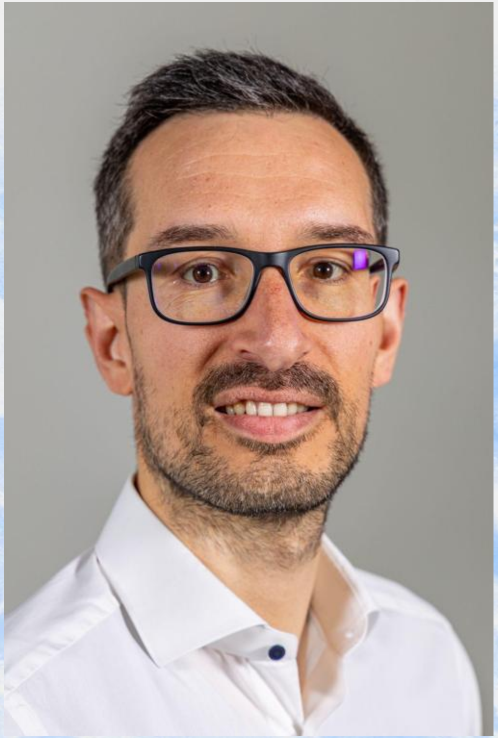
SMR technology overview

Università degli Studi di Padova

Innovation & Technology

03 March 2026 / Padova

About the speaker



Umberto Rossi
Head of Solution Development, Europe

Joined Air Liquide Engineering & Construction in 2020

Located in Frankfurt

14y of experience in syngas generation, purification and conversion

UniPd alumni, Chemical and Process Engineering

Safety moment

Air Liquide Group - Key Figures

2024 figures

~ 66,500
EMPLOYEES

PRESENT IN
60 COUNTRIES

MORE THAN
4 MILLION
CUSTOMERS & PATIENTS

REVENUE
€27.1bn

NET PROFIT RECURRING(1)
(GROUP SHARE)
€3.5bn

INVESTMENT
DECISIONS
€4.4bn

Air Liquide is a world leader in **gases**, **technologies** and **services** for Industry and Health.

(1) Excluding exceptional and significant transactions that have no impact on the operating income recurring,

Innovation & Technology

The Global Business Unit **Innovation & Technology (InnoTech) strengthens Air Liquide's position as a key tech player,** by leveraging the expertise in innovation, technology development and project delivery.

Maritime

Biogas Solutions

Air Liquide Advanced Materials

6,500+
employees(1)

(1) 2024 Figures.

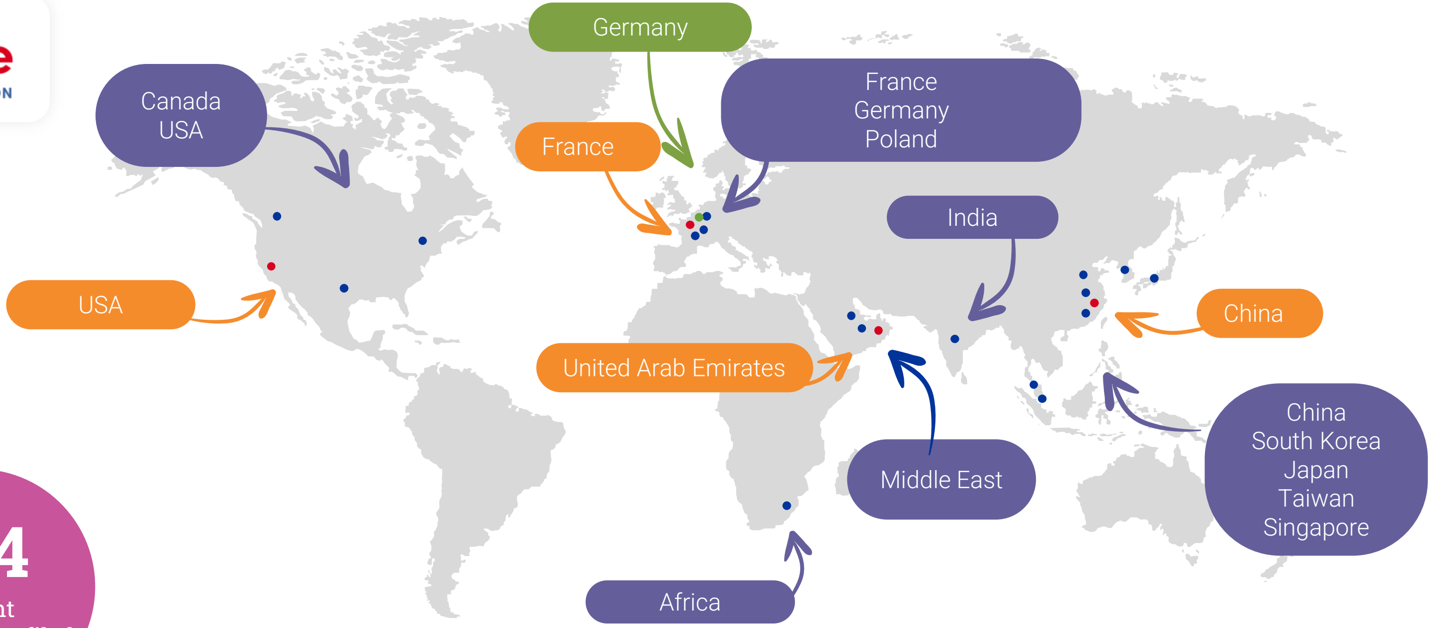
Air Liquide E&C, the Group’s technology and project execution arm

Air Liquide
ENGINEERING & CONSTRUCTION

13
Countries with Technology & Execution Centers & front-end offices

5
Manufacturing Centers incl. one JV Gigafactory

174
Patent applications filed in 2024



- Technology & Execution Centers and front-end offices
- Manufacturing centers
- Air Liquide & Siemens Energy Joint Venture Electrolyzer Gigafactory

