Decarbonization with clean hydrogen
Whitepaper

CLEAN HYDROGEN TECHOLOGIES FOR THE ENERGY TRANSITION

TOPSOE

CONTENTS

INTRODUCTION

According to the International Energy Agency (IEA), annual hydrogen production currently accounts for 830 million tons, or 3%, of global CO_2 emissions.
As such, there is a need to decarbonize hydrogen production. However, the potential role that hydrogen can play in the net-zero carbon economy is much higher, as it can fuel decarbonization of hard-to-abate sectors and also serve as an overseas energy carrier, either in pure form or through its conversion into ammonia. The Hydrogen Council estimates that H_2 production will increase 6-7 times by 2050, emphasizing the need for decarbonized hydrogen production.

Traditionally, hydrogen has been produced by steam methane reforming, using fossil-based feedstocks such as natural gas, LPG, or naphtha.

One method for decarbonizing hydrogen production is by steam or water electrolysis, fueled by renewable electricity. The hydrogen produced leaves virtually no CO_2 footprint from either its production or its use. Companies like Topsoe are commercializing electrolysis solutions that are easy to use as standalone hydrogen units, or in "hybrid" setups that combine these new technologies with traditional hydrogen production. While renewable-powered electrolysis at scale is still dependent on wider renewable power build-out, the "green" hydrogen it produces is a key pathway to global off takers who require e-fuels and e-chemicals made from this grade of hydrogen.

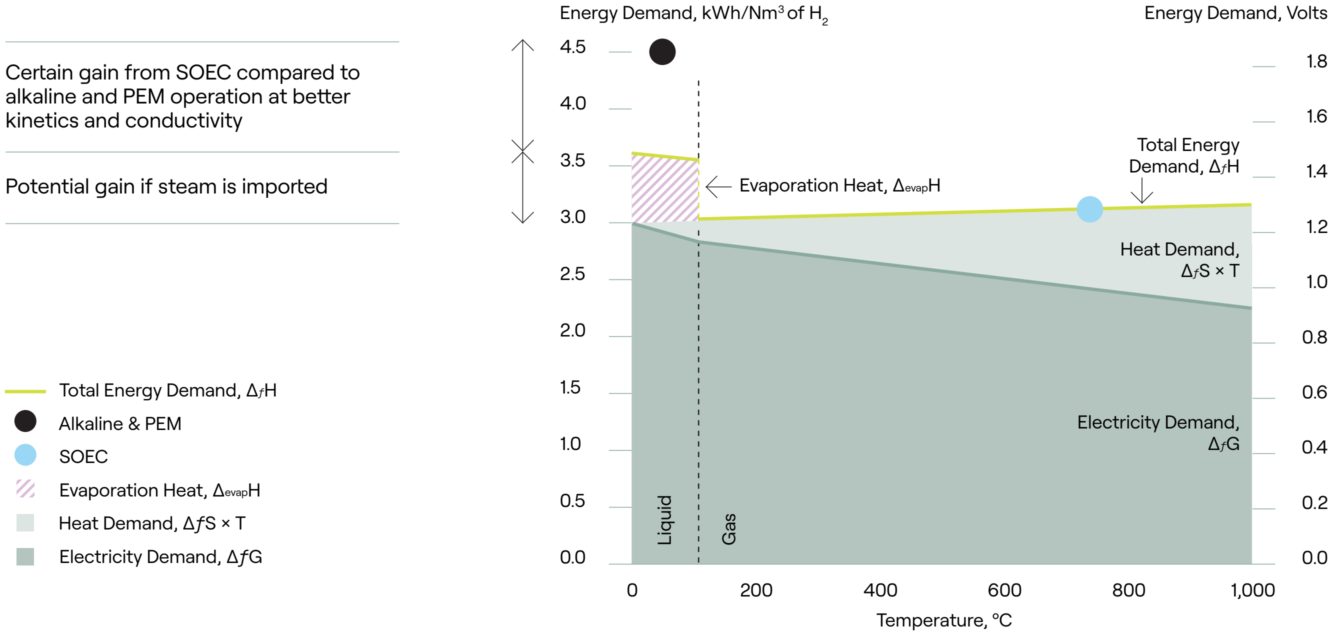
To drive the energy transition in the near-term as renewables and electrolysis capacity continues to scale, green hydrogen must be supplemented with other hydrogen sources with low GHG footprints. This paper also discusses low-carbon hydrogen solutions that combine traditional production methods with carbon-capture and permanent storage — offering a comparative analysis of these technologies to understand which solutions are best suited for at-scale production today. This clean hydrogen can thus be produced either through a revamped grey hydrogen plant that is already in operation, or through a revamped fossil-based hydrogen plant.

