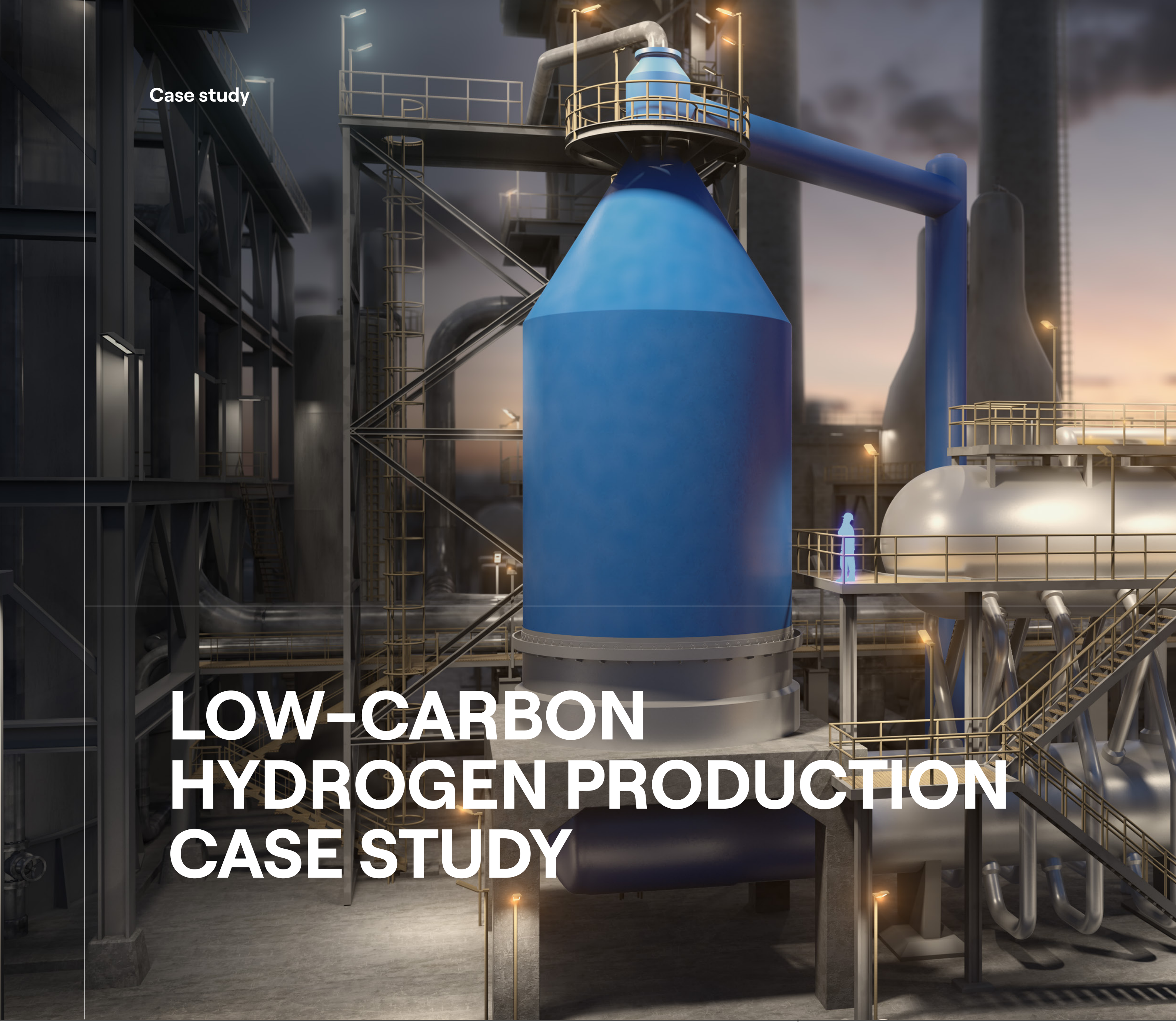


Case study

LOW-CARBON HYDROGEN PRODUCTION CASE STUDY

TOPSOE

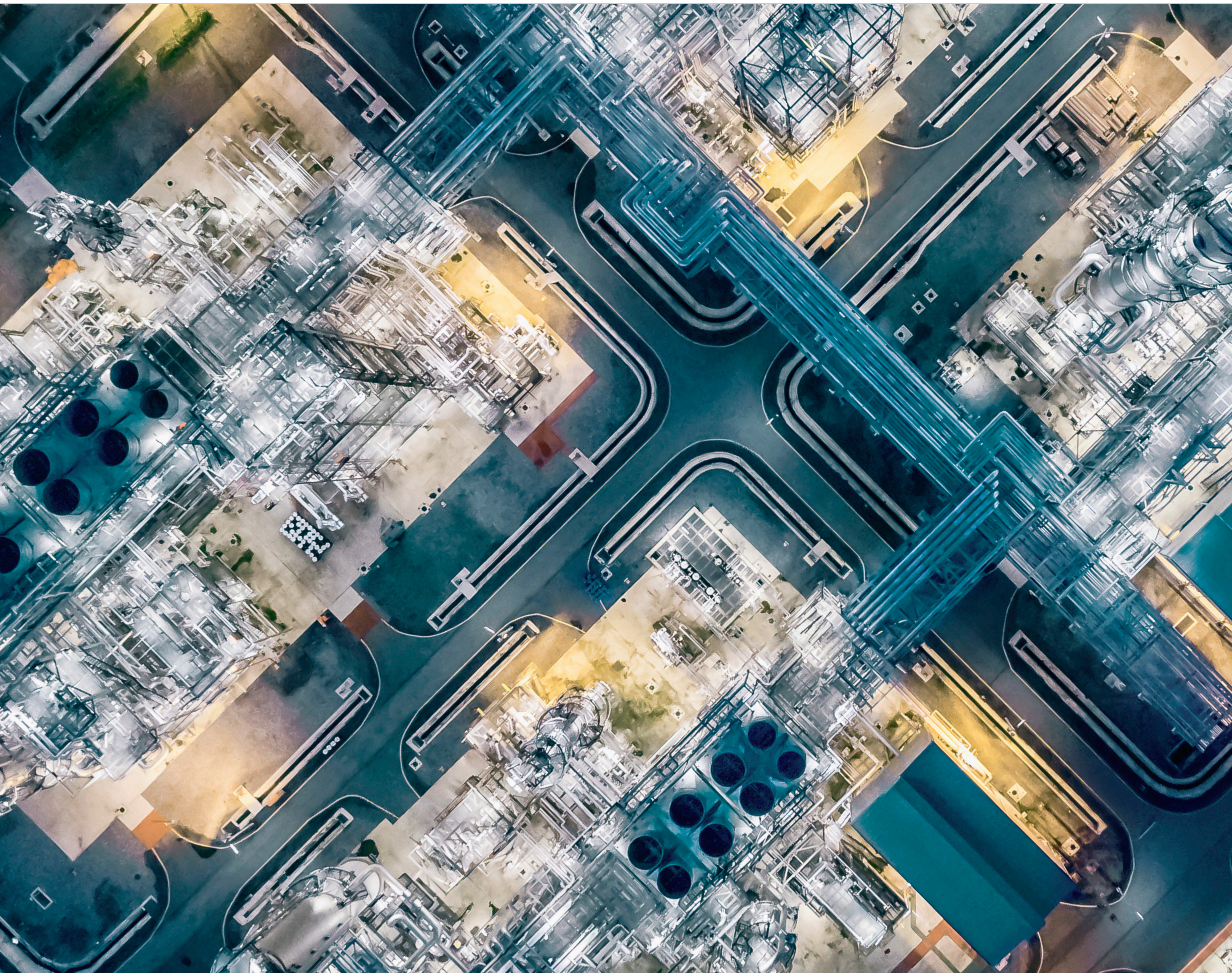
Honeywell UOP

CONTENT

INTRODUCTION

As the world seeks ways to mitigate climate change, the move toward net-zero emissions is critical for the energy sector. Reaching the IEA's Net Zero Emissions Scenario requires a variety of components to come together, with the decarbonization of high-emitting, energy-intensive sectors being among the most significant. Central to success is the use of low-emissions fuel, such as low-carbon hydrogen, often referred to as blue, and its derivatives.

This case study will explore the synergistic benefits of combining Topsoe's SynCOR™ autothermal reforming technology (ATR) for hydrogen production with Honeywell UOP's Cryogenic Fractionation CO_2 Capture Technology, in order to create the low-carbon hydrogen that can help pave the way toward a net-zero future.



A changing energy landscape with new opportunities

Hydrogen, with its high energy density and clean-burning properties, is a potential substitute for fossil fuels in industries such as steel production, refining, and chemicals manufacturing. Similarly, ammonia, which can be used directly as a fuel or as a hydrogen carrier for easier transportation, is another potential source for reducing emissions in industries such as maritime. The effectiveness of these low carbon solutions, however, hinges on the methods used for their production and the efficacy of carbon capture and storage.

A high-impact area

According to the International Energy Agency (IEA), 99 % of globally produced hydrogen is made from fossil fuels. In 2022, global hydrogen production created 900 million tonnes (Mt) of CO_2 emissions[1], more than the aviation industry (just under 800Mt) and significantly surpassing Germany's annual CO_2 emissions. Elsewhere, the Global Energy Perspective 2023 report by McKinsey believes that hydrogen production will increase between four and five times by 2050, highlighting the need for decarbonized hydrogen production[2].

To support this, numerous governments have implemented regulatory frameworks that promote the production of low-carbon hydrogen solutions. For example, the US Inflation Reduction Act enhanced existing carbon capture tax credits and introduced new incentives for low-carbon hydrogen production. Producers of ultra-low CI hydrogen can potentially earn up to $3 in tax credits per kg of hydrogen. Such incentives are driving investments in hydrogen as a decarbonization method.

