Zentrum für Sonnenenergie- und Wasserstoff-
Forschung Baden-Württemberg

Hydrogen Supply Option for Airports

Ludwig Jörissen

April 9th 2025

AERO 2025

The ZSW – At a Glance

A non-profit organization - 340 employees - 85% external funding

Applied Research & Development on New Energy Technologies:

- Batteries & super capacitors: materials, production technologies, systems, qualification
- Fuel Cells: technology, systems, production technologies, test center
- Photovoltaic: thin film technologies (CIGS) & application systems
- Renewable Fuels: power-to-gas, biomass gasification
- Energy politics & economics, wind energy

WIND ENERGY

PHOTOVOLTAICS

BATTERIES

HYDROGEN

FUEL CELLS

POLITICAL CONSULTING

ZSW Locations

Stuttgart:
Photovoltaics, energy policy and energy sources, finance, IT, personnel, law; solar test field in Widderstall & wind test field Stötten (Swabian Alb)

Ulm:
Electrochemical energy technologies with laboratory for battery technology (eLaB), research production line (FPL) and Powder-Up! & research factory for hydrogen and fuel cells (HyFaB)

ZSW – Ulm Site in 2024 (Responsible: Prof. Dr. Markus Hölzle)

Areas of Research:	Fuel Cells, Hydrogen and Batteries
R&D Project funding:	15 MM€ Governmental Projects; 19 MM € Direct Industry
Investments:	25 m €; among 7 m € from ZSW
Number of employees:	> 220

// Helmholtzstraße (from 1993)
- R&D fuel cells and batteries
- Material and components development for Lithium-ion batteries
- Fundamentals & Analytics
- Mechanical / electrical shop

// eLaB (from 2011)
- Batteries with focus on cell-assembly
- Manufacturing pilot line for automotive batteries (“FPL”)
- Battery safety

// HyFaB (from 2022)
- Fuel cell assembly model factory for PEMFC
- Largest independent PEMFC test center in Europe
- Hydrogen-laboratory HyLaB

Powder-Up! (from 2024)
- Production plant for cathode materials in batches of up to 100 kilograms
- Focus on sustainable formulations and improved manufacturing processes

Hydroge – A Few facts to Begin With

- Hydrogen is a **colorless**, **odorless**, **flamable gas lighter than air** and the **most abundant element** in the universe
- **No large scale natural hydrogen deposits** are known so far.
  However, hydrogen is found in some natural gas wells. Furthermore, hydrogen is seeping from the ground. In Mali a self replenishing „natural hydrogen“ reservoir (purity ~98%) was found. Currently, of „natural hydrogen“ deposits are investigated intensively.
  Currently hdyrogen for **techncal use is produced „on-purpose**“:
  - Hydrogen currently is produced from natural gas and (hevy) oil
  - Hydogen production from fossil fuels causes the emisstion of large quantities of CO_2 (~8-10 t CO_2 per ton of H_2)
  - In the future hydrogen will be produced by water electrolysis using „green electricity“
- Hydrogen is the **most used industrial chemical** worldwide (by volume) :
  - No hydrogen, no fertilizer
  - No hydrogen, no Fuels (gasoline, diesel, kerosene …)
  - No hydrogen, no chemicals, polymers, pharmaceutical products …
- Hydrogen typically is **produced at the site of use**. Only 4% of hydrogen production is traded as technical gas. For the broad majority of the population, hydrogen is an unknown
- **Green electricity and hydrogen** will become the backbone of a future energy supply free from (fossil) CO_2

Hydrogen: Backbone and Link in the Energy System

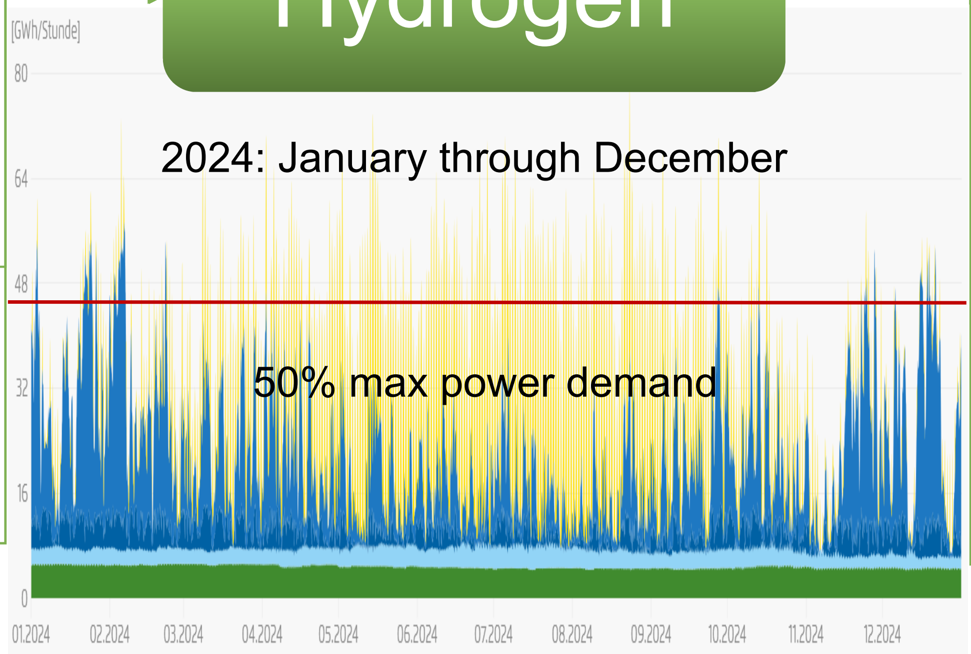
… leveling the fluctuating supply of green electricity withou CO_2 Emissions

Tomasz Wyszoamirski, Getty Images/iStockphoto

Quelle: Focus online

Quelle: biogasanlagen-info.de

Hydrogen



Agora Energiewende: Agorameter

Quellen: Viessmann / Feudenberg / Imago Images / Pixabay / Pixabay / Siemens

Hydrogen Production and use

Wasserstoff wird bereits heute in vielen Anwendungsfeldern und großen Mengen eingesetzt