ACCELERATING RENEWABLE PATHWAYS WITH SOEC

A key part of the road to decarbonization is hydrogen production that minimizes carbon emittance from the very beginning of its lifecycle, such as renewable-powered electrolysis. Topsoe's solid-oxide electrolyzer cell (SOEC) technology leverages high-temperature electrolysis to enable industrial-scale production of clean hydrogen using renewable electricity. Due to the nature of the intrinsic fast-reaction kinetics and optimized conductivity found in high temperature electrolysis, Topsoe's SOEC technology produces up to 20% more hydrogen per total power input when compared to the alternatives of alkaline and PEM electrolysis. When coupled with waste heat-producing technologies (such as those used in ammonia, methanol or steel production), SOEC allows for an additional 10% efficiency gain and the lowest levelized hydrogen cost with the highest level of energy efficiency per megawatt or gigawatt volume, when compared to electrolysis alternatives at commercial scale today.

SOEC is more efficient than both the industry alternatives of alkaline and PEM technologies since it operates at a lower voltage. SOEC operates at a voltage covering exactly the sum of the electricity and heat demand, while alkaline and PEM processes both operate above the sum of these two. The reason for this is SOEC operates at the thermo-neutral voltage, which is the point at which the heat demand is balanced out by the Joule Heat. Joule Heat is produced from resistance that occurs when an electric current is applied to the electrolysis cells. This, in turn, means that temperature gradients do not occur within the SOEC, as the temperature of the steam supplied is equivalent to the temperature of the resulting clean hydrogen product. This avoids the need for additional energy spent on auxiliary cooling, which can affect the overall price and efficiency of plant operations.

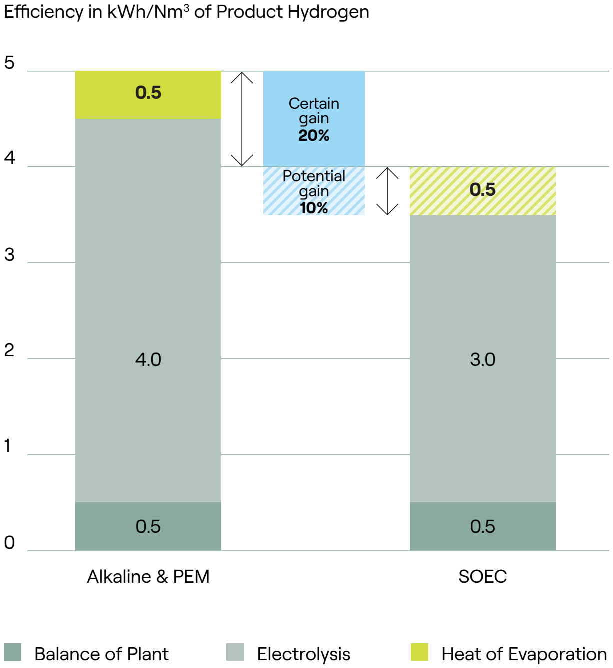
FIGURE 1: Energy demand for water electrolysis



This, paired with heat recovery and reuse, means that SOEC technology is an optimal fit for many of the waste-heat producing industries that could benefit from producing and using clean hydrogen in their processes, including those found in the hard-to-electrify sectors. Steam used in SOEC electrolysis must be produced through the evaporation of water, which requires energy. This part can be provided with heat recovered from the SOEC setup itself. With Topsoe's SOEC solution, 30% of this heat is recovered and used for heating process streams, such as steam, to the SOEC itself. The vast majority of the remaining 70% is obtained through heat integration, by coupling the SOEC with other downstream and waste heat-producing processes, such as ammonia, Fischer-Tropsch, or steel production. In contrast, heat recovered from alkaline and PEM processes exhibits a low temperature, which is unsuitable for heat integration and is expelled as low-grade heat. The low-temperature waste heat from the alkaline and PEM technologies must be removed by water or air coolers. This is emphasized by considering the Higher Heating Value for hydrogen, expressing the energy content, which is 39.4 kWh/kg. By using this value, it is clear that alkaline and PEM technologies have a larger loss of low-grade heat compared to SOEC.

By producing renewable hydrogen with optimized efficiency, SOEC electrolysis can be used to facilitate renewable energy storage, e-Fuel production for international off takers, and ensure a hydrogen product with the lowest possible CO_2 footprint throughout its lifecycle.