Ensuring growing demand is met by low-carbon hydrogen

Traditionally, hydrogen is produced by steam methane reforming (SMR), using fossil-based feedstocks such as natural gas, LPG, or naphtha. Hydrogen produced from fossil sources without CO_2 capture is referred to as "grey" hydrogen. One promising method for decarbonizing hydrogen production is by steam or water electrolysis, powered by renewable electricity. The resulting hydrogen is entirely emissions-free, meaning it leaves no CO_2 footprint. Topsoe has commercialized electrolysis solutions for this method. However, the insufficient availability of renewable power is an obstacle to the large-scale deployment of green hydrogen right now.

To fully harness the potential of hydrogen in the energy transition, particularly in the near term as renewable power projects scale up globally, green hydrogen must be supplemented with other low-carbon hydrogen sources with low GHG footprints. Such low-carbon hydrogen can be produced by combining traditional production methods with carbon capture and permanent storage. This low-carbon hydrogen can be produced either through a revamped grey hydrogen plant that is already in operation or through a newly constructed low-carbon hydrogen plant.

An introduction to two leading technologies

Advanced technology, like Topsoe's SynCOR™ reforming, leverage autothermal reforming (ATR) to achieve higher efficiencies and lower emissions than SMR. SynCOR operates at a steam-to-carbon ratio, markedly lower than the ratio typical of conventional SMR, resulting in reduced water usage and lower capital expenditures.

While efficient hydrogen production is crucial, the other major element is the effectiveness of carbon capture and storage (CCS). Honeywell UOP's Cryogenic Fractionation CO_2 Capture Technology excels in this regard. This technology leverages cryogenic temperatures to separate CO_2 from gas streams, ensuring high purity and enabling its capture in a dense phase, which can be easily liquefied and stored. The combination of Pressure Swing Adsorption (PSA) and cryogenic systems offers unique advantages, including minimal CO_2 emissions, eliminated solvent management needs, and the ability to operate without steam, making it a robust solution for CCS in hydrogen production.

1. Global Hydrogen Review 2023 (iea.blob.core.windows.net)
2. Global Energy Perspective 2023: Hydrogen outlook | McKinsey

Measuring carbon intensity (CI) – a crucial parameter

Carbon intensity (CI) is the amount of CO_2 equivalent (CO_{2e}) emitted per kilogram of produced hydrogen and is now widely considered the most efficient way of measuring the impact of low carbon-hydrogen technology.

The journey of natural gas from the well to the hydrogen-production site needs to be considered, including all associated emissions such as fugitive emissions and emissions from flaring, venting, purging, etc. The emissions associated with hydrogen production, CO_2 capture, transport, and underground storage must then also be considered. Finally, energy consumption from the natural gas well to the final destinations of the hydrogen and CO_2, as well as associated GHG footprint, must also be factored in.

Initiatives to reduce CI are already happening. Several leading oil and gas companies have supported the Oil and Gas Climate Initiative (OGCI), which aims to eliminate methane emissions from oil and gas operations by 2030. OGCI members have reduced aggregate absolute methane emissions by 30% over five years and have committed to further reductions in the future[3].

The contribution to total CI, from both hydrogen production and CO_2-capture, is a crucial parameter in the life cycle assessment (LCA) and heavily depends on the technology for hydrogen production and carbon capture. Proven, commercialized technology advancements, like autothermal reforming with cryogenic CCS – highlighted in this paper – are means to meeting market-based requirements for efficient, reliable performance, while driving further cuts to emissions.

3. Source: OGCI 2022

TOPSOE SYNCOR™ TECHNOLOGY

Topsoe's SynCOR™ reforming, an advanced single step ATR process, has high efficiency, operating at a low steam-to-carbon ratio of 0.6 which is significantly less than conventional tubular steam methane reformer. Typically, tubular steam methane reformers operate at a steam-to-carbon ratio of 2.0-2.5 to avoid any possible carbon formation on the catalyst. However, Topsoe's SynCOR catalyst can operate at a much lower ratio without any carbon formation. Due to the low steam-to-carbon ratio, the SynCOR technology consumes much less water per ton of hydrogen than conventional technologies in the marketplace today. As a result, it has a lower CAPEX.

