Cryogenics for power and energy: a winning ticket?

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Cryogenics is becoming an enabler for the energy transition

Generating electrical power : LTS & HTS > 15 Tesla

- **Fusion** (most magnetic confinement)
- **Offshore wind power** (10-20 MWe turbines)

Transporting electrical power : HTS @ 65 K 0 T, 2000 - 10 000 Amp

- Typically : **1 GW over 100 km ~ 1000 kW@65 K**
- Existing technologies : **Insulated piping** ; **REBCO** (thanks to fusion market pull), **large refrigerators**

Producing, storing, distributing energy with cryogenic liquid carriers

- **LNG BOG** recondensation aboard ship carriers
- **LH2 liquefier** 10 tpd ⇒100 tpd tomorrow
- **LH2 storage** rockets (30 t), trucks (0,1 - 5 t), aircraft (1 t), ship (10 - 10 000 t)

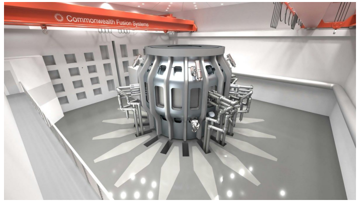
A broad market outlook for cryogenics in the energy transition

Nuclear fusion market looks promising for cryogenics

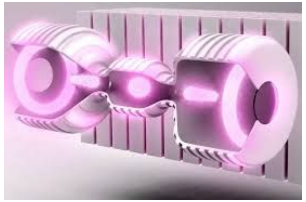
(as said by C Senatore in *Advancing Superconductor Technology for High Field Applications*, ICEC-ICMC-2024)

45 private companies on fusion* (25 in US)

- $7,1 bn funding (94% private)
- Many use HTS for magnetic confinement
- Might generate electricity in the 2030s



SPARC @ 8 K (in US)
Commonwealth Fusion Systems (US)



Inductive fusion
Helion (US)

* Source : Fusion Industry Association - FIA 2024

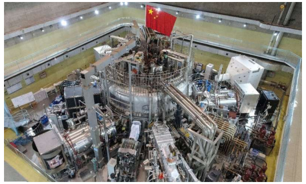
Many institutional projects

- Large TOKAMAK-type
- LTS required (so far)

ITER
(34 countries, in France)

JT60-SA
(Japan)

CFETR
(China)



EAST then BEST
(China)

Offshore wind power market is also promising for superconductivity
Figures from 2023 to 2040

More than 500 GW new offshore wind capabilities

30,000 to 50,000 wind turbines to be installed (10-20 MW each)

Hundreds of long range transmission lines

Superconductivity may address some of the challenges:

- shortage of rare earths (for PMs in generators)
- cost and feasibility of HVDC long range power transmission (offshore and onshore)

H2-powered vehicle market : cryogenics as an enabler

A good regulatory framework is in place

Many OEMs have clear development roadmaps

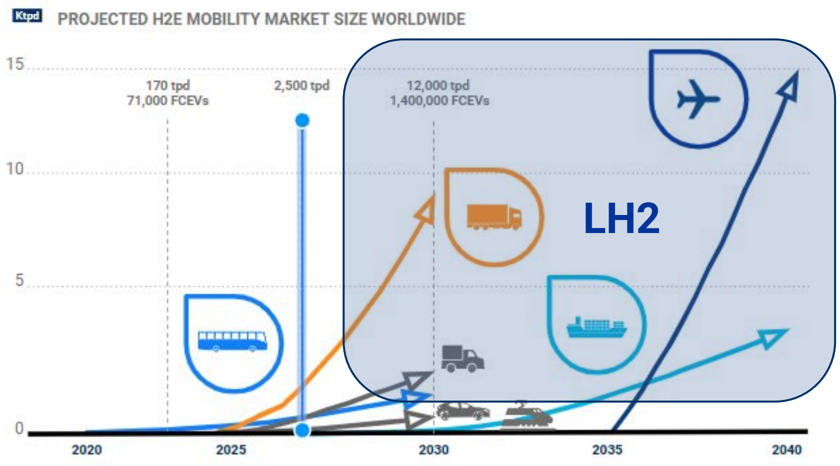
- Producing 1000 H2-trucks/year per OEM is feasible