FIGURE 2: SOEC'S ADVANTAGE OVER ALKALINE AND PEM TECHNOLOGIES



HYDROGEN PRODUCTION TECHNOLOGIES TO ENABLE CARBON CAPTURE

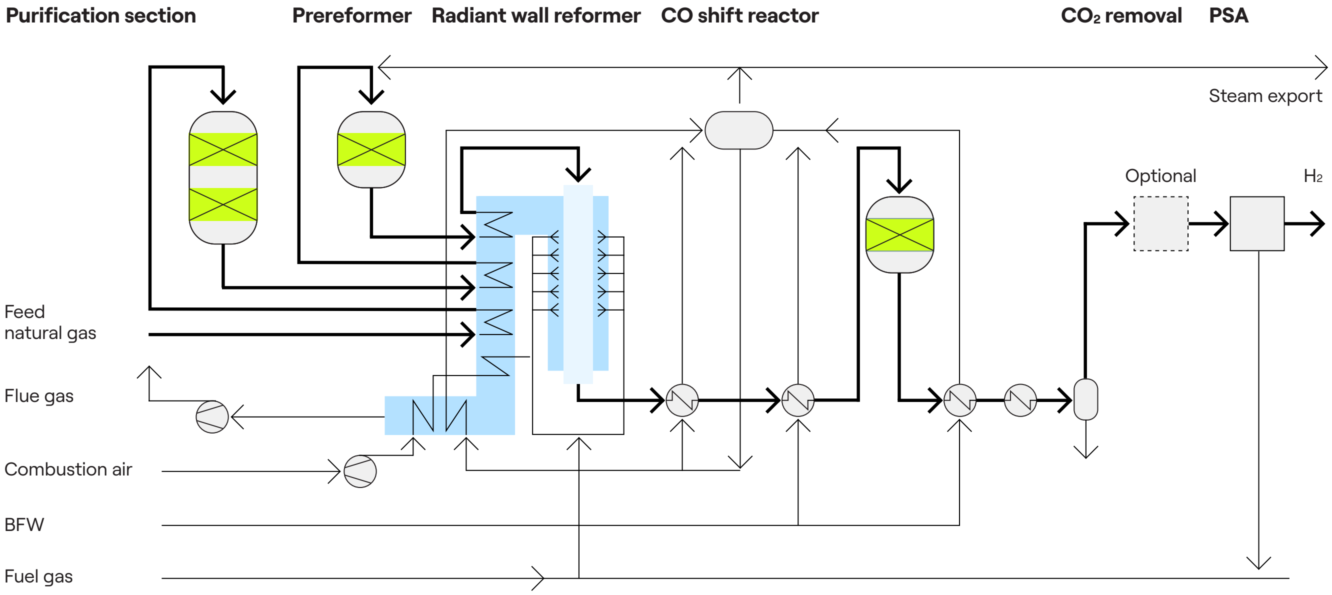
Steam methane reforming

Steam methane reforming (SMR) is the technology most widely used to produce hydrogen today. The main reforming process occurs over nickel-based catalysts inside tubes placed in a heated reformer chamber.

The steam reforming of hydrocarbons can be described by the following reactions:

$C_nH_m + n H_2O$	$\rightarrow$	$n CO + [n+½m] H_2$	- heat	(1)
$CH_4 + H_2O$	$\leftrightarrows$	$CO + 3 H_2$	- heat	(2)
$CO + H_2O$	$\leftrightarrows$	$CO_2 + H_2$	+ heat	(3)

FIGURE 3: TRADITIONAL STEAM METHANE REFORMING



Reformer heat is generated by burning fuel gas, which is usually a combination of natural gas and pressure swing adsorption (PSA) unit off-gas, but which can also include other off-gas streams imported into the hydrogen plant. Waste heat from the flue gas is recovered by preheating the feedstock, and by steam generation that occurs before the CO_2-rich flue gas is vented into the atmosphere. The hot process gas exiting the reformer contains a mixture of steam, H_2, CO, and CO_2; this is cooled in a waste-heat boiler that generates utility steam, after which it is sent to the shift section, where CO reacts with process steam to create more hydrogen and CO_2.

The effluent from the shift reactor is normally sent to a pressure swing adsorption (PSA) unit, in order to separate pure hydrogen from the off gas, which is sent to the reformer as fuel. In low-hydrogen-purity applications, the PSA unit can be avoided or replaced with a methanator.

In a clean-hydrogen scenario, the CO_2 in the process gas from the shift section is recovered in a CO_2-removal unit before being sent to the PSA/ methanator. Depending on CO_2 reduction targets, it may also be necessary to add a flue-gas CO_2-capture unit.