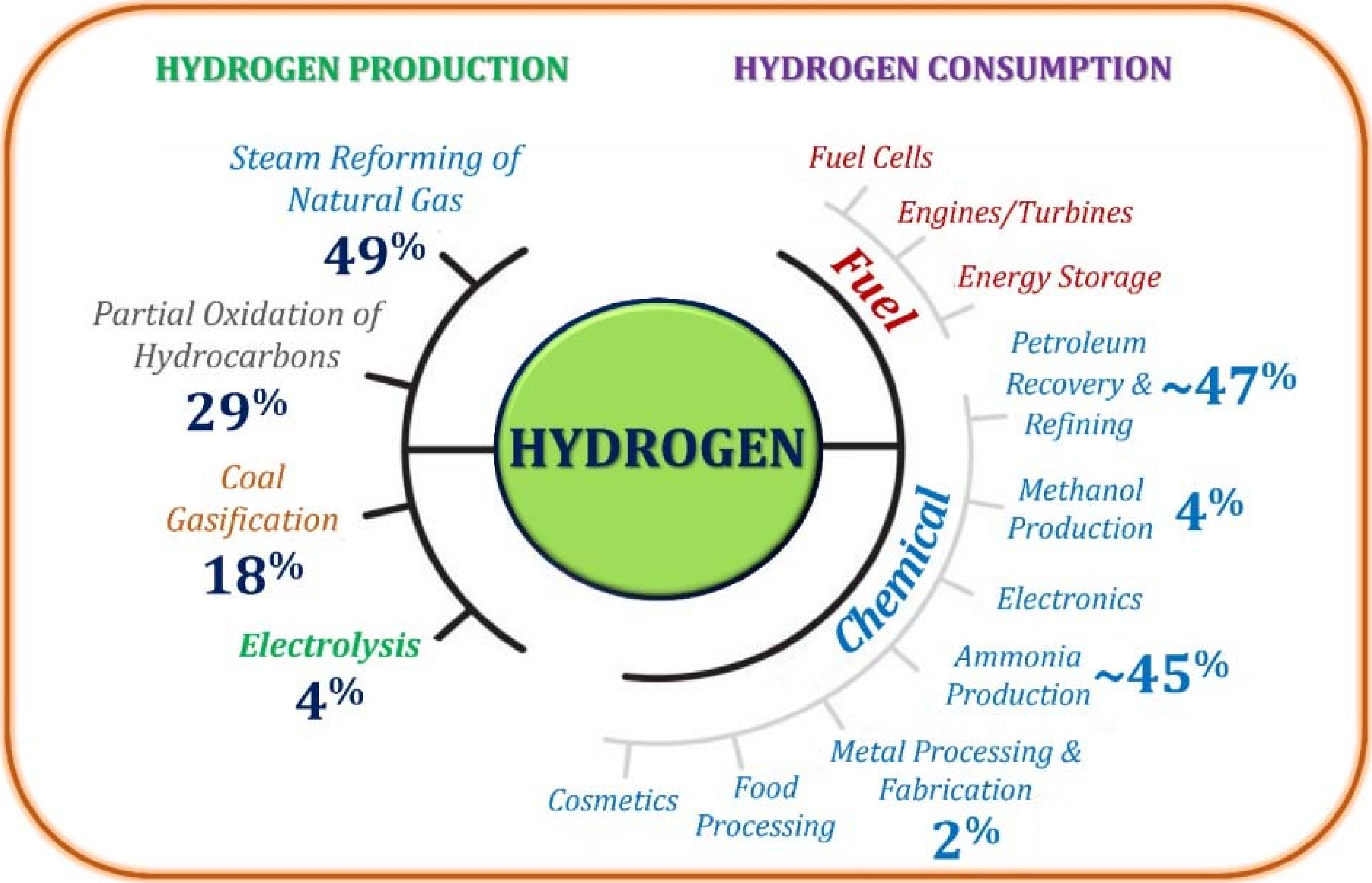
Worldwide production:
- ca. 500 Bil. Nm^3
- 45.5 Mio. t

Electrolyzer productivity:
- ca. 150 t MW^{-1} a^{-1}
  at 8 760 h full load

H_2-demand in Europe:
- 2023: ca. 8 Mio. t
- 2030: ca. 10 Mio. t
- 2050: ca. 50 Mio. t

Resulting electrolyzer demand in 2050
- min. 333.3 GW

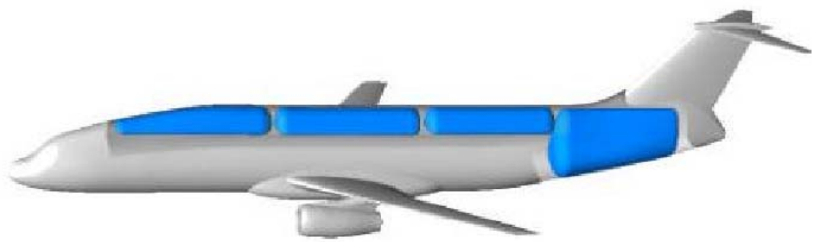
Currently available in EU27 in 2023
- ca. 0.216 GW



S.S. Kumar, H. Lim; *An overview of water electrolysis technologies for green hydrogen production*; Energy Reports, **8**, 13793-13813 (2022)

Hydrogen Powered Aircraft

History

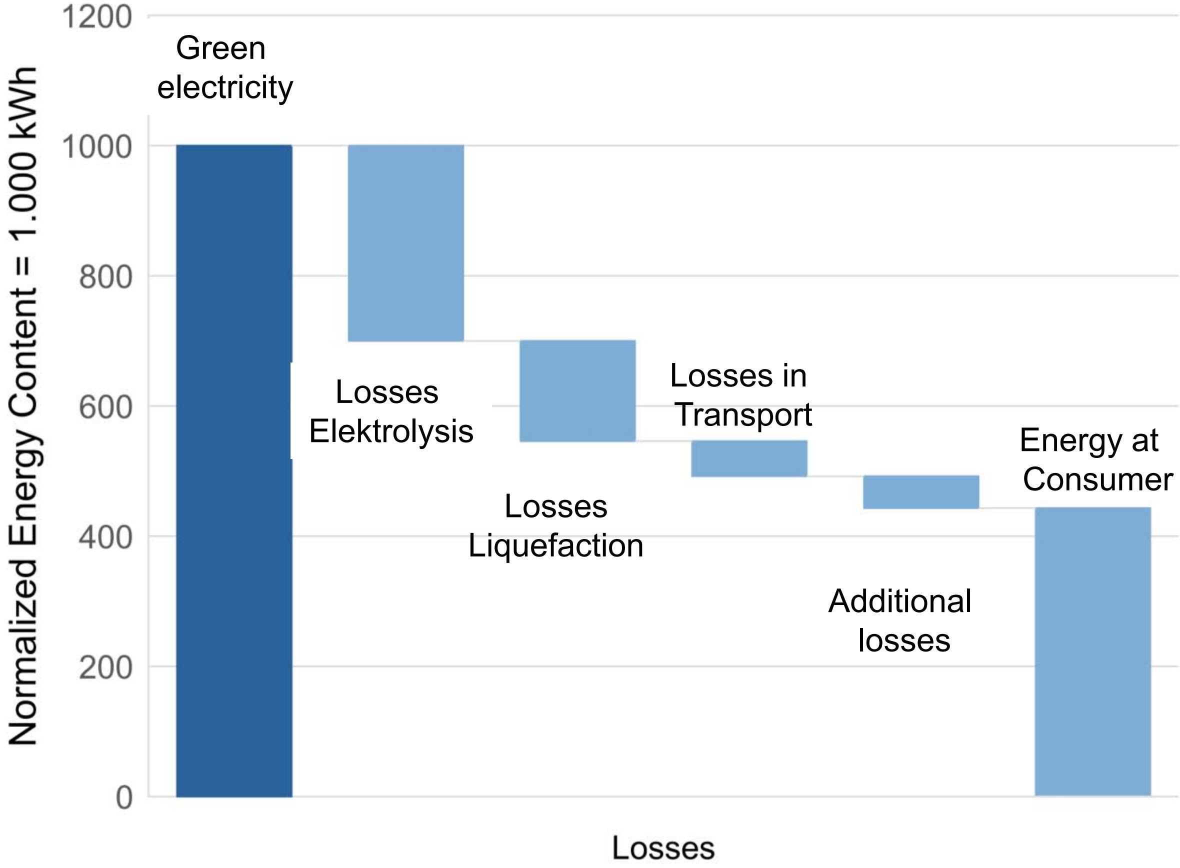


Tupulev Tu 155
Flying testbed using liquid hydrogen (1988)
One engine converted

Vision Cryoplane
Research project early 2000

What‘s the Cost of Green Hydrogen?

Modell calculation of a global supply chain in2022



Lowest shortlisted bid in Saudi 1.47 GW tender was $0.0161/kWh

The shortlisted developers are EDF, Total, ACWA Power, Masdar, First Solar, Marubeni, and Al Blagha Holding.