Liquid H2 more efficient than gaseous H2 for long range trucks > 1000 km, 80 kg of H2

About 2 X 40 kg LH2 tanks needed per truck

- Subcooled state (sLH2 *) = good management of boil-off
  Allows fast refueling

Challenges: Mass production LH2 tanks, deployment of liquid HRS and liquefiers



2030 : 12 000 tpd demand

Current ww LH2 capabilities ~ **450 tpd**, 43 plants

Announced liquefier projects : > **4 000 tpd** (60% in APAC)

* sub-cooled liquid H2; see: *Cryogenic H2 for HDV : Applying Fundamental Thermodynamics to Solve CleanTransportation Challenges*, Petitpas and al. ICEC2024

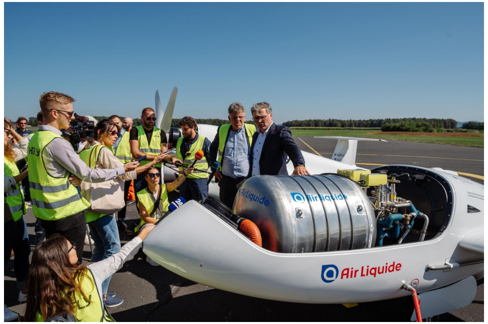
tpd : ton per day

The mobility will require a lot of cryogenics for liquid H2

Liquefaction : - Air Liquide is operating its 30 tpd liquefier in Las Vegas

- 3 X 30 tpd just built for SK Group in Korea

30 tpd = 10 MWe (incl. precool.), 250 kW@20K



On board storage for aircraft (HEAVEN flight in 09/2023)

(see : *Cryogenic Tests of an Airborne Liquid Hydrogen Tank for a Manned Aircraft In the HEAVEN Project, Denis Favier, Loïc Jeunesse, ICEC-ICMC, 2024*)

and trucks (FORVIA - Air Liquide partnership)

Liquide H2 refueling stations (HRS):

- HRS to be supplied with LH2 even for GH2-powered FCVs
- Will also deliver LH2 or sLH2 to heavy duty vehicles (1st LH2 station by Air Liquide for DAIMLER)

(*) FCV : Fuel Cell Vehicle;

Cryogenic liquefiers and refrigerators for the energy transition

Liquefaction of Hydrogen

Pre-cooling down to 80 K with either :

- LN2, Mixed Refrigerant Cycles (MRC) or turbo-Brayton

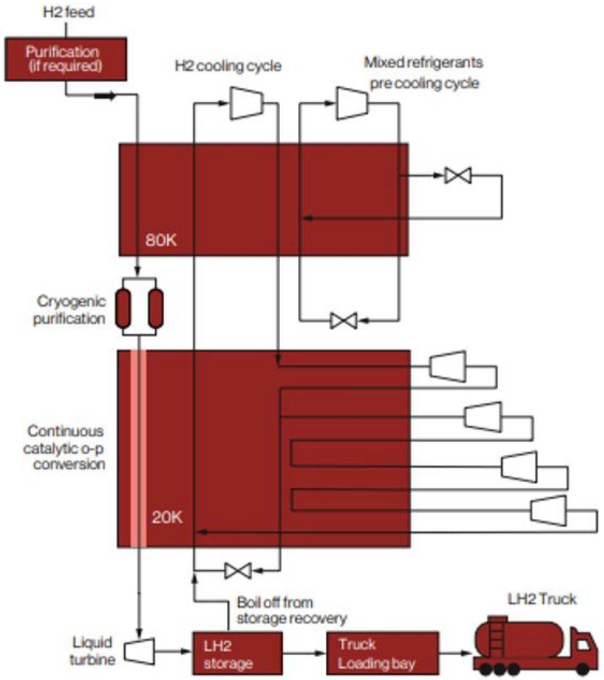
Piston-type compressors (~8-10 MW for 30 tpd)