Agenda

1. Why SMRs
2. What and how SMRs
3. Decarbonizing SMRs
4. Recent Air Liquide SMR projects

Introduction and definitions

- **Steam Methane Reforming (SMR):**

$$CH_4 + H_2O \leftrightarrow CO + 3\,H_2 - \text{heat}$$

- **Steam Methane Reformer (SMR):**

Why SMRs? A bit of history may help us…

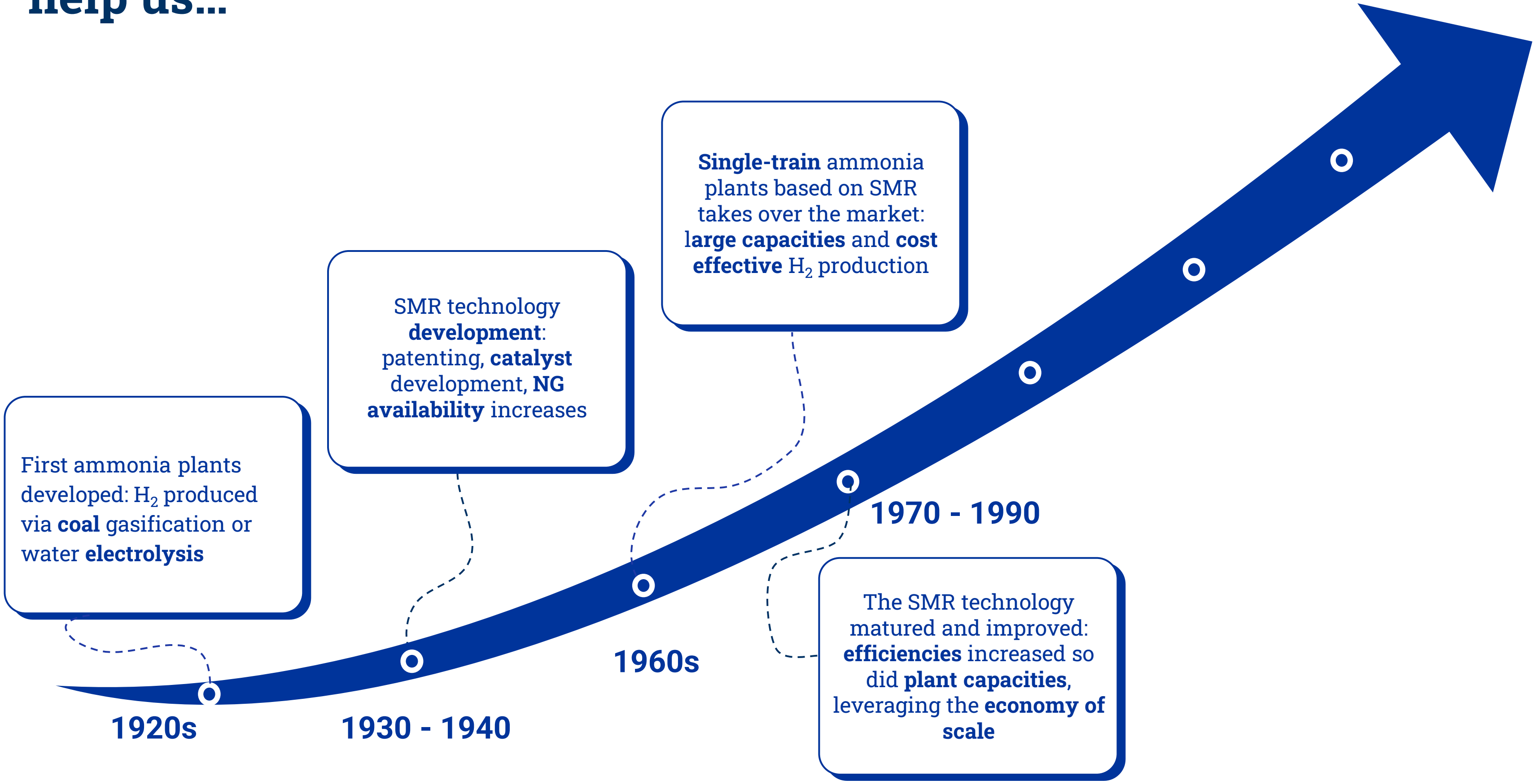
SMR technology **development**: patenting, **catalyst** development, **NG availability** increases

First ammonia plants developed: H_2 produced via **coal** gasification or water **electrolysis**

1920s

1930 - 1940

Why SMRs? A bit of history may help us…



Why SMRs? A bit of history may help us…

1920s
First ammonia plants developed: H_2 produced via **coal** gasification or water **electrolysis**

1930 - 1940
SMR technology **development**: patenting, **catalyst** development, **NG availability** increases

1960s
Single-train ammonia plants based on SMR takes over the market: **large capacities** and **cost effective** H_2 production

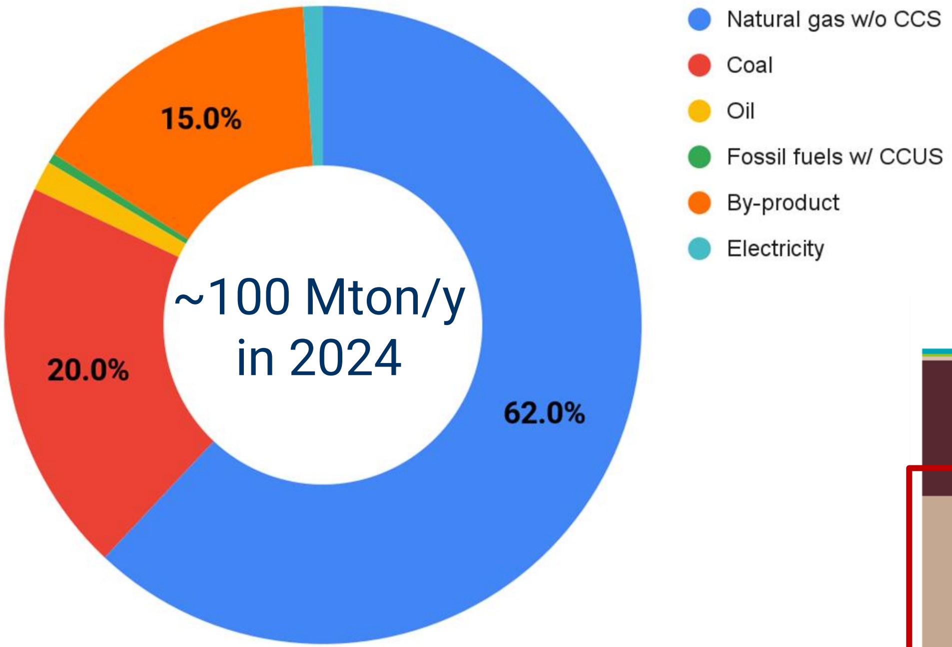
1970 - 1990
The SMR technology matured and improved: **efficiencies** increased so did **plant capacities**, leveraging the **economy of scale**

2000s
Renewable energy (solar and wind) starts becoming more **affordable** and widely **available**, and **carbon emissions** becomes a recognized environmental issue

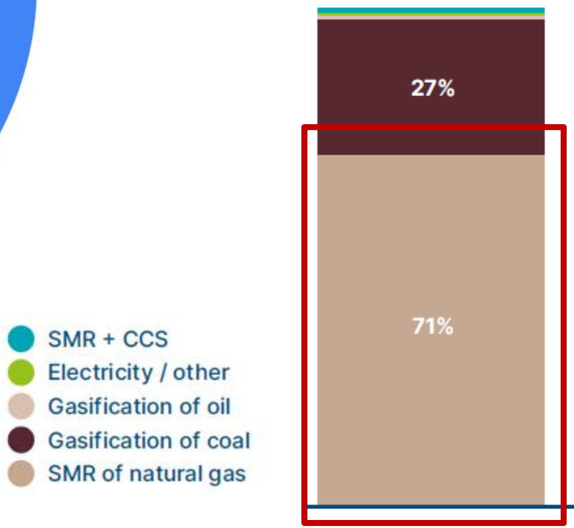
2010 - 2020
Electrolyzers reach **Gigawatt** scale + power **prices + CO_2 tax**: ELY and SMR start **competing**

2020+
The "era" of **energy transition**

How does H_2 production look today?



Adapted from [IEA Global Hydrogen Review 2025]



