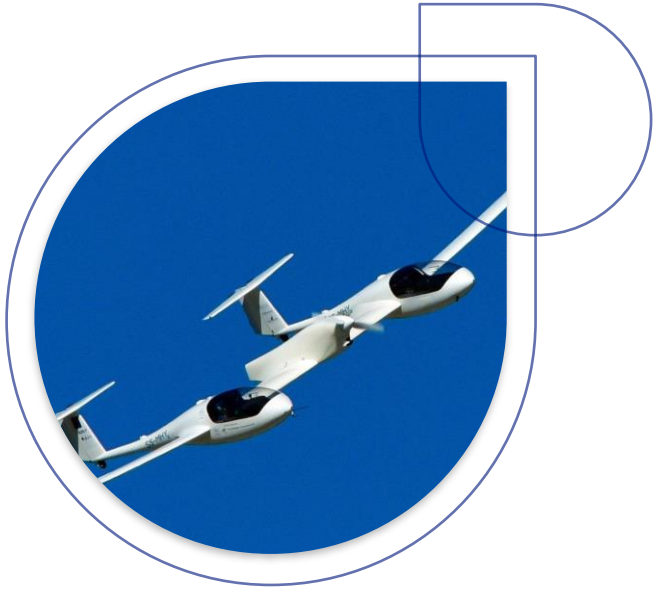
# Cryogenics for power



# and energy :

# a winning ticket?

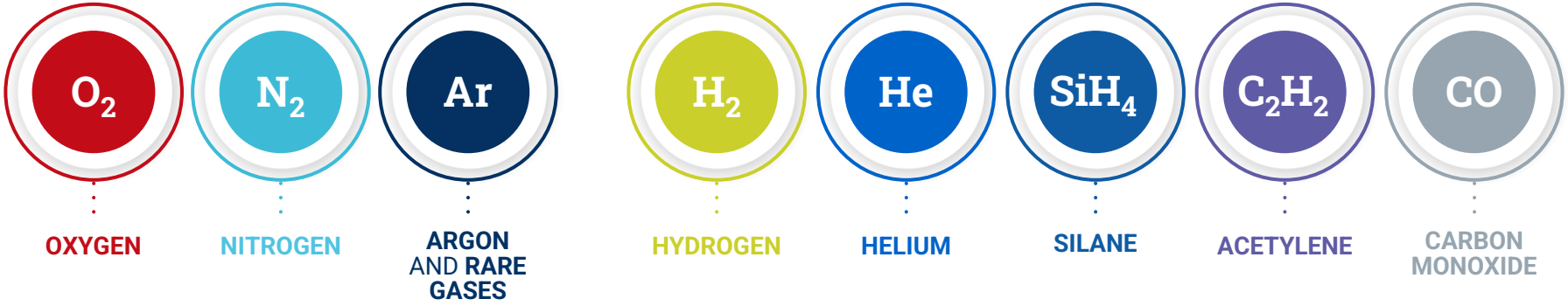
*Pierre Crespi, Head of Innovation*
*Air Liquide advanced Technologies*

