sources.

However, the conventional and widely used technique for air separation is cryogenic distillation and a large amount of energy is consumed for the separation process that involves freezing atmospheric air, reducing its temperature to -200°C.

Alternatives include pressure swing adsorption (PSA) and vacuum pressure swing adsorption (VPSA), but these are bulky and cumbersome to operate.

Membrane technology comprises different characteristics: it is a simple, efficient and economic methodology. Compared with other approaches it has a low cost and low energy consumption.

From a commercial perspective, new methods for preparing and fabricating membranes, such as spinning hollow fibres, reduce the thickness of the membrane layer which significantly improves the permeation rate and results in a larger surface area in the membrane module.

Higher gas permeation reduces the selection of gas molecules and its purity and is a disadvantage of conventional membrane technology. To equalise this, a membrane with a larger surface area is required.

Research and development of mixed ionic, electronic conducting ceramic membranes (MIECMs) have led to defect-free membrane structures, and higher permeation rates and purity of gas molecules. During the operation of the ceramic membrane, a high oxygen (O_2) partial pressure (PO_2') and a low O_2 partial pressure (PO_2'') are maintained at the feed and permeate surfaces of the membrane, respectively, as shown in **Figure 5**.

Flow of O_2 in MIECMs is a five-step process determined by the net O_2 exchange flux crossing the gas–MIECM interfaces and the diffusion of oxygen ion (O^{2-}) electron hole pairs (e–h pairs) in the bulk of the MIECMs. As a result, a stable O_2 gradient is generated across the membrane.

The advantage of using the ceramic mixed ionic electronic O_2 conducting membranes is that O_2 separation is driven by the chemical potential gradient across the membrane because of ambipolar diffusion (through both electrons and O^{2-} ion moving in the opposite direction) at a particular temperature.

This means that the application of an electrical field, or external current, is not required, which makes it easier to integrate this technology with renewable energy sources in order to generate green nitrogen.

Green ammonia synthesis

Amongst many approaches for green NH_3 synthesis, electrochemical routes have the potential to produce NH_3 under very mild conditions of temperature and pressure, and at a lower cost compared with the Haber–Bosch process of NH_3 production. Adopting such routes could result in renewable energy being integrated into the production process.

The various electrochemical routes for ammonia production are differentiated by the type of electrolyte used and the operating temperature regime.

These can be broadly divided into four categories:

- liquid electrolytes, operating near room temperature;
- molten salt electrolytes, operating in the 300–500°C (572–932°F) range;
- composite electrolytes that consist of a solid and a low melting molten salt; and
- solid electrolytes, with an operating temperature range of room temperature (typically for polymers) to 800°C (1472°F) (ceramics).

Other materials of construction are based on the type of system selected. Typical operation of the solid-state electrochemical ammonia production process is described in **Figure 6**.

Hydrogen energy storage

Producing hydrogen using electrolysers powered by renewable electricity could enable alternative sources of variable, renewable energy – such as wind and solar photovoltaic (PV) – to be integrated into the energy system. This is made possible because their electricity consumption can be modified to follow solar PV and wind-power generation. H_2 serves as a source of energy storage for renewable electricity and NH_3 can be then used as a storage medium for H_2.

Ammonia cracking to hydrogen for non-specialised applications

The extraction of H_2 from NH_3 is currently carried out by a two-step process involving catalytic decomposition of NH_3 followed by H_2 separation to produce high-purity H_2 with less than 1 ppm NH_3.

The cracking reaction (**Equation 1**) is endothermic – requiring 383 kJ/mol. The process is typically performed at an elevated temperature within the range 850–950°C (1560–1740°F), in the presence of nickel as a catalyst. The resulting gas mixture is composed of H_2 and N_2 in the proportion 3:1 (75% of H_2 and 25% of N_2) with very little (20–100 ppm) of residual undissociated NH_3 (with a dew point of -51°C to -29°C (-60°F to -20°F)).

The H_2 may be further purified by molecular sieves, resulting in a reduction of the uncracked NH_3 to 1–3 ppm (with a dew point of -80°C (-110°F)).

Ammonia cracking is a process of dissociation of gaseous anhydrous ammonia (NH_3) back into a mixture of H_2 and nitrogen (N_2) according to the reaction:

$$2NH_3 \Leftrightarrow N_2 + 3H_2 \quad (1)$$

The principal flow scheme of an NH_3 cracker is presented in **Figure 7**.

NH_3 cracking is a well-established, simple and cost-effective method of manufacturing H_2 at the point of use. However, it may be used only in applications in which the presence of minimal N_2 impurities may be acceptable, such as:

- annealing furnaces, with a reducing atmosphere, for continuous heat treatment of cold-rolled steel;
- bell-type annealing furnaces;

- sintering of metals;
- metal-powder annealing;
- brazing; and
- hydrogenation of edible oils.

Ammonia cracking to hydrogen for highly specialised applications

Applications in which the presence of N_2 and other impurities are not acceptable include:

- the speciality chemicals industry;
- semiconductor fabrication processes;
- vacuum deposition;
- atomic layer deposition;
- PEM fuel cells; and
- uses in the nuclear-power industry.

The similar operating temperature ranges of a conventional cracker and separation system suggest coupling both functionalities of chemical reaction and separation into a single reactor unit called a catalytic membrane reactor, which is shown in **Figure 8**.

