Introduction to Low Carbon Gas Technologies

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Front cover image: iStock.com/artisteer

At the end of 2023, more than 140 countries had a mid-century carbon-neutrality pledge. Meeting these commitments will require a dramatic and rapid change in the entire global energy system, one which the flexibility and innovation of the gas industry is well placed to deliver.

Reducing emissions in line with the 2015 Paris Agreement on Climate Change will require, as a minimum, the ramping up of three key areas:

1. **Decarbonisation:** improving energy efficiency, and reducing emissions and methane leaks.
2. **Diversification:** using natural gas with low-carbon and renewable alternatives, such as biomethane, e-methane and hydrogen.
3. **Innovation:** supporting the industry, both from a legislative, regulatory and investment perspective to continuously innovate its products and services rendered to markets, consumers and users.

Organic growth: A modern biofuel gas plant.
Photo: iStock.com/Vadym Terelyuk

Aligned to IGU's support of the Paris Agreement's Nationally Determined Contributions to reduce GHG emissions and its commitment to significantly decarbonise the global energy system, this "Introduction to Low Carbon Gas Technologies" provides a brief guide on key low-carbon and renewable gas technologies that are currently available for deployment to ramp up the gas industry's efforts towards deep decarbonisation.

Natural gas and its evolving technologies support the renewable energy supply by overcoming intermittency and instability. Existing natural gas infrastructure will also enable cost-effective and more rapid deployment of low-carbon and renewable gases - critical for deep decarbonisation of the global economy. Together, they can enable net-zero pathways, energy security and access issues.

Future energy mix: There are a range of options on the horizon.
Image: iStock.com/sharfsinn

1.

The first section of the report will review the main five low-CO_2 gas technologies aiming to decarbonise the methane molecule supply chain. These are:

1. **Anaerobic digestion:** biomethane based on wet biomass.
2. **Pyrogasification:** synthetic methane obtained from thermo-chemical process wastes rich in carbon.
3. **Hydrothermal gasification:** synthetic methane based on liquid biomass treatment at high temperatures.
4. **E-methane:** synthetic methane using carbon dioxide as feedstock.
5. **Solar photocatalytic processes.**

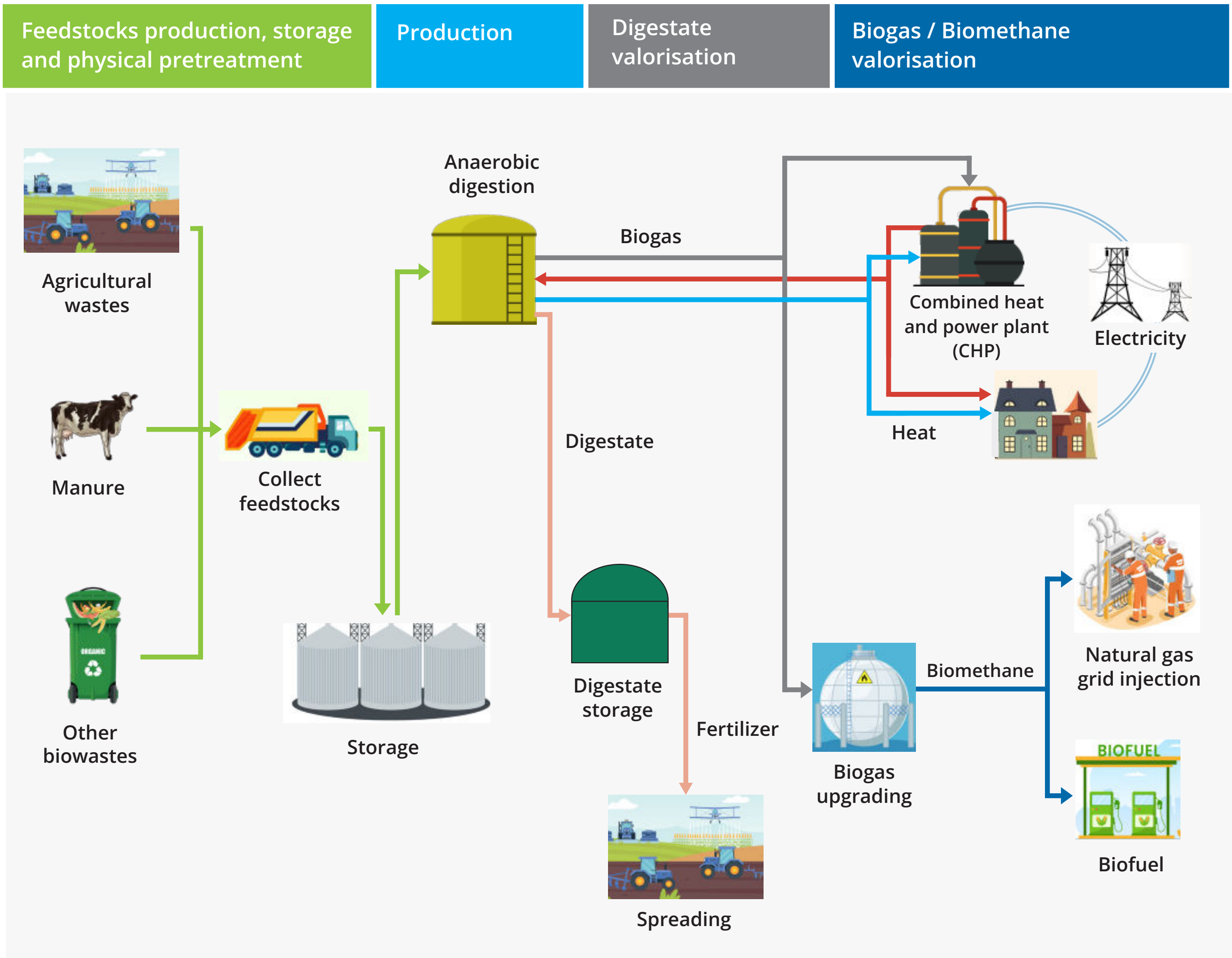
2.