FIGURE 4: SMR-B REFORMER SKETFIGURECH

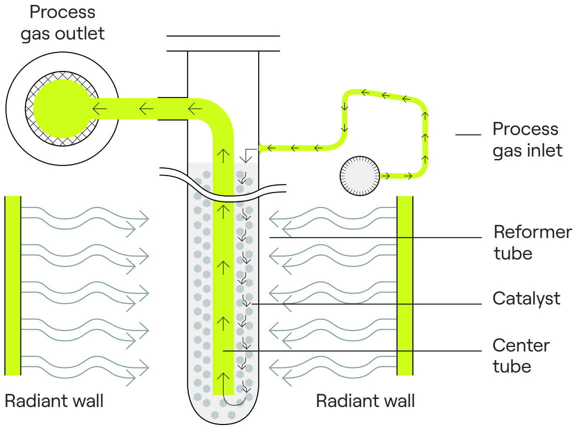
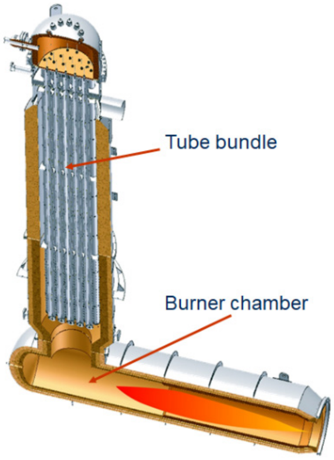


FIGURE 5: HEAT-EXCHANGE REFORMING



Heat-exchange reforming

In some cases, steam generation is not a viable solution due to plant economics or CO_2-footprint requirements. In such cases, surplus energy can instead be utilized to drive additional reforming, either by adding an HTER reactor downstream of the SMR, or by modifying the design and operation of the SMR itself. Both options have been successfully applied in industrial operations. In both the HTER and SMR-B processes, steam export is significantly lower than traditional SMR technology, so fuel consumption decreases relative to hydrogen yield, resulting in a reduced CO_2 footprint.

In an HTER layout, a portion of the feedstock bypasses the SMR, and is instead fed into the HTER reactor, where it is heat-exchanged with the hot effluent from the SMR. The reforming that occurs in the HTER reactor results in a 25–30% larger hydrogen yield, so it is also a good solution for adding capacity to an existing hydrogen plant.

As mentioned above, another option is to alter the SMR design, using advanced “bayonet” catalyst tubes to capture heat from the effluent before it leaves the SMR. This bayonet design is referred to as “SMR-B.”

At high capacities, conventional SMR design is limited by the need to maintain an economic reformer size. Heat-exchange reforming has been successfully deployed to extend single-train capacity limits by up to 207 kNm^3 per hour.

Convection reforming

For hydrogen-production capacities below 30 kNm^3/hour, convection reforming (HTCR) is normally a better option than SMR. In convection reforming, the reformer design is different, since the tubes are bundled in a much smaller chamber and the heat required for the process is generated by a single burner. The tubes remain in contact with the flue gas generated by the burner flame in a convection section.

This HTCR design provides heat integration with no steam export, and is favored in cases where steam is not a desired product – or is less valuable than hydrogen. The compact design of the HTCR unit favors modularization, and has for decades been the preferred choice for small-scale hydrogen production.

SynCOR reforming

SynCOR reforming is an advanced autothermal reforming (A-ATR) process that differs fundamentally from the tubular steam-reforming processes described above; the main reforming process takes place inside a single SynCOR reactor. It is also significantly different from any other ATR process, since it operates at a much lower steam-to-carbon ratio. The SynCOR reactor’s compact design consists of a refractory-lined pressure vessel with a burner, combustion chamber, and catalyst bed.

Process gas enters the SynCOR reactor, where it is mixed with oxygen and additional steam, resulting in a combination of partial combustion and steam reforming.

FIGURE 6: SYNCOR REFORMER

Among clean hydrogen technologies with carbon capture, the SynCOR process exhibits the lowest OPEX, since the reactor operates at a steam-to-carbon ratio of 0.6, which is 3–5 times less than that of SMR or less developed conventional ATR systems. The lower steam throughput also has the benefit of reducing equipment and piping sizes, a benefit that is most pronounced at large scale, since the equipment and piping are kept within standard size ranges – even at very large single-line capacities.

With SynCOR, external fuel demand is extremely low, hence a very high carbon-recovery rate (>99%) can be achieved without having to capture the carbon present within the flue gas. This makes SynCOR very well suited for use in clean hydrogen production.