Membrane reactor

In a membrane reactor used for NH_3 cracking, the H_2 formed (by catalytic cracking) is concentrated and purified by a palladium membrane surrounding the reaction zone. The integration of these two devices is beneficial in terms of producing ultra-pure H_2 (99.999999%). The heat for the decomposition reaction is provided by burning part of the NH_3.

We have prepared supported thin-films of palladium and palladium alloy membranes using unbalanced magnetron sputtering technology and tested them for H_2 permeation using representative H_2/N_2 gas mixtures, at 300–400°C (572–752°F), to demonstrate the membranes' H_2 selectivity, chemical and thermal stability as well as permeability.

An Arrhenius-type dependency was established by studying the effect of temperature on the permeability constant and enabled the activation energy to be calculated.

Meanwhile, the H_2 flux dependence on the pressure drop across the membrane followed the half-power rate of Sieverts' Law[3] and was used to describe the dependence of permeability on the square root of the transmembrane pressure drop.[4]

A plug-flow mathematical model was developed, and the experimental data were used to simulate the performance of a packed-bed catalytic membrane reactor for the decomposition of NH_3 contained in coal gasification streams at different temperatures, pressures and gas hourly space velocities.[5]

The results clearly showed that by using the catalytic membrane reactor, parts per million concentrations of NH_3 can be decomposed completely at affordable temperatures and pressures through the equilibrium-shift effect caused by the continuous removal of H_2 from the reaction zone.[5]

Our experimental and simulation results have been subsequently used for pure NH_3 decomposition in catalytic membrane reactors, like the ones we have developed, with excellent results, thus validating our earlier work.[6]

Promising zero-emission technology for future aircraft, ground and sea transportation

One option is to use liquid organic hydrogen carrier (LOHC) technology (**Figure 9**).

However, to improve economic viability and enable widespread commercial deployment of this technology, further work is required covering the development of new cost-effective catalysts with improved contact-time yield, high activity, selectivity and onstream durability; increasing the number of cycles before a replenishment is required; total cost reductions in LOHC transportation (including the cost of transporting the raw LOHC back to the plant for charging (hydrogenation)); improved purity of the H_2 released during the dehydrogenation reaction; and widespread deployment and system integration of the LOHCs with various industries.

Furthermore, candidate selection of a suitable LOHC must also be considered: it should maintain its liquid state throughout the LOHC cycle and possess a low toxicity and low cost, and have a high hydrogen loading capacity.

Here too, a membrane such as the one discussed earlier (Figure 8) can be reconfigured and incorporated into LOHC technology to facilitate the dehydrogenation reaction for recycling and achieve complete conversion to produce high-purity hydrogen.

Cracking NH_3 to produce H_2 is another option and underpins many of the fuel-based uses of NH_3 and, as such, it is emerging as the lynchpin technology in the case for NH_3 and H_2 energy.

Although NH_3 cracking is, in many ways, a mature technology, systems that are designed specifically for aircraft, ground transportation and maritime applications are extremely rare, and our technology (the underlying principles of which are presented in Figure 8) has the potential to become one of the cornerstones of the zero-carbon economy.

In the air

The global aviation sector, which includes domestic and international; passenger and freight, accounts for 2% of greenhouse gas emissions, which includes all greenhouse gases, not only carbon dioxide (CO_2) – 2.5% of CO_2 emissions and 3.5% of "effective radiative forcing", which is a closer measure of its impact on warming.

It is also considered to be one of the "hardest-to-abate" sectors of the economy. Green H_2 is, therefore, increasingly considered as one of the most promising zero-emission technologies for future aircraft (**Figure 10**). However, even though H_2 has an energy-density per unit mass that is three times higher than traditional jet fuel, a variety of challenges must be addressed before it is possible for this technology to be widely adopted.

Technically, aeronautical engineers will need to take the technologies developed in the automotive and space industries and make them compatible with commercial aircraft operations – notably by bringing down weight and cost.

One specific challenge is how to store H_2 on board aircraft. Today, liquid H_2 storage is amongst the most promising options (Figure 8), whilst storing H_2 as compressed gas poses challenges with current aircraft weight and volume requirements.

In addition, the aviation industry will need to achieve the same or better safety targets than those that have been achieved with existing commercial aircraft. Indeed, extensive safety precautions are currently considered in the design and operation of today's kerosene-powered aircraft. This stringent approach has ensured the industry's consistent safety record throughout the years.

This means that future propulsion systems based on H_2 will need to achieve equivalent or better safety levels before hydrogen-powered aircraft can take to the skies.

To overcome these problems, we propose the use of NH_3 instead of H_2 stored onboard the aircraft. An advanced reactor system (such as the one shown in Figure 8) that is capable of converting NH_3 into ultra-pure H_2 can be used for generating the ultra-high purity gas required by PEMs.

It consists of a fixed bed of catalysts enveloped by a highly H_2 permeable and selective thermally and mechanically stable membrane. As shown in Figure 7 a portion of NH_3 is combusted to provide heat necessary to drive the endothermic NH_3 cracking reaction, using heat-transfer tubes.

This is particularly suitable for use on board long-haul passenger aircraft since this process can be retrofitted to engines that are currently employed, with the main difference being the replacement of fossil fuel with NH_3, and making necessary adjustments for the density and temperature of NH_3.

