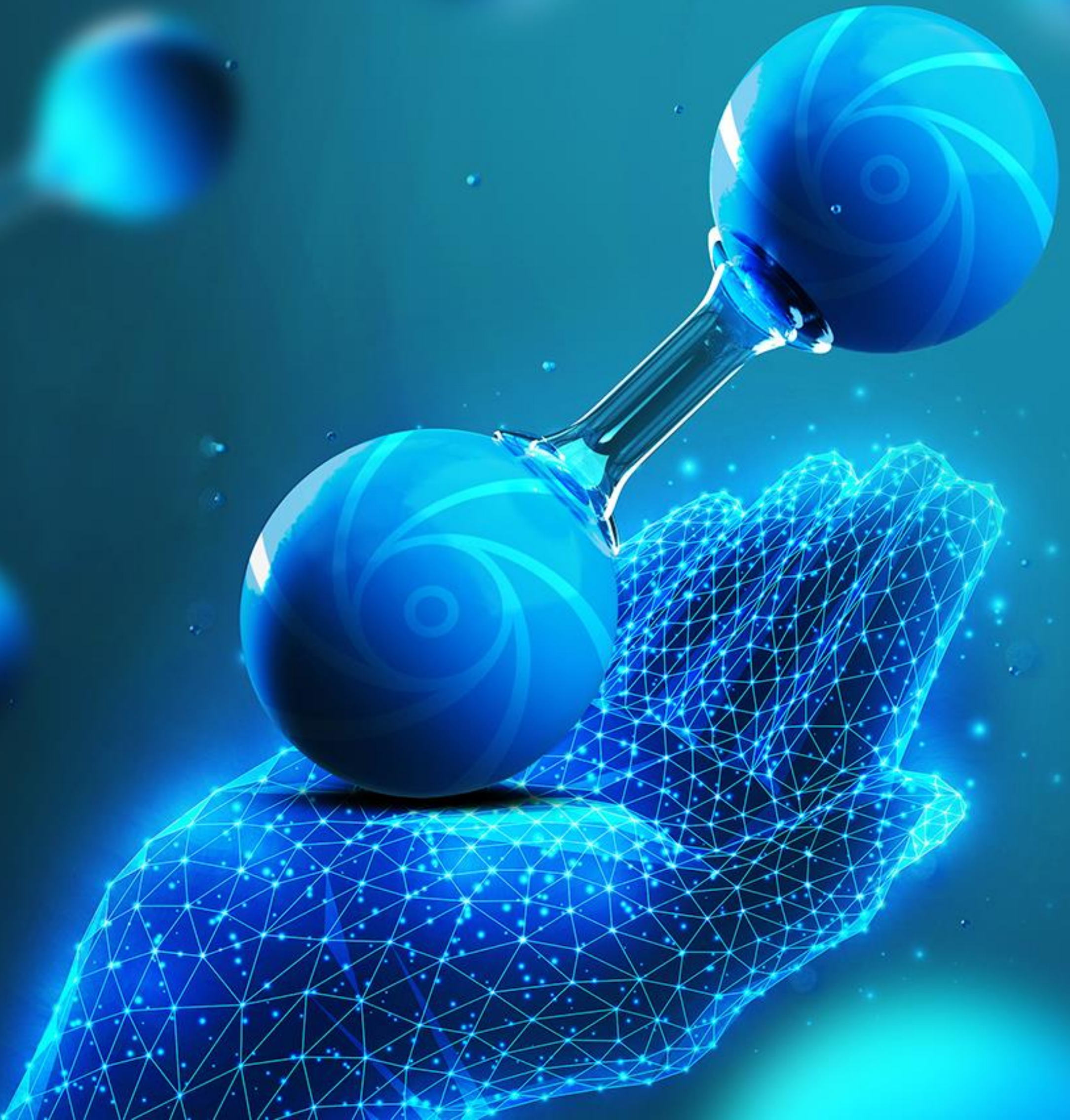
How Turbomachinery Can Support Decarbonization

November 2021

Atlas Copco Gas and Process



Introduction of Our Speakers

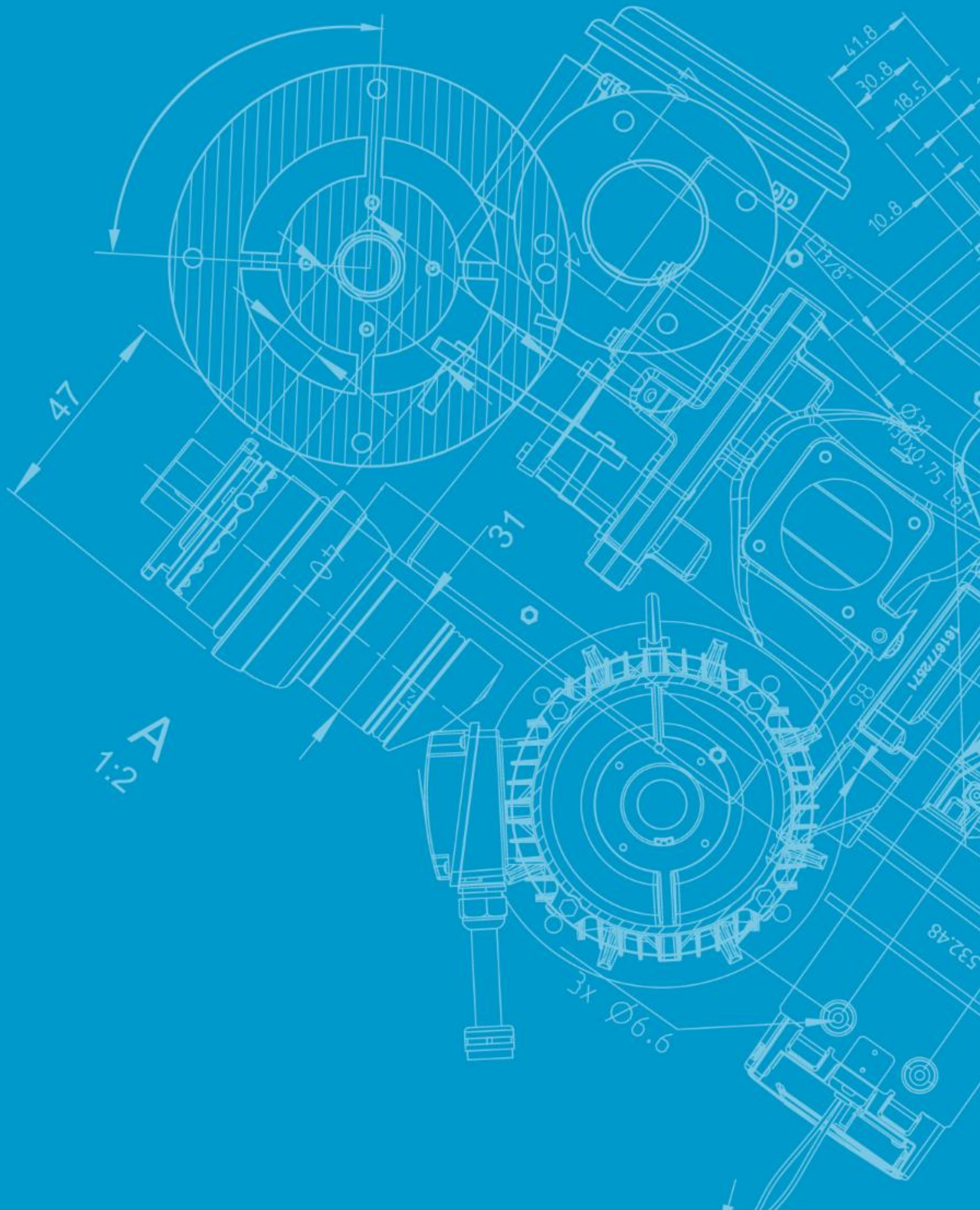
Daniel Patrick
Applications Lead
New Energy & Hydrogen

Ulrich Schmitz
Vice President
Marketing

Table of Content

The Energy Transition

A Challenge and Opportunity



Global Climate and Human Health Protection

The Challenge and the Opportunity

Paris Climate Change Conference

Limit global warming to 1.5 °C

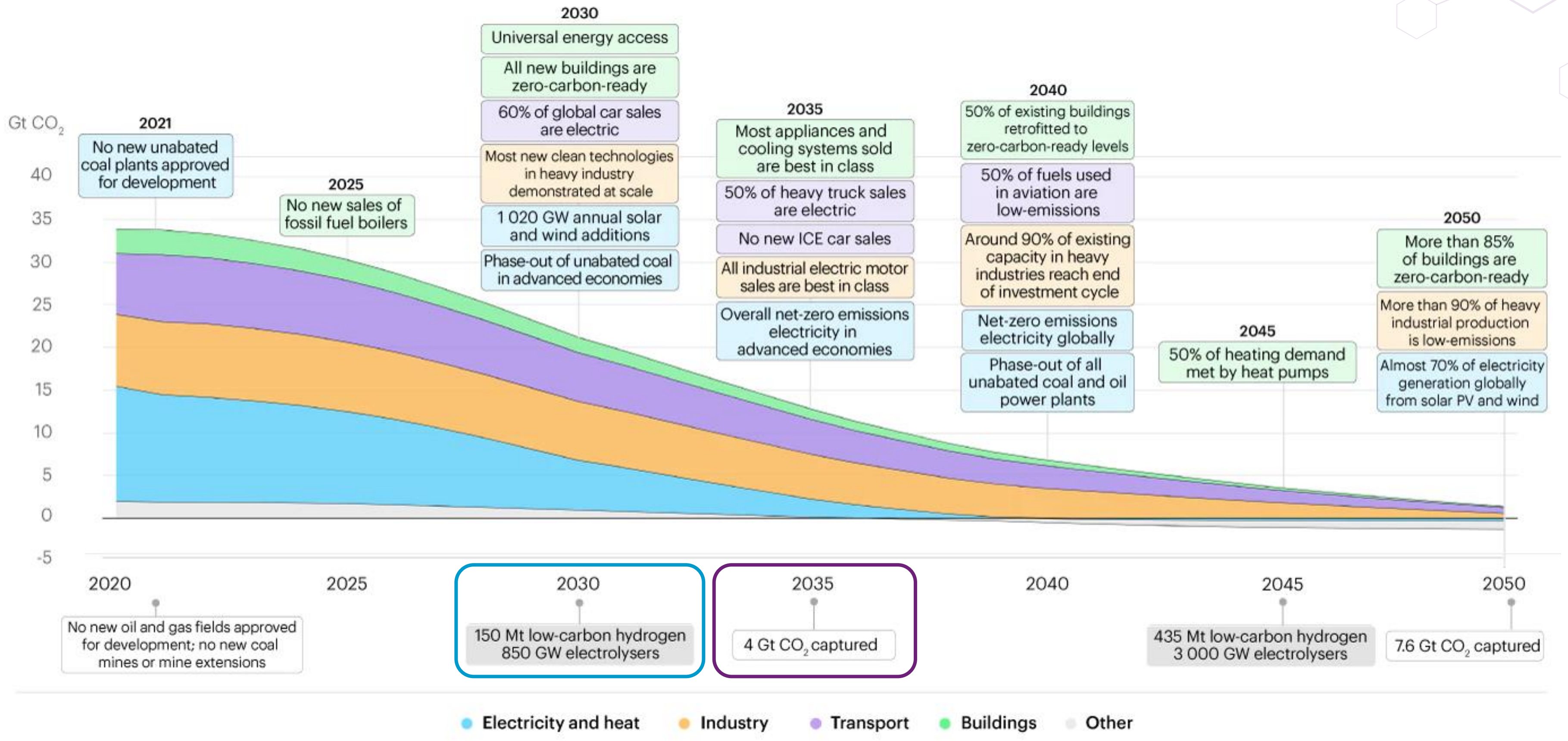
International Maritime Organization (IMO) 2020

As of 01 January 2020, ships will have to use marine fuels with a Sulphur content of no more than 0.5%S against the current limit of 3.5%S.
Emission Control Areas (ECAs) will remain at the 2015 standard of 0.1%S content.