The second section of the report will provide an overview of hydrogen production technologies as energy carriers. Currently, there is a limited number of such technologies in widespread operation, and these must be ramped up by orders of magnitude to be consistent with the world's current climate targets. Only then can we ensure that the priorities of energy security and energy transition do not undermine each other.
The current energy-carrying hydrogen production technologies are:

1. **Methane reformation:** extracting hydrogen from methane molecules and removing CO_2.
2. **Water electrolysis:** using renewable electricity to produce hydrogen from water.
3. **Thermal gasification:** extracting hydrogen from solid material with high heat.
4. **Methane pyrolysis:** extracting hydrogen from methane using a process that does not produce CO_2.
5. **Solar photocatalytic:** using dedicated solar energy installations to produce renewable hydrogen.
6. **Biological production of hydrogen:** through fermentation and photolysis of biomass.
7. **Geological extraction of natural hydrogen.**

I. Decarbonisation

1 Biomethane production through anaerobic digestion

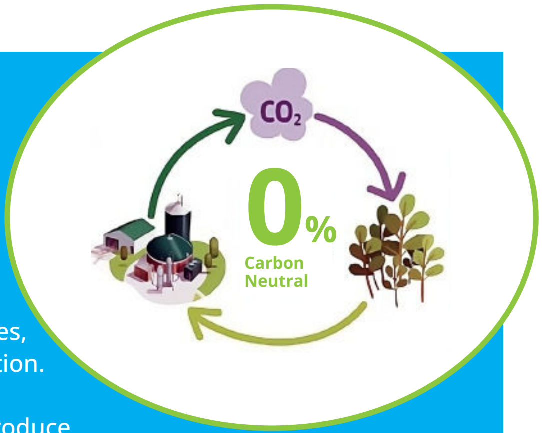


Anaerobic digestion is a process through which bacteria break down organic matter in the absence of oxygen.

This process releases energy-rich biogas, which is relatively high in methane (CH_4) content and can be captured and used as fuel. It can be enhanced either by injecting hydrogen (H_2) in the reactor or by using a light electrical current to improve the CH_4/CO_2-ratio.

There is a wide range of potential organic matter inputs that can be used as feedstock, such as food and feed industry wastes, manure and slurry, green wastes, intermediate crops and sewage sludge.

Biomethane is considered carbon-neutral



Biomethane production captures methane , a strong greenhouse gas, from its bio raw material, and turns it into useful fuel. This process stops methane from escaping into the atmosphere, where it would contribute to global warming.

Biomethane, made from biogas, can be used just like natural gas. It easily uses the existing gas systems without needing any changes, making it a cost-effective and simple way to support decarbonisation.

CO_2 from the atmosphere is captured by organic waste used to produce biomethane. Its combustion produces biogenic CO_2 emissions.

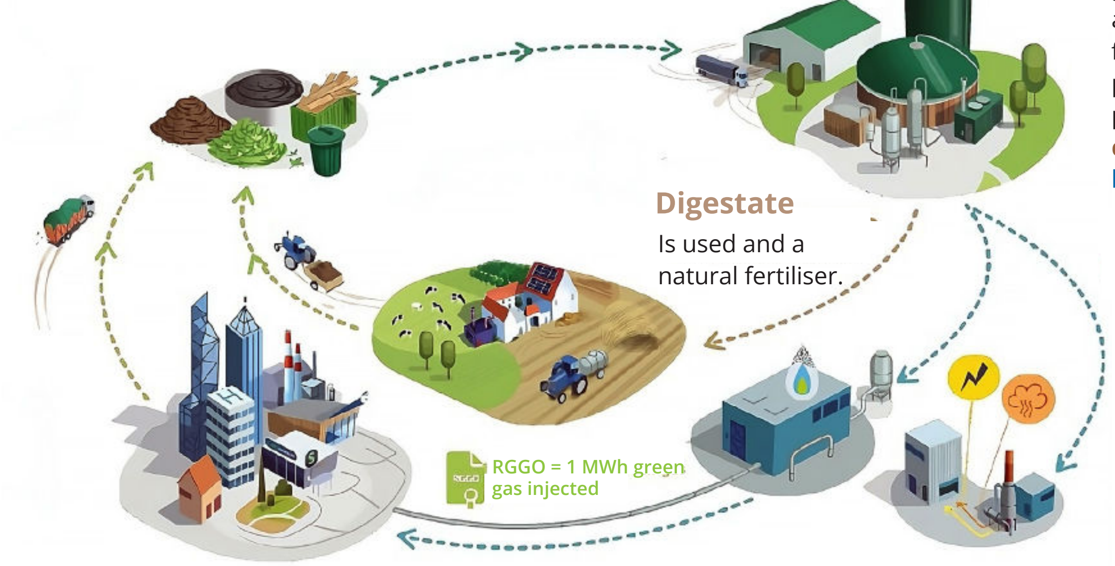
Compensation effect: almost no impact on greenhouse gas emissions.

1. Collection

Organic waste is collected and transported to the methanisation site.

2. Anaerobic digestion

Organic waste goes through an anaerobic fermentation process which produces digestate and biogas.



Biogas

A renewable fuel to generate heat (hot water and steam) and electricity (CHP) on site.

4. End uses

Biogas is purified to be injected into the gas grid for industrial and domestic uses, such as heating and cooking.

3. Upgrade

These feedstocks are collected and transported to the facility (methanisation site), where they are turned into biogas.

The biogas can then be directly used to produce electricity and heat, or it can be purified into Biomethane, which is a one-for-one replacement for natural gas.

Biomethane can be injected into the existing gas grid for industrial and domestic uses, such as heating or cooking, and for mobility purposes. It is important to remember that the efficiency of biomethane production is heavily dependent on the source material.