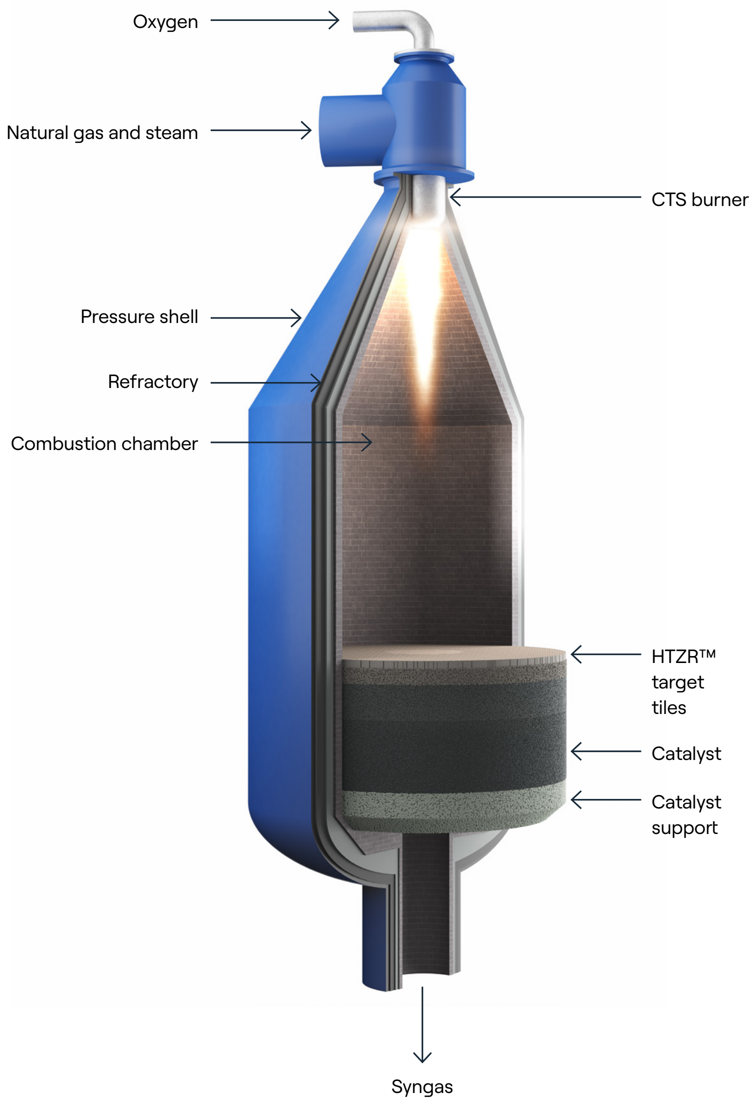
Steam is generated in the process by recovering the heat from process gas due to high temperature downstream the reforming and shift reactors . Part of generated steam is consumed internally by the reforming reaction, while the remaining incidental steam can be converted to power or consumed elsewhere, as per its optimal utilization.

SynCOR is fundamentally different from the conventional tubular steam methane reforming processes because the reforming process takes place inside the SynCOR reactor using steam and oxygen. The reactor has a compact design consisting of a refractory-lined pressure vessel with a burner, combustion chamber and a catalyst bed (Figure 1). The process gas enters the SynCOR reactor and is mixed with oxygen and additional steam resulting in a combination of combustion and steam reforming.

SynCOR technology has undergone 70 years of development and optimization. The first generation SynCOR (called ATR) was developed in 1958. Since then, Topsoe has developed a second generation SynCOR, which operates at a low steam-to-carbon ratio. Following its installation in many large capacity plants for different applications, including GTL (Gas to Liquid), TIGAS™ (natural gas to gasoline), syngas, and so forth, SynCOR has now gained over 300 years of cumulative operational experience. This makes it the most mature technology for low-carbon hydrogen and low-carbon ammonia projects. The largest SynCOR reactor in operation today has an equivalent hydrogen production capacity of 455 MMSCFD, while, for comparison, the highest capacity limit for single ATR train is 735 MMSCFD for hydrogen production.

In the SynCOR hydrogen production process, the firing duty requirement is low, so the external fuel demand is extremely low. This results in a very high carbon recovery (>99%) without the need to capture the carbon in the flue gas. It is, therefore, exceptionally well suited for low-carbon hydrogen.

FIGURE 1: Topsoe SynCOR™ reformer



HONEYWELL UOP CRYOGENIC FRACTIONATION CO_2 CAPTURE TECHNOLOGY

Carbon Capture for Utilization or Sequestration is a relatively new market within gas processing. Unlike historic processing objectives, instead of removing acid gas contaminates to upgrade a natural gas or syngas stream, the goal is to remove CO_2 from streams to prevent it from entering the atmosphere.

Honeywell UOP has an extensive portfolio of gas processing technologies developed over decades of supporting industry needs in carbon capture applications. Within Honeywell UOP's portfolio of gas processing technologies, Pressure Swing Adsorption (PSA) systems have traditionally been used to purify syngas or refinery off-gas streams to produce high purity hydrogen. PSA systems can be flexibly deployed in these applications and to selectively purify CO_2 based on the PSA adsorption cycle and the adsorbents used in a given design. Honeywell UOP Cryogenic separation technologies can also be utilized to conduct separation at low temperatures across NGL, LPG, Refinery off-gas, and LNG applications. Ortloff began designing and supplying these systems in these applications in the late 1970s, and Honeywell UOP fully acquired Ortloff in 2017.