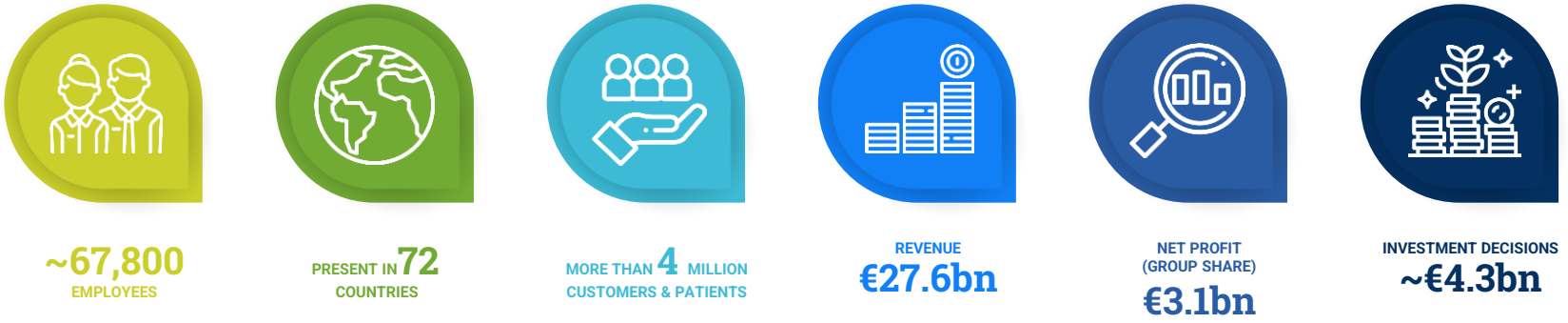
ICEC/ICMC


esa

# Air Liquide : a world leader in industrial & medical gases

## Created in 1902 for air liquefaction : cryogenics is our essence!



# Cryogenics is becoming an enabler for the energy transition

**Generating electrical power : LTS & HTS** **High Magnetic Field**

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

**Transporting electrical power : HTS @ 20K - 65 K** **2000 to 10 000 A, 0 Tesla**

- Technologies available : **piping** ; **REBCO superconductors** ; **large refrigerators**
- Typically : **1 GW over 100 km ~ 1 MW @ 65 K**

**Producing, storing, distributing energy with cryogenic liquid carriers**

- **LNG Boil-Off :** on ships > 80 000 tons
- **LH2 liquefier:** 10 tons/day ⇒ 100 tons/day
- **LH2 storage :** rockets (30 t) trucks (0,1 t) aircraft (1 t) ships (10 – 10 000 t)

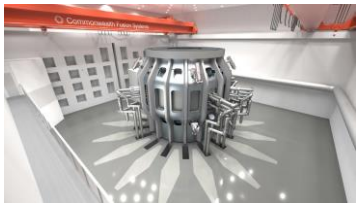
# A broad market outlook for cryogenics in the energy transition

# Nuclear fusion market looks promising for cryogenics

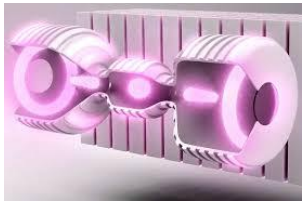
(as said by C Senatore in *Advancing Superconductor Technology for High Field Applications*, ICEC-ICMC-2024)

## **45 private companies on fusion*** (25 in US)

- $7,1 bn funding (94% private)
- Many use HTS for magnetic confinement
- May emulate an agile SpaceX-type model
- Might generate electricity in the 2030s



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



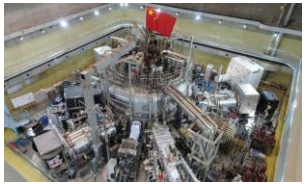
Inductive fusion
Helion (US)

## Many institutional projects

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

JT60-SA
(Japan)

ITER
(34 countries, in France)



EAST then BEST
(China)

CFETR
(China)

* Source : Fusion Industry Association - FIA 2024

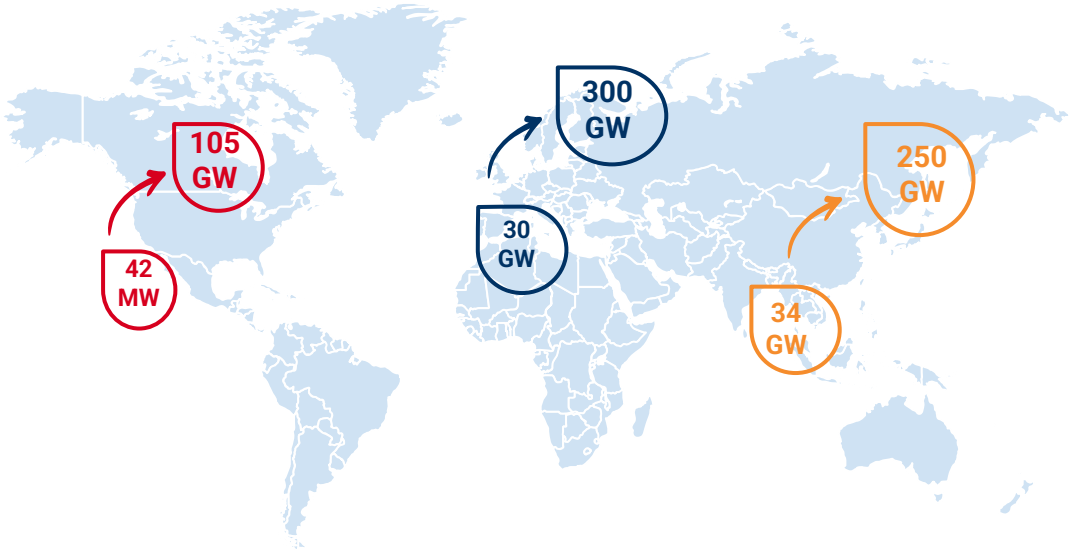
# Offshore wind power market is also promising for superconductivity

