DOI: https://doi.org/10.15480/882.4386
ORCID: https://orcid.org/0000-0001-6300-4218

Hamburg
12.01.2022

Green Hydrogen Webinar Series

Technologies for supply and utilization of hydrogen

Lucas Sens, Ulf Neuling, Martin Kaltschmitt

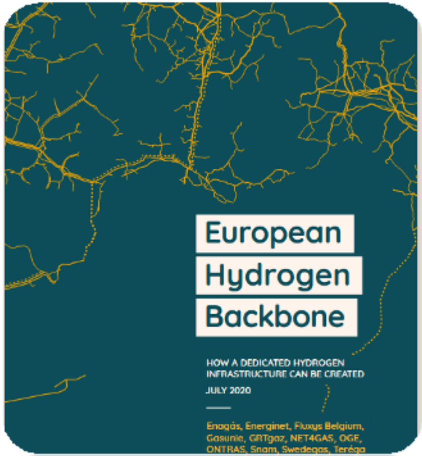
[1] [2] [3] [4] [5] [6]

Hamburg University of Technology (TUHH), Institute of Environmental Technology and Energy Economics (IUE)
www.tuhh.de/iue

Liquefaction (LH_2)

Methanol (CH_3OH)

Compression (CGH_2)



[7]

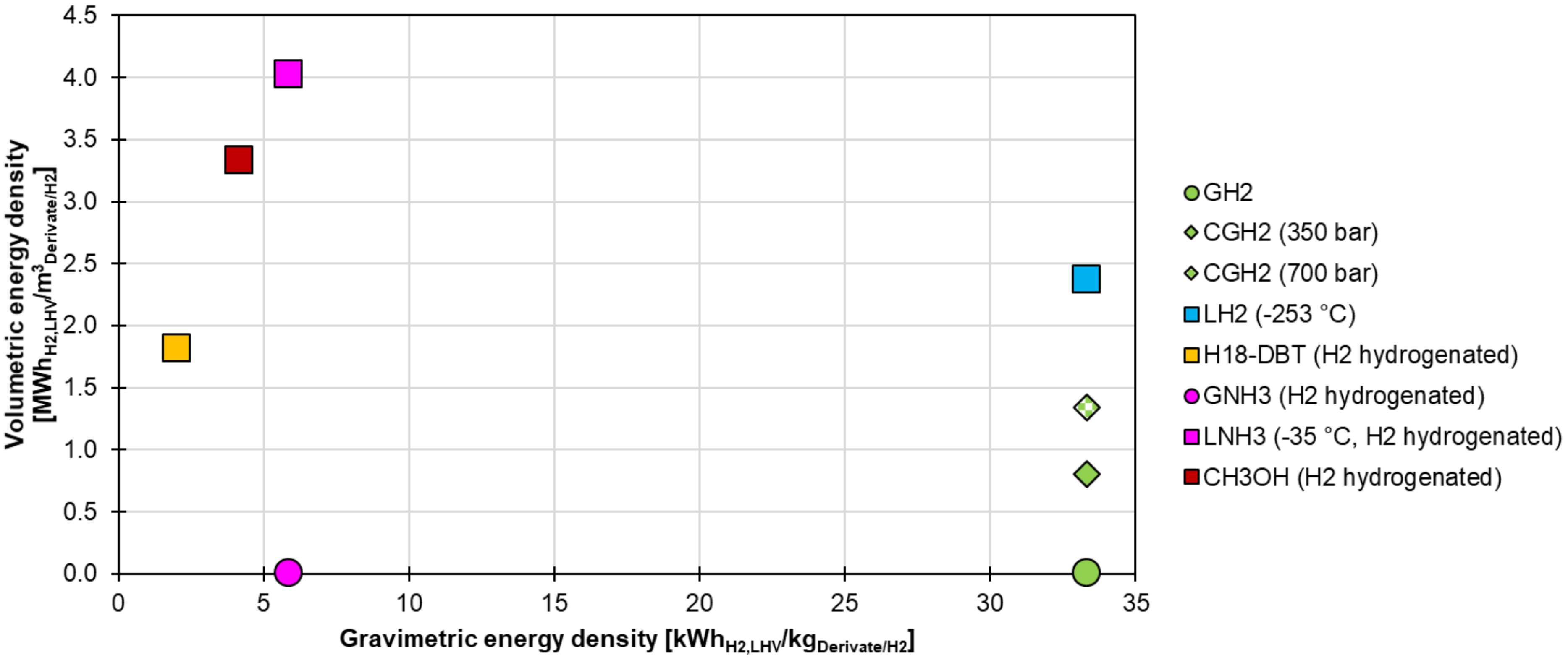
Ammonia (NH_3)

Liquid Organic Hydrogen Carriers (LOHC)

→ Several different conditioned hydrogen options are discussed for low cost hydrogen transportation and storage