There is not a one-size-fits-all approach when it comes to Carbon Capture project development. The following considerations should be evaluated for each potential project to understand the most cost-effective method for addressing CO_2 capture:

- Scale of the capture system required
- Feed stream concentrations and conditions
- Plot space constraints
- Utility costs and availability
- New process build vs. retrofit of existing asset to add CO_2 capture
- CO_2 offtake requirements and specifications
- Project cost drivers (Funding viability, CAPEX, OPEX)
- Site emissions considerations and limitations
- Reliability considerations
- Collaborators in technology value chain.

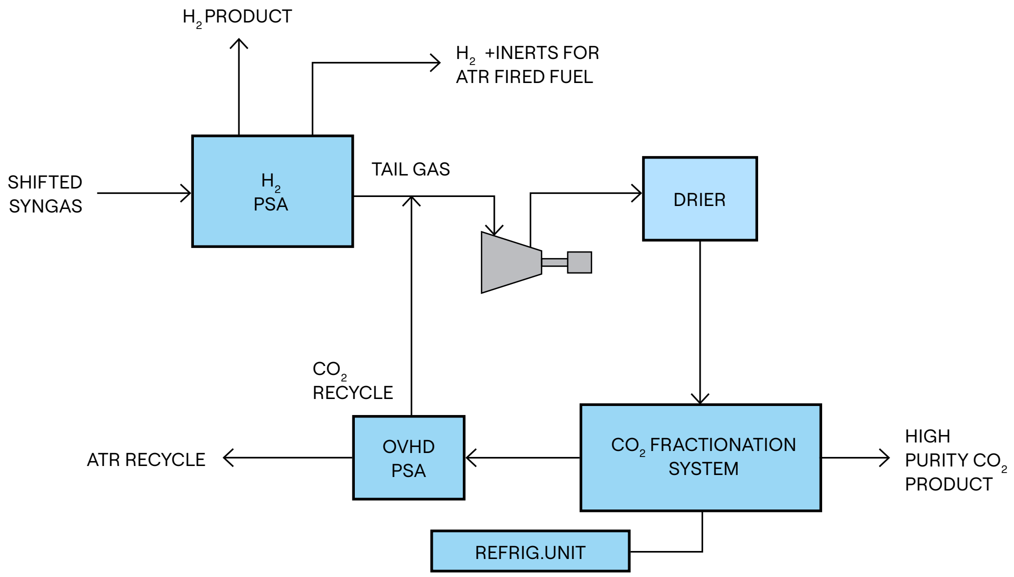
To address CO_2 capture requirements of hydrogen producers in systems where hydrogen is produced from natural gas, Honeywell UOP continues to evaluate its full portfolio of technologies given changes across these project variables, and some technologies. This is to ensure optimal results under certain circumstances. For instance, a combined PSA and Cryogenic system provide some unique advantages in syngas cleanup under the following project conditions:

- CO_2 needs to be produced at dense phase and can be liquified just through pumping
- CO_2 needs to be captured to very pure concentrations
- The project goal is to minimize CO_2 emissions from the process
- An all-electric capture process is preferred (no steam duty required in the operation of a cryogenic system)
- There is a desire to avoid solvent management
- The plot space and equipment size are constrained.

In a combined PSA and CO_2 Fractionation system for the hydrogen purification and CO_2 capture processes, the syngas would be fed to the hydrogen purification and CO_2 capture system after being produced via autothermal reforming and shifted to maximize the composition of hydrogen and CO_2 in the stream. The shifted syngas will be at a pressure that matches the design of a PSA system, and often that syngas stream will be cooled slightly to knock out moisture and optimize feed temperature to the PSA system. Because of the typical scale of syngas produced through autothermal reforming, the PSA system must also be larger than typically designed in purification from SMR systems. The PSA will therefore often require several trains to purify the larger syngas volume.

This, however, provides some benefits, as it enables the hydrogen product to potentially be produced at different purity levels. Furthermore, in the depressurization cycle of the PSAs, a lower pressure decarbonized hydrogen stream can be produced that would only contain inerts from the syngas stream (namely nitrogen and argon), and this hydrogen stream can be used as decarbonized fuel in the reforming process.