*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 underwater transmission lines**




Superconductivity may address some of the challenges :

- **shortage of RE** (for PMs in generators)
- **cost and deployement of many large HVDC converters** for long range power transmission (offshore and onshore)

# LH2-powered heavy duty vehicle market : cryogenics as an enabler

A good regulatory framework is in place for trucks

Many OEMs have clear development roadmaps

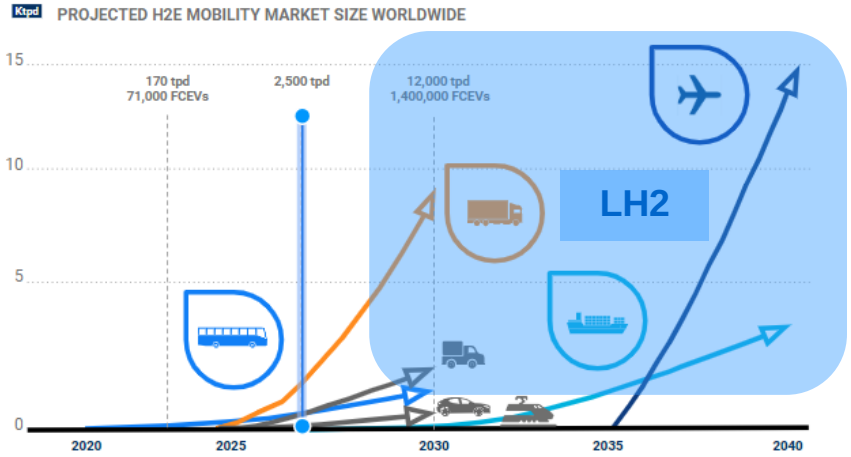
- Producing 1000 H2-trucks/year per OEM is feasible

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 H2 Refueling Stations and liquefiers




2030 : 12 000 tpd demand
Current ww LH2 capabilities ~ 450 tpd, 43 plants
Announced liquefier projects : > 4000 tpd (60% in APAC)

(*) see: *Cryogenic H2 for HDV : Applying Fundamental Thermodynamics to Solve CleanTransportation Challenges,* Petitpas and al. ICEC2024

tpd : tons per day

# Consequences : a lot of demand on 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, more to come

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

On board **storage** for aircraft (HEAVEN flight in 09/2023) and trucks (FORVIA - Air Liquide partnership)


Liquid H2 **refueling** stations (HRS):

- HRS to be supplied with LH2 even for GH2-powered FCVs
- HRS will also deliver LH2 or SH2 to heavy duty vehicles (1st LH2 station by Air Liquide for DAIMLER)


(*) FCV : Fuel Cell Vehicle

# Technologies required for the energy transition :

# Cryogenic liquefiers and refrigerators

# Liquefaction of Hydrogen

Pre-cooling down to 80 K with either :

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

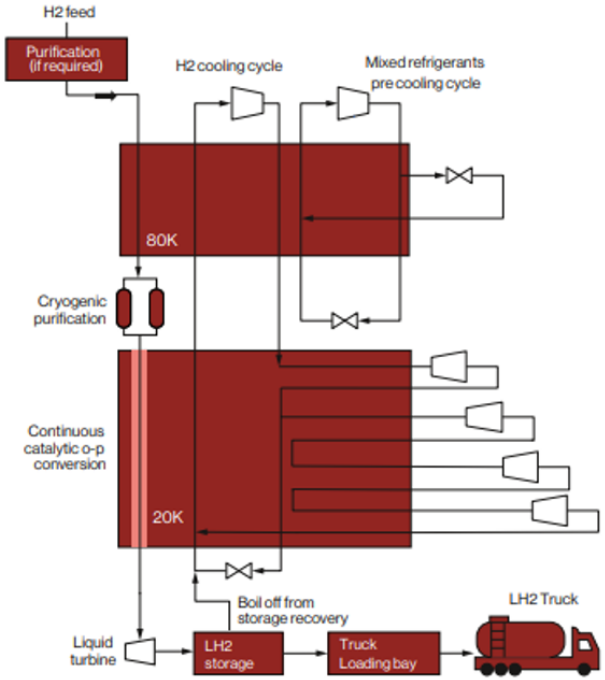
Piston-type compressors (~8-10 MW for 30 tpd)