APRIL 3, 2020 EMILIANO BELLINI

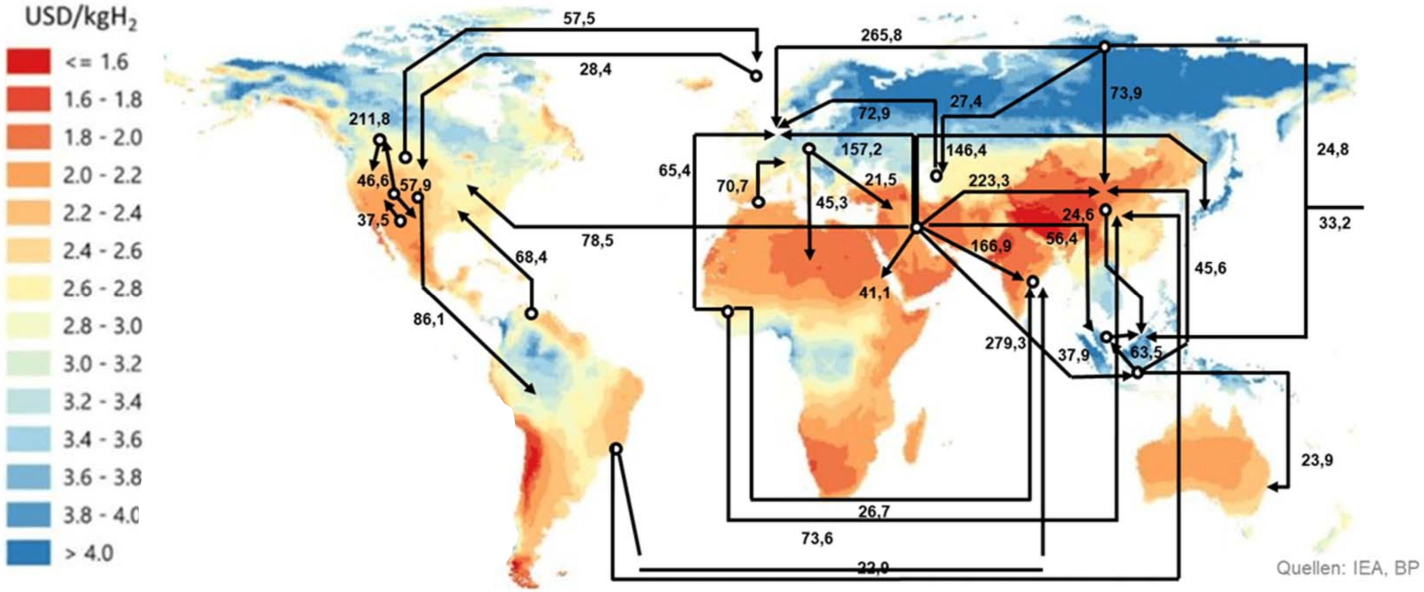
PV-sites in the midle east will alow electricity cost of **1 ct/kWh** which – provided würde supply chains were established – would lead to cost for green hydrogen in Europe of ca. **2,5 ct/kWh.**

Corresponding to **44 USD/bbl crude oil*.**

* including CAPEX (+50%)

Green Hydrogen is a Realistic and Competitive Option for Worldwide Energy Trade

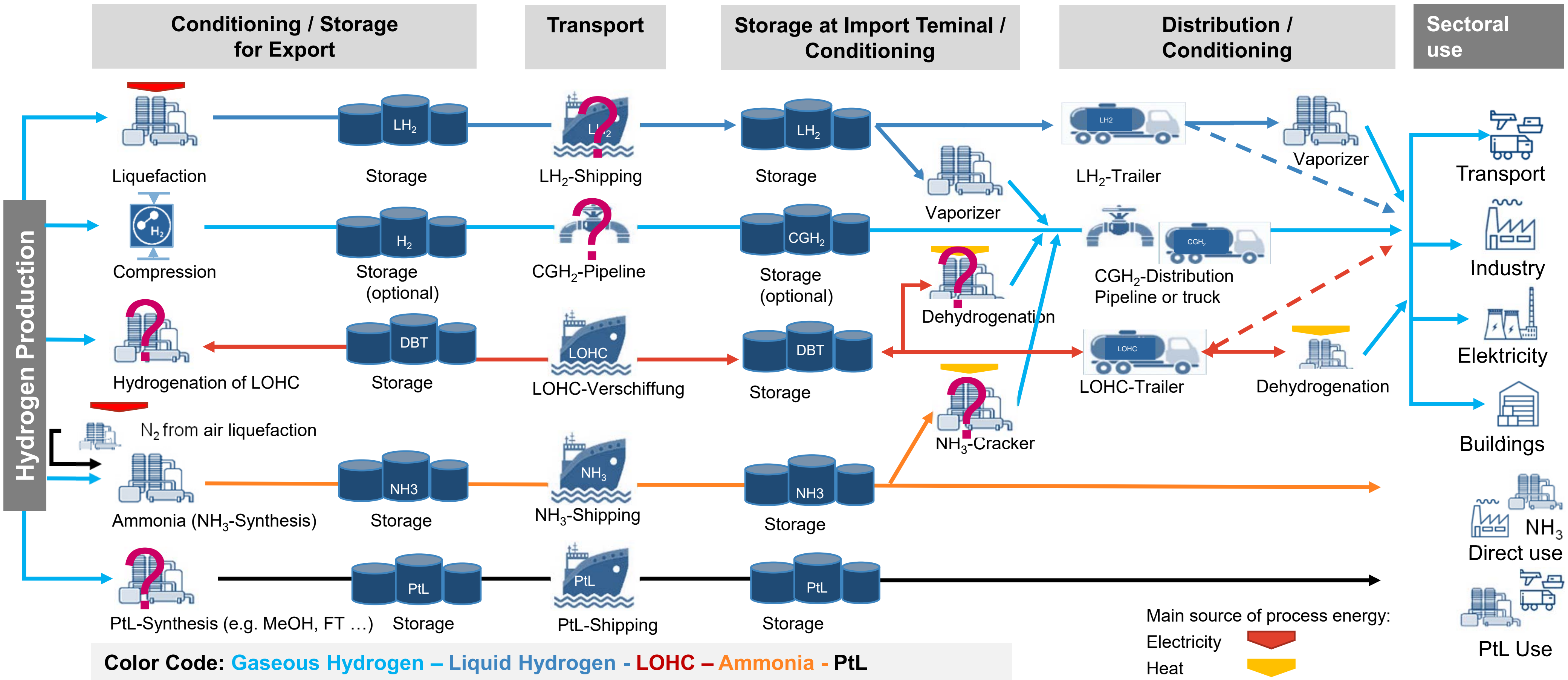
Estimated production cost of green hydrogen in 2021 (USD / kg)



- Hydrogen can be produced at competitive cost once favorable sites for electricity production from wind and / or solar energy are available. Yet, suitable transport hardware (Ships, pipelines) are still missing.
- Existing pipeline networks can be re-dedicated (for example: the natural gas grid in germany is mostly „hydrogen ready“).
- Chance for Europe: Building of a secure supply chain and exporting technology.