FIGURE 2: Block diagram of PSA and Cryogenic fractionation CO_2 capture unit

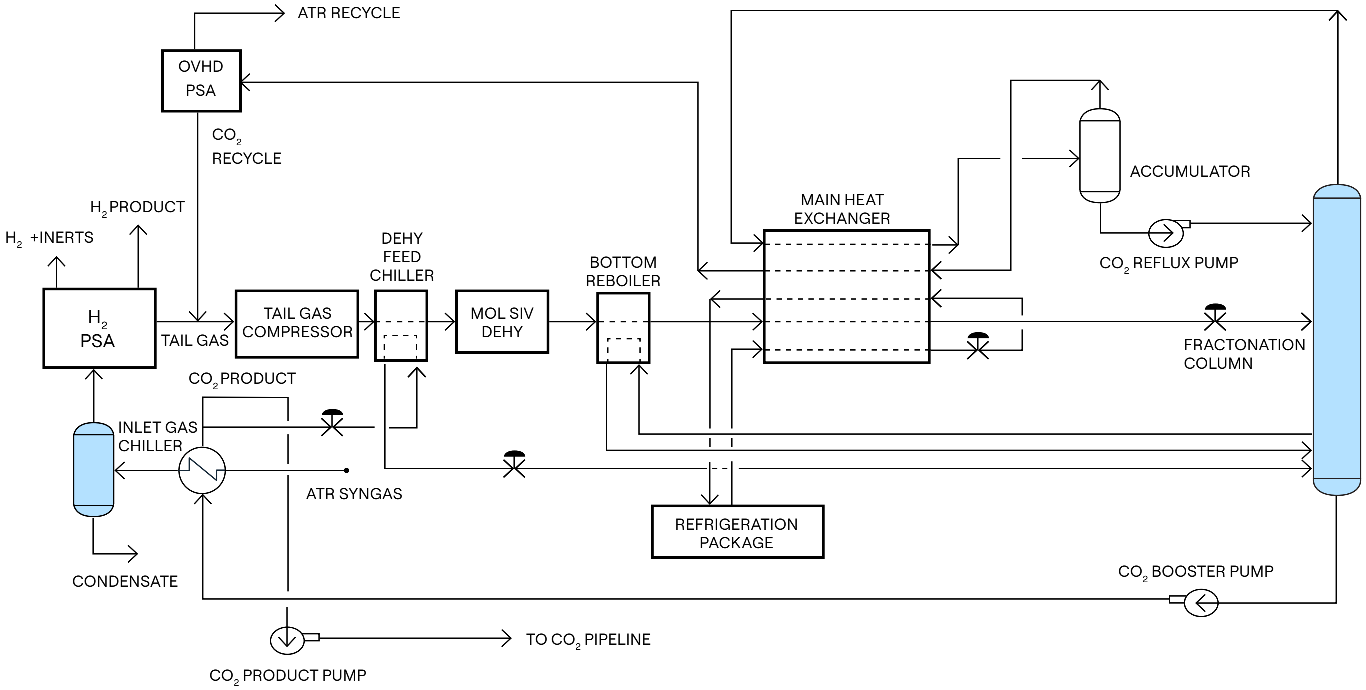


Once the hydrogen is purified for use or offtake, the CO_2-rich tail gas stream will discharge from the PSA units at low pressure at a typical concentration of 70+% CO_2. To separate out the CO_2 from this stream though the cryogenic fractionation process, it must first be compressed up to the feed pressure required for the fractionation process, and it must be dehydrated through a temperature swing adsorption system to ensure that no freezing occurs in the fractionation system.

The CO_2 Fractionation system manages the temperature of a distillation process to separate out the CO_2 from the remaining constituents. Honeywell UOP has designed a three-product Mixed Refrigerant system optimized for the temperature requirements to separate the CO_2, and the refrigerant is circulated through a multi-pass Brazed Aluminum Heat Exchanger alongside the process stream to manage the system temperature. For effective CO_2 separation, the temperature must be managed close to the triple point of CO_2.

There will inevitably be carbon constituents that are not captured in the CO_2 fractionation process, both because there will be unconverted CH4 and unshifted CO from the syngas stream and because the fractionation process cannot perfectly separate out CO_2 in one pass. The off-gas is therefore sent back through the Brazed Aluminum Heat Exchanger and to an overhead PSA system that will selectively recycle CO_2 back to the low-pressure CO_2-rich stream. The balance of the constituents will be recycled back to the ATR feed to ensure that no carbon is lost anywhere besides the CO_2 product.

FIGURE 3: Detailed diagram of PSA and Cryogenic fractionation CO_2 capture unit



A CASE STUDY – UNLOCKING ADDITIONAL VALUE THROUGH SCALE AND INTEGRATION BACKGROUND

Selecting the technology best suited for a particular low-carbon hydrogen project will depend on multiple parameters and vary based on the unique project-specific needs, as noted above and in "Mega-Scale Decarbonization with Blue Hydrogen". A case study for one particular recent FEED-level design for a Topsoe SynCOR with Honeywell UOP Hydrogen PSA and CO_2 Fractionation system to produce low-carbon hydrogen is presented in this section. In this particular case, one design objective was to reduce emissions of both hydrogen product and of a nearby operated chemicals and refining complex.

INTEGRATING REFORMING AND CARBON CAPTURE TECHNOLOGY

The focus for this integrated design of Topsoe SynCOR with Honeywell UOP Hydrogen PSA and CO_2 Fractionation system was to achieve a high level of carbon capture from the process. The design achieves just that and results in >98% of overall carbon capture. The captured CO_2 is produced at high purity (99.5%) and at high pressure/dense phase for sequestration. The simplified block flow diagram is as shown in Figure 4.