Outline

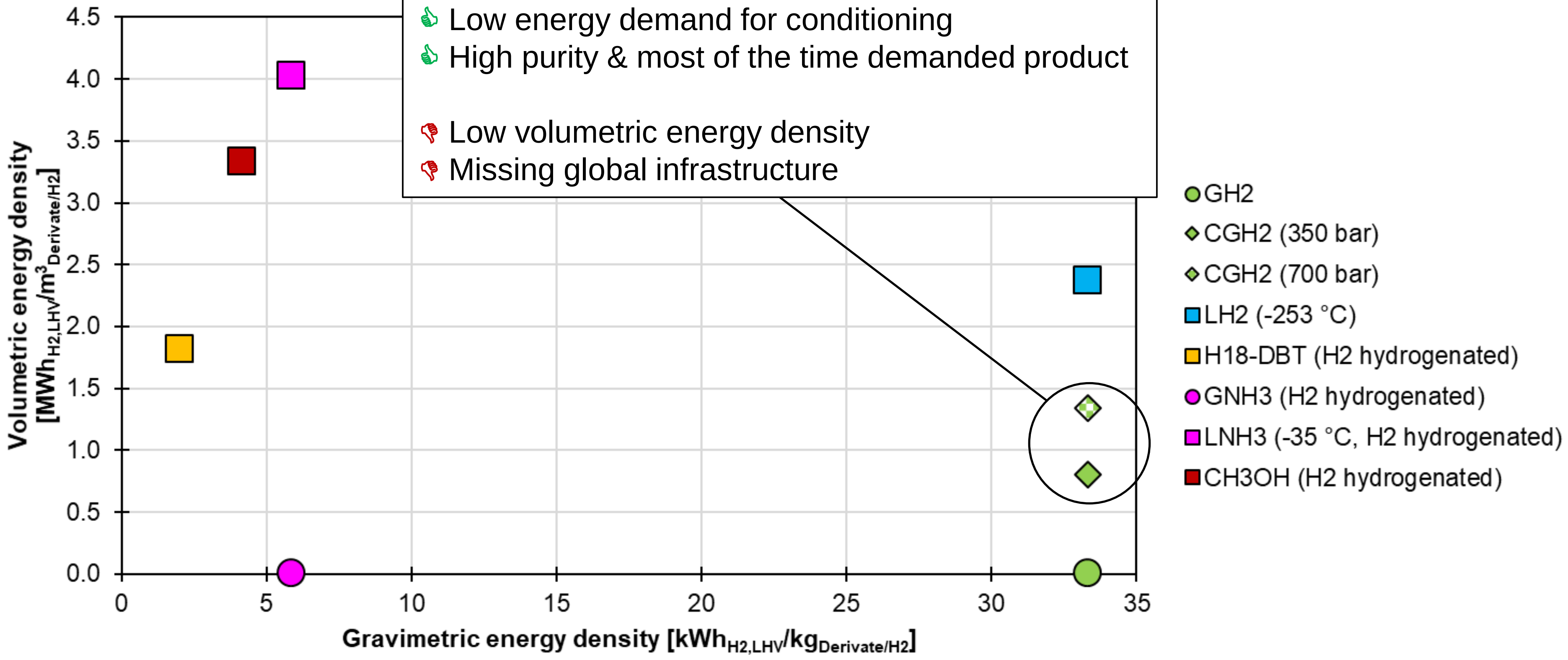
Conditioned Hydrogen Options



Compressed Gaseous Hydrogen (CGH_2)

- Low energy demand for conditioning
- High purity & most of the time demanded product