Source: IEA (2019), *The Future of Hydrogen*

1 Million ton / year of H_2

↓

~ 6 - 10 GW_e ELY plant

↓

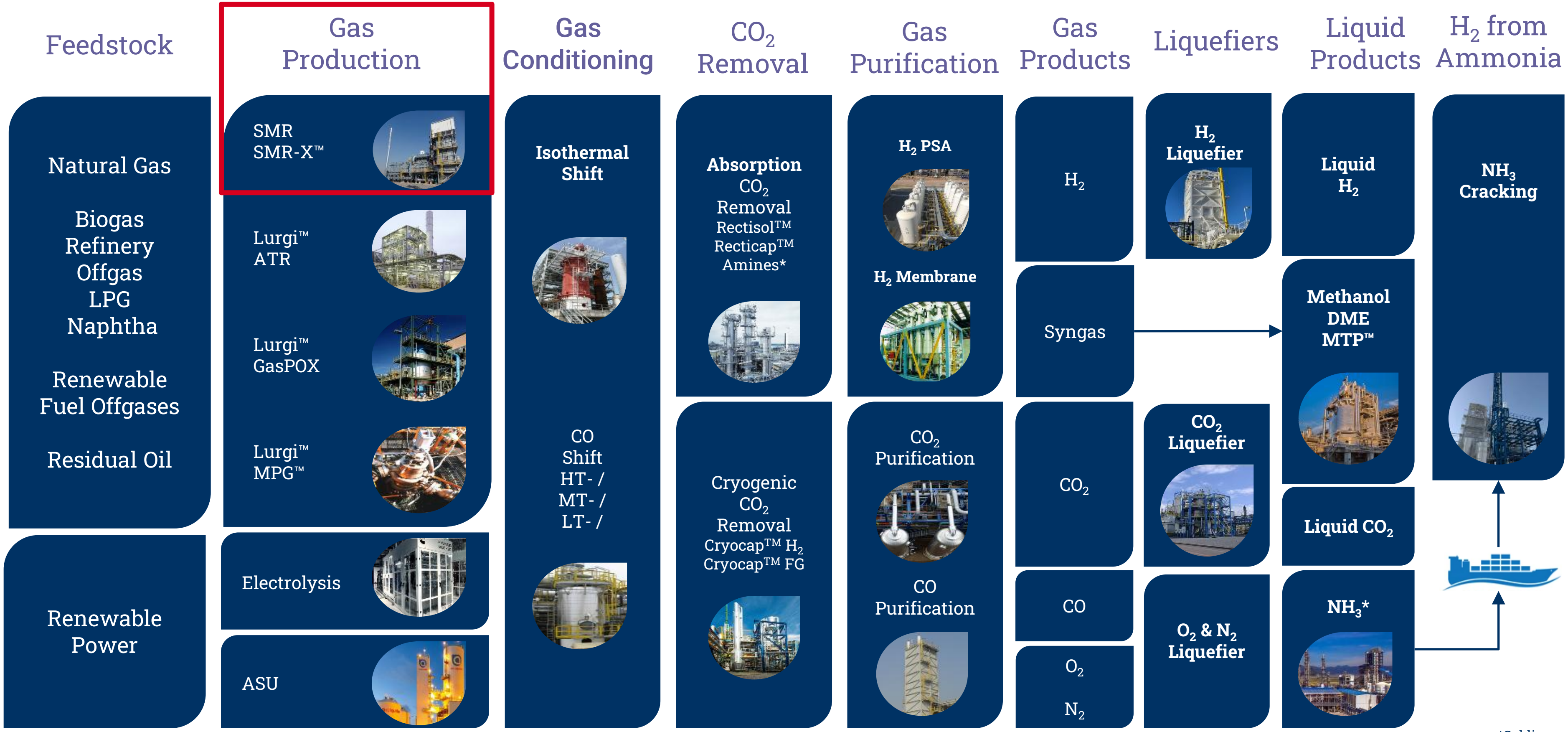
> 50 TW_eh/y

↕

Italy’s power consumption in 2025 ~ 310 TW_eh

The NormandH’y project: 200 MW ELY plant in Normandie, France

Air Liquide Technology Portfolio



*Sublicense

Steam Methane Reforming - The Lurgi™ Reformer

< 20 kNm³/h → < 50 kNm³/h → < 100 kNm³/h → > 100 kNm³/h → up to 250 kNm³/h

Standard & Modularized Plants → Standardized Plant Concepts → Tailormade Flexible Solutions

Air Liquide embraces the **complete plant life cycle**:

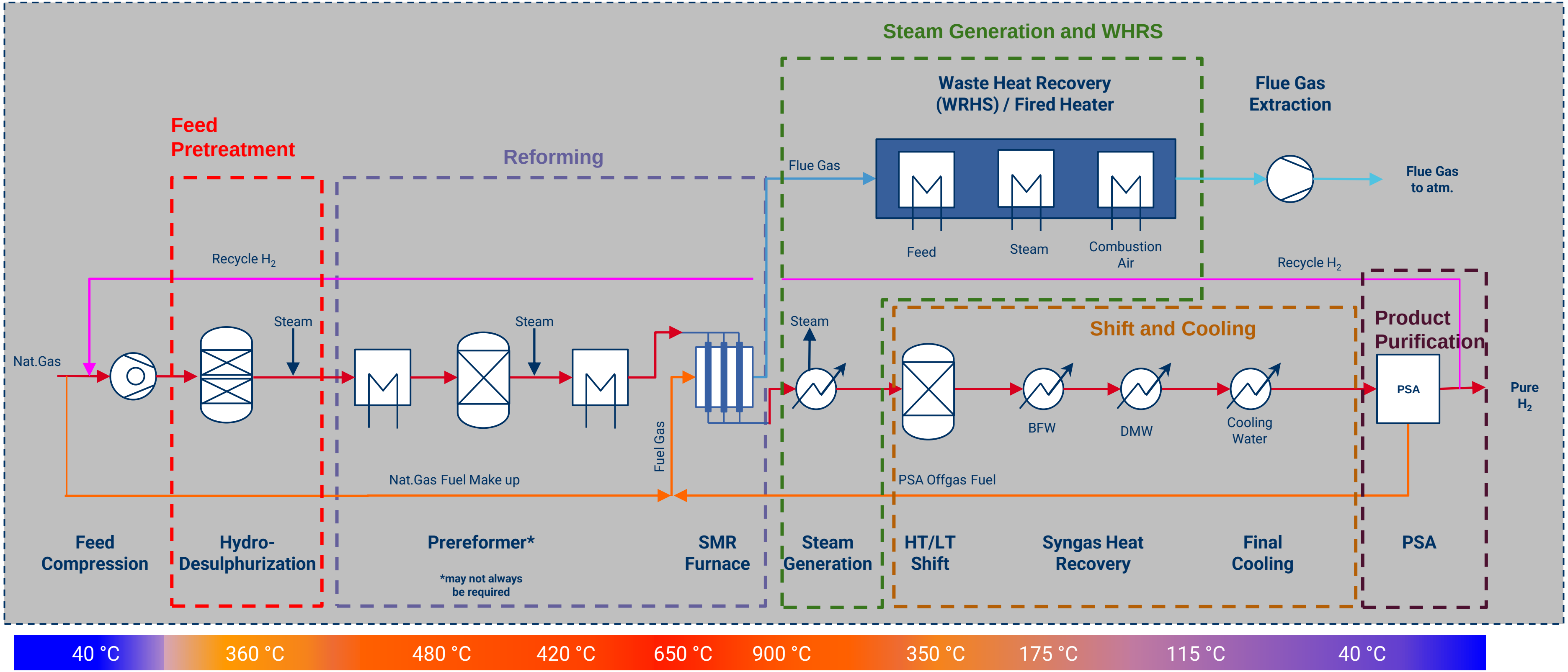
- E&C **designs** and **builds** plants worldwide, with close to **160 references** (incl. Lurgi plants)
  - thereof more than 50 H_2 plants
  - thereof 11 H_2 plants with single train capacity above 100,000 Nm^3/h H_2
- the various Air Liquide entities **operate** more than **75 SMR plants** to generate and sell H2, CO and Syngas