FIGURE 4: Low-carbon hydrogen production process

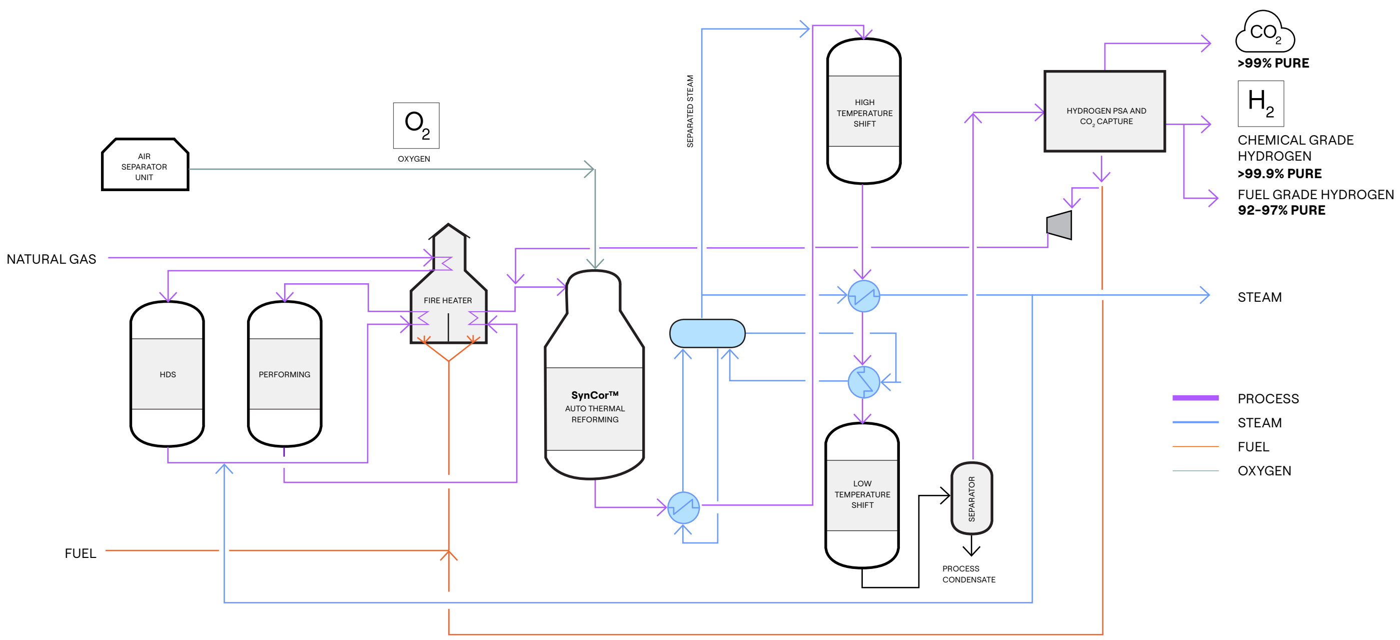


TABLE 1: Case study specific numbers

Hydrogen production capacity (MMSCFD)	515
Carbon recovery, mol%	>98
Hydrogen purity, mol%	Chem grade >99.9 Fuel grade 92-97
CO2 purity, mol%	>99.5

INTEGRATING HYDROGEN PRODUCTION WITH EXISTING CHEMICAL/REFINING OPERATIONS

This integrated system was specifically designed to provide extra advantages to an existing co-located refinery and chemicals manufacturing facility. The SynCOR reforming combined with the Honeywell UOP Hydrogen PSA and CO_2 Fractionation system provides additional cost reduction and decarbonization beyond the scope of just the hydrogen production unit.

HYDROGEN FUEL SWITCHING

Locating the hydrogen production facilities on site enables efficient transportation of fuel-grade hydrogen to local users. Local fuel switching at the customer's existing refinery and chemicals manufacturing facilities reduces existing GHG emissions from hard-to-decarbonize existing point sources.

STEAM CO-PRODUCT

Existing chemical and refining operations require large quantities of steam typically produced via natural gas fired boilers. Steam provides a variety of heating and feedstock needs for chemical and refining plants. However, incidental steam from the SynCOR process can be routed into existing steam systems, displacing conventionally generated steam, and allowing the chemical and refining operations to turn down (or turn off) existing natural gas fired boilers. Additionally, the Honeywell UOP Hydrogen PSA and CO_2 Fractionation system does not require any steam during operation, allowing all incidental steam to be routed elsewhere. If available, steam integration into brownfield systems can provide a net emissions reduction benefit over other alternatives such as power generation.

Emissions associated with electrical power can be abated cost-effectively through the purchase of low-carbon intensity electricity. To maximize total emissions reductions, a combined approach of using low-carbon intensity electricity combined with incidental steam to displace unabated steam generation from natural gas fired boilers is the most effective strategy for maximizing overall emissions reductions from the hydrogen plant and existing chemical/refining complex.