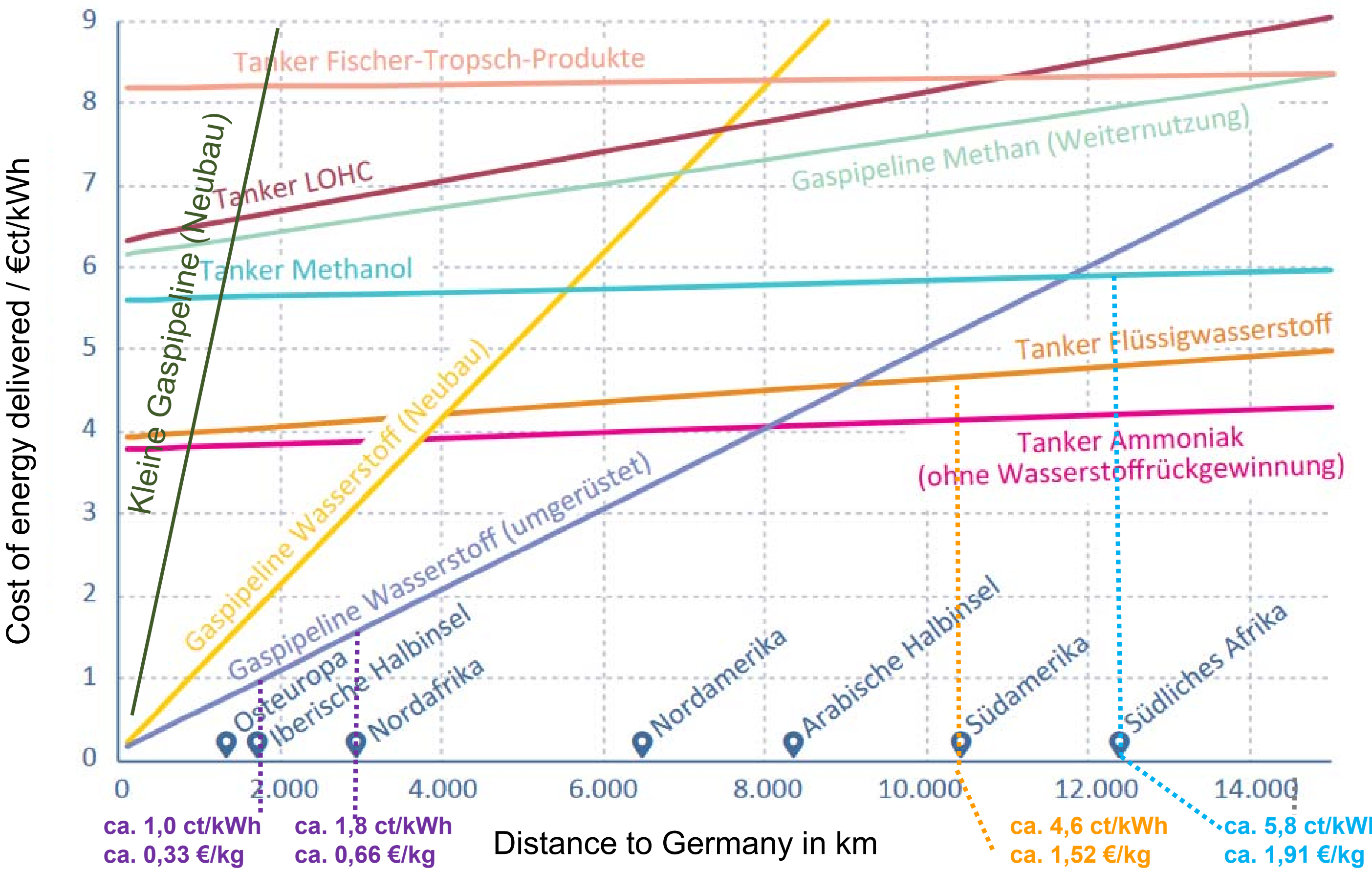
Hydrogen Transport Options

Different processes and carriers are competing



Hydrogen Transport Cost

Transport- and conditioning cost as a function of transport distance (expected in 2030)



Short distance transport (up to 4 000 km) is most efficiently done in pipelines. Use of re-dedicated natural gas piplines doubles this radius

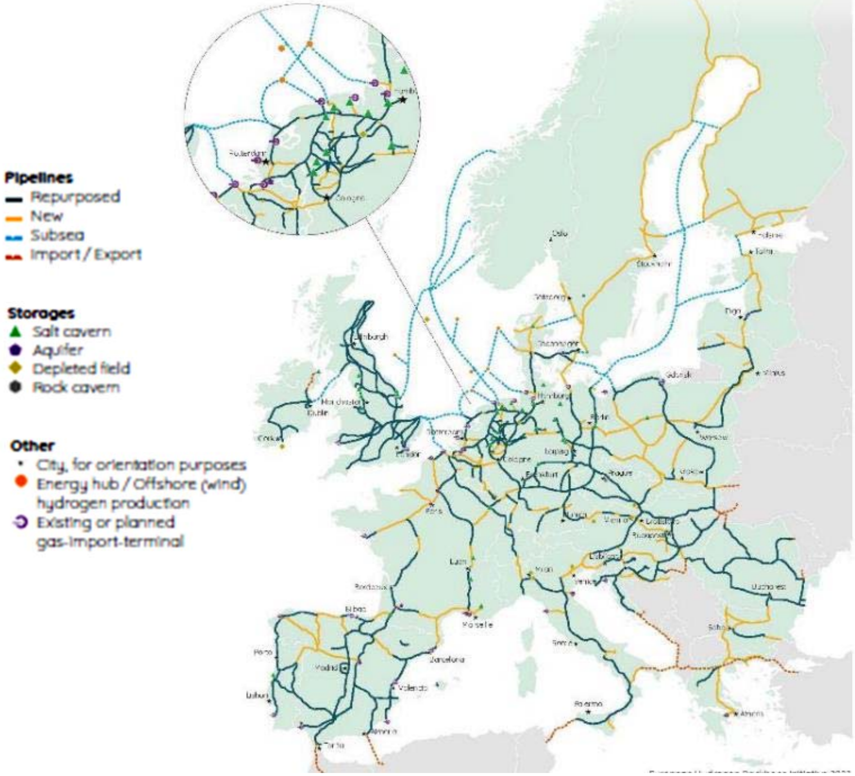
Shipping hydrogen in the form of Ammonia is second in cost. However additional attention must be paid due to ammonias toxicity.

Quelle: Optionen für den Import grünen Wasserstoffs nach Deutschland bis 2030; (2022)

„The European Hydrogen Backbone“

Hydrogen long distance transport at reasonable cost in pipelines

An effective hydrogen pipeline infrastructure for long distance transpor shall be available by 2040:



Source: European Hydrogen Backbone initiative 2022, supported by Guidehouse

- **Hydrogen transport infrastructure,** connecting supply and demand north to south and west to east
- 2030: 28.000 km pipeline network connecting hydrogen clusters in the north of Germany / NRW to hydrogen import hubs
- 2040: Grid extend in all directions at a length of **ca. 53.000 km**
- Investment of ca. **80 – 143 Bil. €** are required to establish the backbone
- 75% re-dedicated natural gas pipelines, 25% newly bult hydrogen pipelines
- Transport cost: **0,11-0,21* €/kg per 1.000 km** – cost efficient long distance transport in Europe

*via sub- sea pipelines: 0,17-0,32 €/ kg Hydrogen per 1.000 km transport distance

Quelle: European Hydrogen Backbone, 2022

RePowerEU – Five Major Hydrogen Pipeline Corridors

Five pipeline corridors are foreseen to build the European Hydrogen Backbone and are of key importance to allow a **sufficient** and **cost effective** access to hydrogen all over Europe.

To deliver the 2030 hydrogen demand targets set by the RePowerEU plan, **five large-scale pipeline corridors are envisaged**.

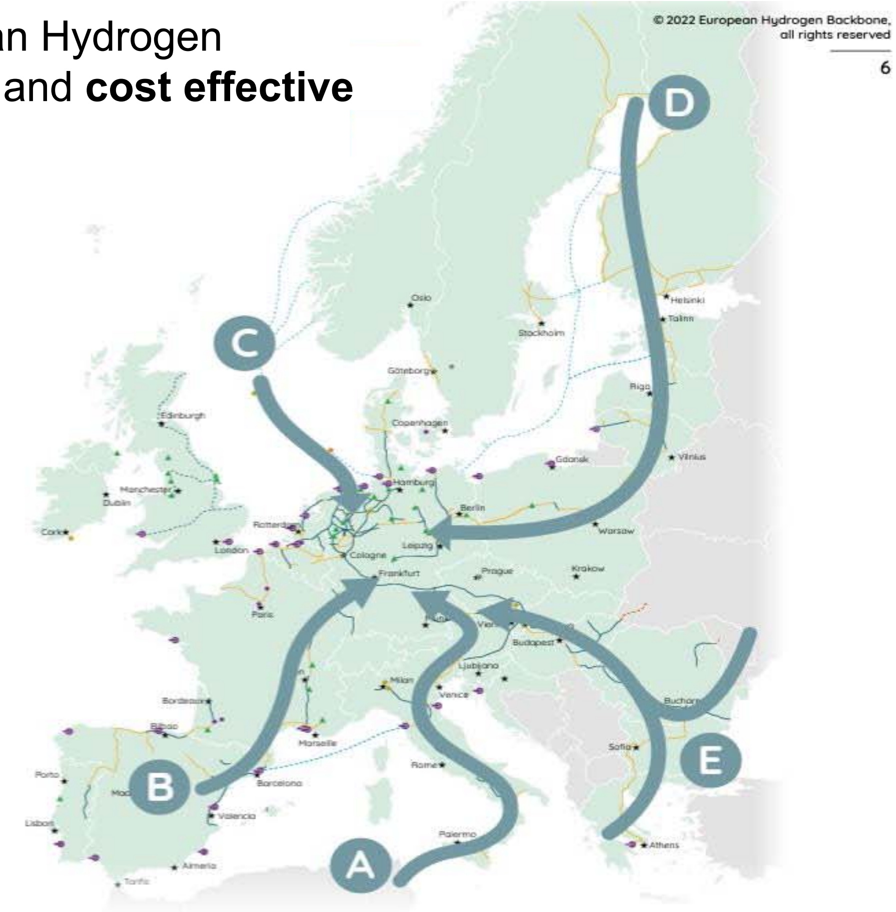
The corridors will **initially connect local supply and demand** in different parts of Europe, before expanding and **connecting Europe with neighboring regions** with export potential.