Switching to green H_2 fuel will help the aviation sector to reach net zero CO_2 emissions by eliminating its cumulative emissions by about 20% in 2050. However, storage of pure H_2 on board passenger airliners is not practical. This is because a cryogenic temperature of -253°C and a pressure of 700 bar for liquid and gaseous-phase pure H_2 storage are required, respectively. In addition, a storage volume four times that of current fuel tank capacities in civil airliners would be needed.

Chemical storage of H_2 in the form of NH_3, which can be obtained via sustainable green technologies, is the most promising approach to onboard H_2 storage. This is because of the high H_2 storage capacity of NH_3 (17.65 wt% H_2).

The proposed process provides a relatively easy way of converting the stored H_2 in NH_3 back into ultra-pure H_2, at a relatively low temperature, by storing NH_3 as a liquid at a moderate pressure of 10 bar at room temperature.

Storing H_2 – with NH_3 as the storage compound – on board hydrogen-fuelled airliners, will be enhanced by the development of a membrane-based approach to NH_3 cracking (NH_3-to-H_2).

A team that consists of researchers from the Robert Gordon University, University of Hull and Cranfield University recently completed an Engineering and Physical Sciences Research Council project, run under the theme ‘Development of a compact and highly efficient onboard ammonia cracking system to produce hydrogen in a hydrogen-fuelled long-haul civil airliner’.

It combined molecular dynamics, laboratory-based testing, process modelling, heat and system integration and techno-economic evaluation to explore the potential of an onboard NH_3-to-H_2 system for a hydrogen-fuelled long-haul Airbus A380 aircraft.[7]

Professor Edward Gobina's team at Robert Gordon University (RGU) prepared thin films of palladium silver alloys, with a thickness of 6 µm. Using an electroless deposition technique this material was applied to a porous gamma alumina support having a mean pore size of 15 nm, and the resulting structure was tested for H_2 transport and selectivity.

Results showed it was completely dense as no helium gas (He) was detected on the permeate side, under the temperature and pressure ranges studied, and only H_2 was able to permeate the membranes.

The results of this investigation were presented during an oral session at the Sixth International Conference on Fossil and Renewable Energy (F&R Energy-2022), which was held on 15–17 February 2022, in Houston, Texas, USA.[8]

On land

Whilst we eagerly anticipate the development of technology for use on board aircraft, on the ground, Amogy Inc, which is based in Brooklyn, USA, has developed a way of powering a vehicle by what it believes will be one of the future's biggest renewable fuels – NH_3. The company is currently developing ammonia-to-power systems.

The start-up, which is less than two years old, recently announced a milestone with its first successful demonstration of an ammonia-powered tractor that uses NH_3 stored onboard as fuel and then cracks the chemical on demand to H_2 to power a 100 kW H_2 fuel cell engine.[9]

Making tractors run with little or zero-carbon pollution has long presented a trade-off: cleaner air, but leaving less power to drag heavy equipment. Therefore, our onboard NH_3-to-H_2 catalytic membrane technology – if also extended to all “non-road mobile combustion” applications – will help manufacturers close the gap, resulting in the removal of an estimated 7.1% of CO_2 emissions from off-road agricultural equipment.

At sea

At sea, The International Maritime Organization (IMO) has established a target for a 50% reduction in CO_2 emissions from international shipping by 2050.

Given that the average vessel has a lifetime of between 25 and 30 years, maritime stakeholders understand that reaching this goal will require early action.

The Getting to Zero Coalition – an alliance of more than 150 maritime, infrastructure and energy companies – is calling for 5% of new vessels entering service by 2030 to be powered by zero-carbon fuels. Likewise, leading supply-chain players have formed the Cargo Owners for Zero Emission Vessels group, with the aim of fully decarbonising their freight operations by 2040.

In this regard, Sweden's Metacon Ab has delivered an “ammonia cracker” prototype unit to Pherousa Green Technologies in Norway for the development of an ammonia-fed, zero emissions maritime propulsion system.

Described as a milestone in enabling hydrogen-based zero emission propulsion for the shipping industry, the development of the prototype unit by Metacon's subsidiary Helbio is capable of NH_3-to-H_2 conversion rates greater than 99.3%. The companies say that this was achieved irrespective of load and the H_2 purification unit was able to remove 100% of the NH_3 traces, satisfying a maximum level of NH_3 according to ISO 14687:2019 and enabling a feed to be produced for a low-temperature PEM fuel cell.[10]

Increasing carbon capture and storage deployment

Carbon capture and sequestration (CCS) technology (**Figure 11**) is a potential answer to concerns over emissions in the power-generating sector, as it prevents the release of large amounts of CO_2 into the atmosphere from fossil-fuelled power plants.

Traditional CCS technology comprises a three-step process where anthropogenic CO_2 emissions are captured, transported and stored in deep geological formations to prevent the release of hazardous gas into the atmosphere.

CO_2 capture processes can be considered new to the power-generating industry, but have been used for the past 60 years in the oil, gas and chemical sectors. The technology has the potential to capture 90% of CO_2 emissions from conventional fossil-fuelled plants.

Direct air capture

The adverse effects of climate change are being felt around the globe, with an urgent need for new policies, lifestyles, partnerships and technologies that will lead to huge reductions in carbon emissions from hard-to-abate sectors such as industry, buildings, aviation, agriculture and shipping.