Systematic improvement

- Safety
- Reliability
- Operability
- Maintainability

by operational feedback

Steam Methane Reforming (SMR) H_2 plant



A 'tasty' analogy…

Water → **Steam**

Salt → **Know-how**

Yeast → **Catalyst**

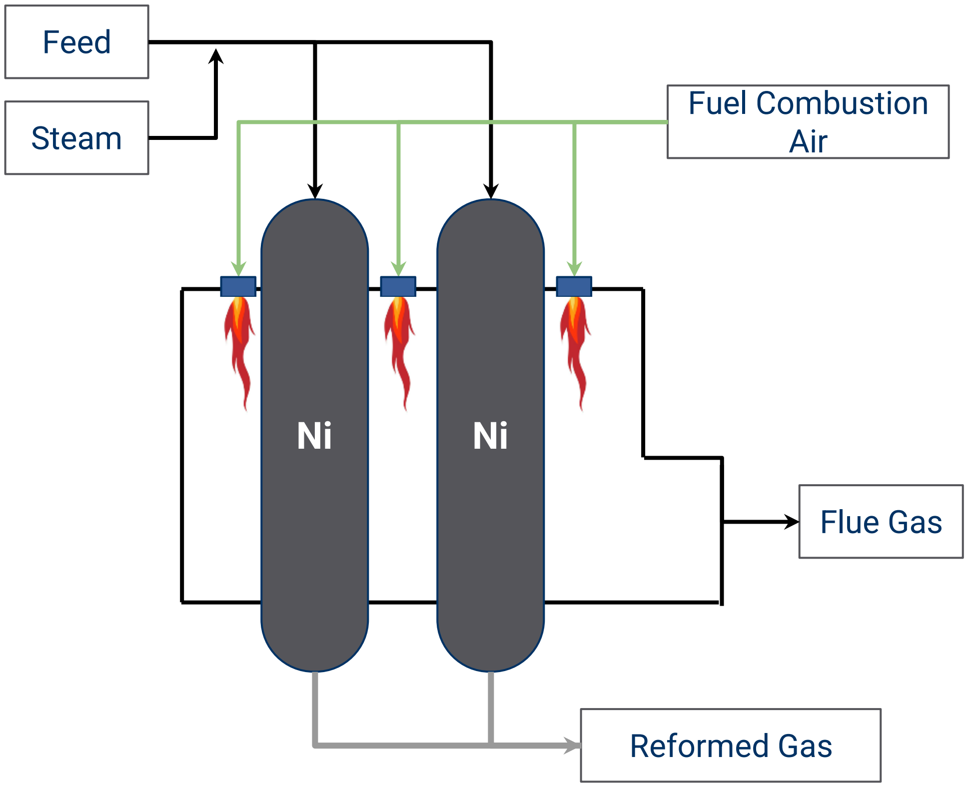
Flour → **Natural Gas**
(hydrocarbons)

Oven → **S**team **M**ethane **R**eformer

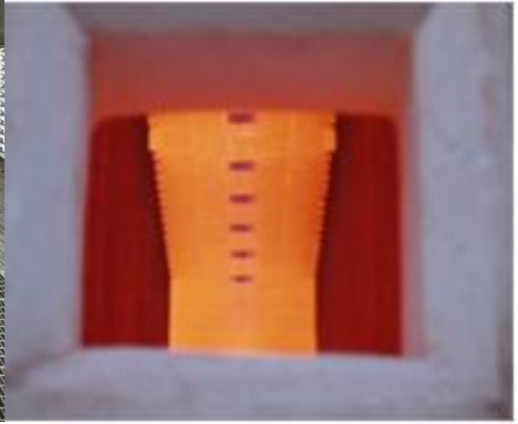
Pizza
↓
Syngas

Steam Methane Reformer (SMR)

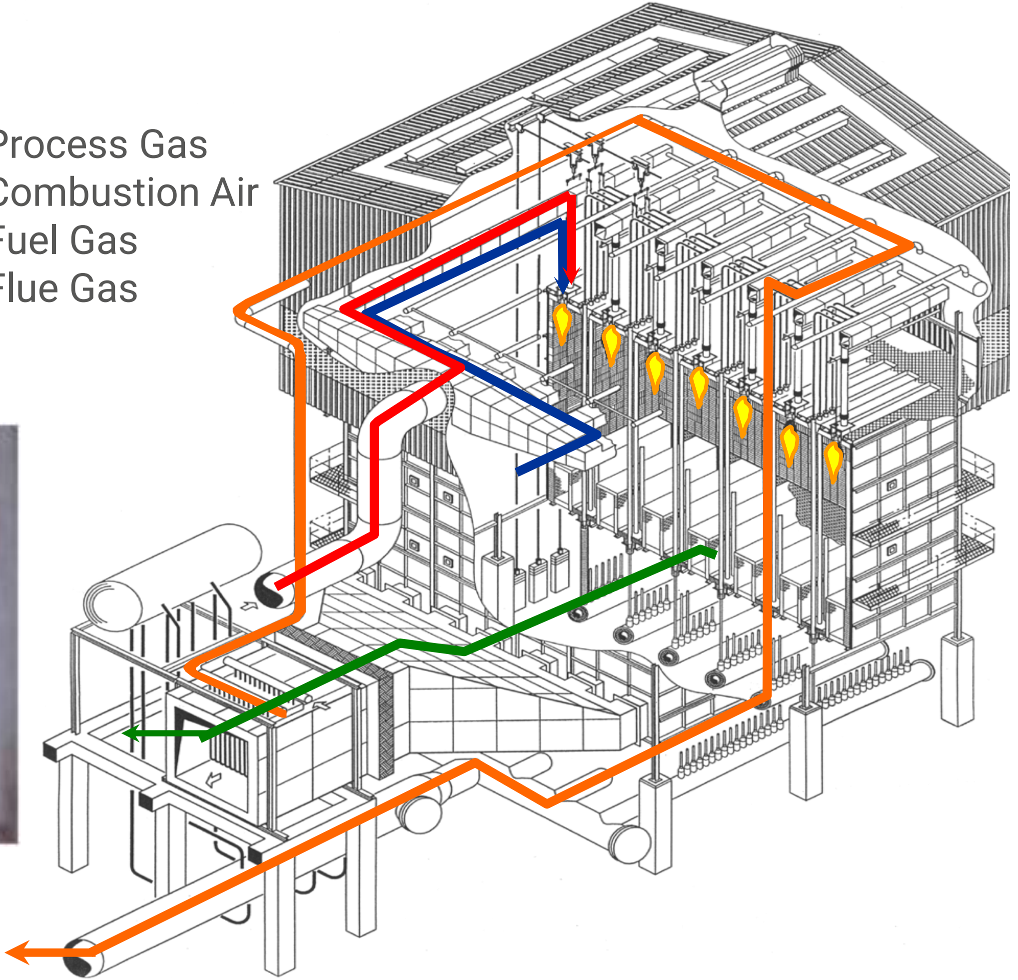
- Reactions:
  - $CH_4 + H_2O \leftrightarrow CO + 3\ H_2$ – heat
  - $CO + H_2O \leftrightarrow CO_2 + H_2$ + heat
  - Net: Endothermic (requires heat input)
- Conditions:
  - T = 750 – 940 °C [process]
  - T up to 1100 °C [flue gas]
  - p < 45 bar
  - H_2O / C = 1.8 – 3.2 mole/mole
- Set Up
  - Catalyst (Ni) in centrifugally cast tubes
  - Heat input by external firing
  - Tubes and burners arranged in rows
- Challenges
  - Carbon formation and deposition



Steam Methane Reformer (SMR)