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

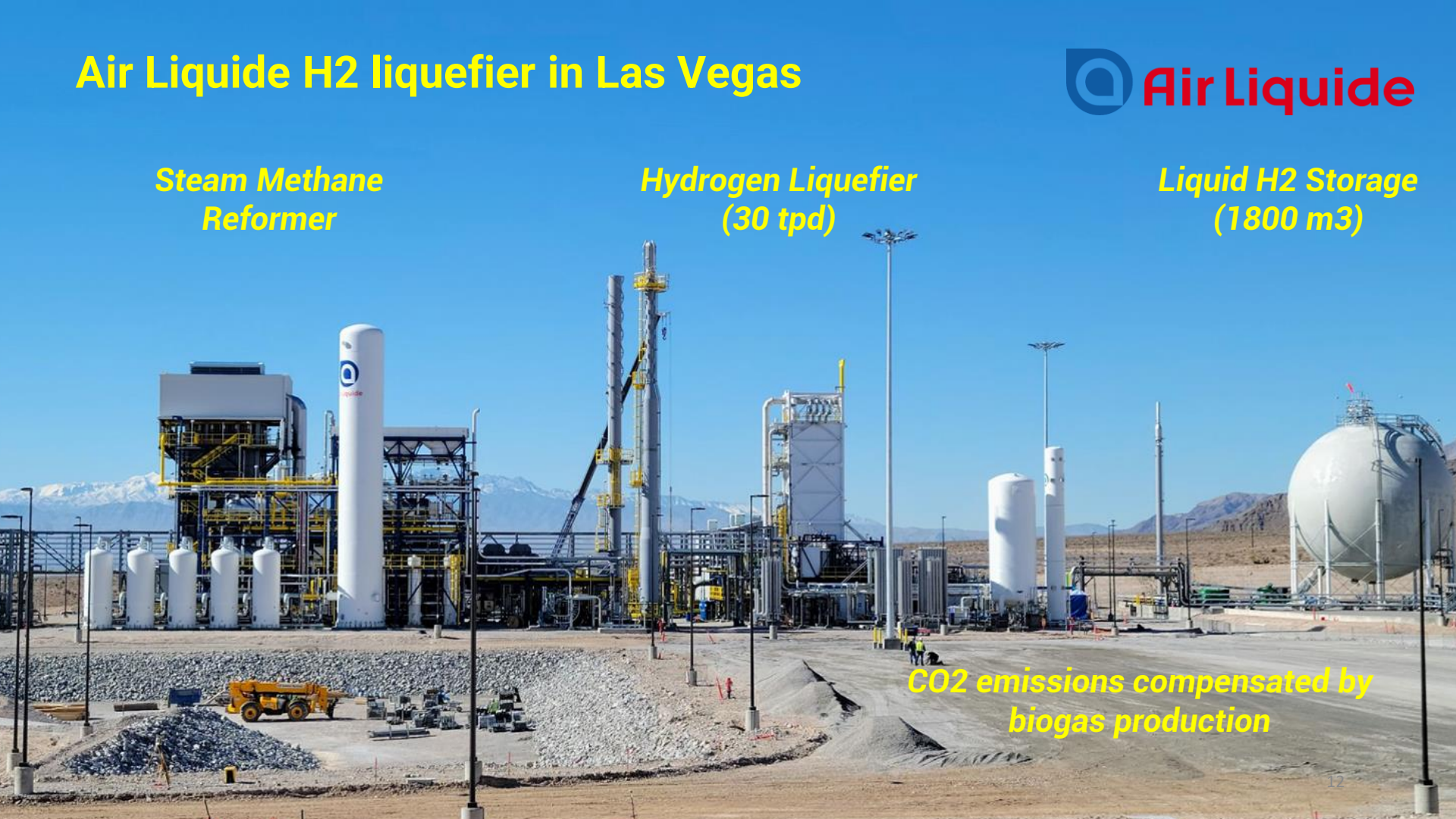
Boil-off from storage & logistics can be recovered
at the liquefier site