A cascade of 4 cryogenic turbo-expanders in the 20 K cold box

Boil-off from storage & logistics can be recovered at the liquefier site

Specific energy : **7-8 kWh/kg** of liquid for large liquefiers (> 30 tpd, pre-cooling included)

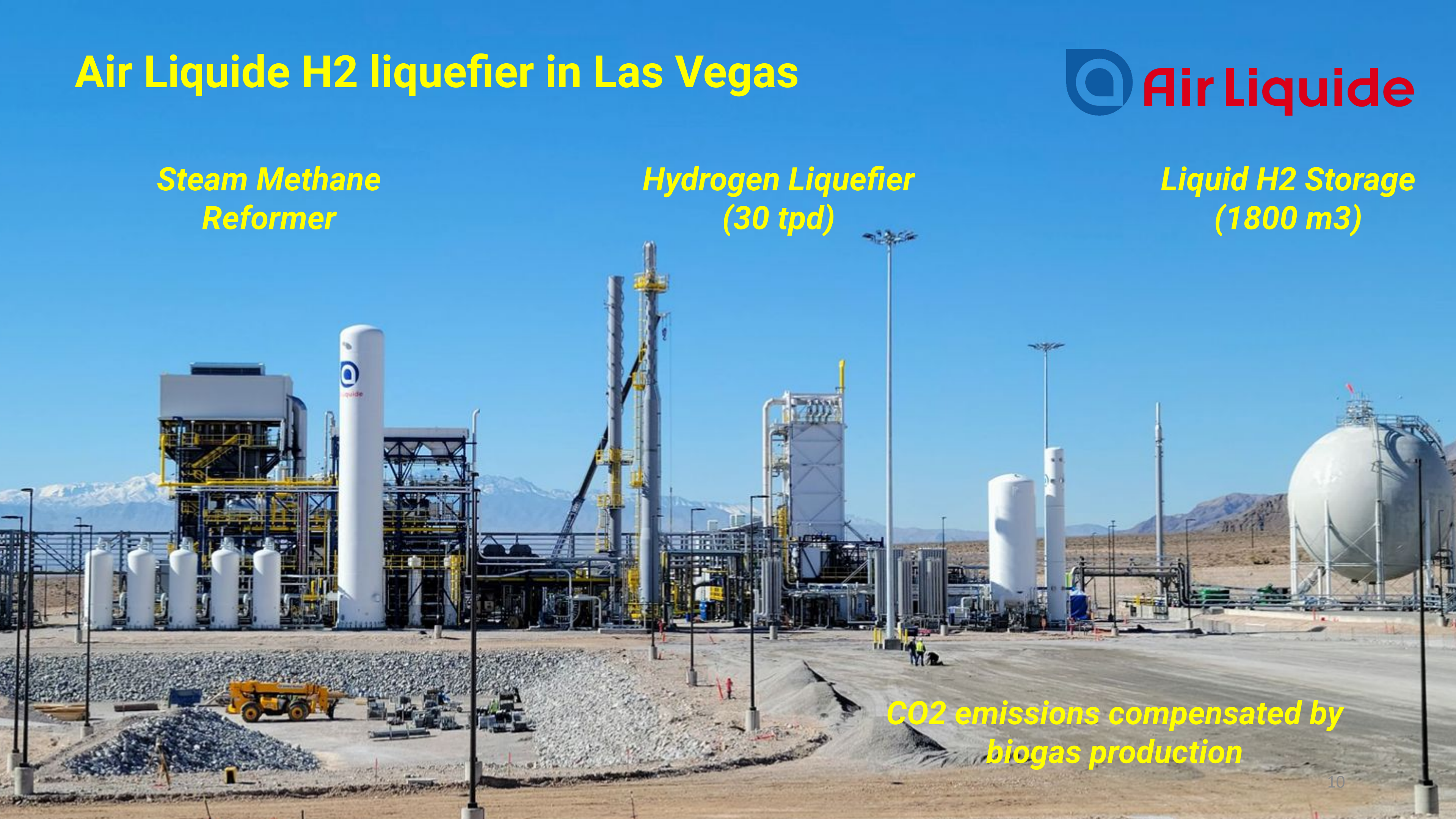
H2 cycle liquefier



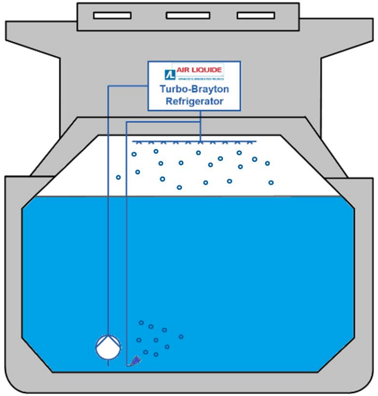
Air Liquide

Air Liquide H2 liquefier in Las Vegas

Air Liquide



Reliquefaction of LNG aboard with the turbo-Brayton



Principle

Bunker vessels

Newbuilt / Retrofit

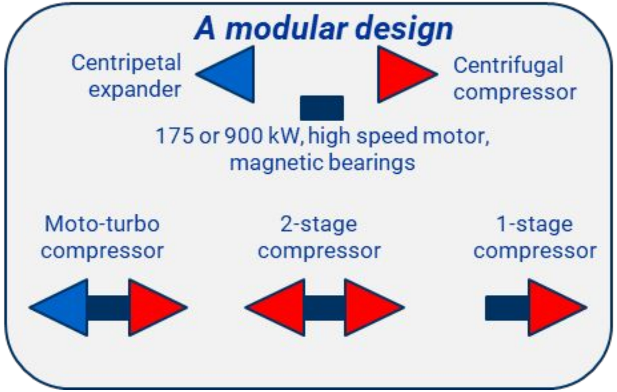