- Process Gas
- Combustion Air
- Fuel Gas
- Flue Gas



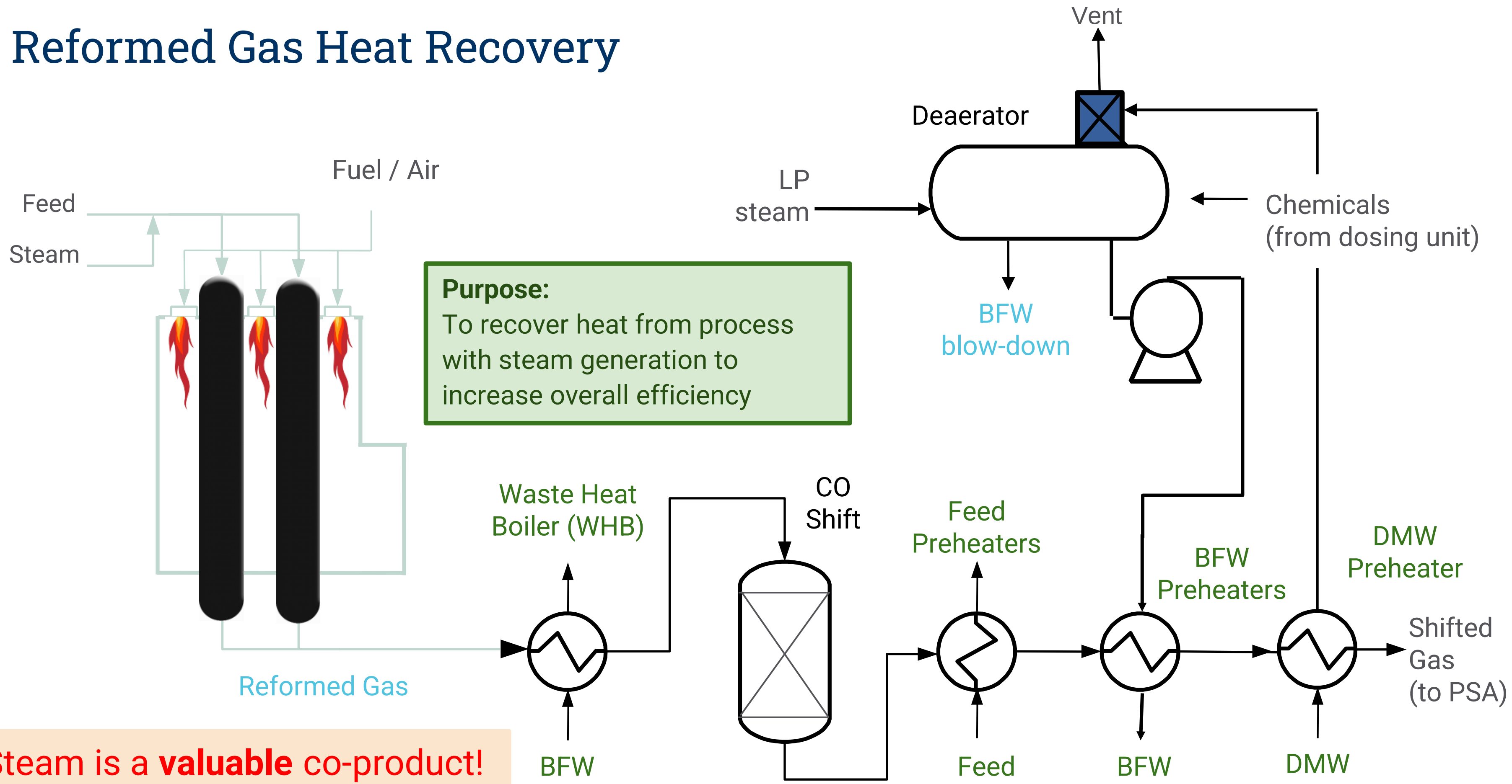
Steam Methane Reformer (SMR)

Cross Collector & connection to Waste Heat Boiler

Tube connection with outlet collector(s)

Internal Refractory Lining

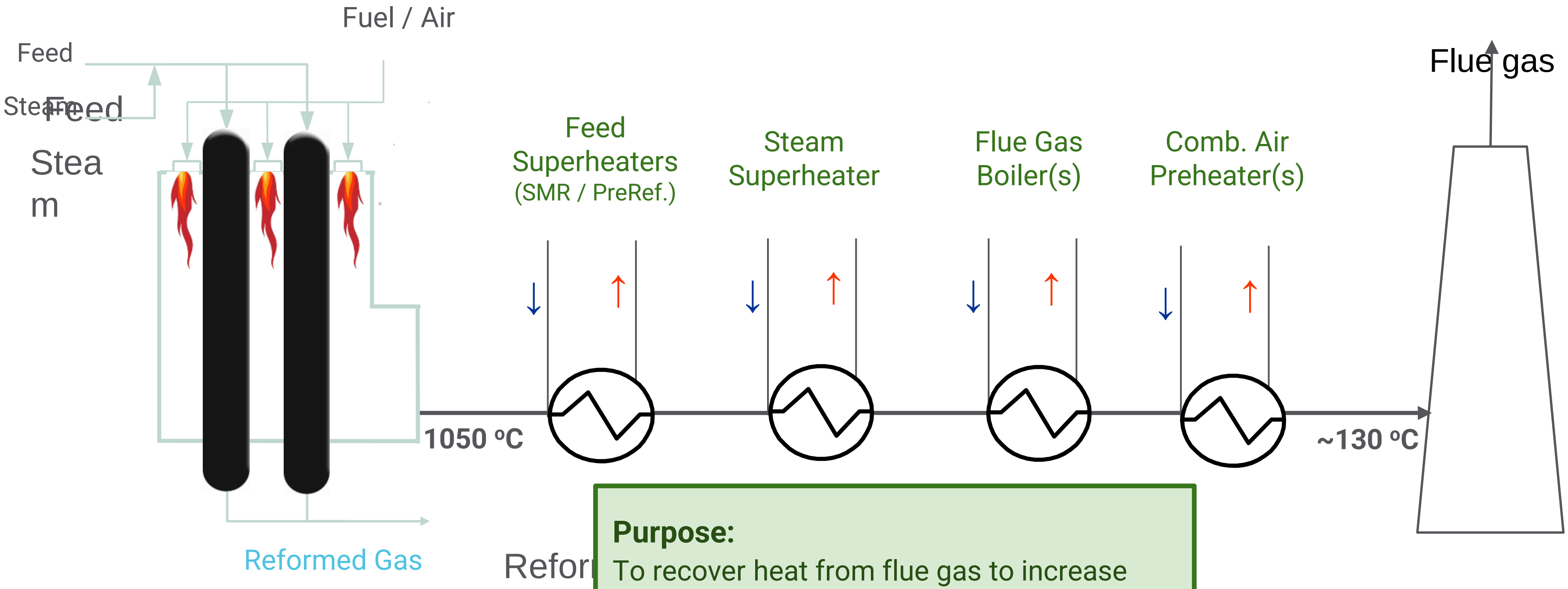
Reformed Gas Heat Recovery



Purpose:
To recover heat from process with steam generation to increase overall efficiency

Steam is a **valuable** co-product!

Flue Gas Waste Heat Recovery System (WHRS)



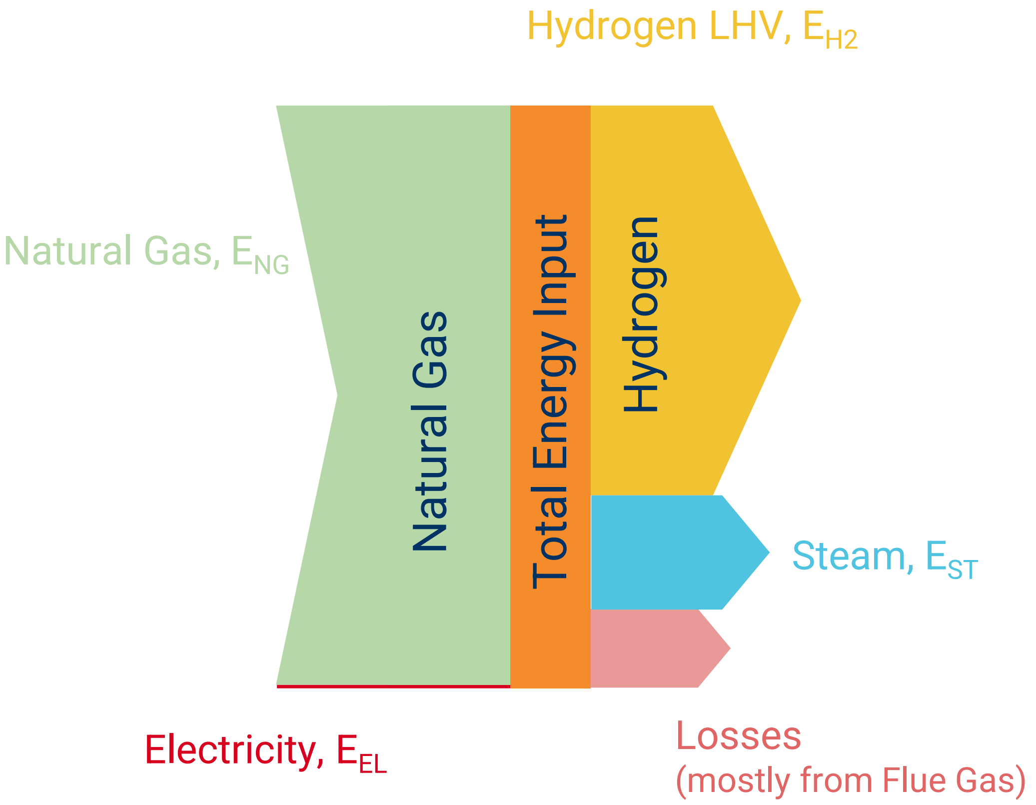
Purpose:
To recover heat from flue gas to increase overall efficiency → **minimize T to stack!**