European Targets in 2030

At least 40% cuts in greenhouse gas emissions (from 1990 levels).
At least 32% share for renewable energy.
At least 32.5% improvement in energy efficiency

Net Zero **2050**



Estimates of 150 MTPA of clean hydrogen by 2030 from current less than 2 MTPA

Estimates of 4000 MTPA of CO_2 captured from current 40 MTPA

Markets Served by Gas and Process Division

Hydrocarbons | **Air Separation** | **Power Generation** | **New Energy** | **Emerging Markets**

- Hydrocarbons: Midstream; LNG; Olefins / Polyolefins; Chemicals / Petrochemicals; Refinery
- Power Generation: Fuel Gas Boosting
- New Energy: Thermal Energy Storage; sCO_2 / Renewables; Industrial Heat Pumps
- Emerging Markets: CCUS; Hydrogen

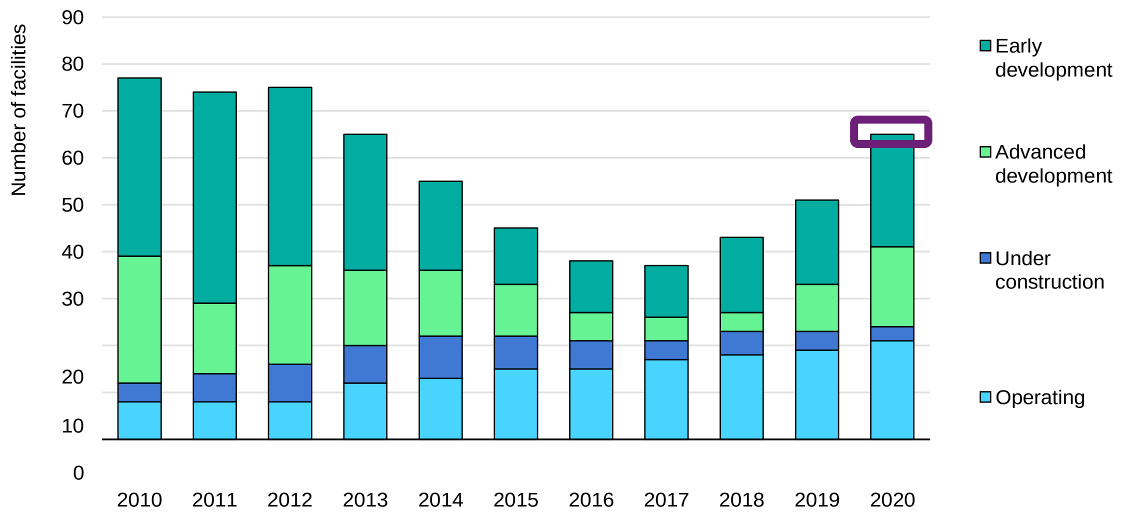
Nov 2021

Emerging Markets

Carbon Capture Utilization and Storage (CCUS)

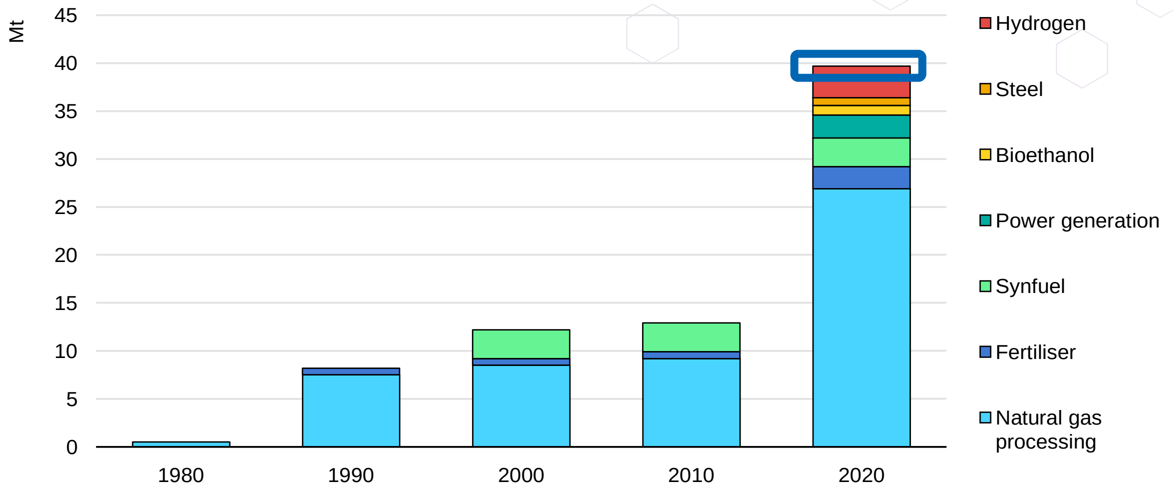
Carbon Capture Utilization and Storage

Figure 1.3 **Global large-scale CCUS facilities operating and in development**



65 commercial CCS facilities in various stages of development

Figure 1.2 **Global CO_2 capture capacity at large-scale facilities by source**

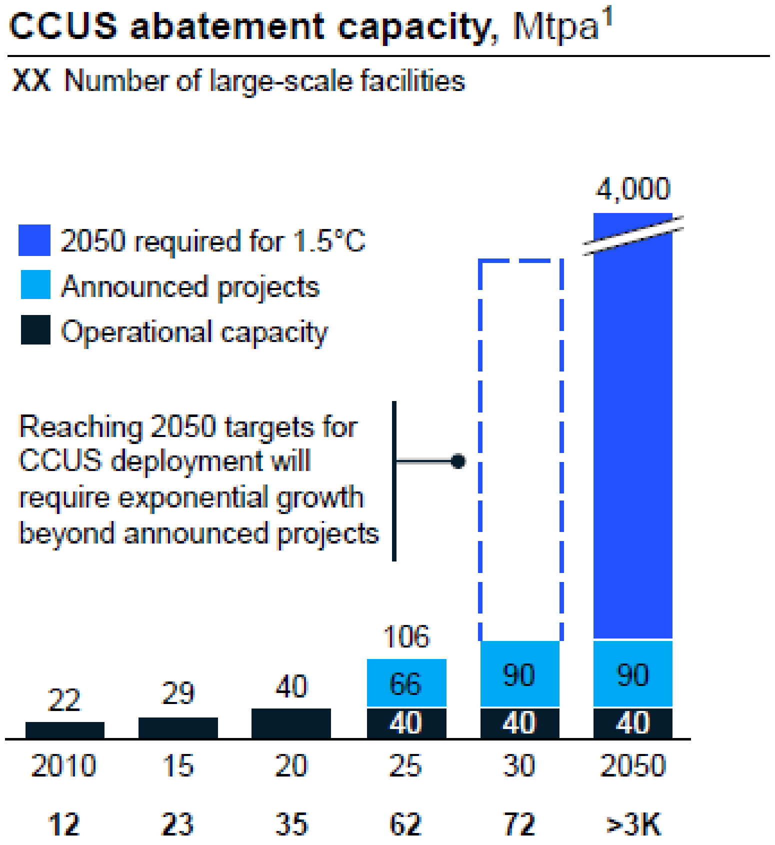


40 MTPA of CO_2 is captured from **25** CCS facilities

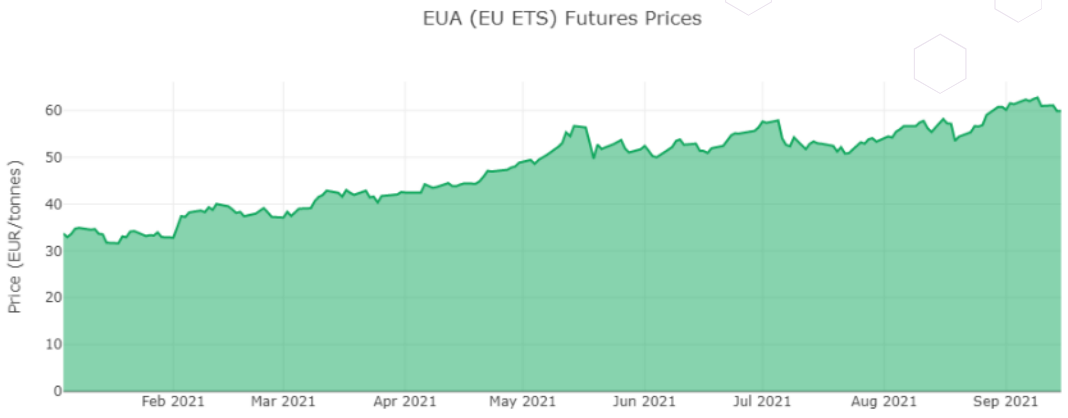
According to: Energy Technology Perspectives 2020

Sixteen advanced projects could represent a potential investment of more than **USD 27 billion** and an additional **50 Mt/year of CO_2** capture capacity.
For several of these projects, an FID is imminent, and construction could begin as **early as 2021**.