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

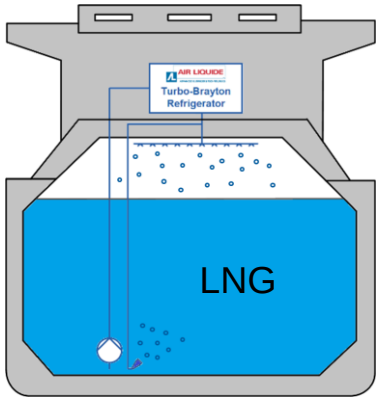
***H2 cycle liquefier***



# Air Liquide H2 liquefier in Las Vegas



# Reliquefaction of LNG aboard ships with the turbo-Brayton




**Principle**

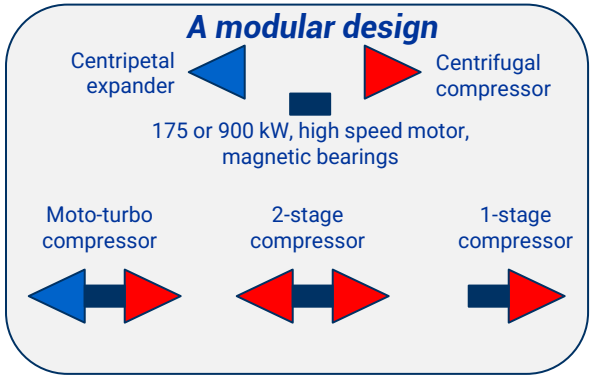
**Bunker vessels**

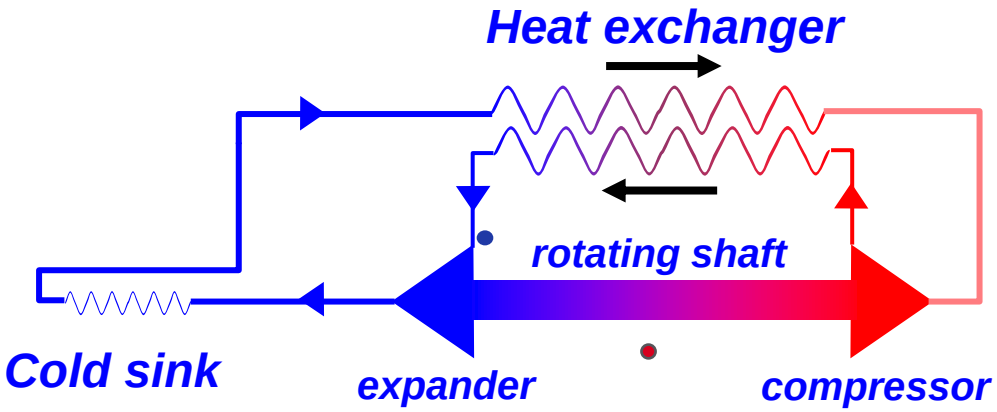
**Newbuilt / Retrofit LNG Carriers (174 000 m3)**

**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
Air Liquide
Air Liquide

**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

For more information, see : *Cryogenic Tests of an Airborne Liquid Hydrogen Tank in a Manned Aircraft in the Heaven Project,* D. Favier and L. Jeunesse, ICEC-ICMC 2024

# 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 ?

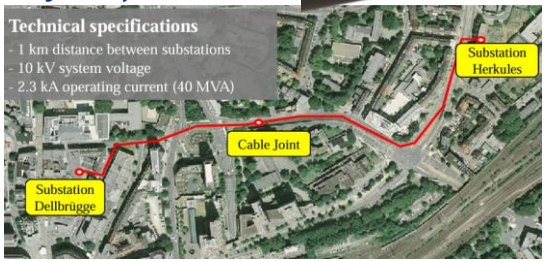
# HTS cables for offshore power transmission lines

HTS cables already exist in the kilometric range

***LIPA (600 m, 640 MW AC)***

The O&G industry can lay down insulated LNG piping on the seafloor ($\phi$ > 400 mm)