Flue Gas Waste Heat Recovery System (WHRS)

Combustion Air preheater(s)

WHRS module assembly at site

SMR-based H_2 plant - Thermal Efficiency



Thermal efficiency (incl. steam):

$$\frac{E_{H2} + E_{ST}}{E_{NG} + E_{EL}} \sim 80\text{-}85\%$$

Thermal efficiency (w/o steam):

$$\frac{E_{H2}}{E_{NG} + E_{EL}} \sim 65\text{-}70\%$$

Steam Export impact vs. CO_2 Footprint

High Steam Value ← → Low Steam Value

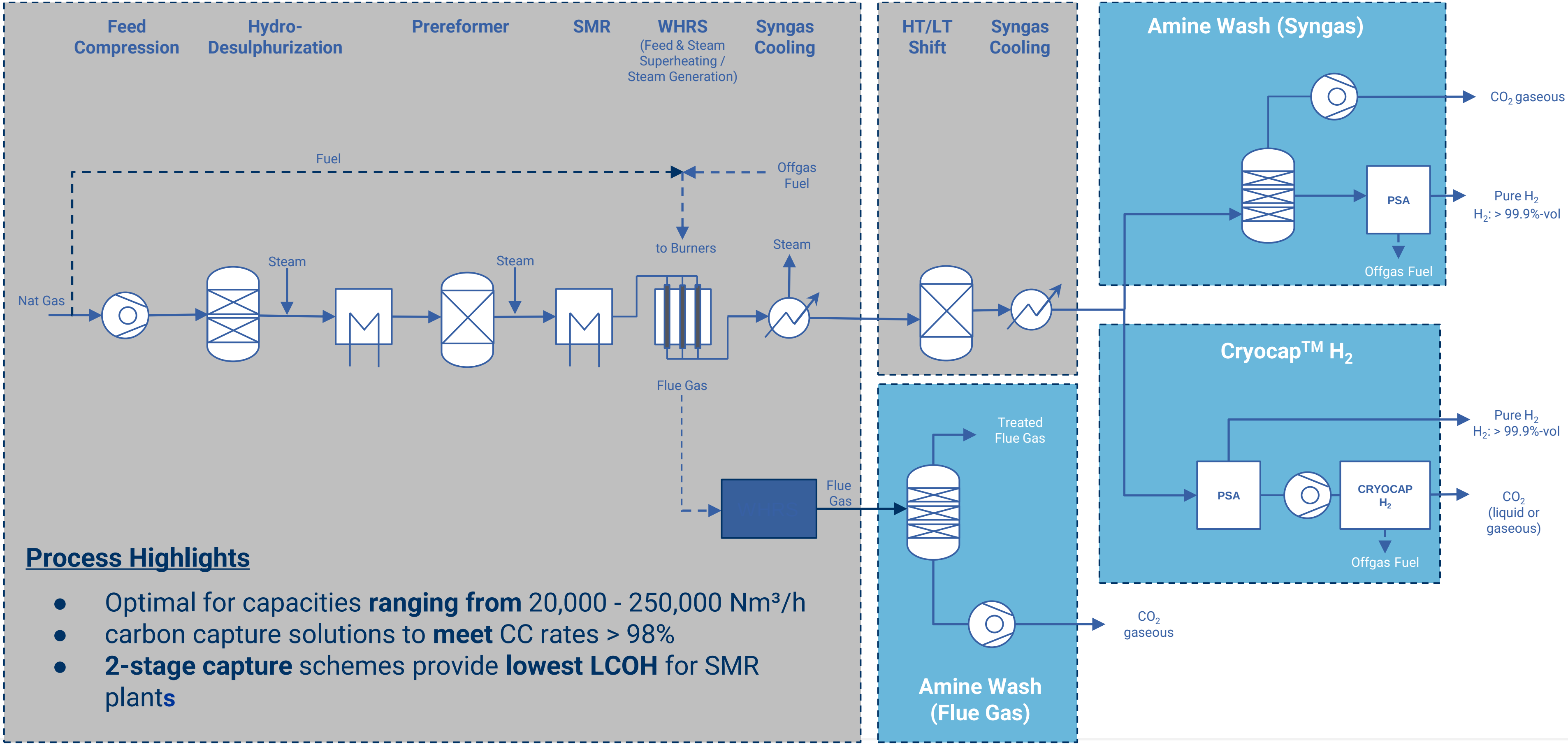
Process Parameter adjustment

	Supplementary Duct Firing	MT-Shift	Typical SMR 560°C, 870°C, S/C 2.9 350°C	Pre-Reformer	Gas Heated Reformer	**SMR-X**
Steam Ratio	**~17 kg / kg H_2**	**~ 14 kg / kg H_2**	**~ 9 kg / kg H_2**	**~6 kg / kg H_2**	**~3* kg / kg H_2**	**Zero Steam**
CO_2 Footprint		**~ 10.5 kg CO_2 / kg H_2**	**~ 10.0 kg CO_2 / kg H_2**	**~ 9.5 kg CO_2 / kg H_2**	**~ 9.0* kg CO_2 / kg H_2**	**~ 8.5 kg CO_2 / kg H_2**

Reduced Steam co-production / CO_2 Footprint →

*** Integrated based on public information**

Decarbonizing SMR-based H_2 Plants



Process Highlights

- Optimal for capacities **ranging from** 20,000 - 250,000 Nm³/h
- carbon capture solutions to **meet** CC rates > 98%
- **2-stage capture** schemes provide **lowest LCOH** for SMR plants

A Complete Portfolio for Carbon Capture and CO_2 Liquefaction

CRYOCAP™

H_2 Production

Cryocap™ H_2

Oxycombustion

Cryocap™ Oxy

Steel

Cryocap™ Steel

>15% Fluegas

Cryocap™ FG

Natural Gas

Cryocap™ NG

CO_2 Liquefaction

Cryocap™ XLL

ABSORPTION

Syngas

Amine Wash (SG)

Flue Gas

Amine Wash (FG)

Large H_2 Production

Recticap™

Gasification

Rectisol™

Suitable for higher concentrated CO2 sources
Electricity powered
CO_2 produced gaseous or liquid

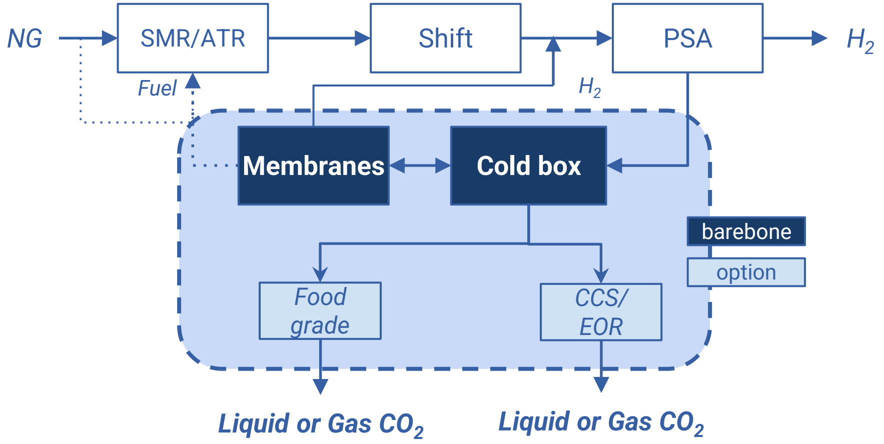
Heat driven CO_2 removal

High efficiency adapted to large scale LC H_2

Air Liquide Cryocap™ H_2 Technology

Syngas CO_2 Capture

- Patented Air Liquide technology
- allows up to **99% CO_2 recovery** from the PSA Tail gas
- Revamp approach
  - **H_2 production increase ~10%**
- Greenfield approach
  - **Feed consumption is reduced by ~4%**
  - **Potential Capex savings for SMR/ATR unit**
- **No toxic solvents** or emissions
- Optional **integrated CO_2 liquefaction**



High CO_2 recovery combined with H_2 production boost

1st industrial-scale plant @ Port Jérôme, France → plant built, owned & operated by Air Liquide since **2015**: 7 years of industrial operation

The challenge of decarbonizing

DISCLAIMER: all the data and information used in the case study are public. They shall not considered in any case as official or approved Air Liquide figures.