2 Pyrogasification

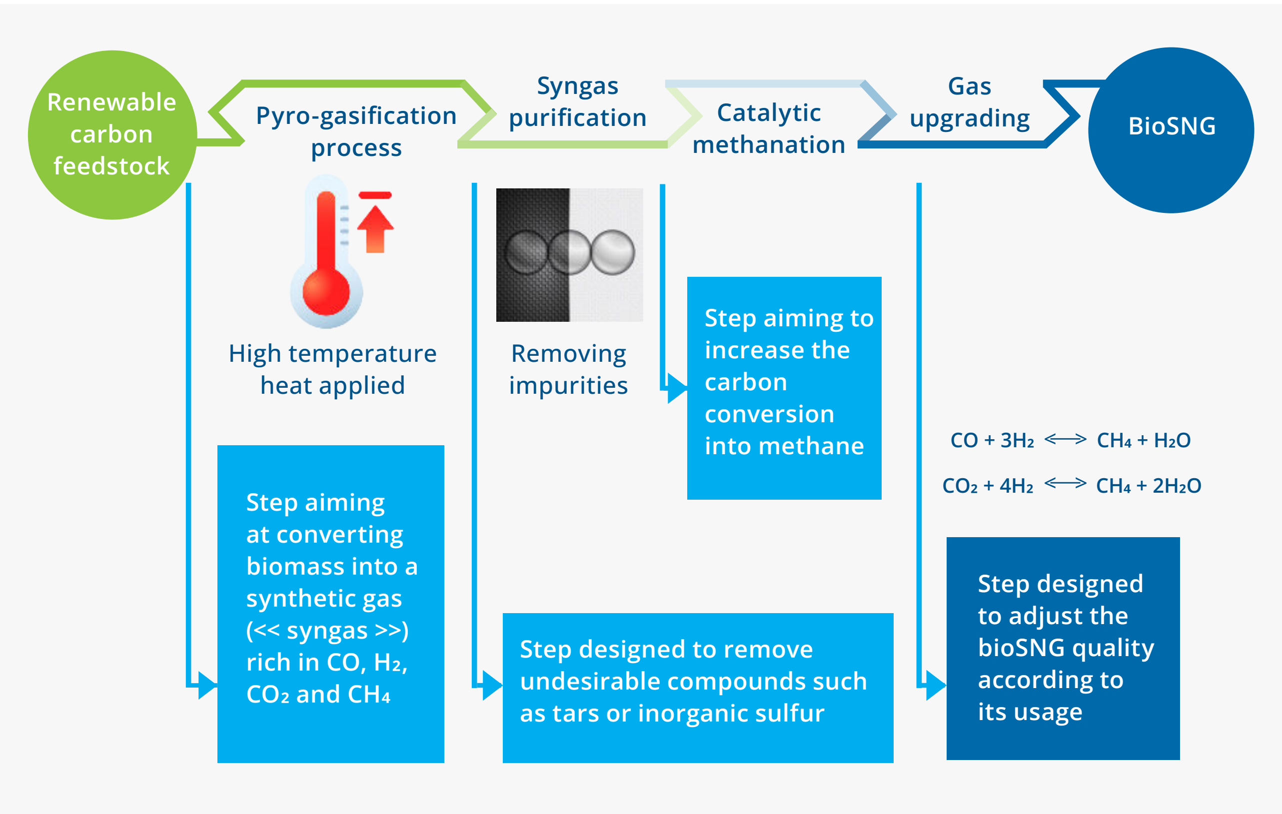
Pyrogasification is a thermochemical process that consists of heating waste in the absence of oxygen to produce a renewable methane. It has two main sources:

- I **Dry biomass:** wood waste, residues from waste management, and most organic waste.
- II **Solid recovered fuels** (SRF) are produced from household recycling waste and general industrial and commercial waste.

Once collected, the waste is heated to very high temperatures (800 to 1,500 degrees Celsius) in the presence of a small amount of oxygen, converting the waste into synthetic gas (syngas). Syngas is rich in carbon monoxide, hydrogen, carbon dioxide and methane and must be purified.

Syngas from SRF contains more pollutants than syngas from clean biomass, such as from plants. Further challenges are found in conventional inorganic gas removal processes, which must be adapted before being useable.

Development is also necessary to purify the syngas according to its future usage, including in making ammonia, methanol or other industrial chemicals and fuels.




Fieldwork: Biogas from corn. Photo: iStock.com/Jan-Otto

3 Hydrothermal gasification

Hydrothermal gasification requires the presence of water to convert wet or liquid organic waste into syngas, through a process which subjects the waste to high pressure and temperatures.

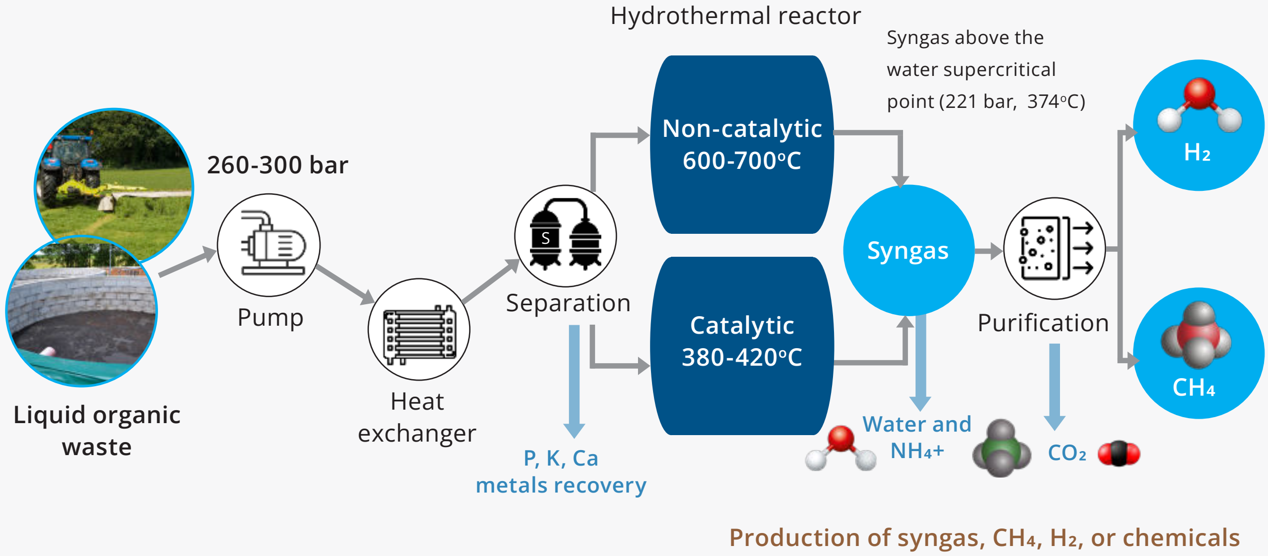
The produced syngas is a renewable gas, composed of methane, hydrogen and carbon dioxide. However, the composition of this syngas varies, according to the characteristics of the inputs.