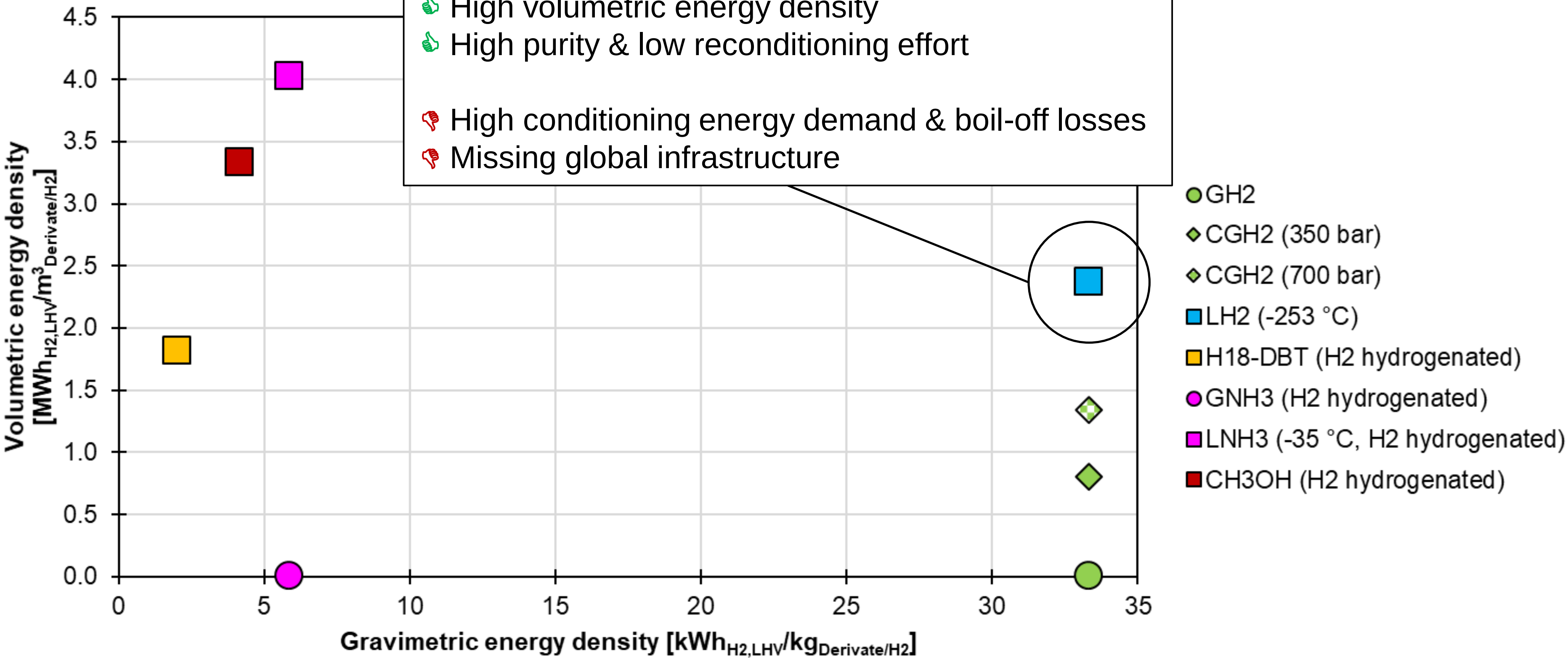
- Low volumetric energy density
- Missing global infrastructure



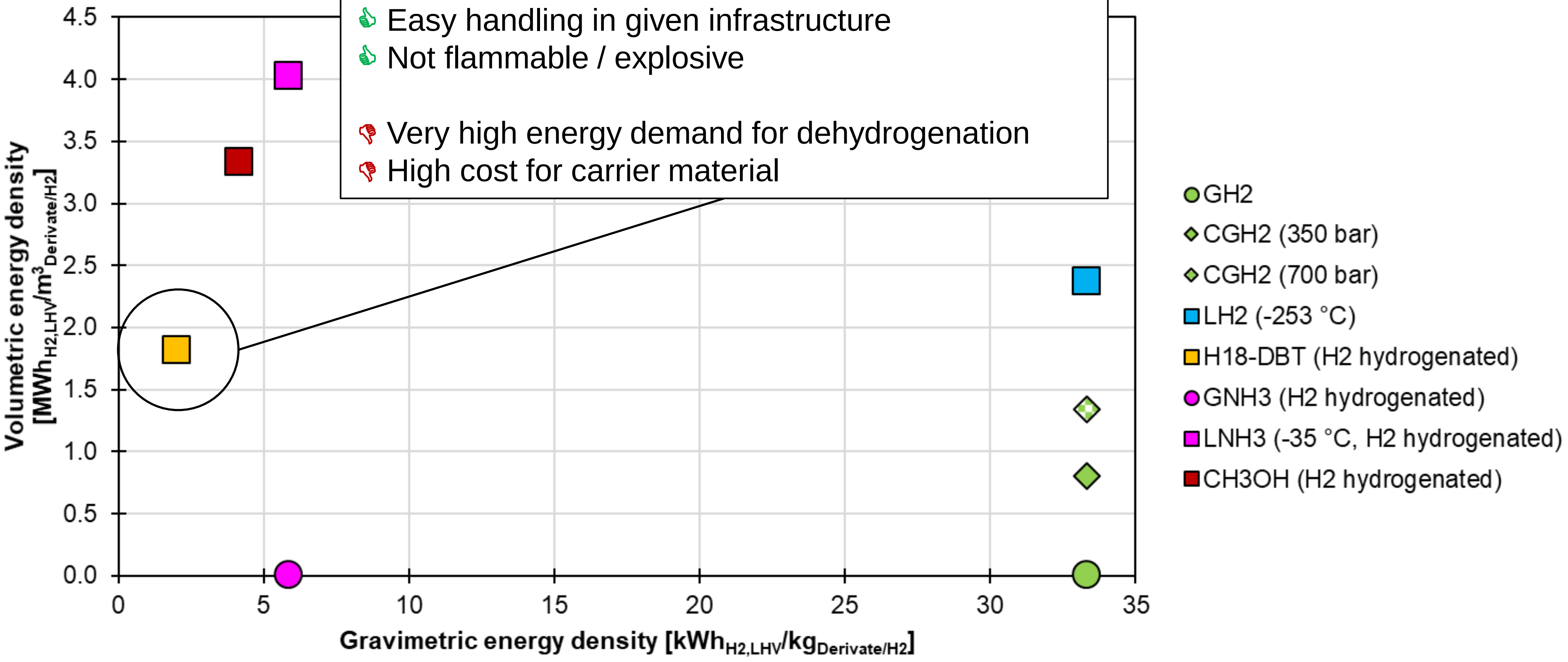
Liquid Hydrogen (LH_2)