The field of carbon capture – removal from the atmosphere, which is also referred to as direct air capture (DAC), and subsequent storage or conversion of the carbon dioxide – is developing rapidly, but technological hurdles remain before it can be deployed at scale. The biggest challenges come from efficiency, particularly in processing atmospheric air directly in DAC systems.

The National Oceanic and Atmospheric Administration (NOAA) has calculated its longtime CO_2 concentration at its atmospheric monitoring station, located in Mauna

Loa, Hawaii – averaging 421 ppm for the month of May 2022 which is when CO_2 gas hits its yearly high.[11]

Chemical reactions with sorbents used in traditional DAC are very slow to act at these CO_2 concentrations and there is also the difficulty of releasing adsorbed CO_2 in more sustainable capture-and-desorption cycles, which can be energy intensive.

Even leading efforts to build traditional DAC plants, such as those using potassium hydroxide (KOH), sodium hydroxide (NaOH) and calcium hydroxide ($Ca(OH)_2$) suffer serious efficiency issues and incur huge recovery costs, making the hunt for new DAC processes notably urgent.

Despite these drawbacks progress is being made on these traditional DAC systems. In June 2022 Climeworks AG, a Swiss company that specialises in CO_2 air capture technology, announced that it had broken ground on its biggest new DAC plant yet. Named Mammoth, it will have the capacity to capture up to 4000 tons of CO_2 per year, for storage in basalt formations.[12]

More recently, a US climate technology company CarbonCapture Inc, in an exclusive partnership with premier carbon storage company Frontier Carbon Solutions, announced in September 2022 that it has plans to build the world's largest carbon capture facility in Wyoming USA. Called Project Bison, it has the potential to capture 5000 tons of CO_2 per year.[13]

A team led by Professor Edward Gobina at RGU has been studying an unconventional DAC system using a class of membrane systems (um-DAC©). This has led to the development of the process known as affinity-CO_2 membrane separation based, in part, on a type of transport mechanism known as selective surface flow (**Figure 12**).

Collaborating with McAlpha of Canada, the technology has been awarded a six-figure grant by the Net Zero Technology Centre (NZTC) to further develop this process to a technology readiness level (TRL) of 4.[14]

Waste to hydrogen technology

Using renewable energy, H_2 can be generated from feedstocks such as biomass, bio-waste and even biogas, landfill gas, and flue gas and CO_2.

New technologies for waste-to-H_2 are being developed by vendors such as Ways2H, SGH2 Energy and Standard Hydrogen. Ways2H has developed waste-to-H_2 projects in Asia, Europe and in the USA.

Biomass-to-H_2 projects are suited to large agricultural counties, whereas cities can rely on municipal waste generated after careful segregation. This results in a near perennial source of material for H_2 production whilst addressing the issue of waste generation.

Our colleagues at Canadian company Solistra have developed chemical reactors driven by solar power that efficiently recycle CO_2 into commodity chemicals normally sourced from fossil fuels, as illustrated in **Figure 13**. Such small-scale projects can be enacted in various cities globally, especially with governmental cooperation.

“Budding niche”

A “budding niche” has developed in the market to convert waste into H_2. The available project capacities are limited in terms of size. However, the prospect of waste elimination is being tested in several low-to-medium-level H_2 production projects.

RGU is developing a flue-gas reforming technology. The university is one of three successful UK institutions selected from a total of 344 submissions (from the 37 countries from 5 continents) that responded to the Climate Change and Emissions Management Corp's (CCEMC) first round of funding from its international $35 million Grand Challenge: Innovative Carbon Uses.[16]

Based on the catalytic membrane reactor concept the technology uses porous sintered metallic or ceramic tubes, which provide a structure for a catalytic coating that is able to promote chemical reactions (**Figure 14**).

Exhaust gases are fed to the device and gaseous components contained in the streams are rehabilitated into value-added chemical products such as H_2 and carbon monoxide (CO), commonly referred to as synthesis gas or simply syngas.

The flue-gas stream comprises CO_2, water vapour (H_2O) and O_2, and is fed methane (CH_4), or flare gas, at an elevated temperature (Figure 14). The highly dispersed catalyst in the form of nanoparticles breaks down the constituents and reassembles them into highly useful chemical constituents, as shown in Figure 14.

Our results have confirmed complete conversion of all the greenhouse gases and H_2 to produce high-quality syngas, which is perfect for onward conversion using Fischer–Tropsch reaction gas-to-liquids chemical engineering technologies to create products such as diesel fuel and important feedstock compounds for the chemical industries.[17]

We are currently working with McAlpha to carry out prototype demonstrations in order to take this process to a TRL of 8.

Conclusion

Membranes are at the heart of the green H_2 economy and are used at every stage along the infrastructure highway – from production of the gas to its end-use.

Their contribution is supported by abundant and cost-effective renewable energy sources, such as wind and solar power, coupled with cost reductions of electrolysers through innovation (increased durability, high efficiency, robust design), plant size reduction (targeting the 20–50 MW range).

Increased availability of assembly lines for component and mega-factories will help reduce costs by two to three times. The breakthrough will be scale: terawatts of electrolyser capacity, compared with the promises, thus far, of hundreds of gigawatts (and current global installed capacity is only a meagre 200 MW).