SynCOR technology has a proven track record of over 300 combined years' industrial operation, with availability factors exceeding 99%. More than 150 years of SynCOR industrial experience have been carried out with a steam-to-carbon ratio of 0.6 or below, providing Topsoe with ample experience in this severe and demanding form of operation.

Due to this low steam-to-carbon ratio, it is economically favorable to employ SynCOR in mega-scale plants. The large st SynCOR reactor currently in operation has a hydrogen production capacity of 50 0 kNm³/hour, and the economical limit for single-train capacity is 825 kNm³/hour. Because of such favorable economics, SynCOR is likely to remainthe dominant technology for large-scale hydrogen production.

Partial Oxidation (POx)

Hydrogen can also be produced by partial oxidation (POx). This is a non-catalytic process whereby a fuel-oxygen mixture is partially combusted, resulting in a hydrogen-rich syngas which is shifted before being sent to product purification.

The partial-oxidation reaction occurs when a sub-stoichiometric fuel-oxygen mixture is partially combusted in a series of partial-oxidation reactors. This chemical reaction takes the general form:

$$C_nH_m + {}^{n}/_{2}\, O_2 \rightarrow n\, CO + {}^{m}/_{2}\, H_2$$

The POx technology has certain well-known limitations, including:

1. Continuous formation of soot, which must be removed frequently.
2. Relatively high CAPEX, owing to the need for a multiple-reactor design, large air-separation unit (ASU), and soot-removal unit.
3. High consumption of oxygen and power.
4. The need for complicated water-cooled oxygen burners
5. Very high operating temperatures (1300–1400°C), which significantly limits the service life of the burners.
6. Complicated water-cooled oxygen burner

Electrified steam methane reforming (eREACTTM)

Another new hydrogen-production method is Topsoe's electrified steam methane reforming, dubbed "eREACT". In this method, the main reforming reactions occur inside a catalytic reactor heated by an electrical current. This eliminates the need for hydrocarbon fuel as a heat source, which in turn eliminates reformer flue-gas emissions. The energy density of an eREACT process results in a reactor size that is a fraction of an SMR unit.

Furthermore, almost all CO_2 in the shifted process gas can be recovered, at low cost, by a CO_2-removal unit, making this process an excellent candidate for clean-hydrogen production in cases where electricity prices are favorable.

The eREACT process has been successfully tested at pilot scale, and will soon be tested in a demonstration plant.

CO_2-REMOVAL TECHNOLOGIES

Efficient carbon-capture is an essential requirement for large-scale production of ultra-low carbon-intensity hydrogen. Currently, there are three relevant CO_2-removal options available on the market.

CO_2 removal from process gas

Once natural gas is reformed into syngas, CO_2 can be captured at high pressure prior to the hydrogen-purification stage. This form of CO_2 removal is typically a solvent absorption-based process. The CO_2 gas is compressed after the capture in preparation for permanent storage.

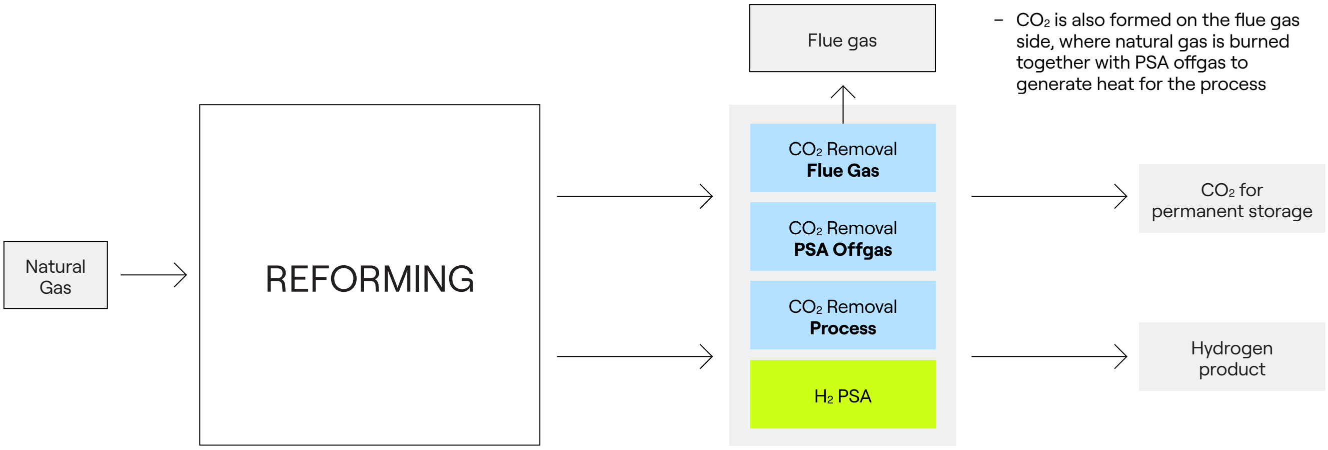
When CO_2 is captured in this high-pressure environment, it becomes easy to separate, requiring less energy and capital expenditure relative to CO_2 removal from the flue gas. This process-side CO_2 removal has been used for decades in the traditional ammonia production process, and is regarded as a well-proven method of CO_2 capture.