- High volumetric energy density
- High purity & low reconditioning effort

- High conditioning energy demand & boil-off losses
- Missing global infrastructure



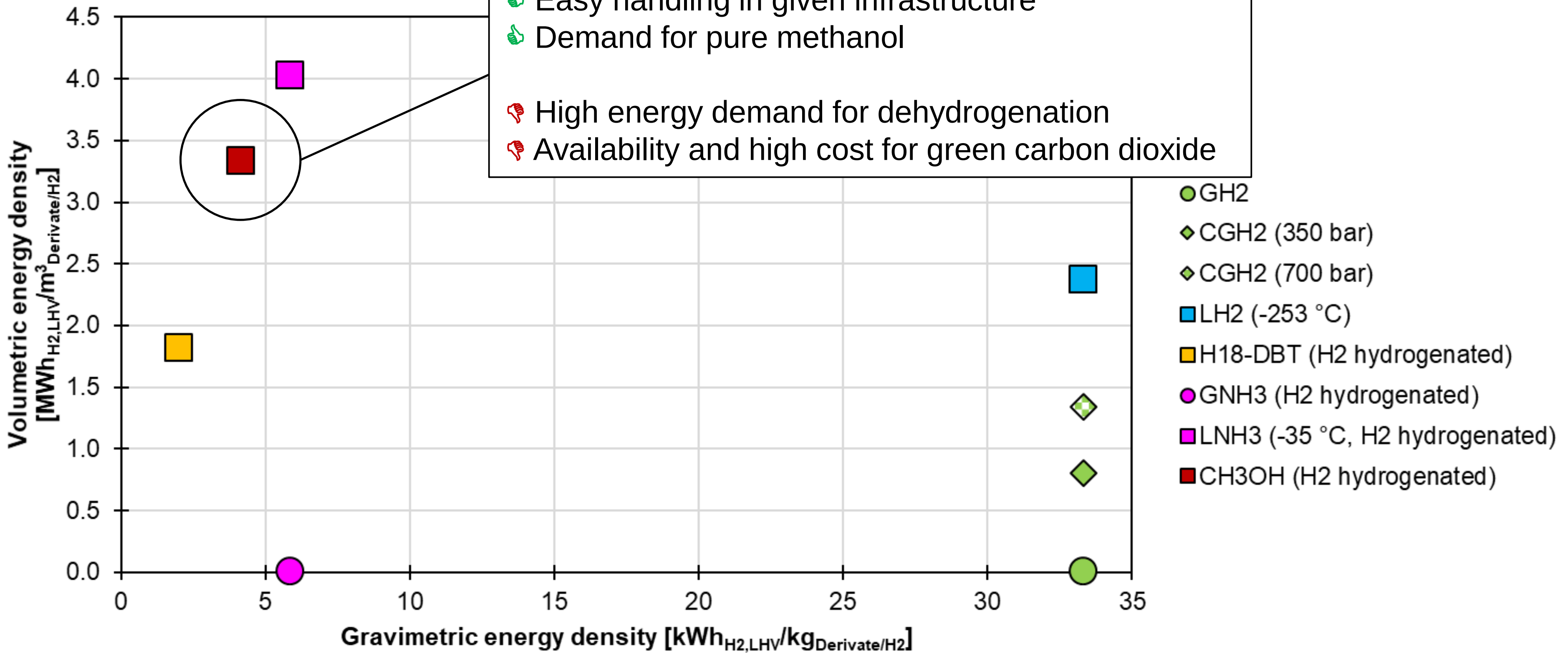
Liquid Organic Hydrogen Carrier (LOHC)



- 👍 Easy handling in given infrastructure
- 👍 Not flammable / explosive

- 👎 Very high energy demand for dehydrogenation
- 👎 High cost for carrier material

Methanol (CH_3OH)