Certainty about the deployment of this infrastructure will **enable market actors to develop** supply and demand more rapidly

The five hydrogen supply corridors are:

- Corridor A: **North Africa & Southern Europe**
- Corridor B: **Southwest Europe & North Africa**
- Corridor C: **North Sea**
- Corridor D: **Nordic and Baltic regions**
- Corridor E: **East and South-East Europe**

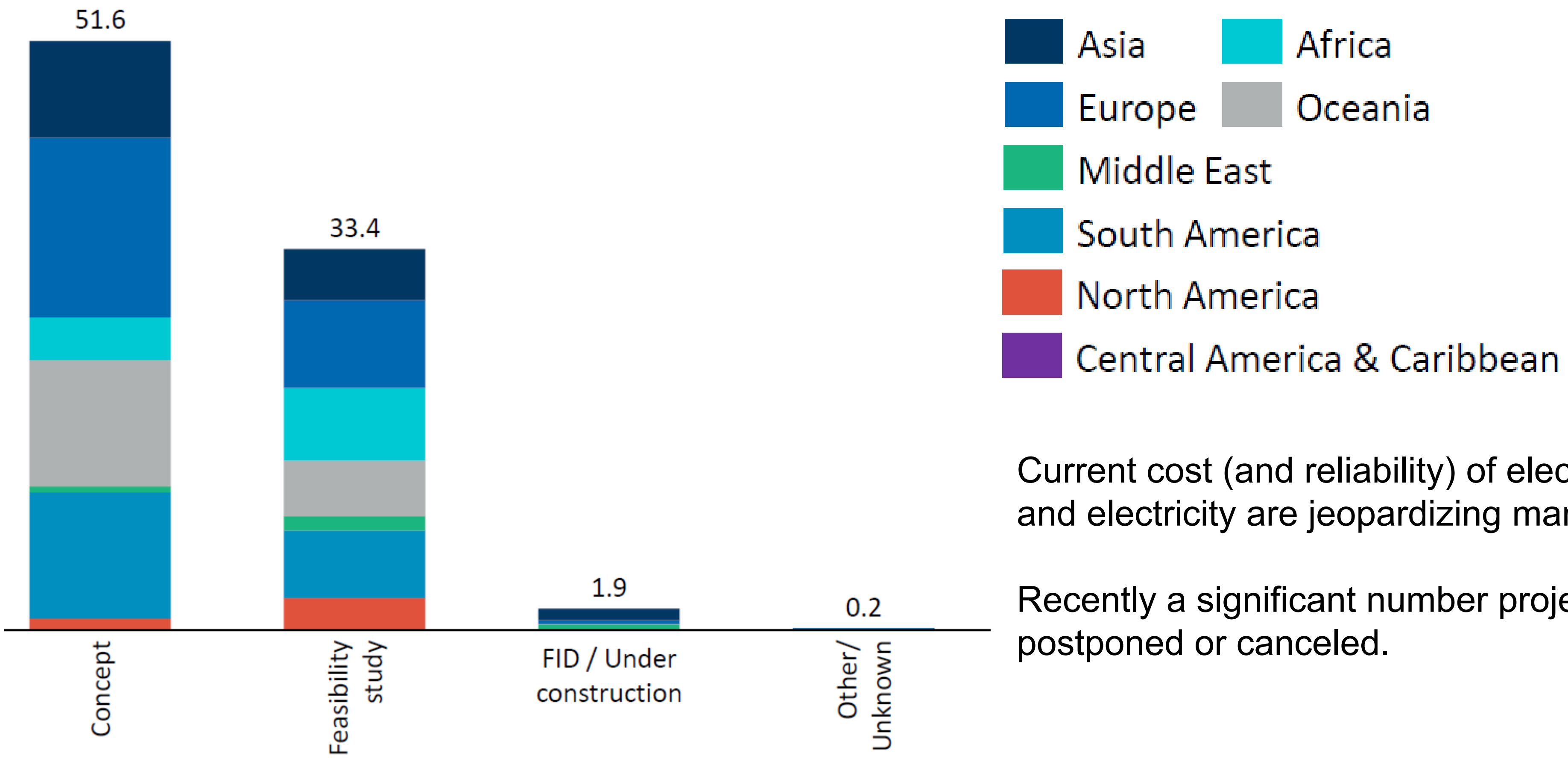
These five corridors **span across both domestic and import supply markets**, consistent with the **three import corridors** identified by the RePowerEU plan, including a corridor via the **Mediterranean** (Corridors A and B), via the **North Sea** (Corridor C) and via **Ukraine** (Corridor E)



bayernets energie transport systeme HyPipe Bavaria Wasserstoff für Bayern terranets bw Wasserstoff für Baden-Württemberg Eine Initiative der terranets bw ZSW

Planned / Announced Hydrogen Production Capavity (in Mt p.a.)