CO_2 removal from PSA off gas

Hydrogen purification is typically performed in a Pressure Swing Adsorption (PSA) unit. After separation of the hydrogen from the syngas in a PSA, the CO_2 leaves the PSA together with an off gas, which would usually be burned as fuel in a steam methane reformer. The CO_2, however, can be removed from this stream, using (for example) a cryogenic-separation technology to condense the CO_2, whic h allows it to be transported as a high-pressure liquid.

FIGURE 7: CLEAN HYDROGEN

Topsoe offers one single license for all steps in a clean hydrogen facility



- CO_2 is formed in the process side together with the Hydrogen product. This portion of the CO_2 can be captured before or after the PSA
- CO_2 is also formed on the flue gas side, where natural gas is burned together with PSA offgas to generate heat for the process

Figure 6: Interplay between reforming and CO_2-removal technologies in a clean-hydrogen facility.

CO_2 removal from flue gas

The CO_2 from the flue gas, which is generated by the combustion of fuel gas as well as PSA off gas, can be captured as well. While technically demanding, due to the larger equipment dimensions needed to capture CO_2 from the low-pressure gas, this solution is well suited for revamping existing plants, or implementation in new small-capacity plants.

Perhaps the most important factor in the selection of a carbon-capture technology is its potential for integration with the hydrogen-production process, in order to ensure optimal energy use. Topsoe serves its customers by integrating the hydrogen-production and carbon-capture processes in one facility, and by offering a single technology license with a combined carbon-intensity process guarantee for the entire facility.

BENCHMARKING OF HYDROGEN-PRODUCTION TECHNOLOGIES WITH CARBON CAPTURE

All the hydrogen-production and carbon-capture technologies mentioned above can be used to produce clean hydrogen. Selecting the technology best suited for any project will depend on multiple parameters, including production capacity, hydrogen yield, process carbon intensity, and the levelized cost of hydrogen (LCOH).

A technology comparison of the main parameters is presented below, starting with production capacity in Figure 7.