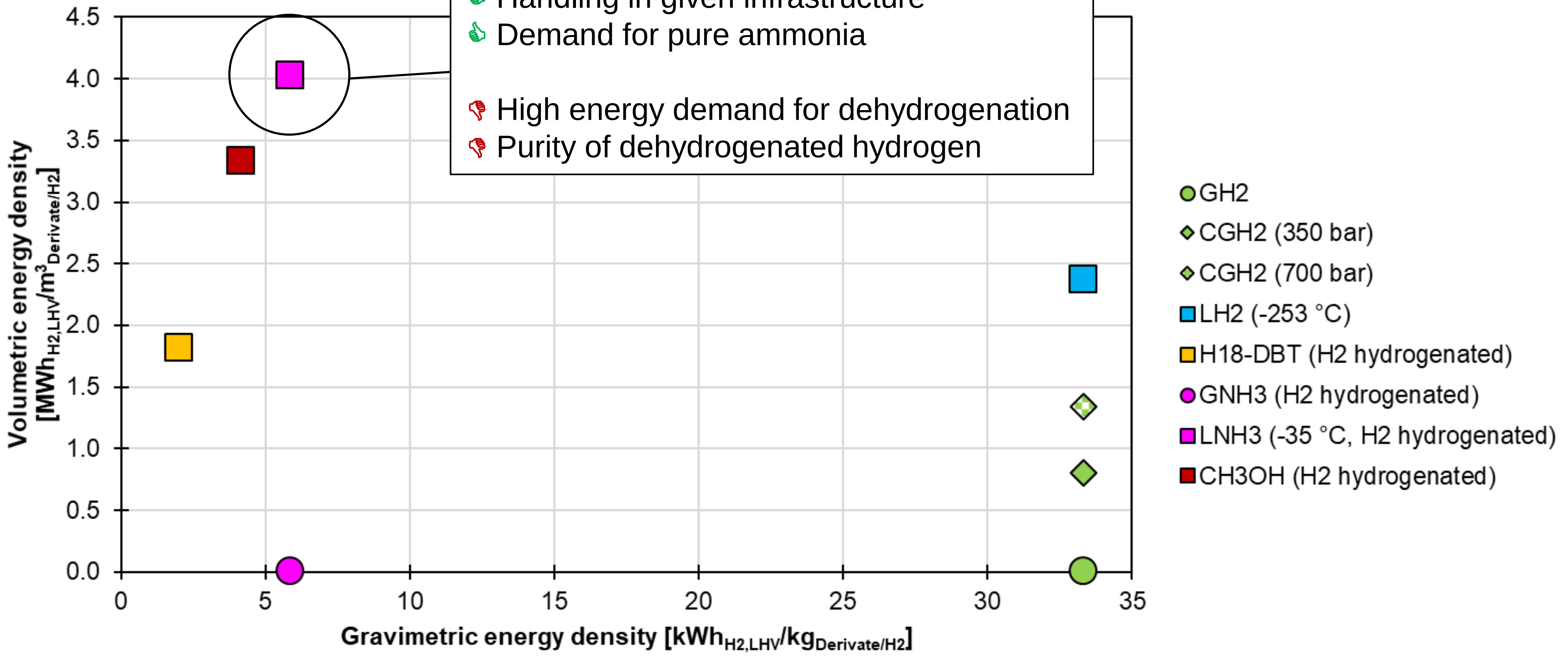
- 👍 Easy handling in given infrastructure
- 👍 Demand for pure methanol

- 👎 High energy demand for dehydrogenation
- 👎 Availability and high cost for green carbon dioxide

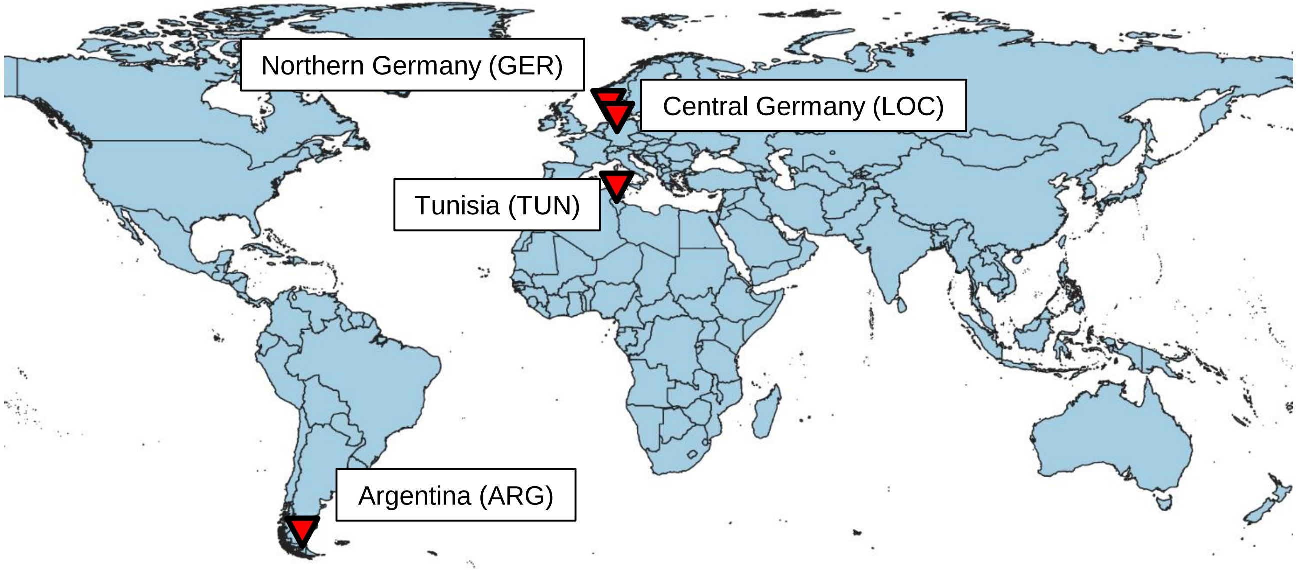
Ammonia (NH_3)