Data IEA 2024: A lot of pojects are announced but few are in realization

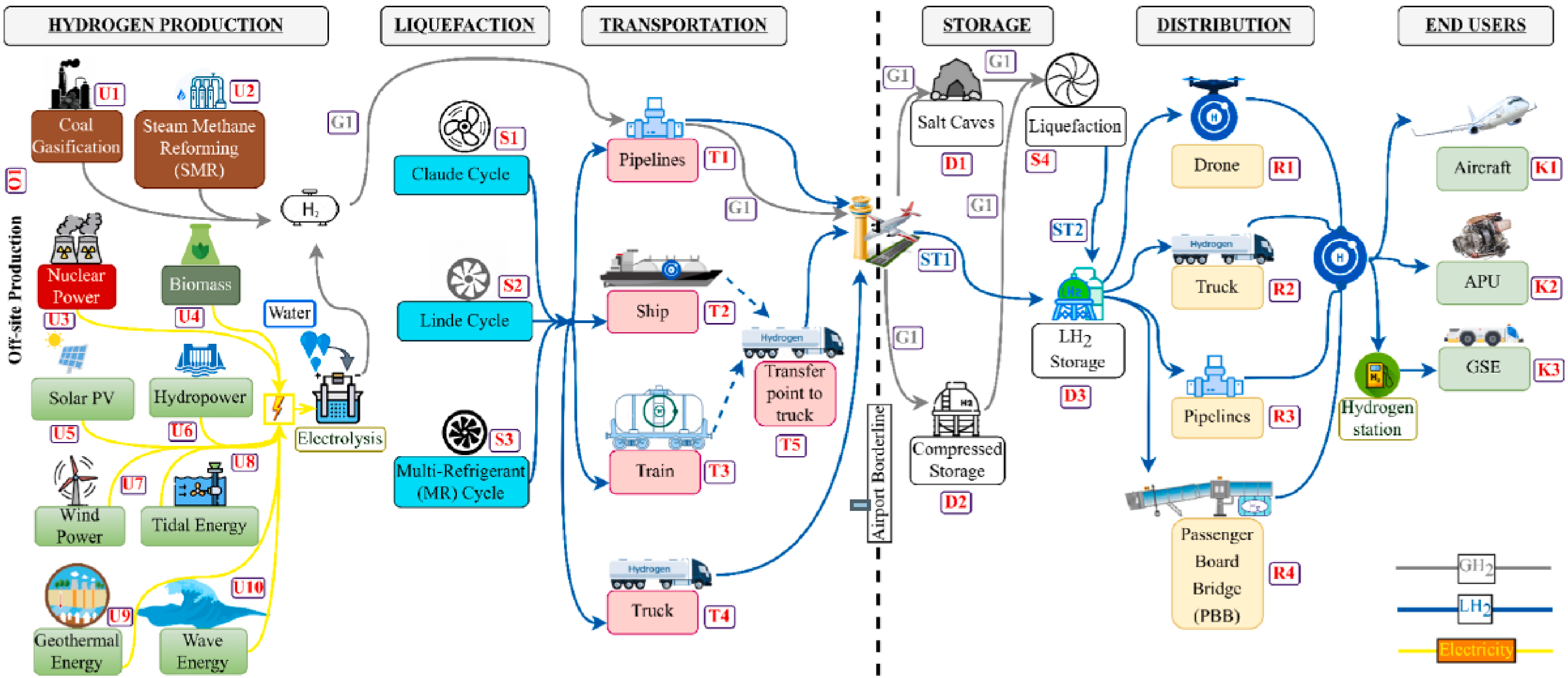


Current cost (and reliability) of electrolyzers and electricity are jeopardizing many projects.

Recently a significant number projects were postponed or canceled.

https://www.fticonsulting.com/insights/reports/green-hydrogen-global-market-price-model

Hydrogen Supply Options for Airports

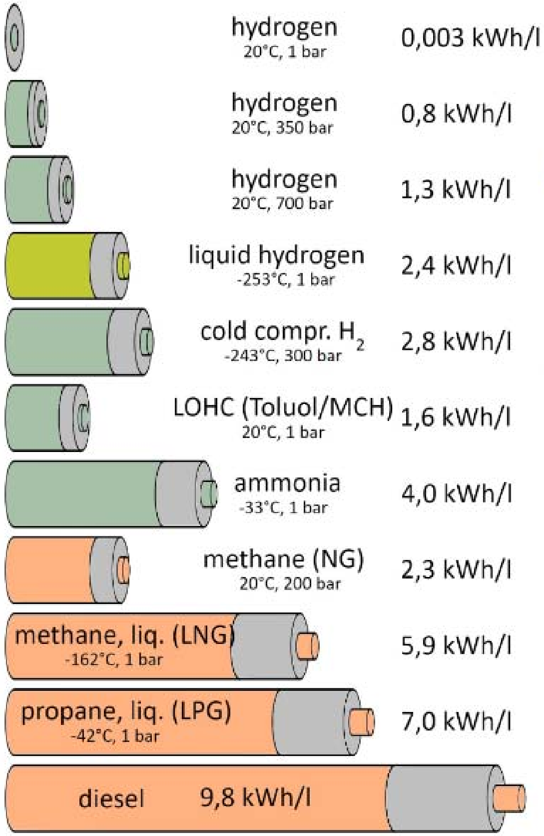


Source: H. Degrirmenci et al. Energy Conversion and management 293 (2023) 117537

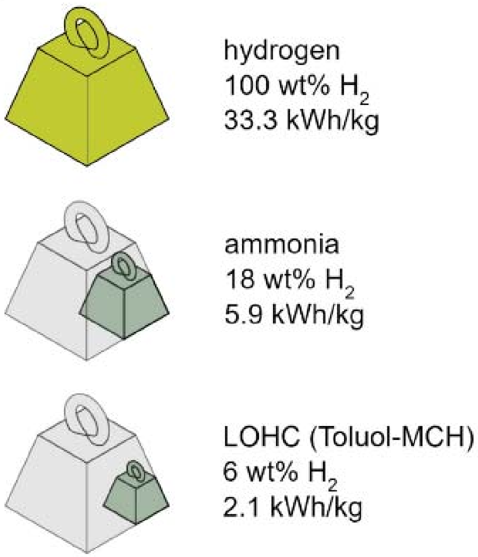
Hydrogen: Comparison of Energy Density and Specific Energy