LNG Carriers

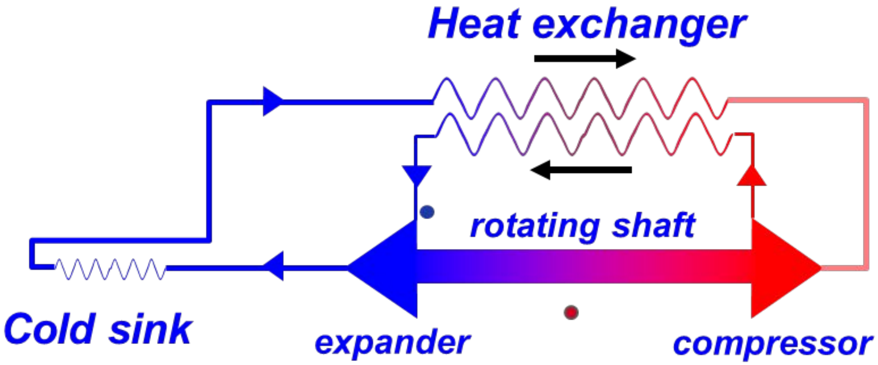
(174 000 m3)

FSRU

200+ Turbo Brayton (TBF) already sold since 2015

From LNG to HTS with the turbo-Brayton





From 1 to 8 turbomachines: from 175 kW to 8000 kW

Product range	TBF-175	TBF-350	TBF-700	TBF-1800-1.5	TBF-1800-2.1	TBF-1800-2700
Expected LNG flow @113K	0.2 t/h	0.5 t/h	1 t/h	1.5 t/h	2.1 t/h	Up to 3 t/h
Theoretical cooling power @65K	17 kW	35 kW (*)	70 kW	90 kW	90 kW	130 kW
Theoretical cooling power @~20K	4 kW	8 kW	17 kW	45 kW	45 kW	65 kW