Green H_2 can compete head-on with blue H_2 (fossil-based H_2 production with CCS) by 2030 if rapid scale-up occurs in the next decade. Therefore, the most critical issue is the economics of renewable power generation as it will spur growth of green H_2 adoption.

Recent levelised cost of energy (LCOE) analysis[18] indicates that technologies, including onshore wind and utility-scale solar power systems have become very competitive with the marginal cost of existing conventional generation technologies.

The cost of energy from renewables, particularly new wind and solar projects commissioned in 2021, fell below the costs of over 800 GW of existing coal-fired power plants globally.[19]

Technological advancements in wind power, such as larger wind turbines and longer wind turbine rotor blades, along with the increasing efficiency of solar PV cells, should prove beneficial for green H_2 project deployments.

The costs of new solar PV projects have fallen below $1000 per kWh, whilst average new wind projects costs have fallen to about $1400 per kWh. This improves the levelised costs of green H_2 projects. [19]

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(Also see ‘Research aims to develop an energy-efficient way of capturing CO_2 directly from the atmosphere’, *Membrane Technology*, Vol. 2022, No. 7, https://doi.org/https://doi.org/10.12968/S0958-2118(22)70080-8, and ‘Unconventional membranes for direct air carbon capture’, *Membrane Technology*, Vol. 2022, No. 7, https://doi.org/https://doi.org/10.12968/S0958-2118(22)70077-8.)

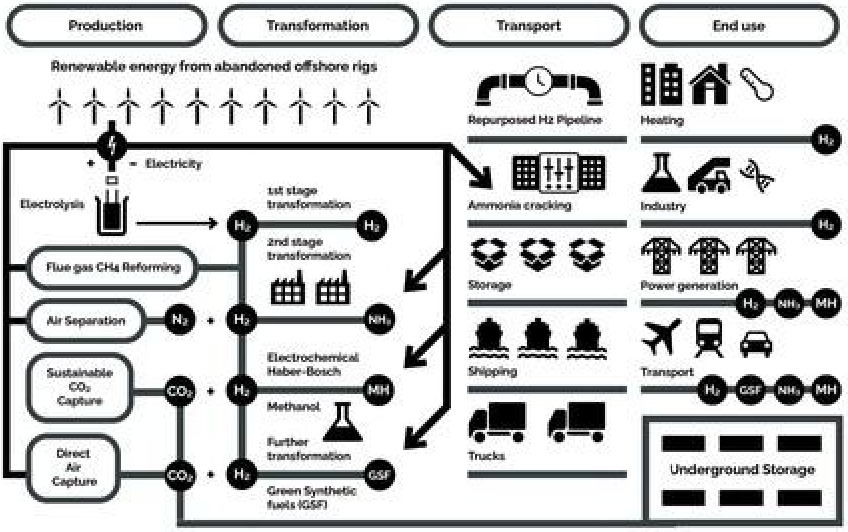


Figure 1. Future zero-carbon H_2 infrastructure chain.

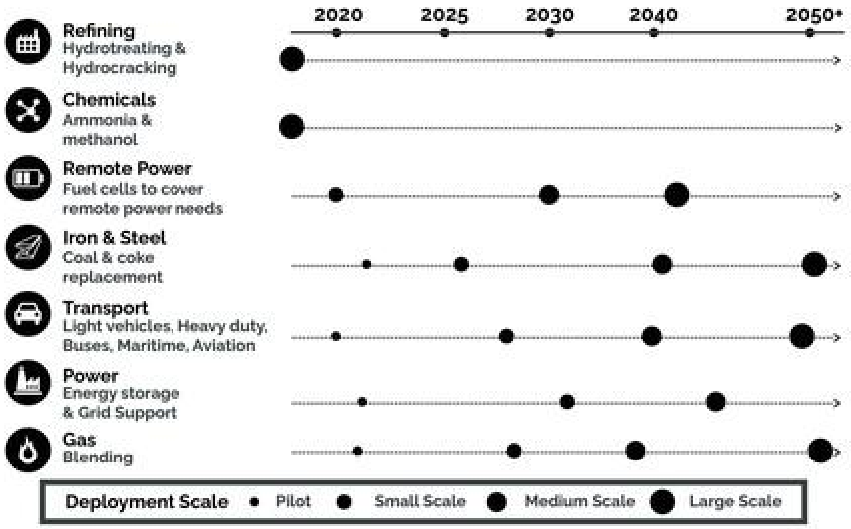


Figure 2. H_2 adoption in key industries.

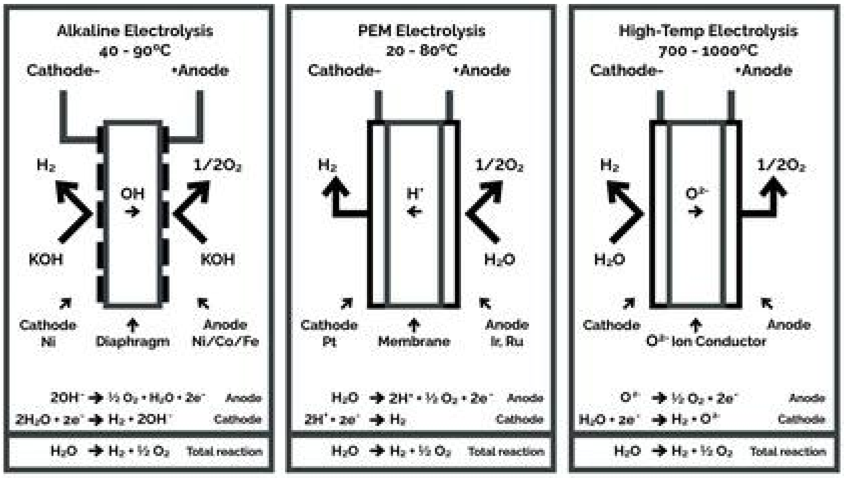


Figure 3. Workings of the three types of electrolysers *(from left to right)*: alkaline (AEL); acidic (polymer electrolyte membrane); and solid oxide electrolyser cells (SOECs).