Let's compare fossil H, with its low carbon equivalent.

How much does "grey" H_2 cost today? To calculate the H_2 cost, we need:

- the Operating Expenditure (OpEx), i.e. feedstock (NG), utilities (power, cooling water)
- the Capital Expenditure (CapEx), i.e. how much the plant cost (incl. building it)
- an economic model, e.g. how do depreciate the CapEx over time

NG consumption	45 kWh/kg H2	40 €/MWh HHV	~1.6 €/kg H2
Power consumption	0.5 kWh/kg H2	100 €/MWh	~0.1 €/kg H2
Steam co-production	6 kg/kg H2	Fuel Value	~0.2 €/kg H2
CO_2 emissions	9 kg/kg H2	65 €/ton	~0.6 €/kg H2
OpEx H_2 price w/o CO2 tax	-	-	**~1.5 €/kg H2**
OpEx H_2 price w CO2 tax	-	-	**~2.1 €/kg H2**

The challenge of decarbonizing

DISCLAIMER: all the data and information used in the case study are public. They shall not considered in any case as official or approved Air Liquide figures.

For the CapEx, we need to define a **plant size**: **100 kNm³/h** is a typical large plant capacity.

Estimating the **CapEx** is very project and site specific: acc. to Gemini, a reasonable ballpark for such capacity in Europe is between 250 and 300 m€ → let's take **275 m€**

For our economic model, let's make some assumptions:

- we need to **depreciate** the investment: 10 years
- we want to make money out of it (e.g. for our shareholders): **ROI** = 6%/y
- we have **maintenance** and other fixed cost: 2%/y
- out **capital charge** sums up to: (1/10+0.06+0.02) = **18%/y**

Let's calculate out CapEx component for the grey H2 price:

- 100 kNm3/h = 215.8 ton/d
- 275000*0.18/(215.8*350) ~ **0.7€/kg H_2**

The total grey H_2 price results: ~2.2 €/kg (w/o C tax) / 2.8 €/kg (w/ C tax)

The challenge of decarbonizing

DISCLAIMER: all the data and information used in the case study are public. They shall not considered in any case as official or approved Air Liquide figures.

Syngas Capture:

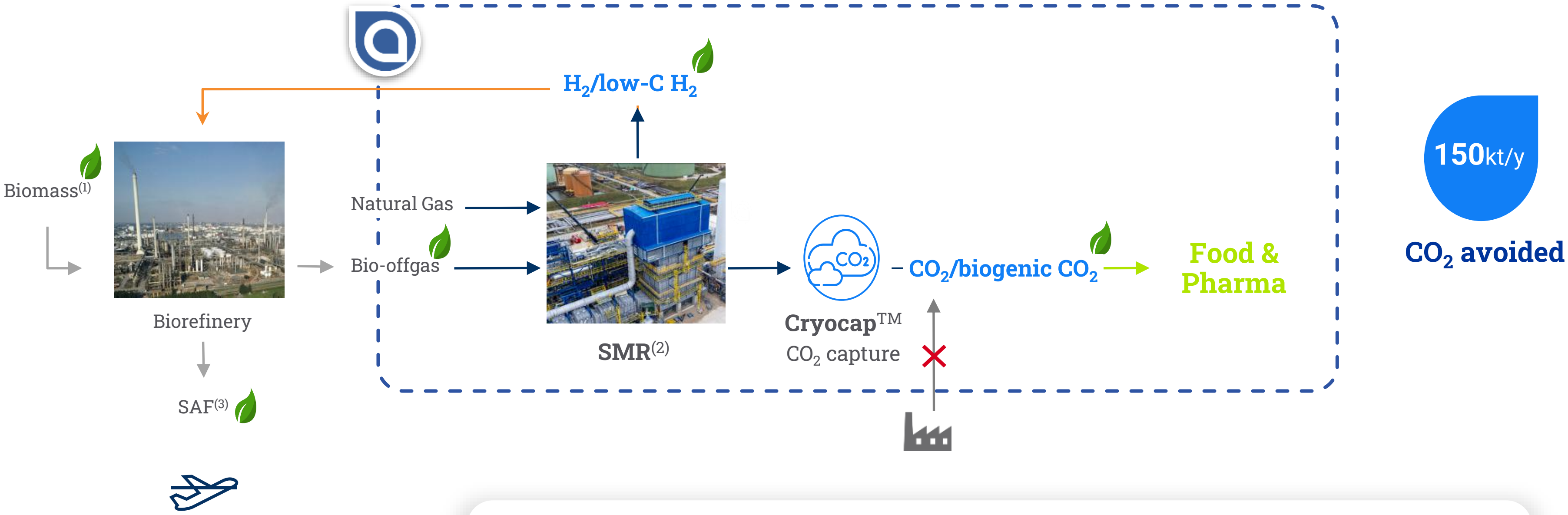
- Capture Rate: ~55% to 60% of total plant emissions
- Technology: Amine Wash (aMDEA)
- Additional LP Steam: Requires ~1.0 -1.5 GJ of thermal energy per tonne of CO_2 captured
- Power: ~0.1 kWh/kg H_2 for CO_2 compression for transport
- Additional CapEx: ~30% over the base plant

Flue Gas Capture:

- Capture Rate: ~90% to 95% of total plant emissions
- Technology: Amine Wash (MEA)
- Additional LP Steam: Requires ~3.0 - 4.0 GJ of thermal energy per tonne of CO_2 captured
- Power: ~0.2 - 0.3 kWh/kg H_2 for CO_2 compression for transport
- Additional CapEx: ~50 - 80% over the base plant → let's take 65%

		Syngas	Flue Gas
OpEx adder	€/kg	0.06	0.29
CapEx adder	€/kg	0.20	0.43
H_2 gas price adder	€/kg	0.26	0.71
Yearly adder	m€/y	19	54

Synergies to create value: the Grandpuits project



- Leveraging **synergies** between technologies and businesses
- Addressing **promising markets**: SAF[3] and biogenic CO_2
- Combining **innovative technologies**: SMR and Cryocap™
- Optimizing **Circular Economy**

(1) Biomass from waste: used cooking oil / animal fat
(2) SMR: Steam Methane Reformer
(3) SAF: Sustainable Aviation Fuel

From conceptual development to reality…

NH3 cracking: the SMR knowledge in action

Students and Young Graduates at Air Liquide

We connect with students and young graduates through global partnerships with universities, internships and apprenticeships, and 3 main programs:

- ***Summer School*** - every year, we provide an exclusive opportunity for 30 top students from around the world to connect at the Air Liquide head office in Paris in a week-long immersive experience
- ***Collège des Ingénieurs*** - an integrated "action-learning" MBA program combines management classes with consulting assignments in a company over 10 months
- ***International Volunteer Program (V.I.E)*** - opportunity for young graduates from the European Economic Area to go beyond borders and experience a full-time responsibility working for Air Liquide while discovering new cultures and languages through a mission varying from 12 - 24 months

Find out more on:

- https://www.airliquide.com/join-us/students
- https://www.airliquide.com/join-us/graduates