The process creates green gases using liquid organic waste, which is otherwise difficult to dispose of, such as digestates from anaerobic digestion, sewage sludge from industrial or municipal wastewater treatment plants, macro and micro-algae, liquid and solid farming waste, food industry residues and by-products.

The hydrothermal gasification consists of the following:

- Liquid organic waste is pumped at high pressure (260-300 bars).
- The matter then passes through a heat exchanger, which separates phosphorus, potassium, calcium and metals which are extracted and recovered.

Hydrothermal gasification is gasification in hot compressed water which uses water in a supercritical state



- Raw syngas can be valorised either directly for heat and/or electricity production, or purified to clean CH_4 or H_2, or converted into chemicals.
- CH_4 content reaches 50-60% in catalytic conversion, and up to 90% when H_2 is co-injected in the gasifier.
- H_2 concentration can achieve 50-75% in syngas.

Source: 2020. Le Cadre E. Mertens J. Emerging Sustainable Technologies

The process is possible at both higher and lower temperatures (as long as a catalyst is used). There are positives and negatives for both, as higher temperatures require more energy, and the use of a precious metal catalyst at lower temperatures is costly and has a finite lifespan.

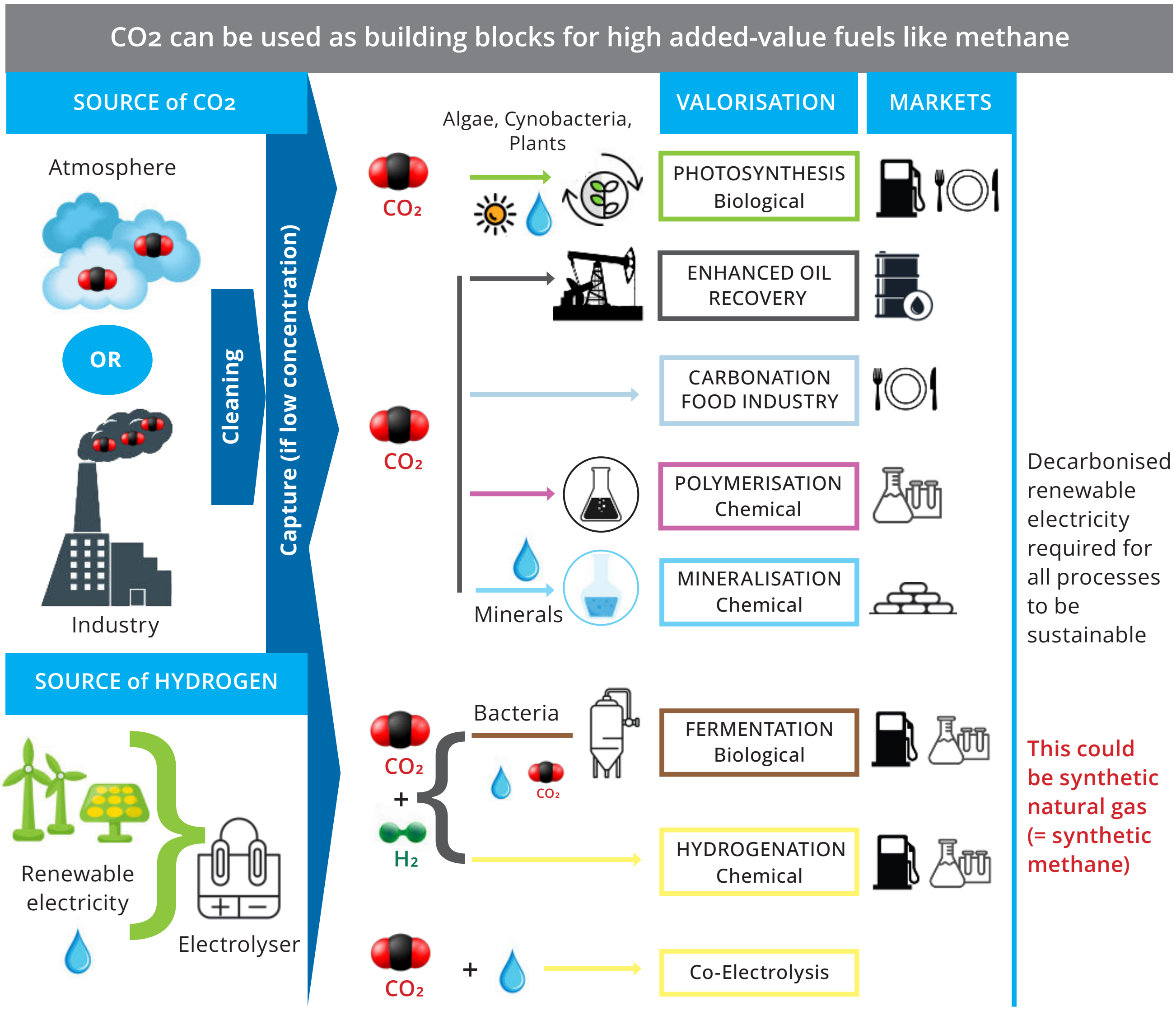
The resulting syngas is then purified to extract unwanted carbon dioxide, leaving methane and hydrogen. This raw syngas has the potential to be used directly for heat and electricity production. Alternatively, the hydrogen can be used to convert some of the carbon dioxide into additional methane through a methanation step, after which the resulting gas can be treated so it is ready to inject into the gas transmission system.

Methane content reaches 50-60% in catalytic conversion and even up to 90% when additional hydrogen is also injected into the gasifier. The process produces methane or hydrogen efficiently.

4 E-methane

Methanation can also be used to combine carbon monoxide (CO) or carbon dioxide (CO_2) with hydrogen to produce e-methane, in a process that also produces heat. Methanation is a process through which hydrogen is converted into methane, which can be used in the existing natural gas infrastructure.

Carbon dioxide can be obtained from many sources, such as methanisation plants (biogenic CO_2) or from industrial production and capture from the atmosphere, supporting the development of a wide range of new technologies that may have the potential to reduce greenhouse gas emissions.