- Handling in given infrastructure
- Demand for pure ammonia

- High energy demand for dehydrogenation
- Purity of dehydrogenated hydrogen

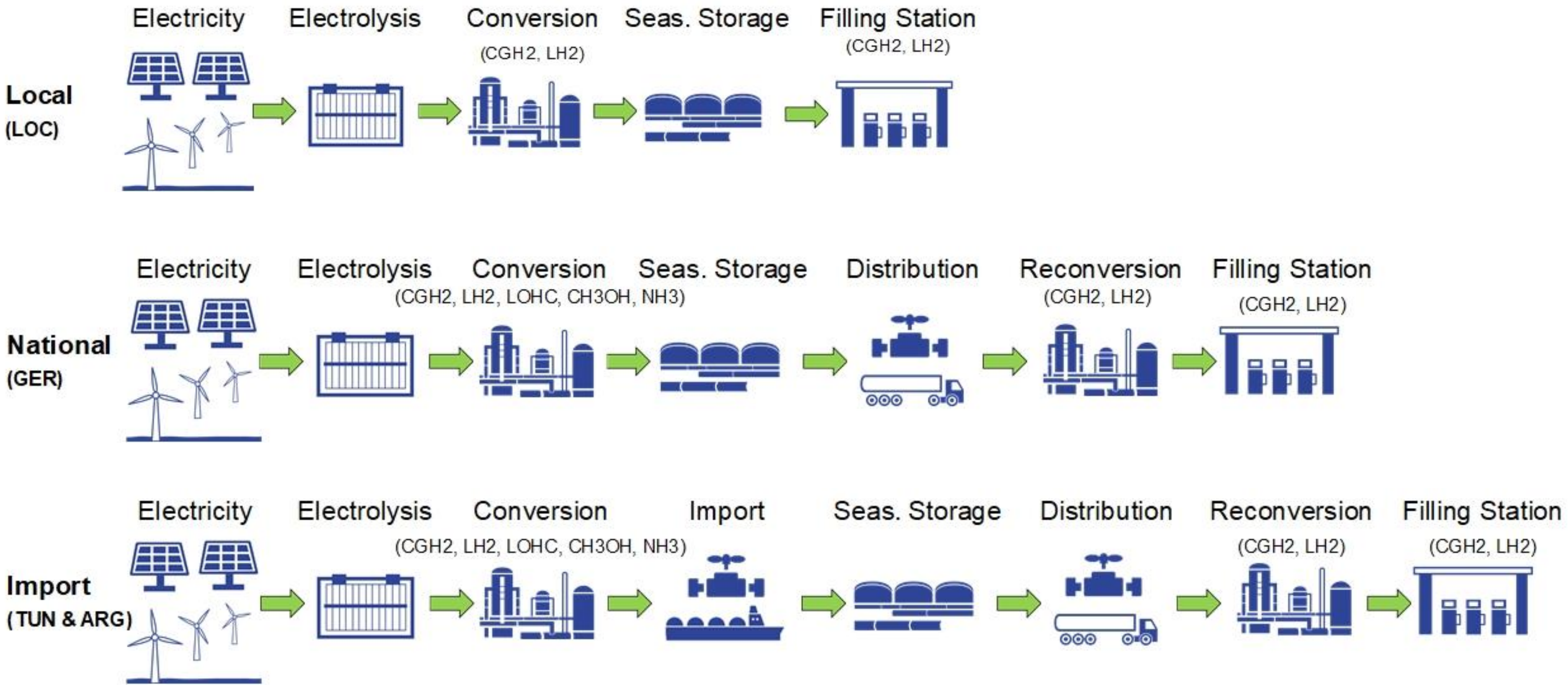


Production Locations



- **Central Germany (LOC):** PV ≈ 1,100 AFLH; Onshore Wind ≈ 2,600 AFLH
- **Northern Germany (GER):** PV ≈ 1,000 AFLH; Offshore Wind ≈ 5,000 AFLH
- **Tunisia (TUN):** PV ≈ 1,800 AFLH; Onshore Wind ≈ 3,500 AFLH
- **Argentina (ARG):** PV ≈ 1,000 AFLH; Onshore Wind ≈ 5,500 AFLH