Carbon Capture Utilization and Storage



***Source**: Global CCS Institute / Mc Kinsey & Company*



Carbon price at 59 €/ton

CCUS plant potential up to 2050	Today (2022)	Over 28 years, plants per year	Total OR potential [Million €] (5 M€ per unit assumed)	GAP OR [Million €] (20% MC assumed)
3000	65	105	524	105
2000	65	69	346	69
1000	65	33	167	33
500	65	16	78	16

Carbon Capture Mapping

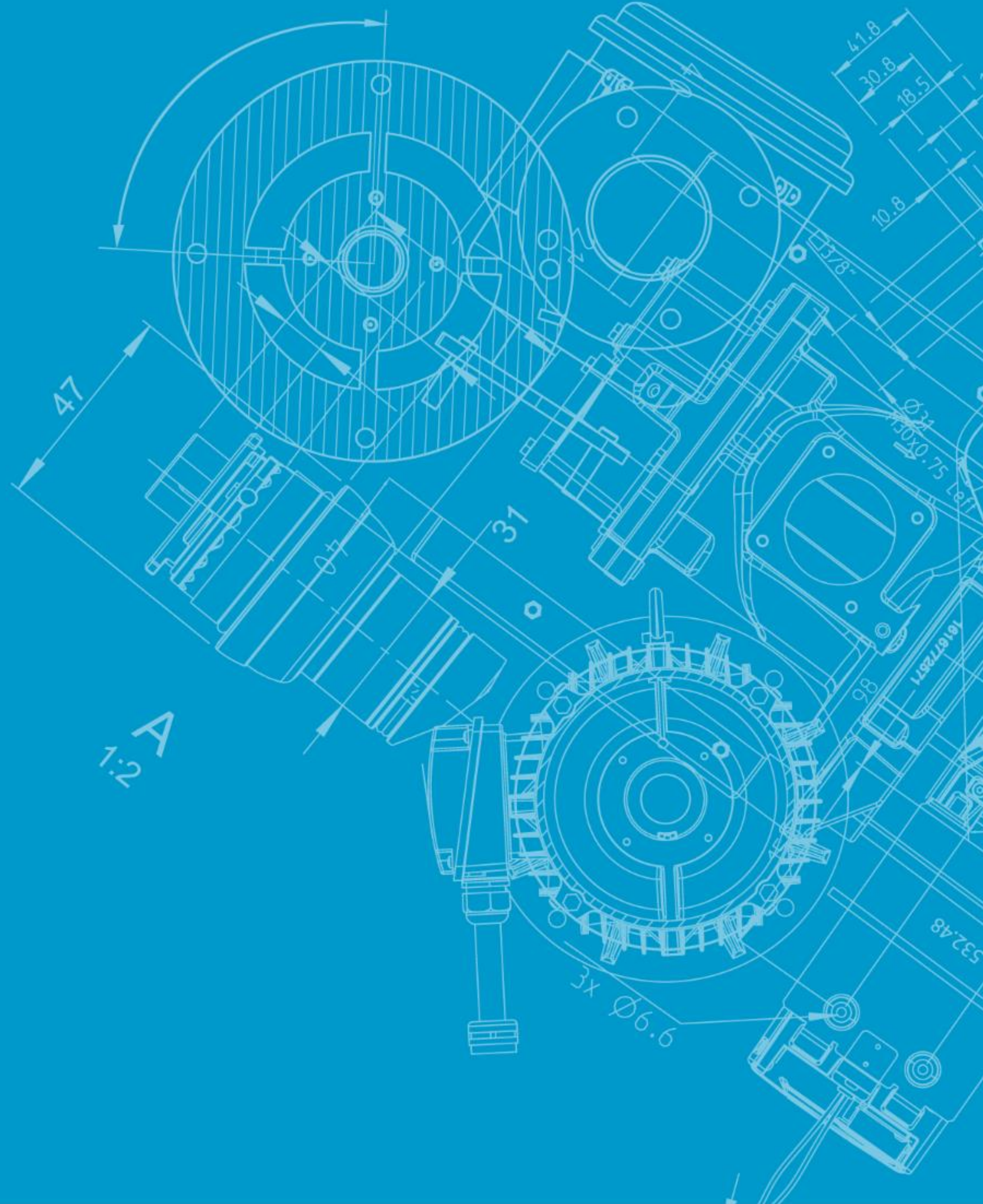
Technology Licensors

Carbon Capture Technologies

- Oxy Fuel
- Direct Air capture
- Pre combustion
  - Chemical adsorption (amine)
  - Membranes (PSA)
  - Cryogenic
- Post combustion

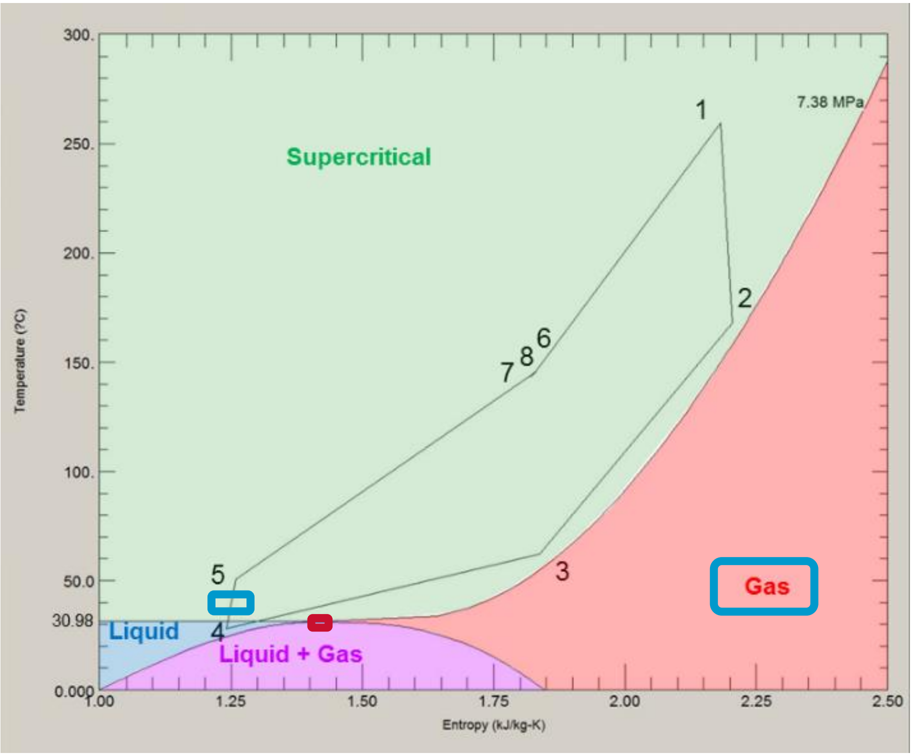
CO_2 vs. sCO_2

Projects and Applications



sCO_2 and CO_2 Compression

Important References



Critical point
P = 73.3 bara
T = 31.1 Deg C

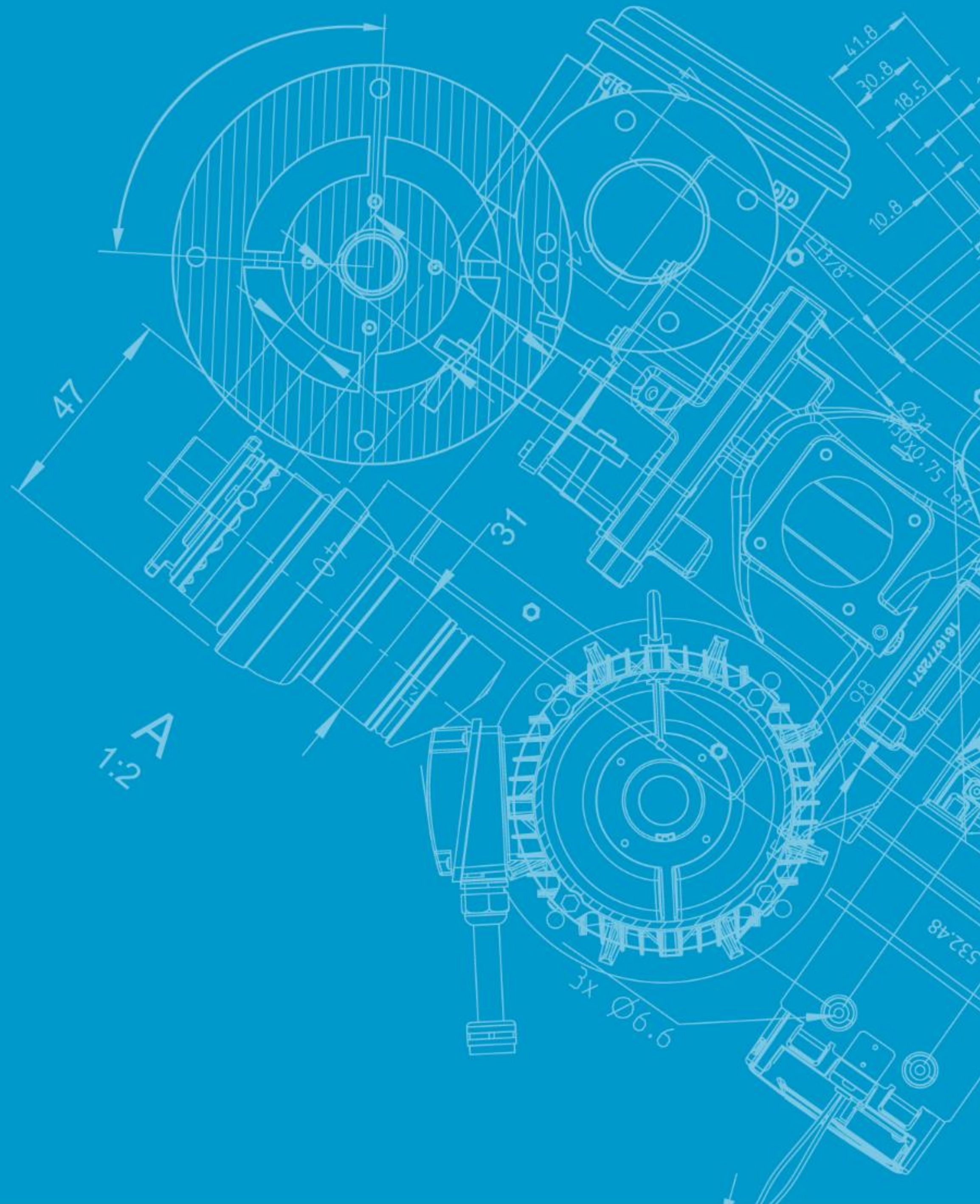
sCO_2 (Compander)
"**HHI/Kepco**"
Delivery 2019, **delivered**