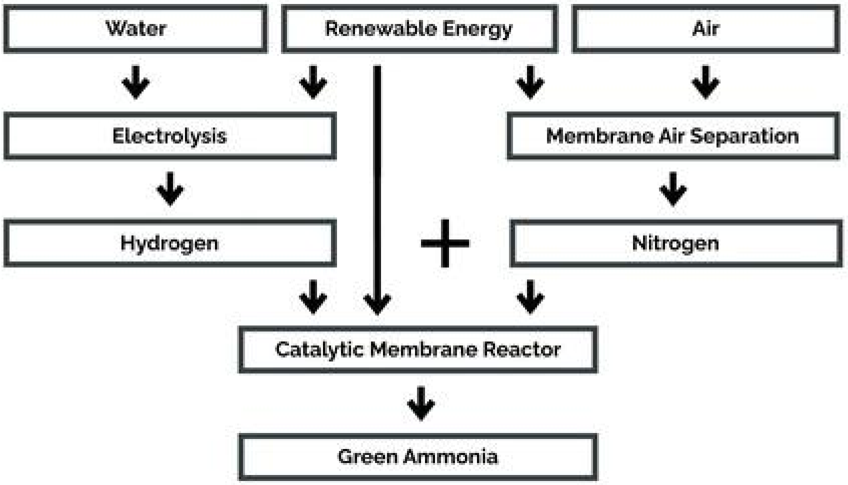


Figure 4. Green ammonia production.

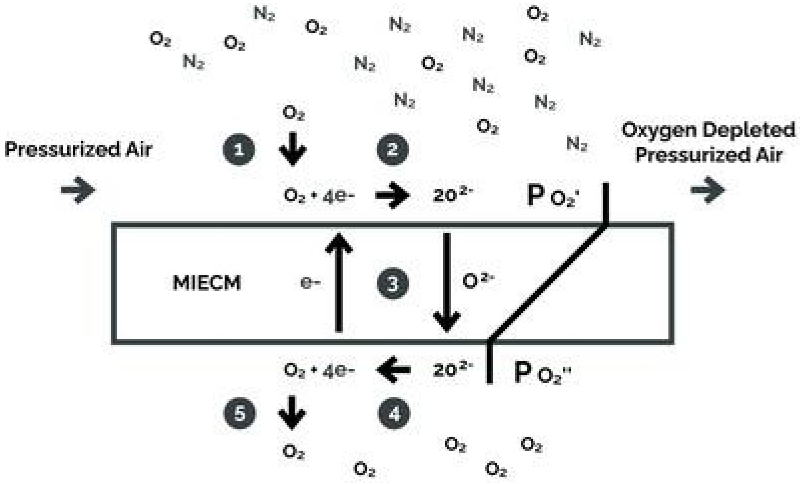


Figure 5. Schematic representation of the four-step oxygen transport process through a mixed ionic electronic ceramic membrane (MIECM), with different oxygen partial pressure ($PO_2' > PO_2''$) on both sides.

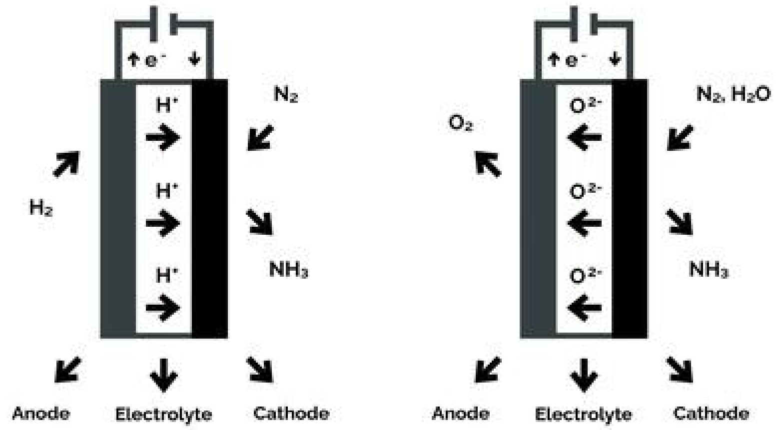


Figure 6. Diagrammatic illustration of solid-state electrochemical ammonia synthesis – proton-conducting membrane electrolyte *(left)*; and oxide-ion membrane electrolyte *(right)*.