TAIL-GAS/REFINING GAS

Existing chemical and refining operations often have waste processing streams that are unable to be sold or processed and are often burned as fuel. Examples include refinery off-gas and tail gas. The SynCOR autothermal reforming process is capable of accepting refinery off-gas or tail gas as part of its feed. This provides chemical and refining operations an outlet for the off-gas or tail gas that supplements the overall natural gas feed required for hydrogen production. The carbon from these off-gas or tail gas streams will ultimately get captured in the CO_2 Fractionation system, thereby decarbonizing the stream and allowing chemical/refining operations to replace the off-gas or tail gas fuel with a lower emissions alternative, such as hydrogen .

SUMMARY

There are a number of factors to drive choice of technology to deploy for low-carbon hydrogen production, depending on project-specific objectives and circumstances. Topsoe's SynCOR and the Honeywell UOP Hydrogen PSA and CO_2 Fractionation system's carefully engineered integration with an existing chemical and refining complex can accomplish a dual objective of lower-cost operations and reduced overall operation emissions. This was accomplished by:

- → Carbon capture rate
- → Hydrogen fuel switching for the integrated complex
- → Maximizing steam export to chemical and refining operations to displace steam otherwise produced by natural gas boilers, while still operating the SynCOR process at an optimal steam to carbon ratio
- → Tail gas waste stream used as feedstock for the hydrogen plant, which ultimately becomes a decarbonized fuel source.

When the opportunity exists to integrate a mega-scale low carbon production with an existing industrial facility, the combination of Topsoe and Honeywell UOP technologies are equipped to deliver world-scale hydrogen with industry leading capture rates, while also reducing overall GHG emissions for existing facilities.

CONCLUSION

Decarbonizing the world is a big challenge that needs big answers. Topsoe's SynCOR's low-carbon hydrogen production technology is a leading option for the industry, boasting superior cost-based economics and a proven record in producing hydrogen at mega-scale. The SynCOR technology makes low-carbon 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.

As described in the case study, Topsoe's SynCOR technology integrated with UOP H2 PSA and CO_2 fractionation system have been utilized for a mega-scale low-carbon hydrogen project. This technology not only attained > 98 mol% CO_2 recovery within the process plant, but also integrated the hydrogen production with existing chemical/ refining operation.

The case study's particular challenge within the production of low-carbon hydrogen was met by Topsoe's SynCOR technology, which was flexible enough to meet the customer's specific demands regarding plant capacity, carbon intensity, product quality, and other key stipulations.

Low-carbon hydrogen can help decarbonize many sectors that are hard-to-abate. But to do that effectively, low-carbon hydrogen must be made in a responsible way, from start to finish. This involves efficient capture and storage of CO_2 permanently. The Honeywell UOP Hydrogen PSA and CO_2 Fractionation system enables that strategy.

Ultimately, the combination of Topsoe's SynCOR reforming with Honeywell UOP's Hydrogen PSA and CO_2 Fractionation system provides a pathway to producing low-carbon hydrogen and ammonia. This integrated approach offers several benefits:

→ Lower emissions: The advanced reforming process reduces CO_2 generation, while cryogenic fractionation ensures efficient capture of any emissions, achieving over 99% carbon recovery

→ Cost efficiency: Reduced water usage and lower CAPEX in the SynCOR™ process, coupled with the operational efficiencies of fractionation, result in significant cost savings

→ Qualification for incentives: By meeting low carbon thresholds, the combined technology aims to give producers the possibility to apply for various low carbon incentives and credits, providing economic benefits within projects

→ Versatility and scalability: The technologies are scalable and adaptable, suitable for both new builds and retrofits, ensuring they can be deployed across a range of industrial applications

→ Brownfield Integration: Topsoe SynCOR technology provides flexibility to utilize various feedstock as well as integration of incidental steam for displacing a fuel consumption reduces the overall cost as well as net emissions of the complex.

The combination of Topsoe's SynCOR™ reforming and Honeywell UOP Hydrogen PSA and CO_2 Fractionation system represents a best-in-class solution, delivering high efficiency, lower emissions, and cost-effective operations. By leveraging these advanced technologies, industries can reduce their carbon footprints, align with global decarbonization goals, and help secure a lower emissions future.

ABOUT TOPSOE

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**.

ABOUT HONEYWELL

Honeywell is an integrated operating company serving a broad range of industries and geographies around the world. Our business is aligned with three powerful megatrends – automation, the future of aviation and energy transition – underpinned by our Honeywell Accelerator operating system and Honeywell Forge IoT platform.

We help organizations solve the world's toughest, most complex challenges, providing actionable solutions and innovations through our Aerospace Technologies, Industrial Automation, Building Automation and Energy and Sustainability Solutions business segments that help make the world smarter, safer and more sustainable.

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