CO_2 (2 stage) "**Netpower**"
Delivery 2017, **demo plant**

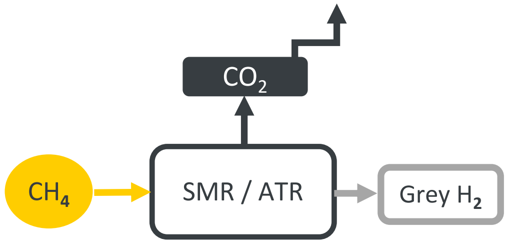
CO_2 (8 stage) "**Urea**"
Delivery 2015, **in operation**

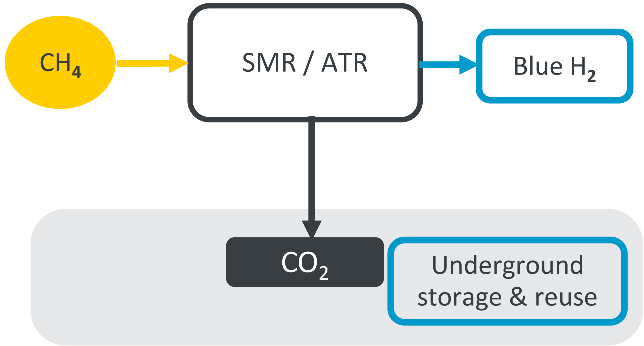
Emerging Markets

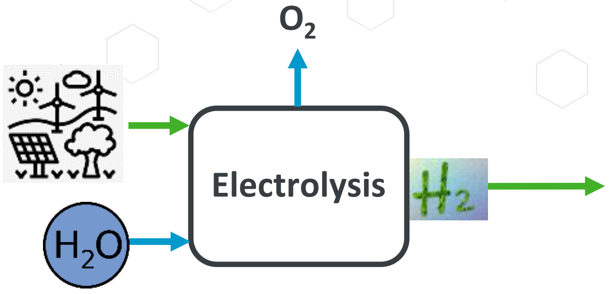
Hydrogen



Colors of Hydrogen







Grey Hydrogen

- Convert CH_4 into CO_2 and H_2
- CO_2 emitted to atmosphere
- Status: **Proven, low cost**

Blue Hydrogen

- Split CH_4 into CO_2 and H_2
- CO_2 reused and stored
- Status: **Pilot stage**

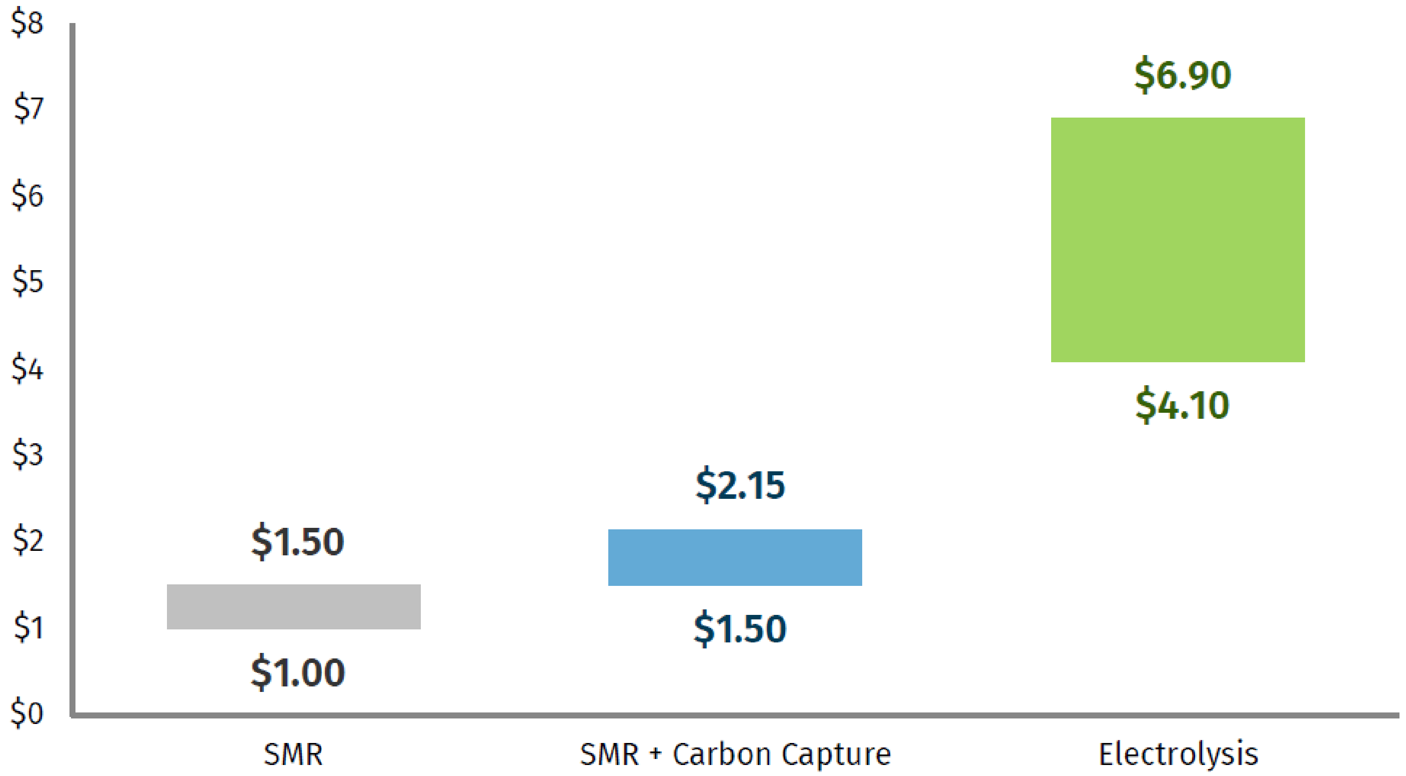
Green Hydrogen

- Split H_2O into O_2 and H_2 by electrolysis powered by wind and solar
- No CO_2 emitted
- Status: **Pilot stage**

FIGURE 1

US cost estimates for select hydrogen production methods

$/kg of hydrogen



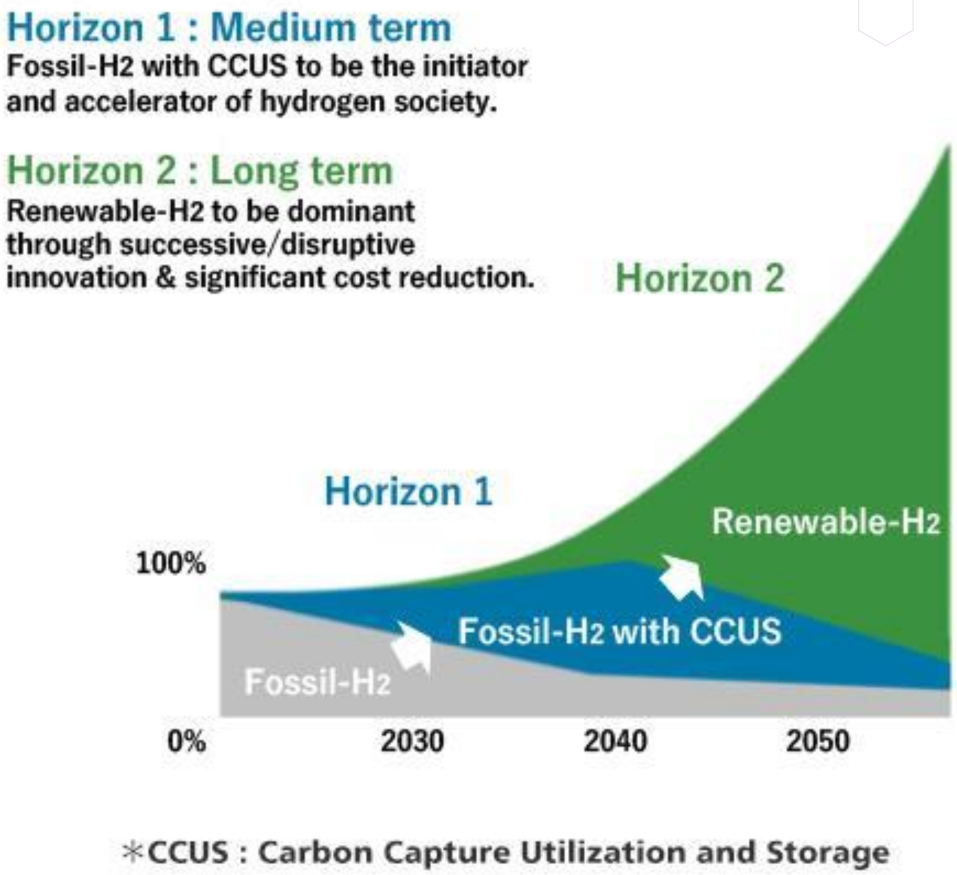
Source: Citi Research, Center on Global Energy Policy at Columbia University SIPA, Rhodium Group analysis. Note: the SMR + carbon capture cost estimates above reflect retrofitting an SMR hydrogen plant to capture about 90% of on-site carbon emissions. The green hydrogen cost estimates are for a polymer electrolyte membrane (PEM) hydrogen plant powered by renewable energy.

Hydrogen Production

With cost of CO_2 at 25-35 $/t, blue H_2 becomes competitive against grey. Green H_2 may still be double the price of blue by 2030. Some forecasts indicate cost parity in 2045.

Hydrogen Production

Going green



Source: Mitsubishi Power

- 120Mt of "dirty" hydrogen is produced annually;
- 75Mt of pure hydrogen mostly used in refining (39Mt) and ammonia production (33Mt).
- 45Mt mixed with other gases, predominantly carbon monoxide (CO) in syngas (synthesis gas).