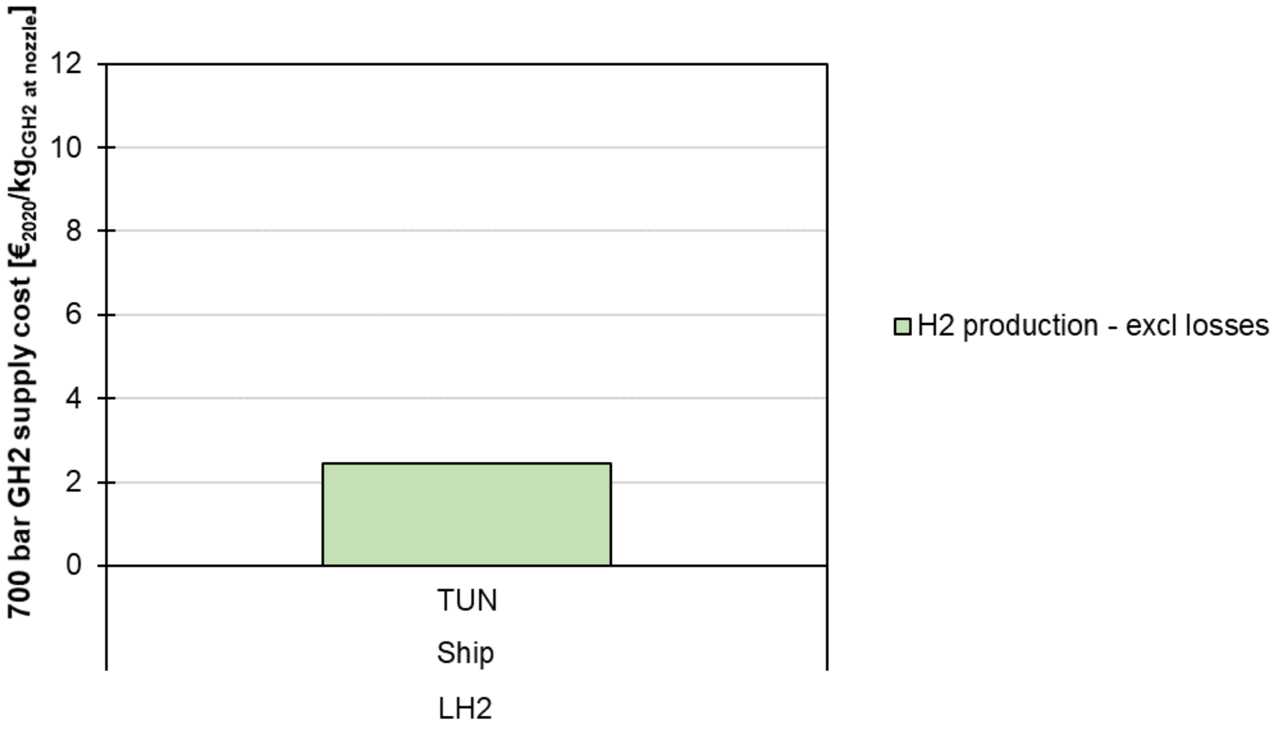
AFLH = annual full load hours


Electricity
Electrolysis
Conversion
(CGH2, LH2)
Seas. Storage
Filling Station
(CGH2, LH2)
Local
(LOC)
Electricity
Electrolysis
Conversion
Seas. Storage
Distribution
Reconversion
Filling Station
(CGH2, LH2, LOHC, CH3OH, NH3)
(CGH2, LH2)
(CGH2, LH2)
National
(GER)
Electricity
Electrolysis
Conversion
Import
Seas. Storage
Distribution
Reconversion
Filling Station
(CGH2, LH2, LOHC, CH3OH, NH3)
(CGH2, LH2)
(CGH2, LH2)
Import
(TUN & ARG)