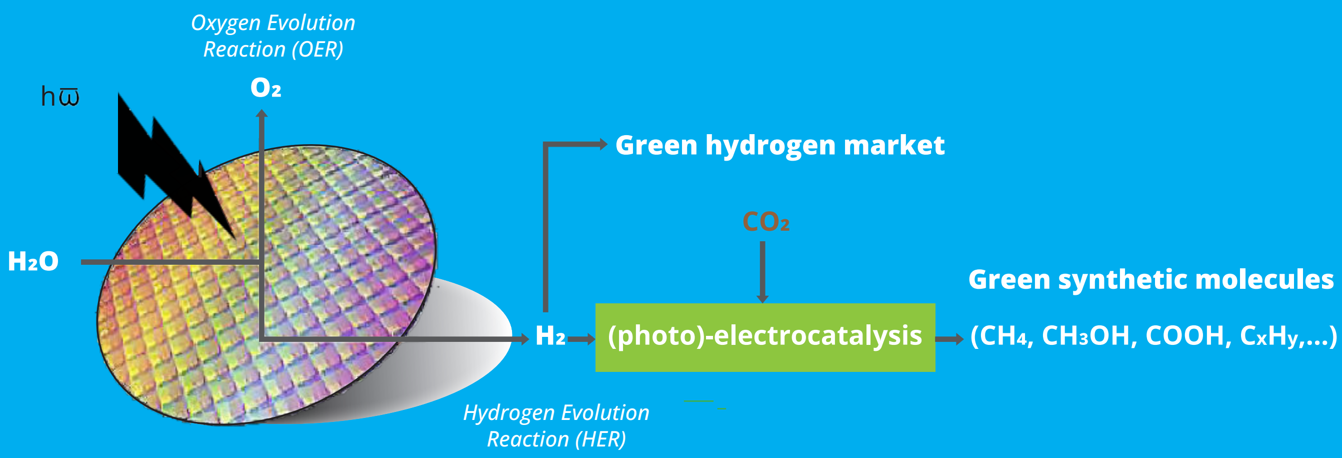


5 Solar photocatalytic processes

Artificial photosynthesis (AP), also known as solar photocatalytic process, has the potential to produce synthetic methane. This process decreases or removes the need for using electrical power and GHG emissions, as well as biomass, in the production of low-CO_2 methane.

Artificial photosynthesis seeks to replicate the natural photosynthesis process. It widely uses semi-conductors as the photocatalyst, and it often splits the process into two steps:

- I Production of hydrogen by splitting water through the method of photocatalysis.
- II Carbon dioxide production, and its subsequent reactions with hydrogen, to form lightweight hydrocarbons, by using different approaches.

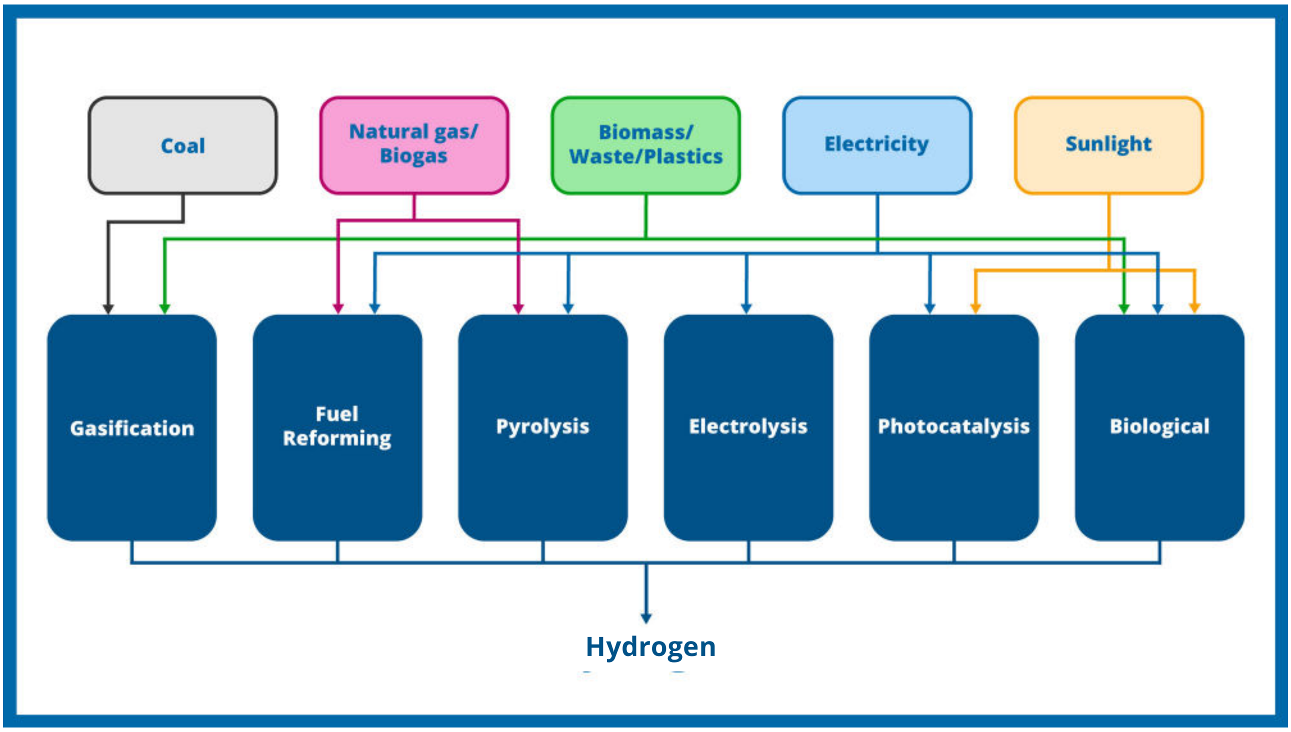


Conversion: Photovoltaic power supply systems Photo: iStock.com

2. Diversification

Hydrogen is set to play a growing role in the energy sector, with several emerging technologies aiming to convert various inputs into hydrogen, which can then be utilised within the power and heating industries, and as feedstock in the chemical industry.

The graph below illustrates hydrogen production technologies and their potential energy sources:



In addition to these technologies, geological H_2 is emerging as a potential source.

Most existing hydrogen markets are very specific, consisting mainly of industrial use and supplying inputs into ammonia and methanol production, acting also as a reducing agent for the petrochemical, chemical, steel and food industries.

Present uses of hydrogen as an energy carrier remain limited, and often experimental and pilot; however, global plans to expand them are significant. There are several technology advancement priorities to address for these plans to materialise:

- Lowering costs and growing their commercial track record.
- Storage and transportation technologies, infrastructure, and standards.
- Certification development.
- End-user equipment conversion to support hydrogen as fuel.