TB 1400 successfully tested with 8 turbomachines

Well suited for High Temperature Superconductivity

Can provide more than 35 kW @ ~ 25-30K

Breaking news : **July 16, 2024 :18th anniversary of 3 turbo-Brayton in orbit**

Technologies required for the energy transition:
On-board cryogenic storages for H2-powered vehicles

HEAVEN : the 1st flight of an electric-LH2 plane with pilots aboard

LH2 in the Shipping industry : for transportation or propulsion

SUISO FRONTIER built by Kawasaki

- 1250 m3 of liquid H2
- January 2022 between Australia and Japan

- Other projects in progress like Energy Observer 2 for propulsion, in partnership with Air Liquide

Energy Observer

Future LH2 tanker
4 x 40 000 m3

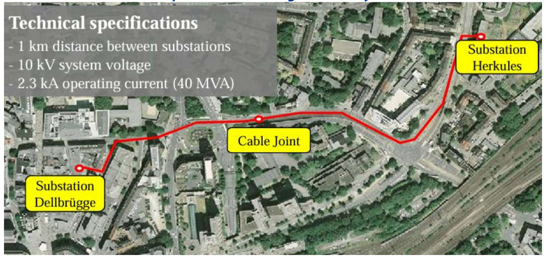
What about new applications?

HTS cables for offshore power transmission lines

LIPA (600 m)

Long distance HTS cables already exist

AMPACITY (1 km, 7 years)



The O&G industry can lay down insulated piping on the seafloor

1 MW @ 65 K with turbo-Brayton for 100 km

without intermediate station

Much cheaper & efficient than conventional 1 GW, HVDC power transmission lines

Off-shore wind power : storm warning on rare earths!

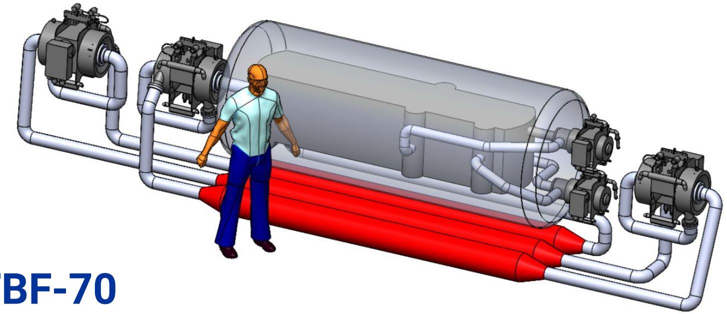
600 à 1200 GW / 2050
66 / 2020 **20X**

7 t rare earth / 10 MW ⇒ 800 000 tons
⇓
Critical Raw Material Act(EU)
WindPower Europe, April 2023

EcoSwing (2021)
3,4 MW - 400 W @ 25K, MgB2
cooled by commercial GM coolers
(Sumitomo)

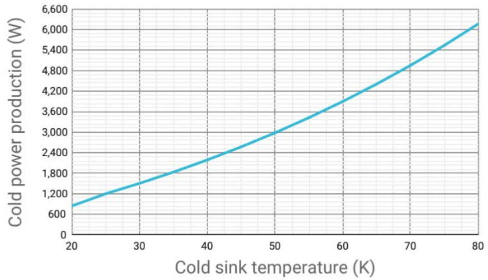
The EcoSwing Project, by T Winkler and al., in CEC-ICMC 2018

far less rare earths needed;
lighter mast and floater (TCO)