Low carbon "clean" hydrogen

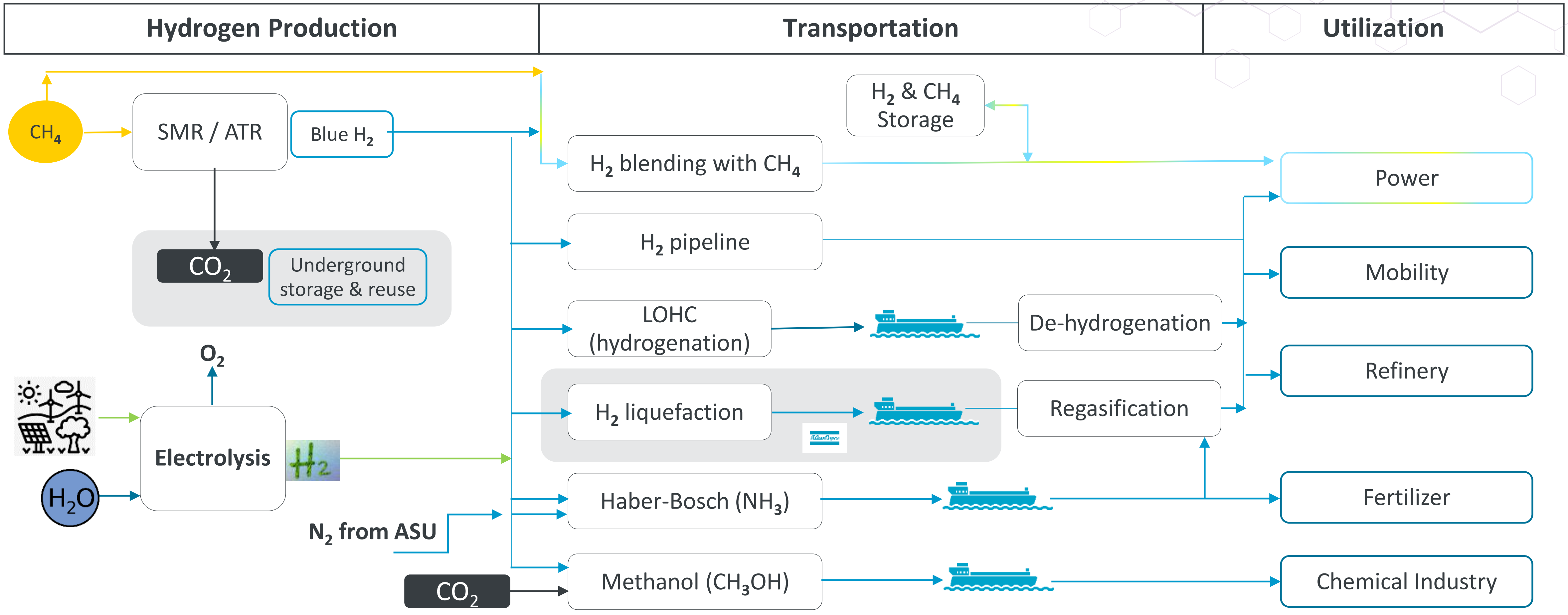
IEA: 2030: 150Mt

IEA: 2045: 435Mt

Source: IEA

Hydrogen Technologies

Developments in an Emerging Market



Nov 2021

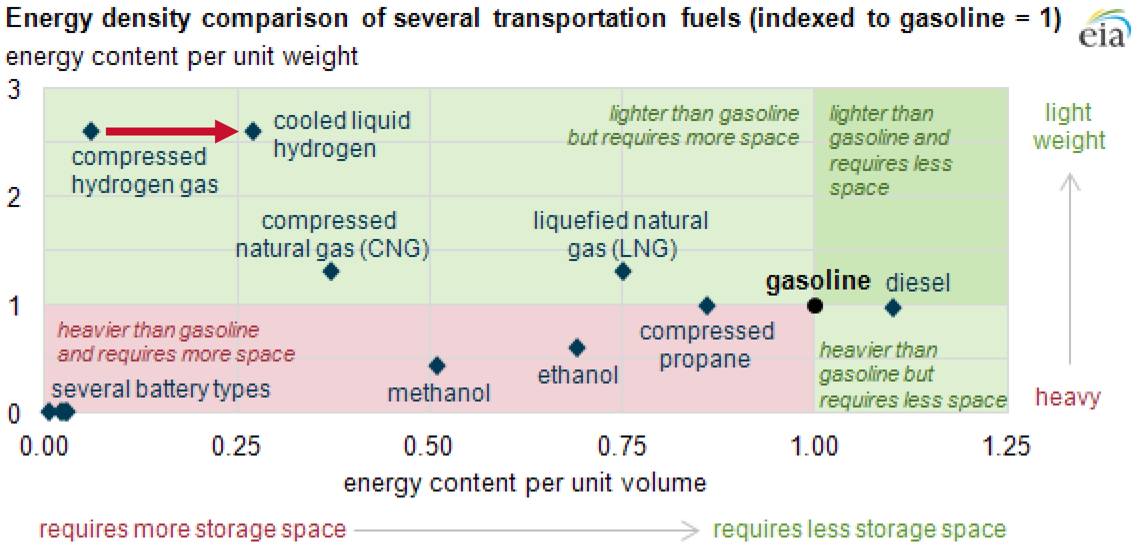
Hydrogen Transportation

Hydrogen | A Clean Energy Carrier

Facts

- Hydrogen is the smallest, lightest, and most abundant element in the universe and it makes up more than **90%** of all matter!
- The use of Hydrogen (either through combustion or by a fuel cell) creates zero greenhouse gas emissions
- At 120MJ/kg, H2 has the highest energy density (by mass) of all elements!

Energy density comparison of several transportation fuels (indexed to gasoline = 1)



Options for H_2 Transportation

Gas Pipeline

Expensive capital cost

1600 miles of H_2 pipelines exist in the US, mostly in the gulf coast.

Blending H_2 (up to ~15%) in existing NG pipelines is possible.

Best for large volumes

Compressed Gas Trucks

Special tube trailer required for high pressure (180 bar / 2,600 psi)

Significantly lower energy density per truckload compared to liquid form

Best for short distances and small amounts

Liquid Trucks and Ships

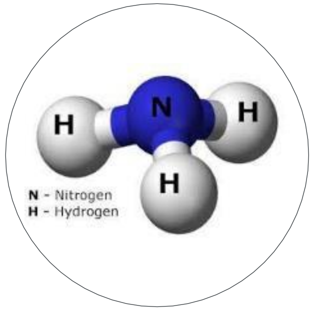
Additional energy required to liquefy

Special insulated tanks required for cryogenic temperatures

High energy density – LH_2 is 1/800th the volume of its gaseous form

Photo courtesy of HySTRA

Chemical Carriers



In liquid form: Hydrogen in Ammonia (NH_3) or Methylcyclohexane (MCH).

In solid form: Metal Hydrides

Must extract the Hydrogen from the carrier at point of use

Options for H_2 Transportation

Gas Pipeline

Expensive capital cost

1600 miles of H_2 pipelines exist in the US, mostly in the gulf coast.

Blending H_2 (up to ~15%) in existing NG pipelines is possible.

Best for large volumes

Compressed Gas Trucks

Special tube trailer required for high pressure (180 bar / 2,600 psi)

Significantly lower energy density per truckload compared to liquid form

Best for short distances and small amounts

Liquid Trucks and Ships

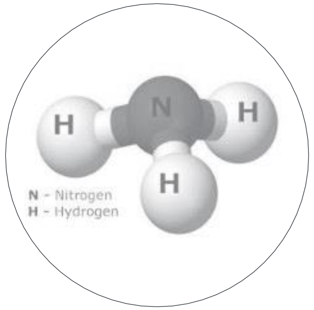
Additional energy required to liquefy

Special insulated tanks required for cryogenic temperatures

High energy density – LH_2 is 1/800th the volume of its gaseous form

Photo courtesy of HySTRA

Chemical Carriers



In liquid form: Hydrogen in Ammonia (NH_3) or Methylcyclohexane (MCH).

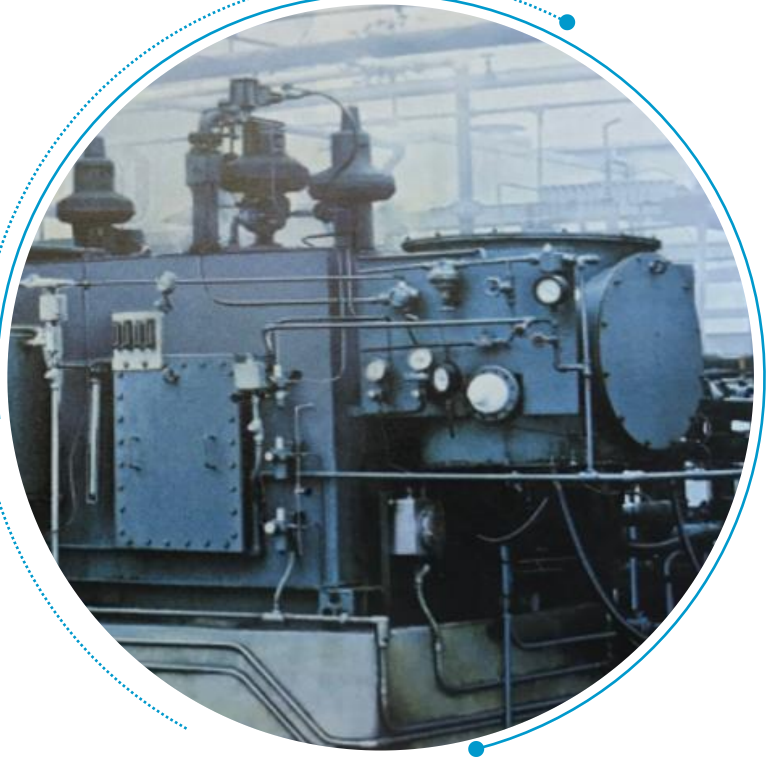
In solid form: Metal Hydrides

Must extract the Hydrogen from the carrier at point of use

Hydrogen Liquefaction

Let’s talk about cold

History



Atlas Copco expanders for hydrogen liquefaction (Circa late 1980s).
3-stage Expander Hydro brake (EHB)