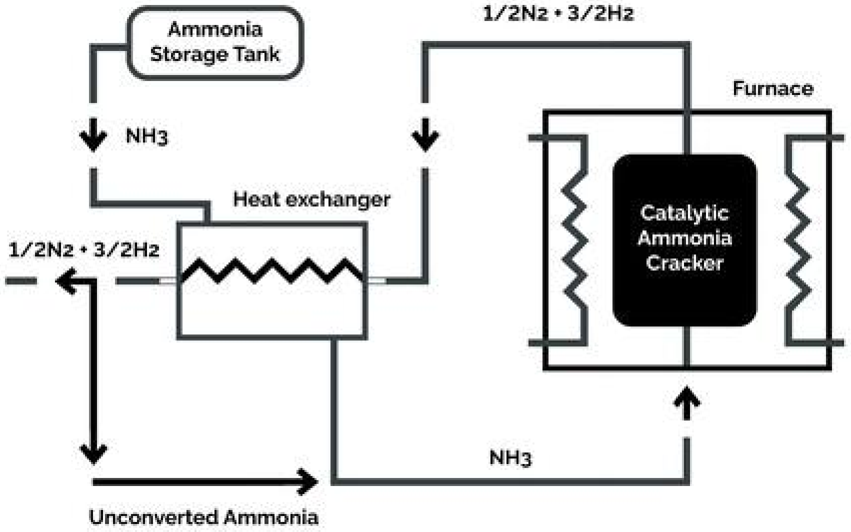


Figure 7. The principal flow scheme of a conventional ammonia cracker.

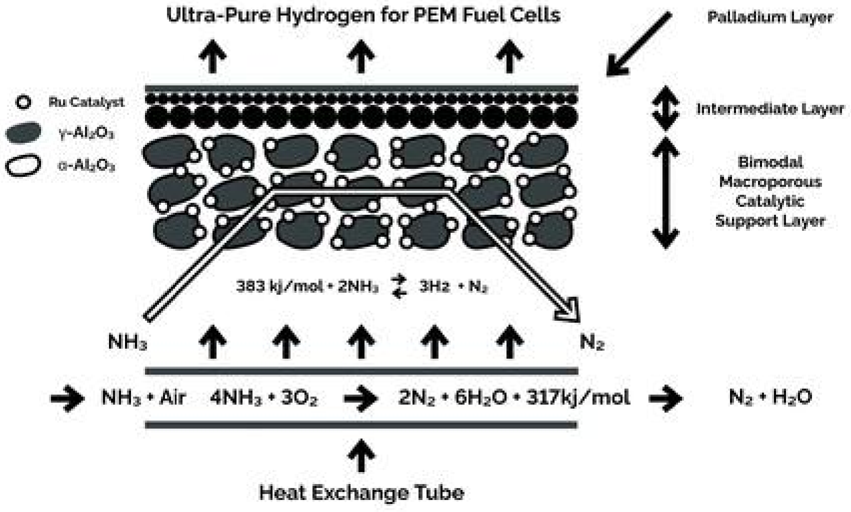


Figure 8. Combined ammonia cracking with ultra-pure H_2 production in a catalytic membrane reactor with a heat-exchange jacket (CMR-HEJ®).

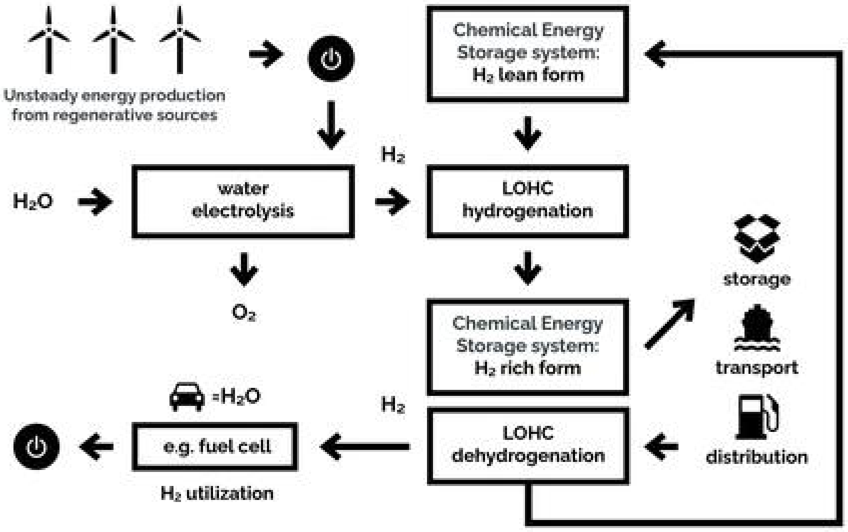


Figure 9. Liquid organic hydrogen carrier technology.