1 Methane reformation

Methane (CH_4) can be utilised to create pure hydrogen using the following process of steam methane reformation:

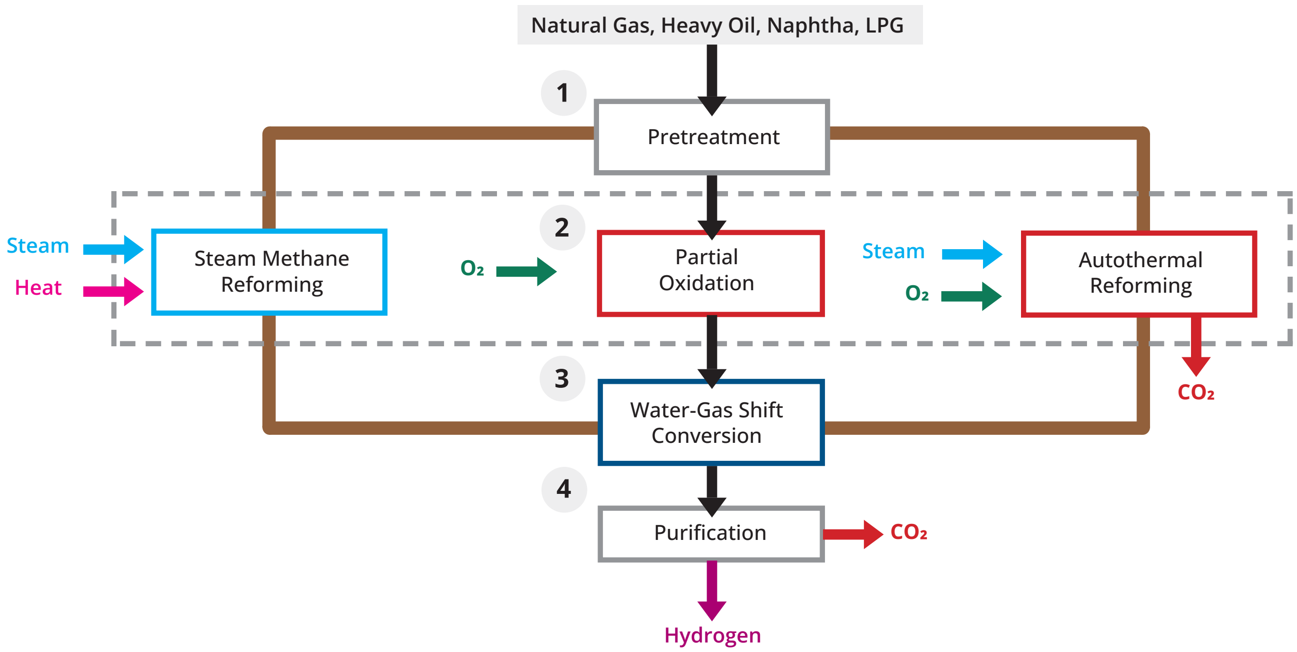
- I By using heat, steam and methane react together with a catalyst to form carbon monoxide and hydrogen; this is an energy-intensive process.
- II In the water-gas shift reaction, carbon monoxide is combined with more steam, producing hydrogen and carbon dioxide. The carbon dioxide can then be captured through carbon capture technologies, as it is in a controlled environment.

If carbon capture and sequestration are not utilised during this process, there will be carbon emissions associated with it. However, when carbon capture and sequestration are added to the process, the hydrogen produced is considered low carbon, also called “blue hydrogen”.

Methane reforming process for pure H_2 production

This process consists of four stages:

- I Pretreatment unit to pre-form feedstock and to eliminate sulphur compounds.
- II Reforming step to produce syngas using either steam methane reforming, partial oxidisation or autothermal reforming. It is possible to combine these technologies.
- III Shift reactor(s) to convert syngas and (increase H_2 content and decrease CO).
- IV The purification unit separates the hydrogen from the product stream. CO_2 can be captured through carbon capture technologies.



Catalysts:
- The relative catalytic activity of metals in the SMR reaction: Ru > Rh > Ir > Ni > Pt > Pd
- Conventional iron-chromium for high temperature WGS and copper alloys for low temperature WGS

Steam Methane Reforming
$CH_4 + H_2O \longleftrightarrow CO + 3H_2$
$\Delta H = 206$ kJ/mol

Partial Oxidation
$CH_4 + {}^1/_2O_2 \longleftrightarrow CO + 2H_2$
$\Delta H = -36$ kJ/mol

Autothermal Reforming
$CH_4 + H_2O \longleftrightarrow CO + 3H_2$
$CH_4 + {}^1/_2O_2 \longleftrightarrow CO + 2H_2$

Water-Gas Shift
$CO + H_2O \longleftrightarrow H_2 + CO_2$
$\Delta H = -41$ kJ/mol

2 Water electrolysis

Water electrolysis is a way of producing hydrogen that uses electricity to split water into hydrogen and oxygen. When the electricity used in the process is renewable or nuclear, there are no GHG emissions produced in the process, and this can be referred to as renewable, “green” and “pink” hydrogen, respectively.

An electrical circuit is created by combining an electrolyte and two electrodes to form an electrolytic cell. These charged electrodes then split the water, with the resulting negatively charged electrode attracting the positively charged hydrogen ions and, conversely, the positive electrode attracting the negatively charged oxygen ions forming separate bubbles of oxygen or hydrogen that can then be collected.