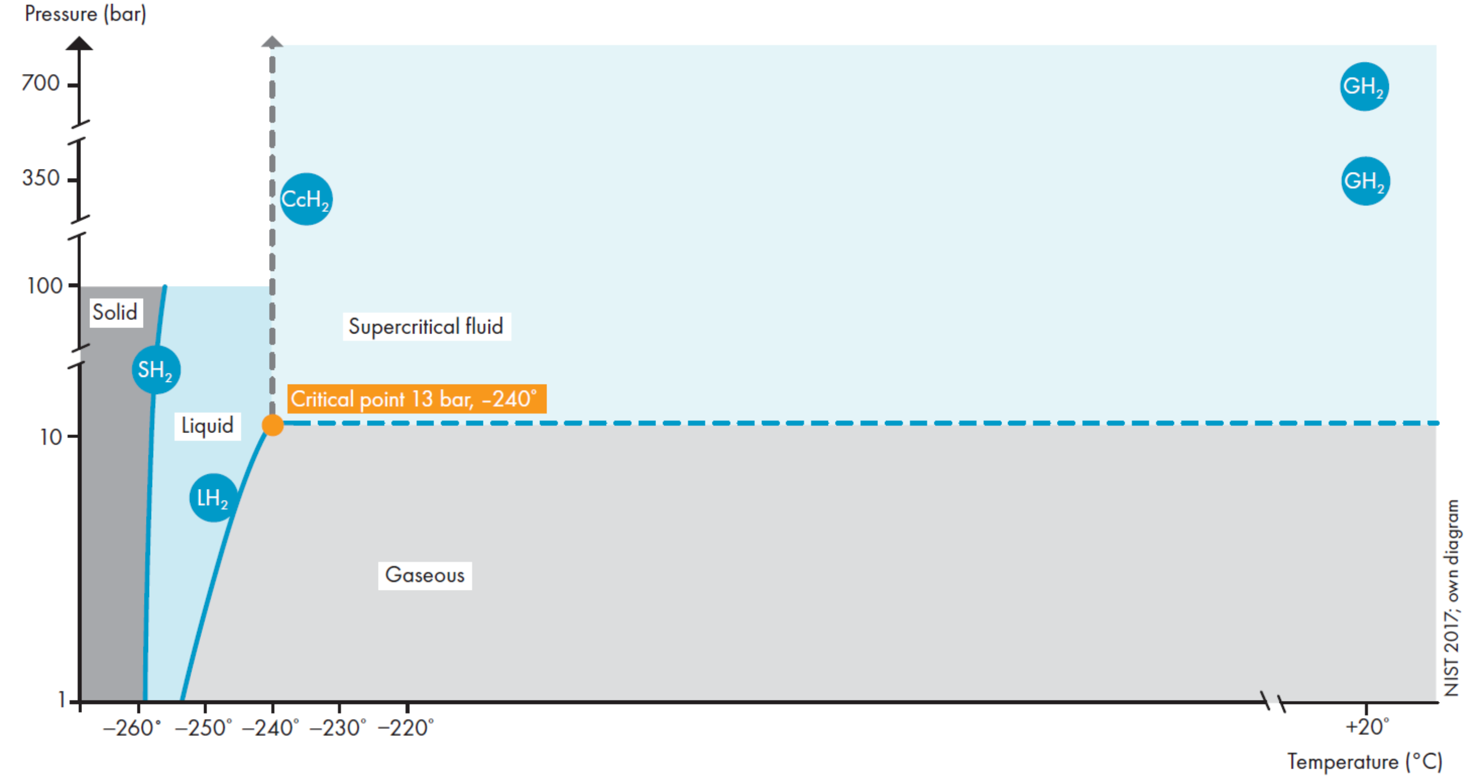
Hydrogen was first liquified in 1898 by James Dewar

Hydrogen liquefaction has been around for decades, although only in relatively small quantities

Atlas Copco

Phase Diagram

3 PHASE DIAGRAM HYDROGEN

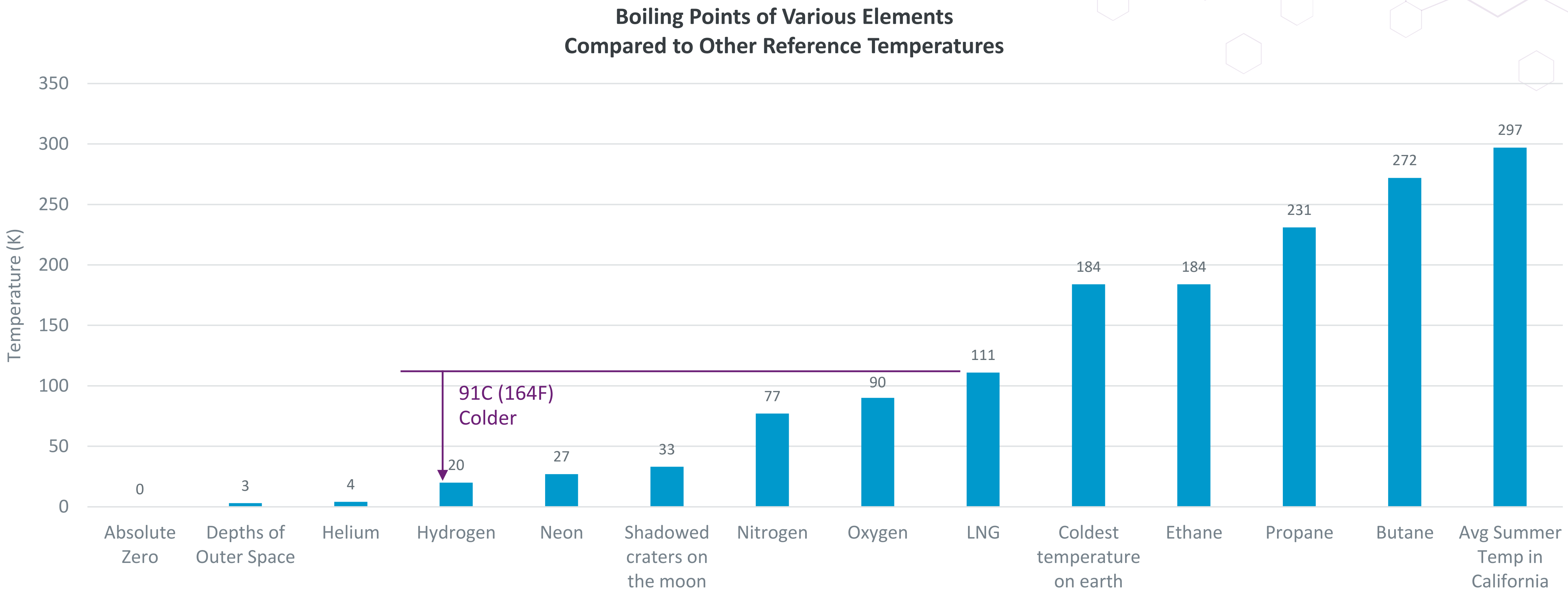


Source: Shell H_2 Study

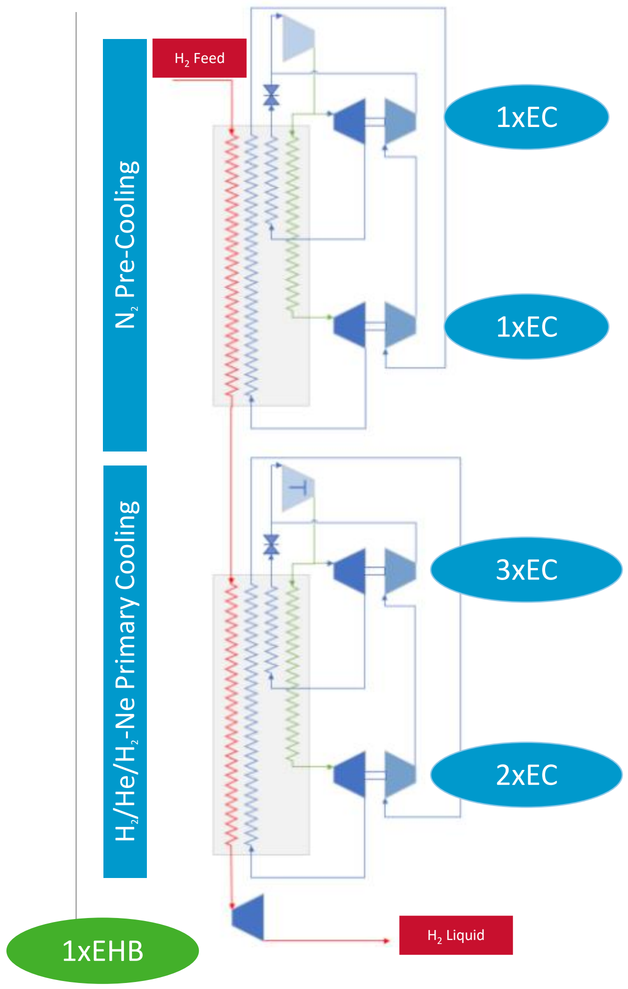
Definition

The critical temperature of a substance is the lowest temperature at which vapor of the substance cannot be liquefied, no matter how much pressure is applied.