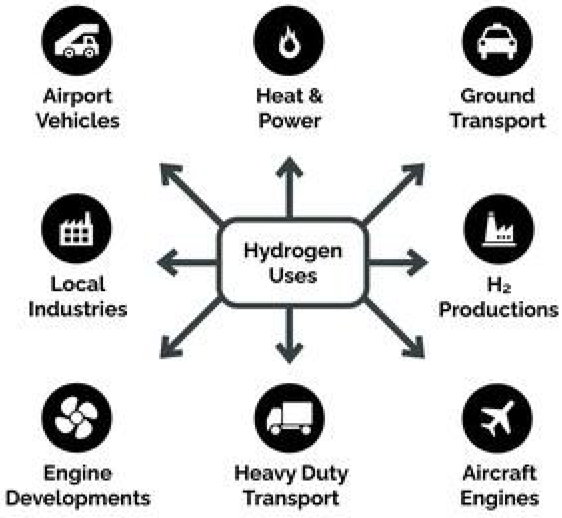
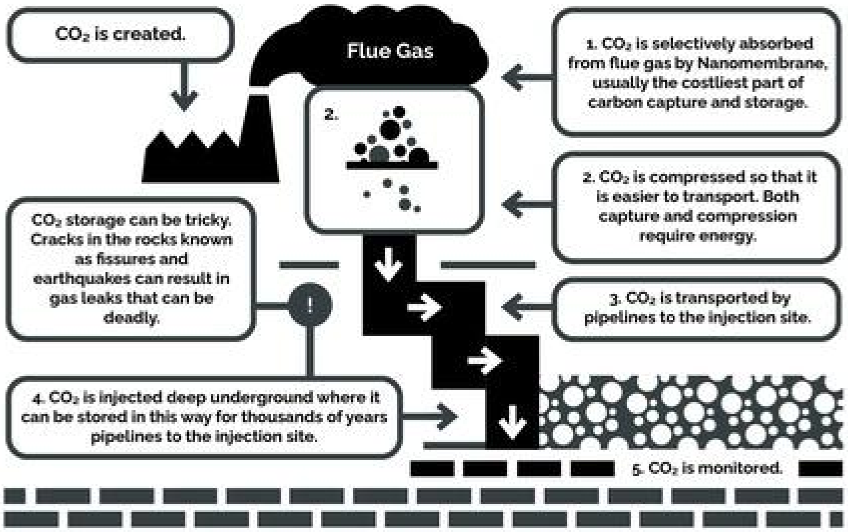


Figure 10. Hydrogen adoption in air transportation.



1. CO_2 is selectively absorbed from flue gas by Nanomembrane, usually the costliest part of carbon capture and storage.

2. CO_2 is compressed so that it is easier to transport. Both capture and compression require energy.

3. CO_2 is transported by pipelines to the injection site.

CO_2 storage can be tricky. Cracks in the rocks known as fissures and earthquakes can result in gas leaks that can be deadly.

4. CO_2 is injected deep underground where it can be stored in this way for thousands of years pipelines to the injection site.

5. CO_2 is monitored.

Figure 11. Traditional membrane carbon capture technology and sequestration.

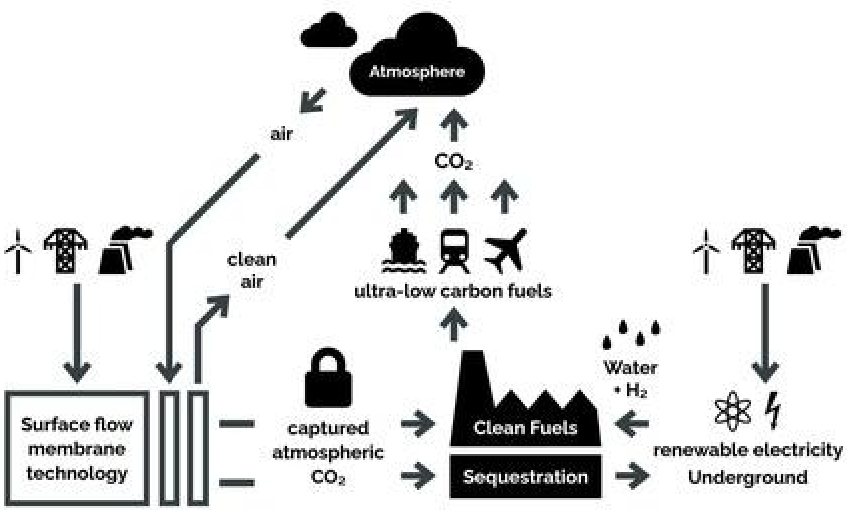


Figure 12. Direct air capture using CO_2-affinity ceramic membrane technology (um-DAC®).

Figure 13. Solar dry reforming technology.[15]

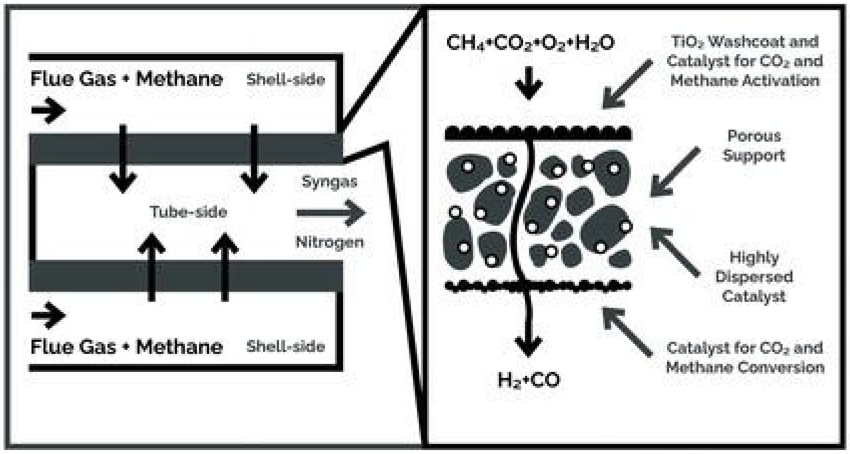


Figure 14. Forced flow-through catalytic membrane reactor showing reactor operating configuration *(left)* and enlarged view of the membrane surface and cross-section, revealing nano-dispersed catalysts and pathway of reactants to generate syngas *(right)*.