There are five main technologies used to perform water electrolysis, which differ in terms of the materials used for the electrodes and plates:

- I Alkaline electrolysis
- II PEM (Proton exchange membrane) electrolysis
- III SOEC (Solid oxide electrolysis)
- IV PCEC (Photoelectrochemical)
- V AEM (Anion exchange membrane)

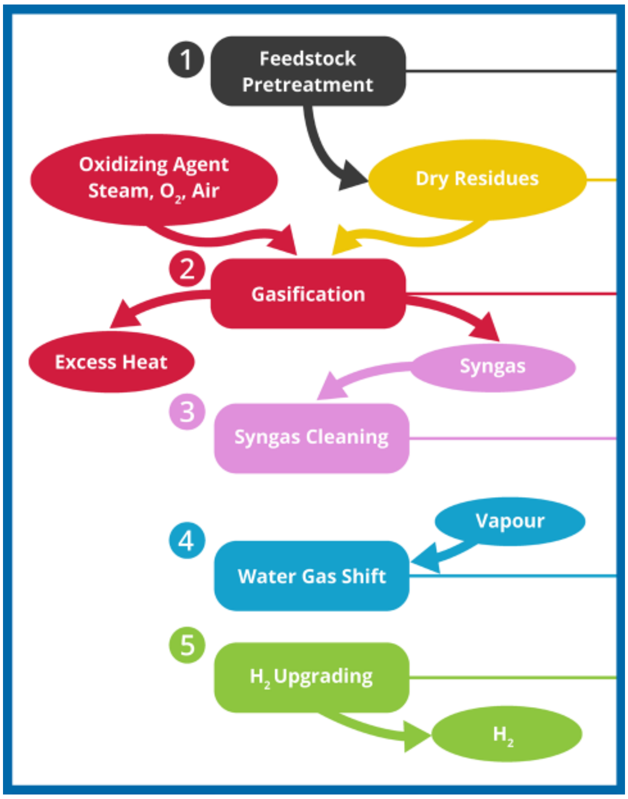
Each of these five technologies has benefits and drawbacks, ranging from cost, efficiency, and durability. This is why further research to improve performance and viability of water electrolysis is currently ongoing.

3 Thermal gasification

Thermal gasification is a process that uses solid organic matter (such as coal, biomass-based feedstocks, SRFs and fractions of non-recyclable plastics) and converts them into syngas using high temperatures (ranging from 700 - 1500°C). The reaction occurs under stoichiometric conditions (meaning all reactants are controlled and fully used), turning solid residues into syngas.

The syngas is then purified to remove organic pollutants (such as light and heavy tars) and inorganic pollutants (such as hydrogen sulphide, ammonia, and hydrochloric acid). This is then followed by the gas-water shift reaction, which means that the carbon monoxide produced can be converted into additional hydrogen and carbon dioxide.

The gases produced are collected, and hydrogen is extracted from the other gases produced (mainly carbon dioxide, carbon monoxide and methane) to give the hydrogen a purity of over 99.9%.



4 Methane pyrolysis

Methane pyrolysis uses methane as feedstock and, by applying energy to break the chemical bond between carbon and hydrogen, it produces hydrogen gas and a solid carbon product.

The process requires less energy than electrolysis, and its GHG footprint is low due to the absence of emissions.

Using natural gas as feedstock also provides the benefit of access to the existing infrastructure.

There are different ways of generating the heat for methane pyrolysis:

- I **Plasma pyrolysis:** electric currents are used to create a hot plasma which breaks down the methane into hydrogen and carbon.
- II **Thermal pyrolysis:** hot baths of molten salts or metals are used to break down the methane into hydrogen and carbon.
- III **Catalytic pyrolysis:** methane is passed through a fluidised bed containing a catalyst which breaks down the methane with increased efficiency.
- IV **Microwave assisted pyrolysis:** microwaves are used with a catalyst to break the methane molecule into hydrogen and carbon.

5 Solar photocatalytic processes

Solar photocatalytic processes avoid any GHG emissions as they rely exclusively on solar power: a photocatalytic installation which could be further enhanced by the addition of solar PV panels. In this process, a photo-absorber (typically a semi-conductor) absorbs light, leading to the separation of positive and negative charges. The reduction creates hydrogen, and oxidation produces oxygen, hydrogen, and e-charges, making them available for redox reactions (transfer of electrons) to produce hydrogen from water. This basic concept is utilised in several technologies:

- I **Photocatalysed (PC) water splitting:** this system is the simplest one and consists, typically, of a photocatalyst immersed in a solution, at the surface of which the reactions take place. Oxygen and hydrogen must be further separated.
- II **Photo-ElectroChemical (PEC) water splitting:** this system is based on the principle of electrolysis where the anode and/or cathode are implemented with photocatalysts. The difference, compared to photocatalysed water splitting, is that this system is electro-assisted, allowing the current to be increased for higher yields.
- III **Photo-ElectroChemical (PV-EC) water splitting:** this last system is often associated with PC and PEC processes and consists of an electrolyser equipped with an integrated highly efficient multijunction III-V PV cell.

6 Biological production

There are two main biological processes that can be used to produce hydrogen: fermentation and bio photolysis.

The fermentation process harnesses macro-nutrients (long molecules) from biomass, which are broken down into hydrogen, and short molecules such as alcohols, simple sugars, and volatile fatty acids. Various fermentation technologies are listed below, and it should be noted that photo fermentation and MEC must be coupled with the first step of dark fermentation in a two-step process.

I **Dark fermentation** (fermentation without light), where the substrate used is a complex organic matter. Large-scale bacteria can perform dark fermentation.

II **Photo-fermentation** (fermentation assisted by light), where the substrate used is small organic acids.

III **MEC fermentation** (assisted by a low electrical current), where the substrate used is a simple carbon source such as C_2 to C_6 (volatile fatty acids, single sugar and alcohols).

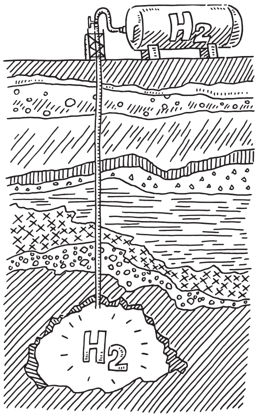
While Biophotolysis produces hydrogen from light and water, cyanobacteria and green algae can split water into hydrogen and oxygen using their hydrogenase or nitrogenase enzyme system.

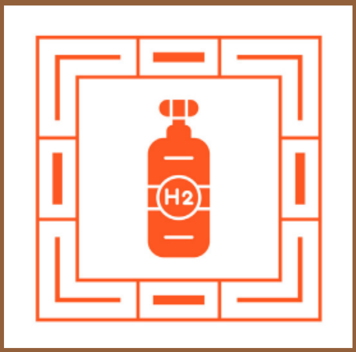
7 Geological extraction

There are two main ways of producing H_2 through geological extraction:

Natural hydrogen production ("white" hydrogen)

H_2 is mainly produced through natural water-rock reactions, such as serpentinisation, where water reacts with iron-rich minerals within the Earth's crust. This hydrogen percolates through the Earth's crust and can accumulate in underground traps. Its value chain is similar to natural gas production. It includes prospection, selection of sites, drilling, extraction and separation of products.