Cryogenic Temperatures – Switching to Kelvin



Hydrogen Liquefaction Process



Pre-cooling refrigeration cycle

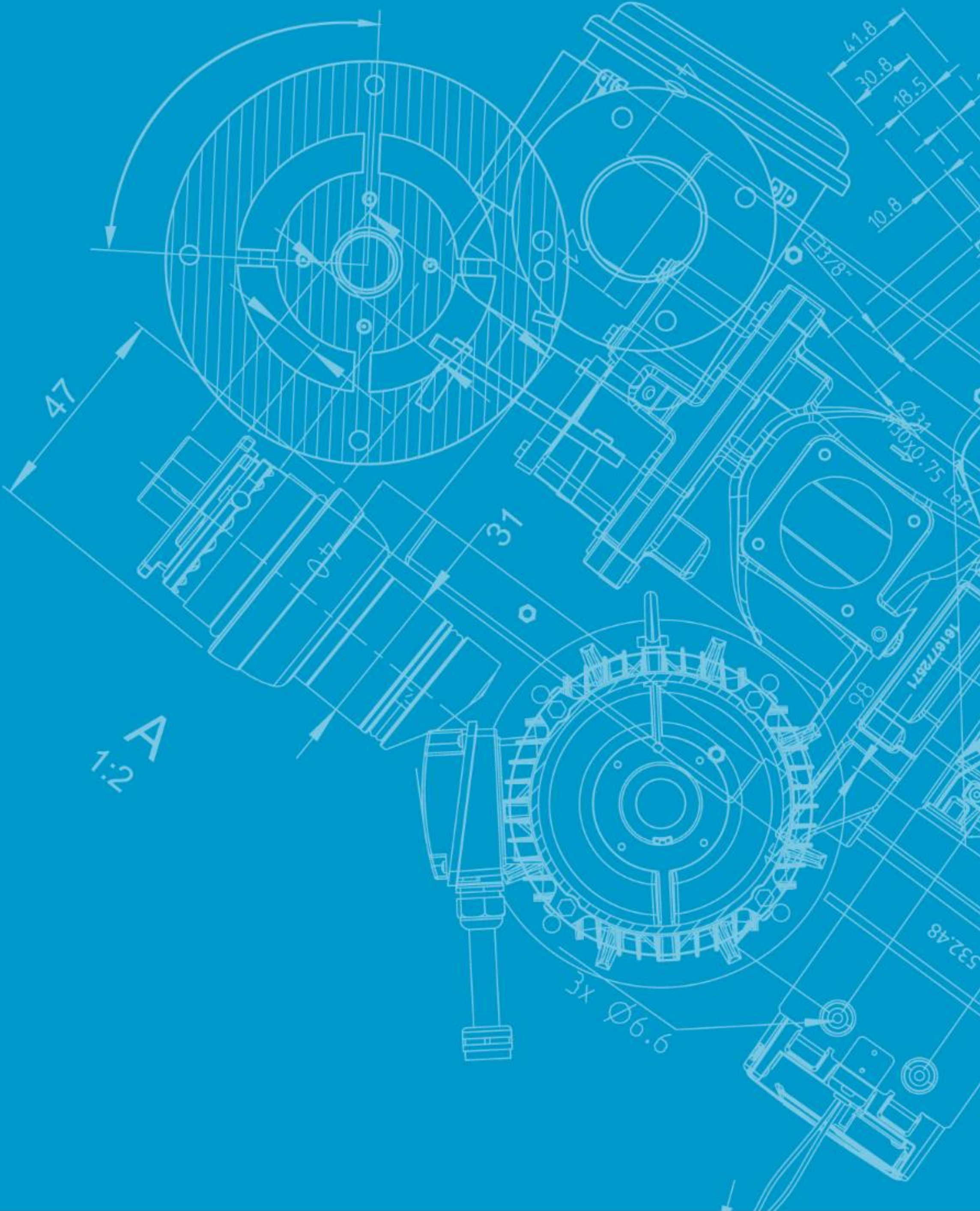
N_2 using two expander stages

Primary cooling refrigeration cycle

H_2 using 3-5 expander stages in series

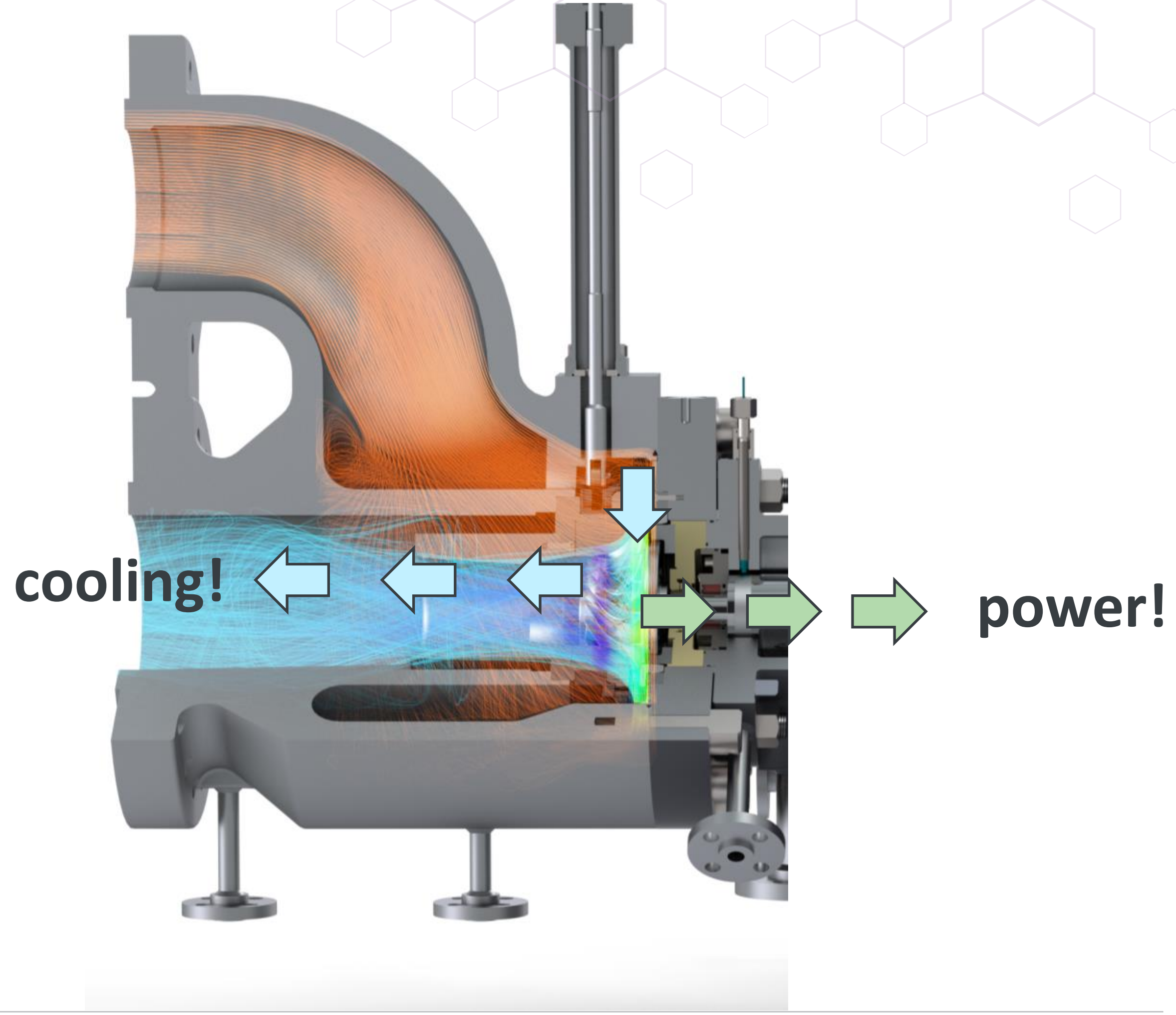
Efficient LH_2 Production

How Atlas Copco turboexpanders decrease specific energy consumption



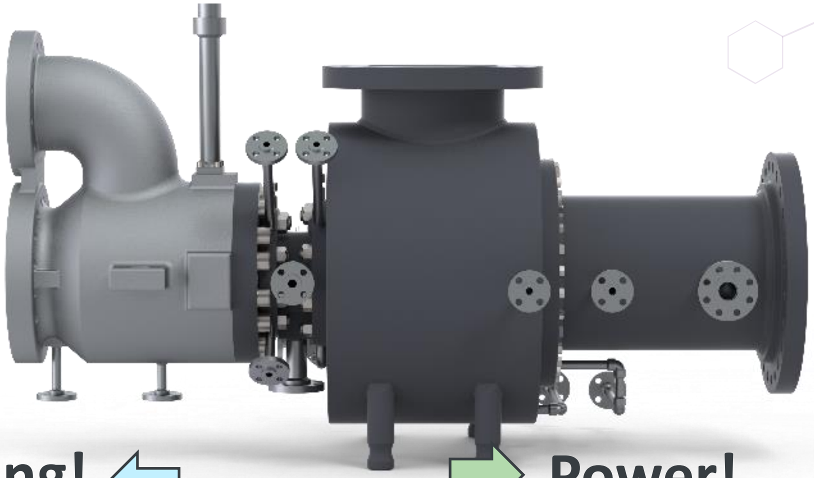
What is a **Turboexpander**?

A **turbomachine** that continuously expands a fluid from a **higher pressure** to a **lower pressure**



Power Recovery

Buy one get the other free!



Expander ⇨ **Compressor** (Mechanical)

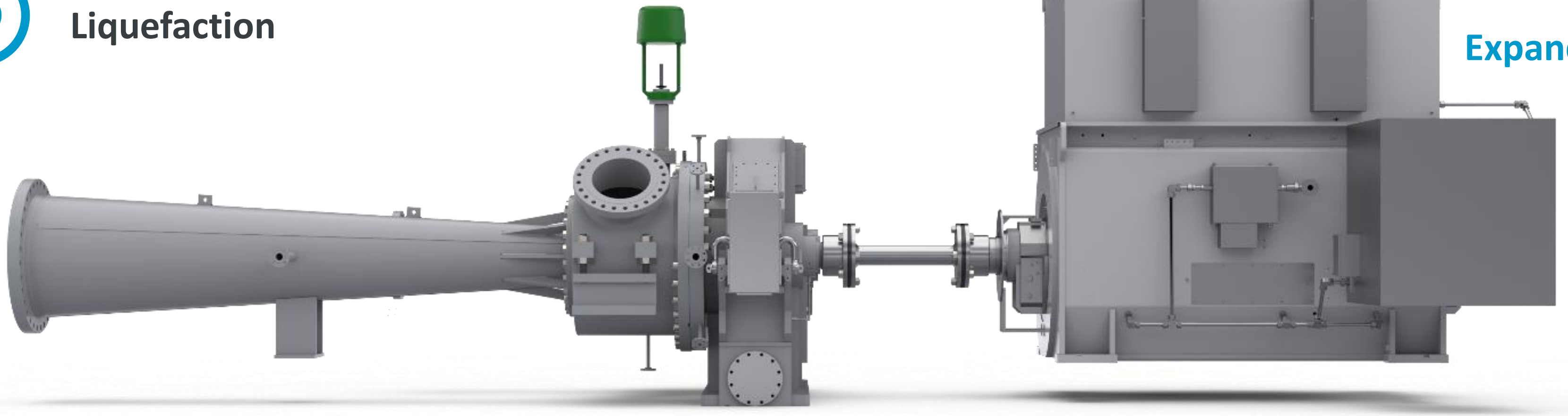
Why Cool?