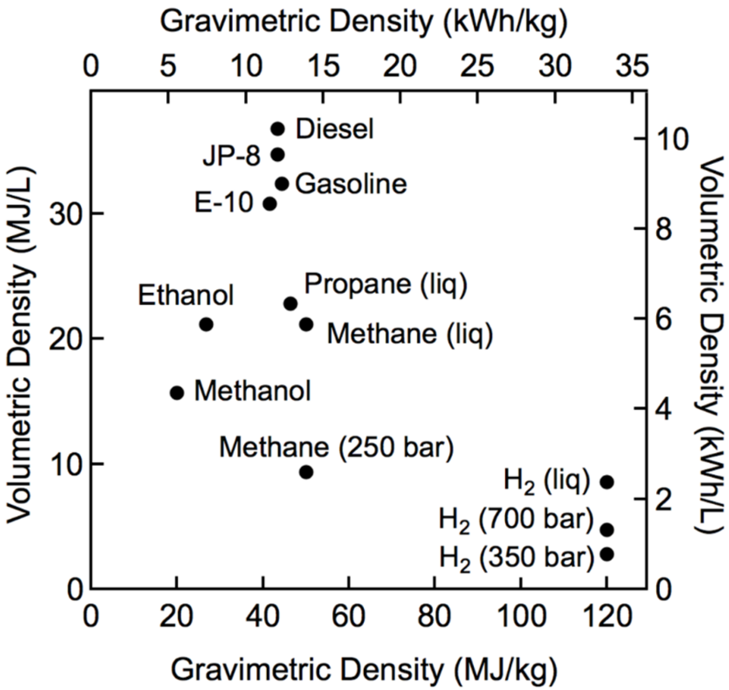
Material base only

Energy Density



Specific Energy

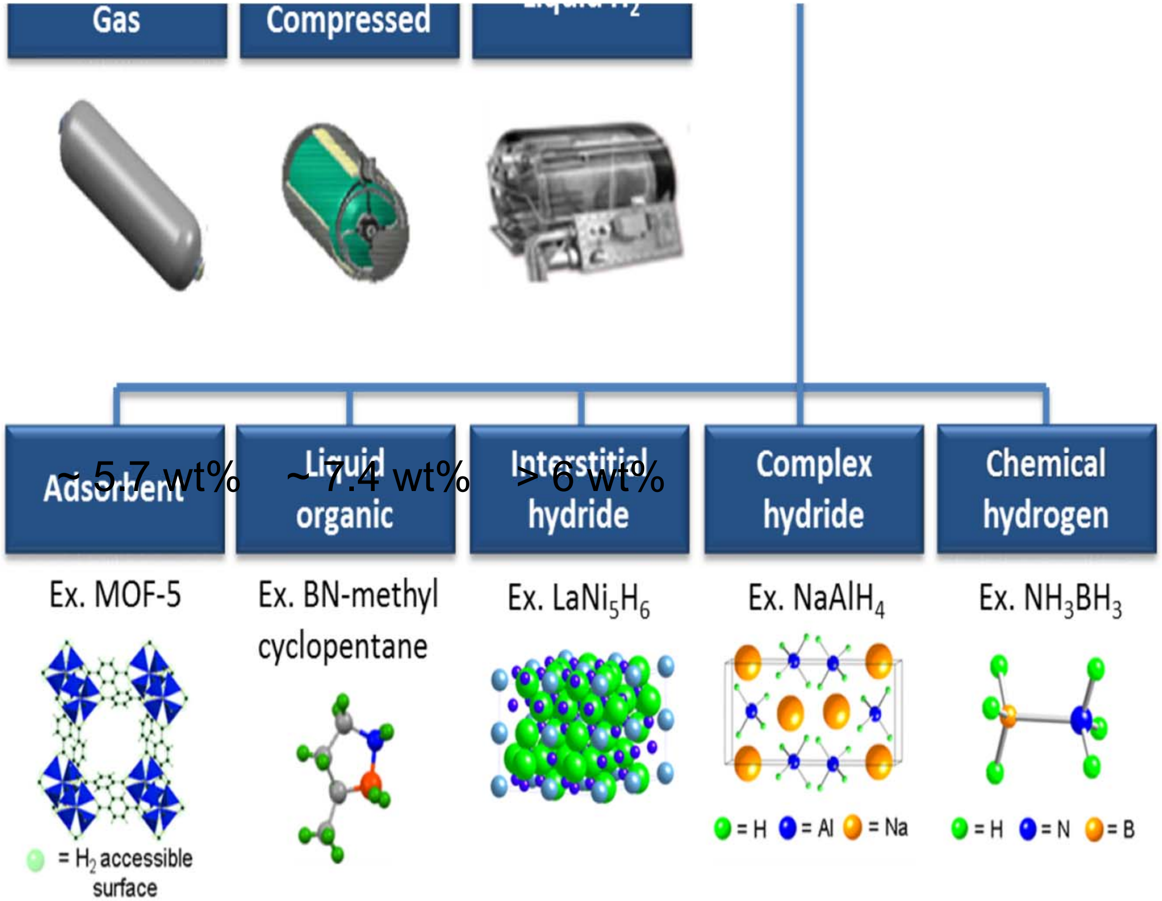


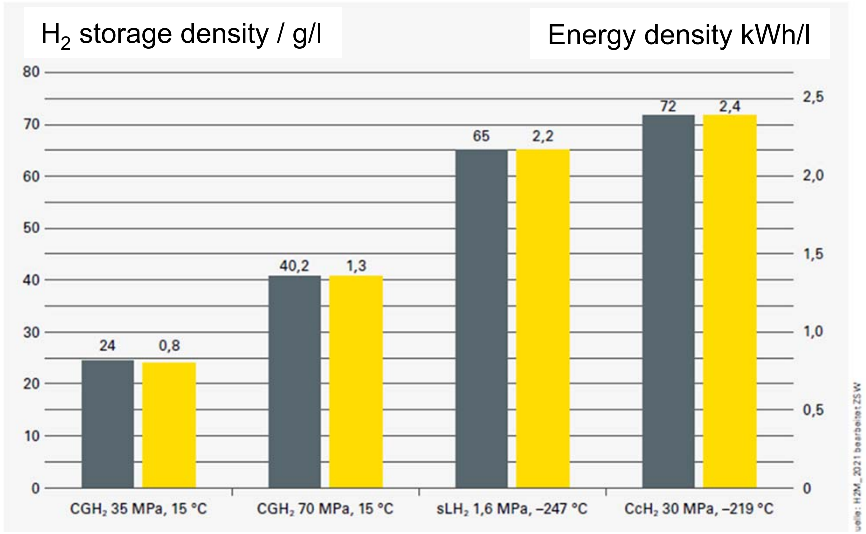


A. Alekseev et al., (2023) Hydrogen liquefaction, storage, transport and application of liquid hydrogen. DOI: 10.5445/IR/1000168281

How is Hydrogen Stored

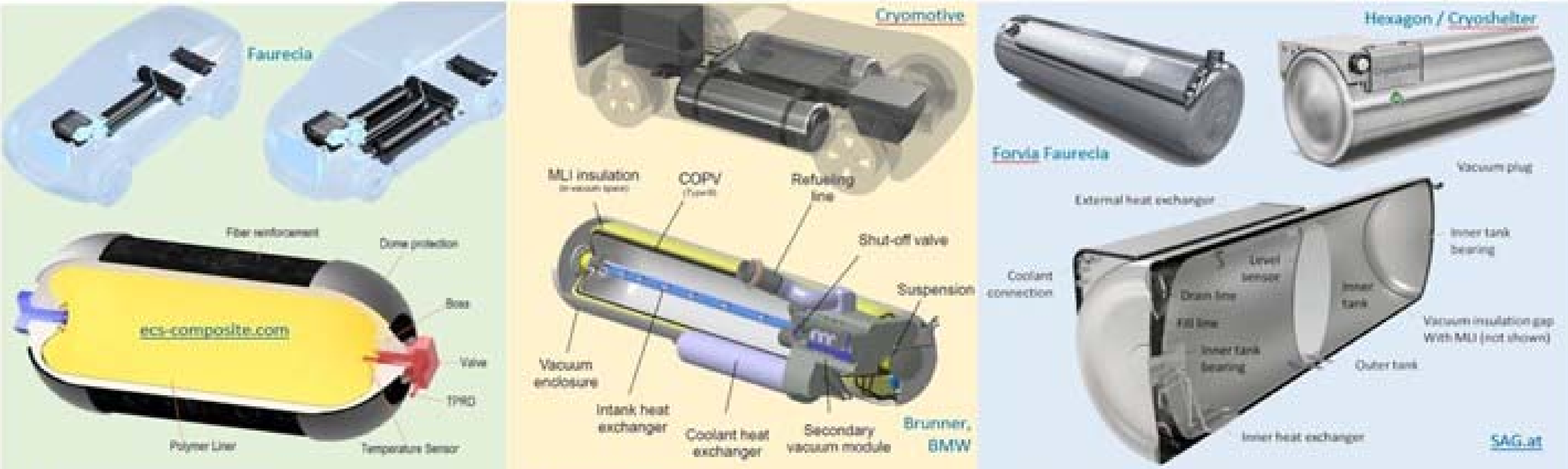
Cryogenic storage preferred





https://www.energy.gov/eere/fuelcells/hydrogen-storage

Comparison of Storage Options



Compressed Gas (CGH_2)	Cryo-compressed (CcH_2)	Subcooled Liquid (sLH_2)
Type IV	Type III inner/MLI + vacuum/metal outer	Type I inner/MLI + vacuum/metal outer
350 – 1,000 bar | 290 K/ 17°C	350-400 bar | 20-340 K/ -253 to 67°C	< 16 bar | 28 K/ -245°C
40 kg/m³ | Carbon Fiber: 1	72 kg/m³ | Carbon Fiber: 0.20	62 kg/m³ | Carbon Fiber: 0

https://www.gardnerweb.com/articles/cryo-compressed-hydrogen-the-best-solution-for-storage-and-refueling-stations