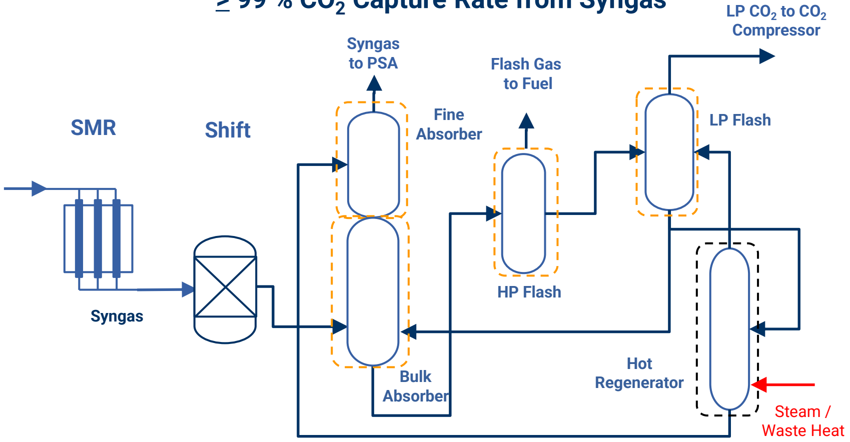
Q&A

Thank you

CO_2 Capture - Amine Wash Unit

Amine Wash Syngas

≥ 99 % CO_2 Capture Rate from Syngas

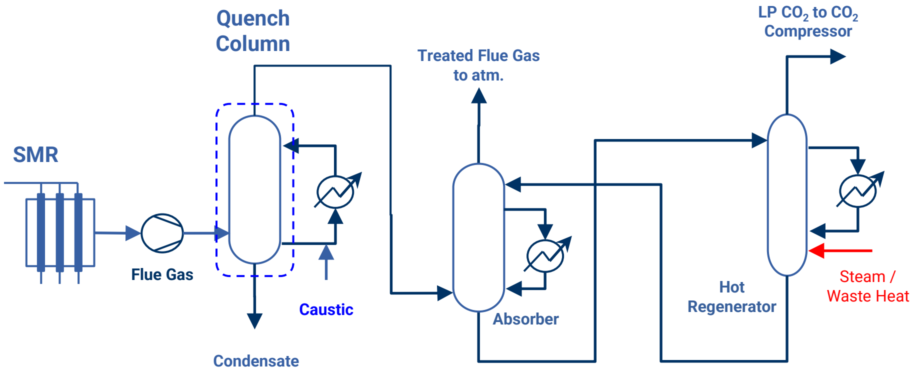


Features

- Very high CO_2 removal rates
- CO_2 absorption at high pressure and high CO_2 concentration
- Various schemes to improve energy efficiency
- Efficient use of low-grade waste heat from syngas possible
- Low-pressure & water saturated CO_2 Product

Amine Wash Flue Gas

≥ 98 % CO_2 Capture Rate from Flue Gas

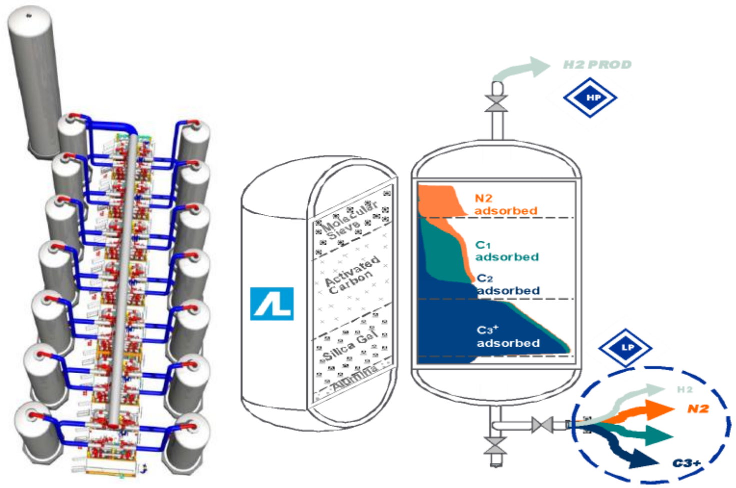


Features

- CO_2 Removal rates up to 98% from Flue Gas
- Cooling of Flue Gas by Water Quench
- SO_x removal by Quench Water
- CO_2 absorption at low pressure and low to medium CO_2 concentration
- Efficient use of low-grade waste heat from syngas possible
- Low-pressure & water saturated CO_2 Product

Pressure Swing Adsorption (PSA)

- **Overview**
  - Purifies syngas to **meet target H_2 spec**
  - Via selective adsorption of components with larger molecules (non cryogenic separation)
- **Application**
  - Producing **pure H_2** from syngas
  - Producing pure H_2 from off-gases



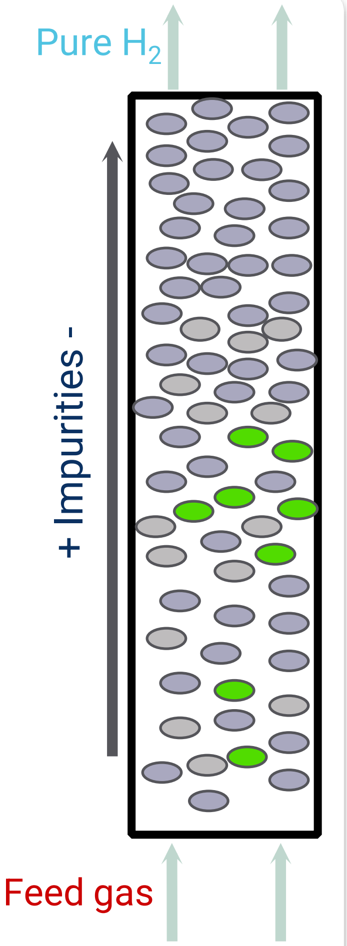
Molecular Sieve: N_2, CO

Activated Carbon:
Ar, CO_2, O_2, CH_4

Pre-filter Carbon: C_nH_m, H_2S, BTX

Or

Alumina: H_2O, MeOH, NH_3



Capturing and Storing CO_2: the Porthos project

SMR-X™ - SMR Technology for zero steam export

56,000 Nm³/h H_2 production
Operating since 2020

High Efficiency Heat Exchange Reforming

- Combined SMR & HER within reformer tubes
- **20%** reforming duty from internal HER

Summary of Benefits

- Maximum H_2 yield - **> 5%** 1)
- Minimized CO_2 emissions - **> 5%** 1)
- **20% less** fuel firing 1)
- **Zero steam** export
- Lower H_2 cost vs. conventional steam designs
- Compact, bottom fired furnace -> Low CapEx
- Smaller flue gas WHRS -> Low CapEx

1) Compared to a conventional SMR plant with zero steam export

Less CO2 capture required → most efficient low carbon H2 reforming technology (@zero steam)

The NormandH'y project: 200 MW ELY plant in Normandie, France

Appendices

InnoTech activities cover slide examples

The main challenges in material science can be listed as [1]:

- Creep: similarly to Steam Methane Reformers application [2] [3] [6], the lifetime of tubular catalyst reactors is primarily limited by creep damage, driven by a combination of high service temperatures and hoop stresses that can evolve into catastrophic failure. Creep life exhaustion is evidenced by progressive diameter deformation and changes in the alloy microstructure.

Creep damage is the permanent, time-dependent deformation and structural degradation of materials (commonly metals) subjected to high stress and elevated temperatures (typically > 40% of melting point). It progresses through cavity

- Hydrogen service [7]: Many metallic materials can suffer embrittlement in hydrogen gas environments. These include steels (especially high strength steels), stainless steel, and nickel alloys. There are several variables which can affect the severity of the embrittlement mechanisms encountered, such as purity, temperature, and pressure. It is generally recognized that the tendency for embrittlement in hydrogen atmospheres increases with increasing pressure.

Hydrogen embrittlement is the reduction of a metal's ductility and load-bearing capacity due to the absorption of atomic hydrogen, leading to sudden, brittle cracking and failure, particularly in high-strength steels and titanium. It occurs when hydrogen atoms, introduced during processing or service, diffuse into the metal and concentrate at stress points. www.twi-global.com +4