Water injection induced hydrogen ("orange" hydrogen)

Orange hydrogen is a proactive take on natural hydrogen, combining CO_2 sequestration with H_2 generation by creating a chemical reaction in iron-rich geological formations. Water, including saltwater, is charged with CO_2 and injected into the target formation where it reacts with the iron ore, leaving the CO_2 behind and enriching the material with hydrogen. The hydrogen-saturated water can then be collected from recovery wells surrounding the injection point. This is, in effect, artificially creating the conditions for natural hydrogen development, all while sequestering CO_2, thus giving it a net-negative emissions profile.

3. Innovation

By maximising operational efficiencies and decarbonisation, the gas industry continues its path to be future-ready and, with a focus on innovation, skills and partnerships, is deploying technologies to minimise its environmental footprint by driving down supply chain emissions.

Natural gas supply and infrastructure investments must happen in parallel with accelerated investment in decarbonising gas technologies, which must be ramped up by orders of magnitude to be consistent with climate targets. Only then can we ensure that the priorities of energy security and energy transition do not undermine each other.

Access to financing and enabling policy environments, especially, will be essential to reach the necessary scale of investment in decarbonising technologies, including carbon capture and storage (CCS) and carbon capture and utilisation (CCU), renewable gas and hydrogen, and continued innovation in the low-carbon gaseous energy, together with the no-regrets infrastructure investments that enables them all.

Together, gas and renewable energy can become a powerful force in tackling climate change, energy security and access issues, a particularly acute issue given that more than 3 billion people worldwide lack access to clean energy.

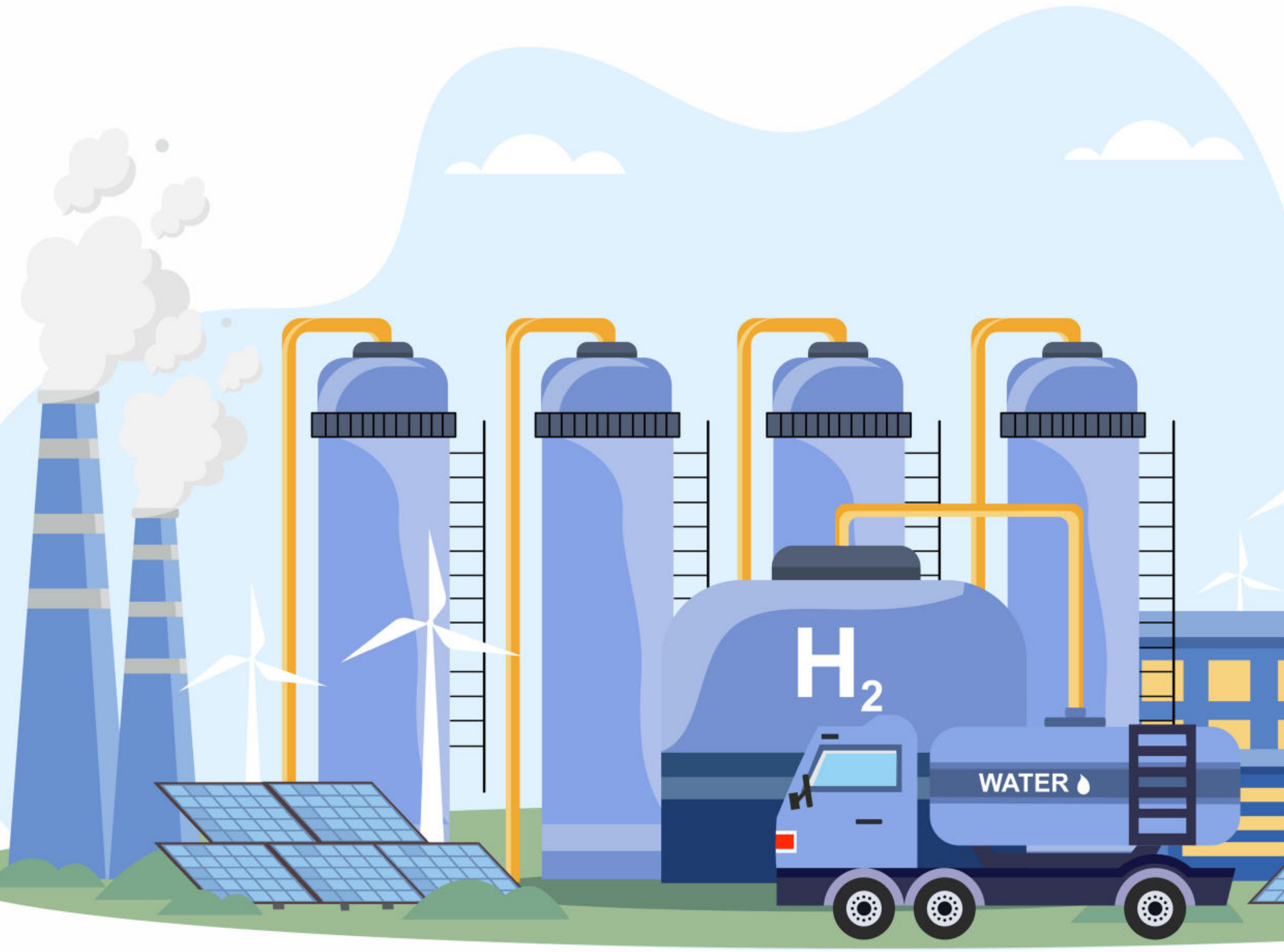
The way forward: Gas separation plants can provide eco-energy for sustainable energy saving.
Photo: iStock.com/Sakorn Sukkasemsakorn

Acknowledgements

This document was developed with the support of IGU's Carbon Neutrality Taskforce, Sustainability Committee and Research, Development, and Innovation Committee.

We would like to express our appreciation to:

- **Jean-Marc Leroy,** Chair of IGU's Carbon Neutrality Taskforce and Lead Author of this report.
- **Elodie Lecadre** and **Philippe Buchet**.
- **Engie** for providing graphical materials and illustrations.



Design & Layout: Mackenzie Media, Oslo, Norway

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