FIGURE 8: COMPARISON OF CLEAN HYDROGEN TECHNOLOGIES

SynCOR™ is the only technology capable of mega scale production in a single line

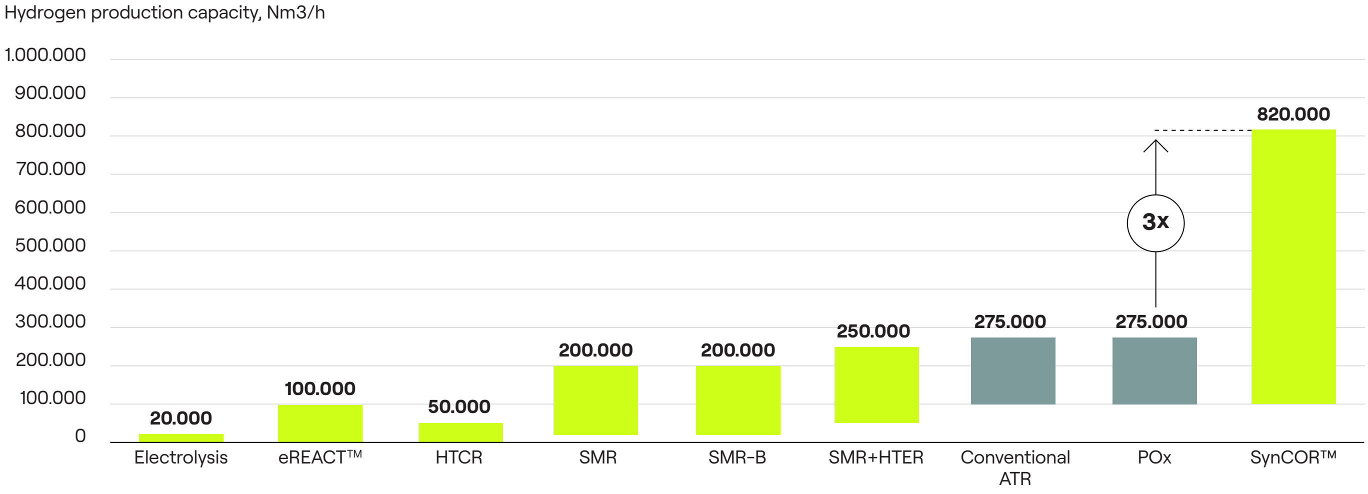


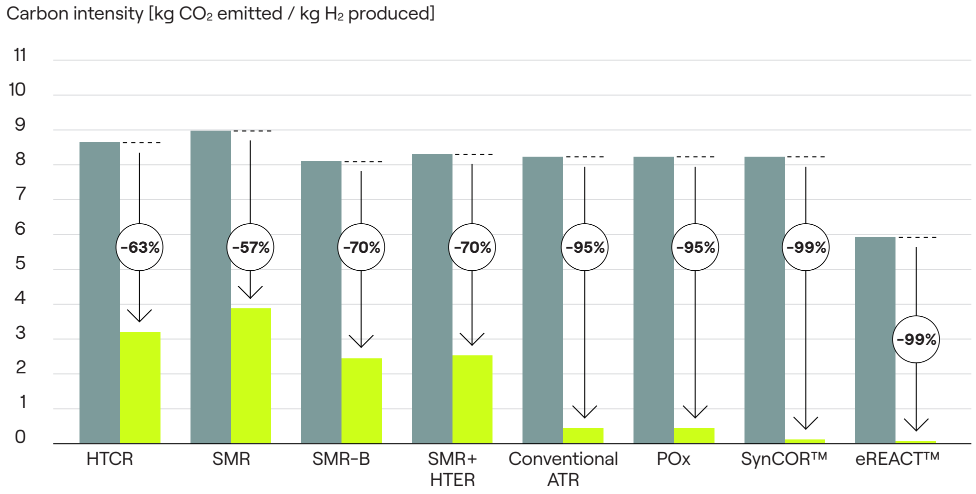
Figure 7: Optimal single-line hydrogen production capacity with different reforming technology layouts.

🟩 Topsoe technology
▨ Competitor technology

At small capacities, HTCR and eREACT are most suitable technologies, due to their compact design, whereas SynCOR is the preferred choice at higher capacities because of its low CAPEX. Its single-reactor layout, and very low steam-to-carbon ratio, enable the SynCOR design to benefit more from economy of scale.

FIGURE 9: COMPARISON OF CLEAN HYDROGEN TECHNOLOGIES WITH CARBON CAPTURE

SynCOR™ and eREACT™ can achieve 99%+ Carbon intensity reduction



- CO_2 capture is easier from the process gas or PSA off-gas rather than flue gas due to higher partial pressure.
- In SynCOR™ clean hydrogen technology, it is possible to achieve a CI lower than **0.1 kgCO₂/kgH₂** solely by capturing the CO_2 in the process. In eREACT™ this is even lower.
- Topsoe does not offer conventional ATR or POx technology.

Figure 8: Carbon intensity of different clean-hydrogen technologies.

▨ Carbon intensity (no CO_2 capture)
🟩 Carbon intensity (With process CO_2 capture – without flue gas CO_2 capture)

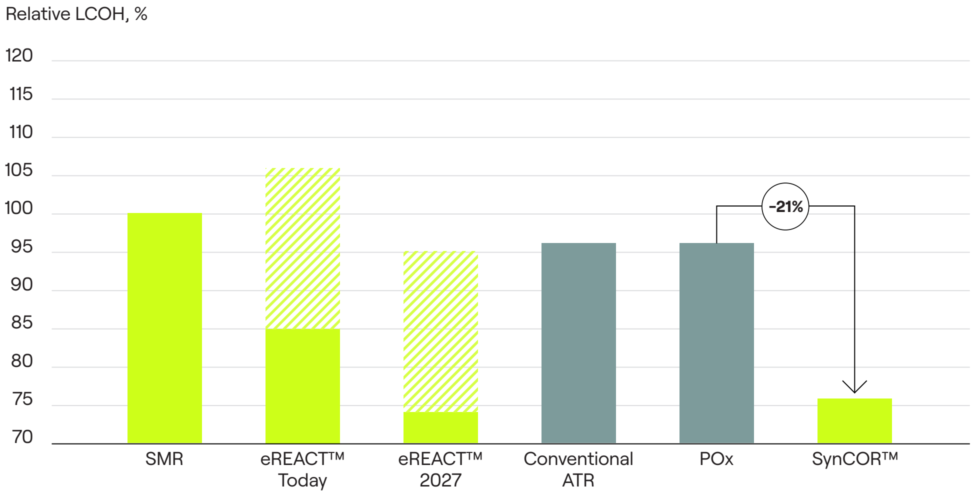
Figure 8 shows the CI measured in kilograms of CO_2 emitted per kilogram of hydrogen produced. The grey columns, which show CI with no carbon capture, are highest for the SMR design, due to its lower efficiency and higher fuel consumption, which converts waste energy to high steam-export volume. SMR-B has the lowest inherent CI among conventional technologies, since it has no steam export, whereas the CI of eREACT is a step-change better due to the nature of electrified reforming.