Separation

Purification

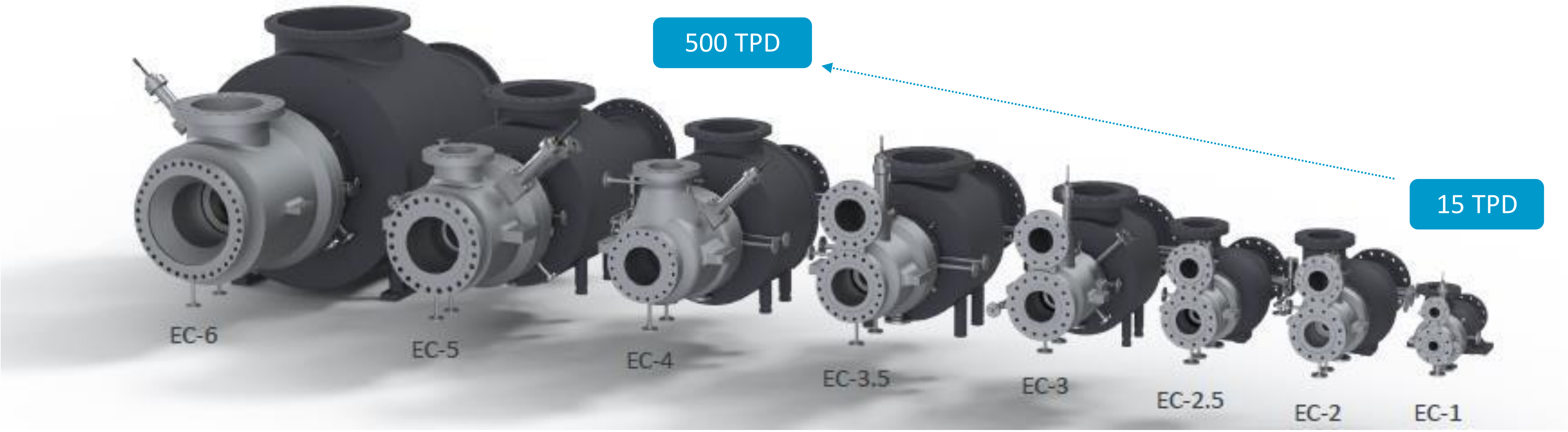
Liquefaction

Cooling! ⇦ ⇨ **Power!**

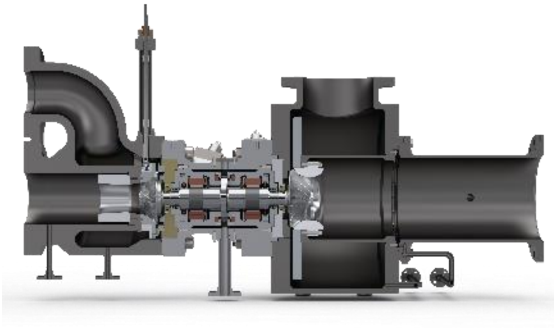


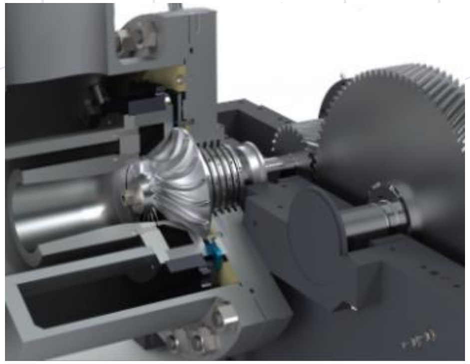
Expander ⇨ **Generator** (Electricity)

Plant Sizes



Old vs **New**





	Traditional H_2 Liquefaction	Future H_2 Liquefaction	
Plant size	Small-scale (< 15TPD)	Medium to large scale (≥ 15TPD)	Large scale (>50TPD)
Braking load	**Hydraulic Brake** Dissipates power Oil bearing	**Compressor** Power is recovered Hermetically sealed Oil-free (mag bearing)	**Generator** Power is recovered Multiple stages on one gearbox
Subcooling by	JT valve	Liquid Expander	Liquid Expander

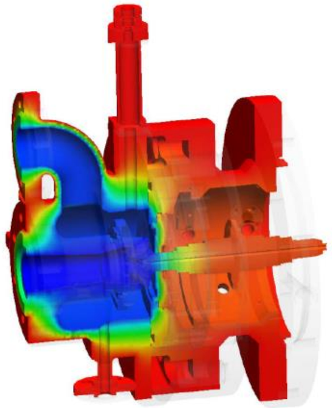
Technical Challenges

Pure hydrogen gas creates unique challenges for turbomachinery

Aerodynamic optimization

Low molecular weight and high enthalpy drop requires unique design features

Thermal management



Extreme cryo temperatures for H_2 liquefaction (20K)

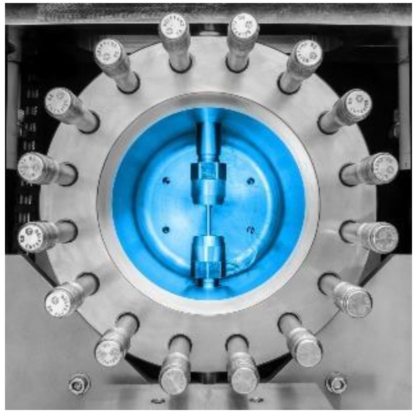
Special insulation design

Sealing design requires special attention to minimize losses

Cold box interface

Collaborating with HX / cold box manufacturer

Material selection



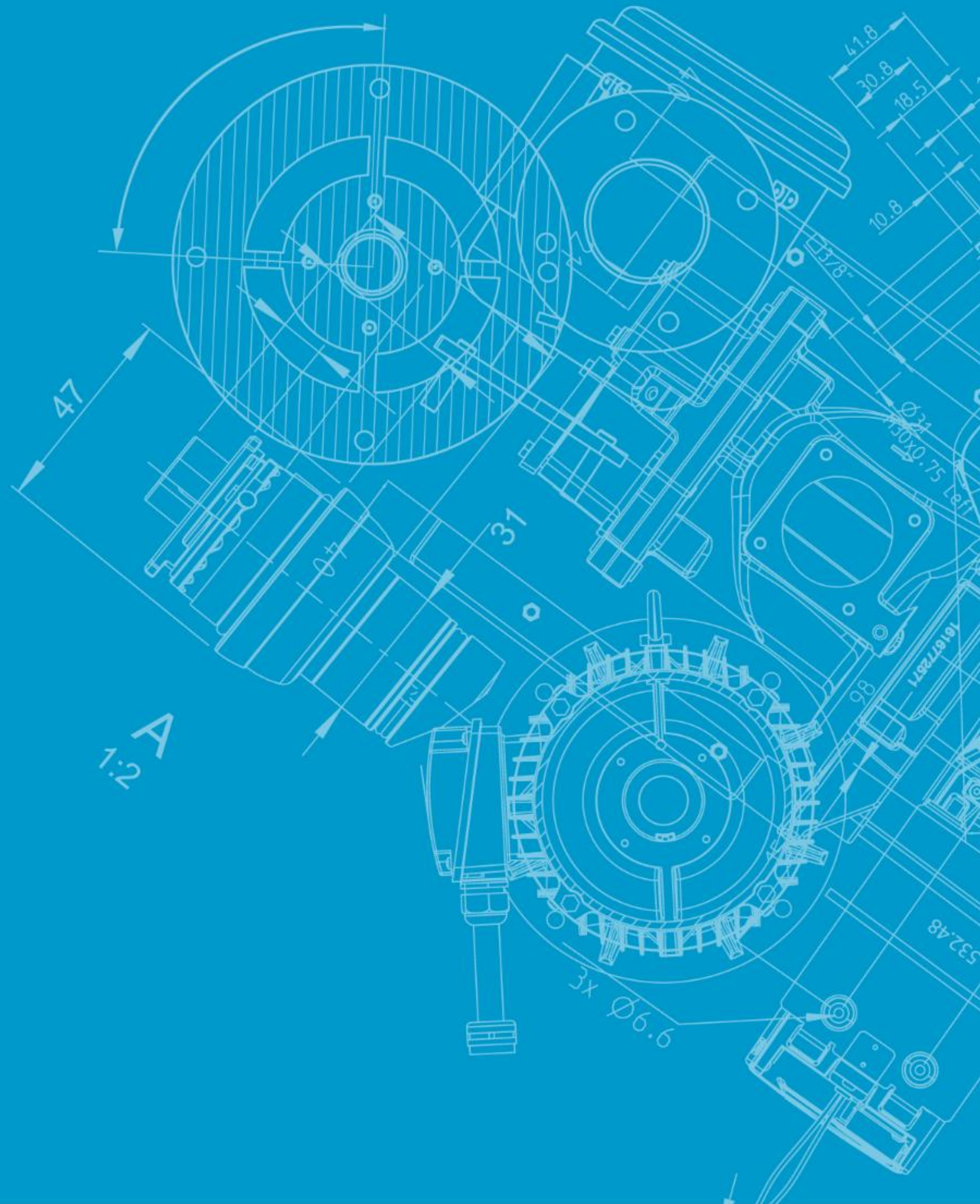
Must consider hydrogen embrittlement for all wetted parts

Cryogenic material testing

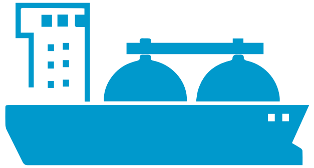
Nov 2021

Case Study

Our H_2 BOG Compressor for Carrier Hydrogen



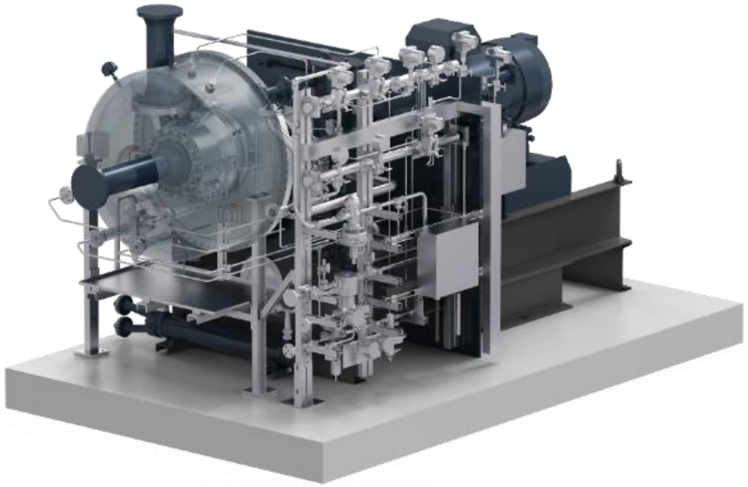
Hydrogen Transport by Ship



- LH_2 transport ship
- Applying technology and lessons learned from LNG industry
- In the future, commercial vessels are expected to be hydrogen-propelled
- *Photo courtesy of HySTRA*

Liquid Hydrogen

year	Code Word	Name of Buyer	Compressor type	Qty	Gas Handled	Mol weight	Volume Flow	Inlet Temp.	Inlet Press.	Outlet Temp.	Outlet Press.	Pinion Speed	Shaft power	Power	End-user Destination
						Kg/kmol	kg/h	°C	bar(a)	°C	bar(a)	rpm	KW	KW	
2020	N1740	KHI	GT021T1K0	1	H_2 (100%)	2,016	2271	-251	1,06	-242	2	33 211	76	90	KHI Japan



- - 253 °C BOG compressor GT021 for H_2 BOG (150 kW, delta P = 0.9 bar)
- Mol weight: 2 kg/kmol
- Features newly designed vacuum-insulated volute and special selected materials to handle gaseous H_2 at 20K
- Prototype vessel as „pilot ship“ to carry LH_2 from Australia to Japan

Summary and Outlook

01

Emerging Markets

- The energy transition is here and the markets for clean energy technology are growing

02

H_2 Liquefaction

- As demand for hydrogen increases, many hydrogen liquefaction plants will be needed to support the transportation of this key fuel

03

Carbon Capture

- As governments increase taxes on greenhouse gases (especially CO_2 and Methane), demand for carbon capture technologies will increase
- As demand for hydrogen increases, the need for carbon capture utilization and storage (CCUS) will also increase due to the desire for blue hydrogen