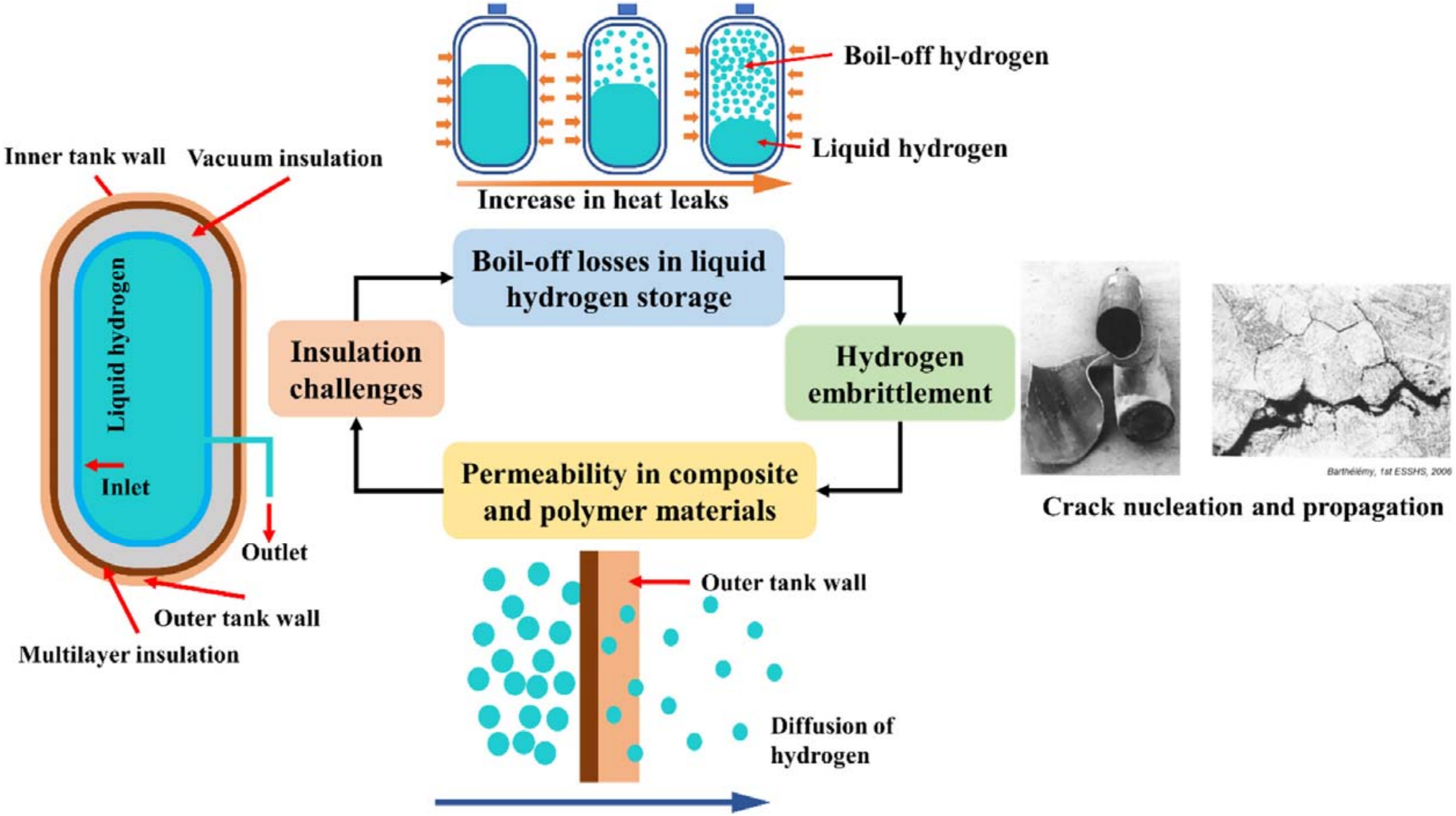
(Flight) Testing Liquid Hydrogen

Image H2fly

H2FLY
Successful filling and flight test in 2023
Range: up to 1500 km

Universal Hydrogen
Ground testing of an „iron bird“

Liquid Hydrogen Storage Challenges

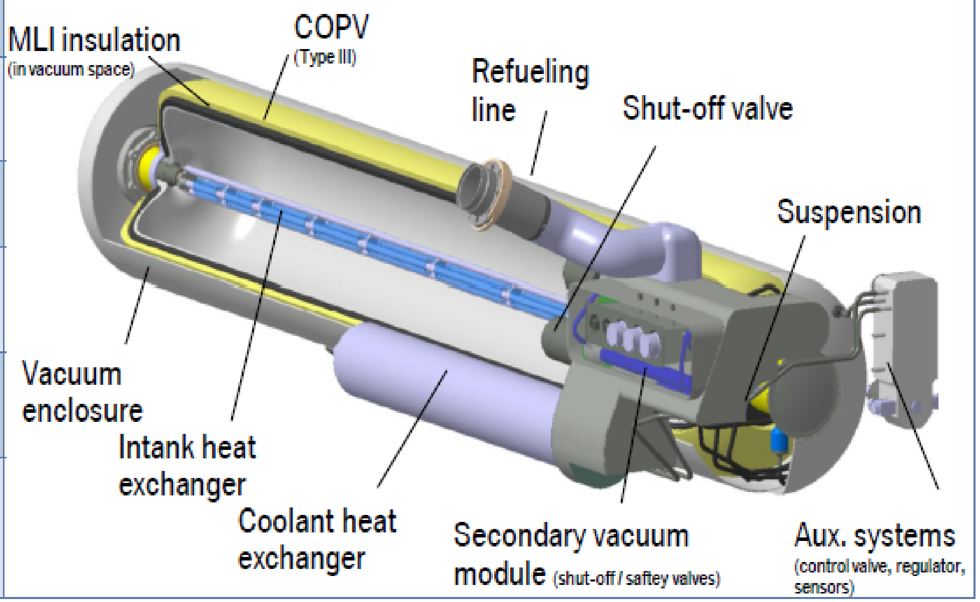


Cryo-Compressed Hydrogen

Modular Super-insulated Pressure Vessel (Type III)

Max. usable capacity	CcH_2: 7.8 kg (260 kWh) CGH_2: 2.5 kg (83 kWh)
Operating pressure	≤ 350 bar
Vent pressure	≥ 350 bar
Refueling pressure	CcH_2: 300 bar CGH_2: 320 bar
Refueling time	< 5 min
System volume	~ 235 L
System weight (incl. H_2)	~ 145 kg
H_2-Loss (Leakage I max. loss rate I infr. driver)	<< 3 g/day I 3 – 7 g/h (CcH_2) I < 1% / year

+ Active tank pressure control
+ Load carrying vehicle body integration
+ Engine/fuel cell waste heat recovery



Hydrogen Liquefaction Challenge

Currently, there are only 3 hydrogen liquefaction plants in Europe having a total capacity of 25.5 t per day

• Leuna:	Linde	2 x 5 t/d
• Lille	AirLiquide	10.5 t/d
• Rozenburg	Air Products	5 t/d

- Largest hydrogen liquefiers currently 36 t/d

- For comparison:
  - Fuel capacity of a Do 228 aircraft: 2 390 l
  - Corresponding to 81 834 MJ
  - Corresponding to 689 kg hydrogen
  - A 5 t per day hydrogen liquefier could serve about 7departing flights per day (50% of the daily traffic at Friedrichshafen airport)
  - A 10 MW electrolyzer would be needed to feed the liquefier
  - A major airport would need 5 880 t H_2/d

Image: Linde

Hydrogen Logistics

Outside Pipeline networks

Image: Linde AG

Trailer 350 bar

Most frequent use today
Ca. 400 kg / truck

Compression energy demand:
9% of hydrogen transported

Image: Linde AG

Trailer up to 500 bar

Current limit
Bis 1.100 kg / truck

Compression energy demand:
12% of hydrogen transported

Image: Linde

Liquid Hydrogen

Current state of the art
Temperature: – 253 °C
Ca. 4.000 kg / truck
Single source in DE: Leuna

Energy demand for liquefaction:
33% of H_2 transported

Vision Hydrogen Onsite Liquefaction and Storage at Airports

Causing a large footprint

Image: amd.sigma strategic airport development GmbH

Summary

- Hydrogen is a promising clean fuel for regional and short range aviation
  - Lightweight (but heavy storage containers)
  - Bulky (low density as gas and liquid)
  - Range limitations due to volume and weight of hydrogen storage
- Hydrogen logistics needs to be developed
  - Long range via pipelines (European Hydrogen Backbone)
  - Short range via Trucks
- Hydrogen as an aviation fuel will be most likely in liquid form
  - Currently limited liquefaction capacities
  - Airports need large scale hydrogen storage facilities (regulatory framework to be developed)
  - Liquefaction at airport premises?
  - Specific regulations are required
  - Partnerships are forming
- Establishing economically viable supply chains (production, storage, distribution …) will be a major challenge in the coming decade(s)

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THANK YOU VERY MUCH FOR YOUR TIME!

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Liquid Hydrogen: Coefficient of Thermal Expansion

Significant temperature and pressure dependence