***AMPACITY (1 km, 7 years)***




1 MW @ 65 K with turbo-Braytons for 80-100 km, >1 GW

without intermediate station

**Might be much cheaper & efficient than conventional offshore or onshore power transmission lines**

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

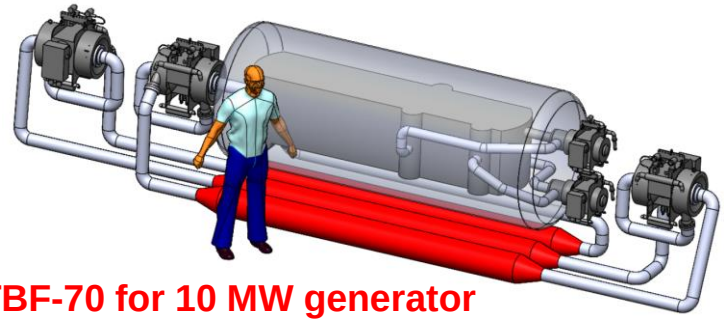
600 à 1200 GW / 2050
66 / 2020 **20X**

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

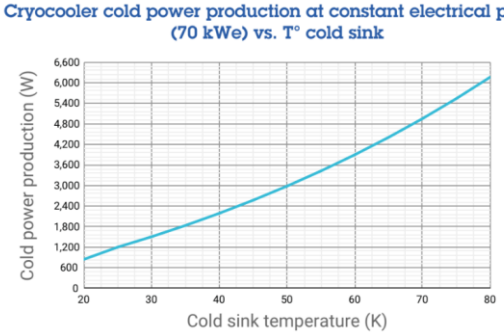
*EcoSwing (2021) :*
*3,4 MW, 400 W @ 25K, REBCO*
*cooled by commercial GM coolers*
*(Sumitomo)*

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

**far less rare earths needed**
**lighter nacelle (TCO)**

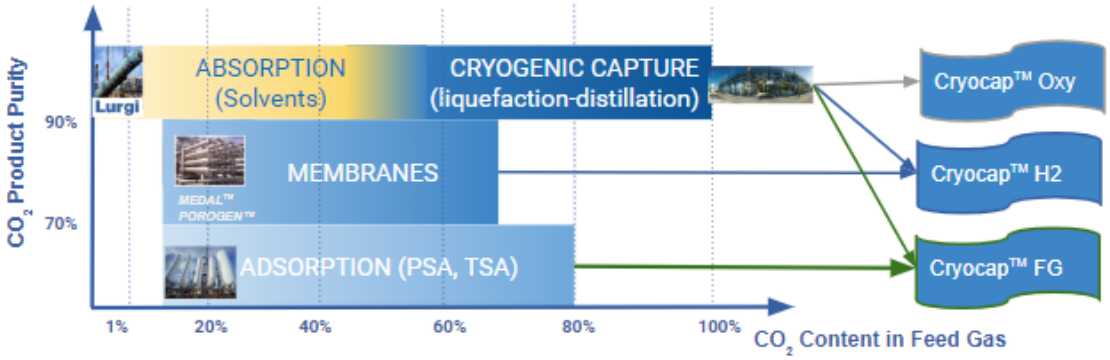


**TBF-70 for 10 MW generator**
**based on marinized turbo-Brayton technology**



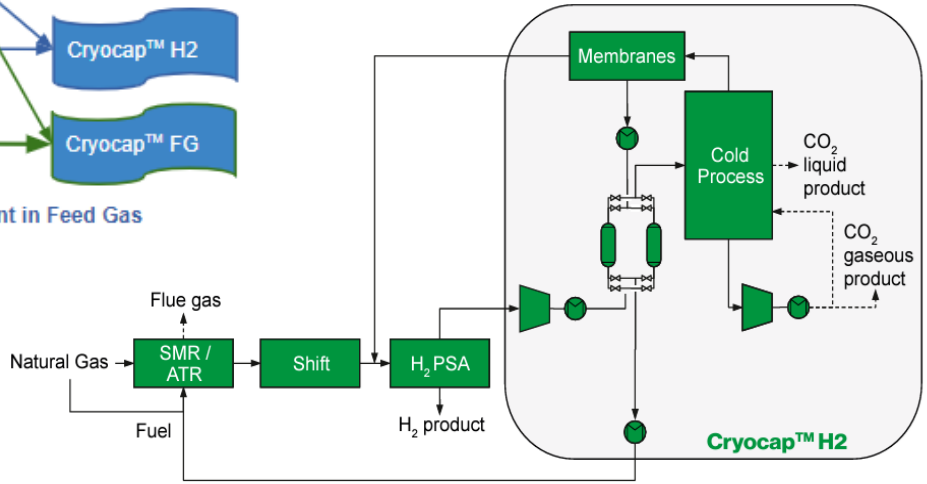

**No pre-cooling required**

# 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

# Removal of 100 000 tons of CO2 per year with Cryocap ™ for blue H2

# Conclusions

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

- Electrical energy generation and transmission, with superconductivity
- Chemical energy storage and transportation, with cryogenic energy carriers
- Capture, purification and transportation of CO2

All technology bricks are there

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

**Dear cryogenist fellows: it is now our turn!**