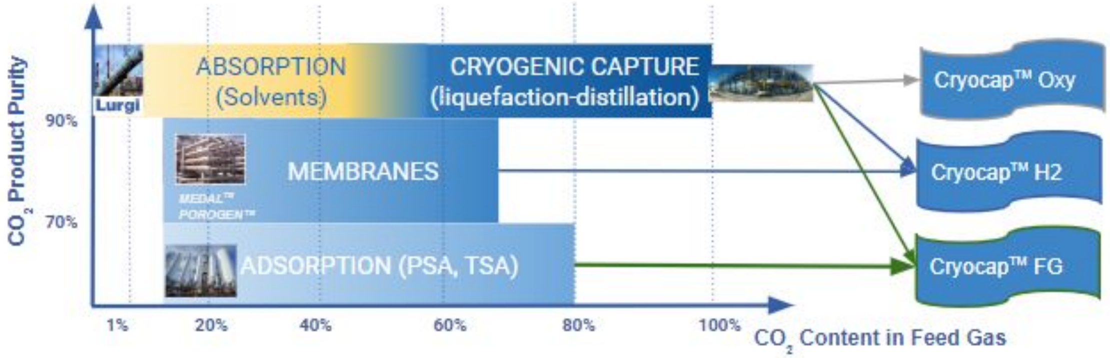


TBF-70
For a 10 MW generator

Cryocooler cold power production at constant electrical power (70 kWe) vs. T° cold sink

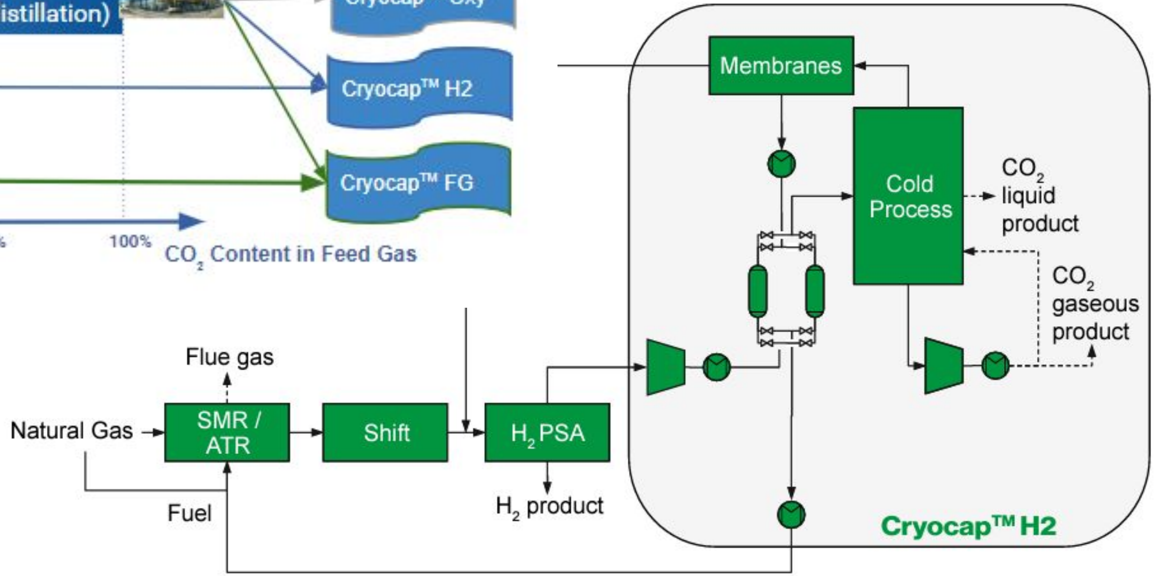


Cryogenic distillation is well suited for CO2 concentration > 40%



-50°C < T < -20°C

Cryocap ™ H2



Captured CO2 can be used for :

- Food industry
- E-fuel synthesis
- Sequestration

All require ultra-purity (<ppm level)

« warm » cryogenics but similar technologies and competencies

Air Liquide

Removal of 100 000 tons of CO2 per year with Cryocap ™ for blue Hydrogen

Air Liquide

Conclusions

In a society which is becoming more and more electrical, cryogenics is now expected to play a major role, with its potential for :

- Electrical energy generation and transmission, with superconductivity
- Chemical energy storage and transportation, with cryogenic energy carriers
- Capture, purification and transportation of CO_2

All technology bricks are there

Powerful and industrial cryogenic refrigerators and liquefiers are available on a wide range of temperatures and cooling powers

Cryogenist fellows: it is now our turn!