CI can also be reduced by capturing CO_2 from the process gas. This is more economical than capturing CO_2 from flue gas, and is therefore normally the first step in CO_2-capture. In Figure 8, this is represented by green columns; for SynCOR and POx, which are both oxygen-fired processes, as well as for eREACT, achieving very low CI is fully feasible through removal of the CO_2 formed in the process gas alone. This feature makes these processes ideal for clean-hydrogen production.

The technology chosen ultimately depends on whether a certain target cost can be achieved as effectively as possible. Figure 9 shows the relative differences in LCOH for each technology.

FIGURE 10: COMPARISON OF CLEAN HYDROGEN TECHNOLOGIES WITH CARBON CAPTURE

Levelized cost of hydrogen (LCOH) of SynCOR™ / eREACT™ are much lower than alternatives



- **SynCOR™** offers the lowest levelized cost of hydrogen (LCOH) today.
- For **eREACT™**, the LCOH is a function of renewable electricity cost.

Main assumptions:
- NG cost: USD 4/MMBTU
- Power cost: USD 75/MWh
- CO_2 credit: USD 100/ton

Figure 9: Levelized cost of hydrogen (LCOH) for different reforming technologies.

▨ LCOH differtial for eSMR case with change in power price from EUR 15 to 40 per MWh
■ Topsoe technology
■ Competitor technology

At the same operational targets and conditions, the hydrogen produced with SynCOR has the lowest levelized cost, owing mainly to a combination of high yields, lower CAPEX, and lower OPEX. This is the main reason why SynCOR has become the preferred choice for mega-scale clean-hydrogen production. However, eREACT is considered a better technology choice in niche conditions with favorable natural gas and electricity costs, or for small-to-medium production capacities.

CONCLUSION

There is no doubt that the task of decarbonizing the world is a huge challenge, and that near- and long-term solutions are required. For near-term clean hydrogen production, SynCOR is the industry's most promising solution; it boasts superior economics and is already proven at scale. SynCOR enables production of ultra-low carbon-intensity hydrogen with less than 0.1 kg CO_2 emitted in the process per kg hydrogen produced, eliminating more than 99% of the CO_2 formed during the hydrogen-production process.

Long-term, SOEC electrolysis shows significant potential in pairing hydrogen production with expanding renewable power grids. These renewable pathways are ideal for storing renewable energy, enabling local hydrogen production as well as creating the e-fuels and e-chemicals that will be central in decarbonizing the hard-to-electrify sectors globally.

Clean hydrogen production with carbon capture has the potential to become one of the main near-term enablers for decarbonization.

It must be produced responsibly from well to gate, including utilizing permanent underground CO_2-storage, and minimizing upstream greenhouse-gas emissions associated with natural-gas production and transport.

Some producers have already succeeded in driving down their upstream GHG emissions, mainly by avoiding routine flaring and maintaining effective control of methane leakage. Most other oil and gas majors have set ambitious targets for minimizing their natural-gas GHG intensity, and aim to achieve near-zero methane emissions from their operations by 2030. Coupled with ultra-low carbon-intensity clean hydrogen, the road towards net zero is set to become significantly shorter.

Topsoe is a leading global provider of technology and solutions for the energy transition. We combat climate change by helping our customers and partners achieve their decarbonization and emission reduction goals.

Based on decades of scientific research and innovation, we offer world-leading solutions for transforming renewable resources into fuels and chemicals for a sustainable world, and for efficient and low-carbon fuel production and clean air.

We were founded in 1940 and are headquartered in Denmark, with over 2,800 employees serving customers all around the globe.

To learn more, visit www.topsoe.com.

Get in touch today
topsoe.com/contact

TOPSOE

Topsoe A/S
Haldor Topsøes Allé 1
2800 Kongens Lyngby
Denmark

Tel. +45 45 27 20 00
CVR no. 41 85 38 16

Topsoe A/S,
CVR 41853816
0352.2022/Rev.1