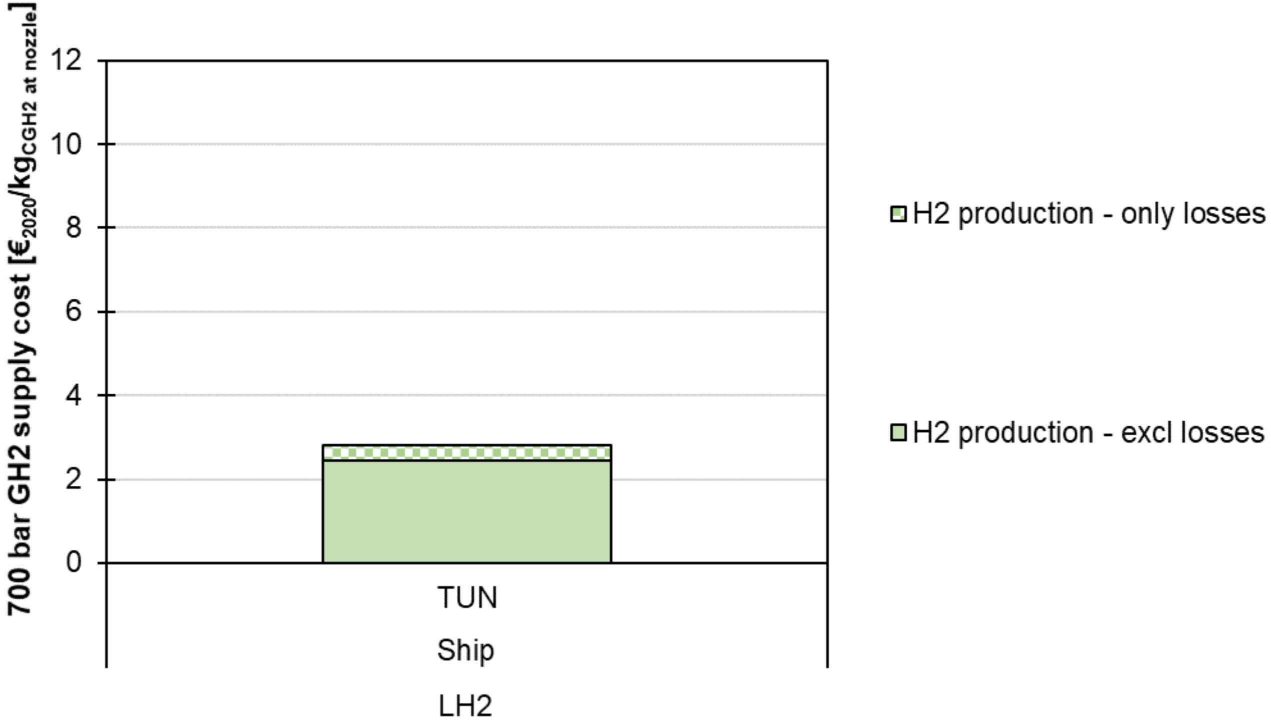
Assessment Approach

- Supply efficiency based on hydrogen (LHV) filled in tank divided by the overall chain energy input from well to tank
- Hydrogen supply cost considers the well to tank costs and is calculated with the annuity method
- Depreciation equals the technology lifetime
- Real weighted average cost of capital set to 6%

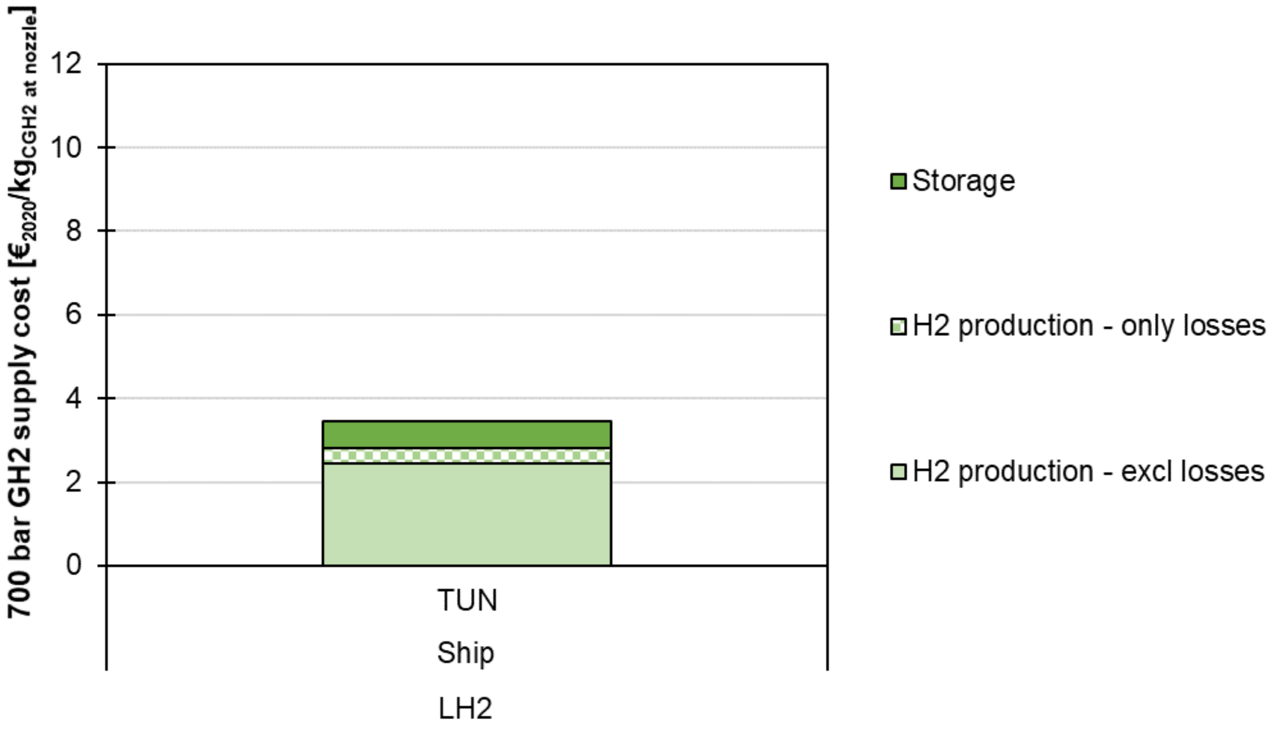
Gaseous Hydrogen Supply Cost in 2030



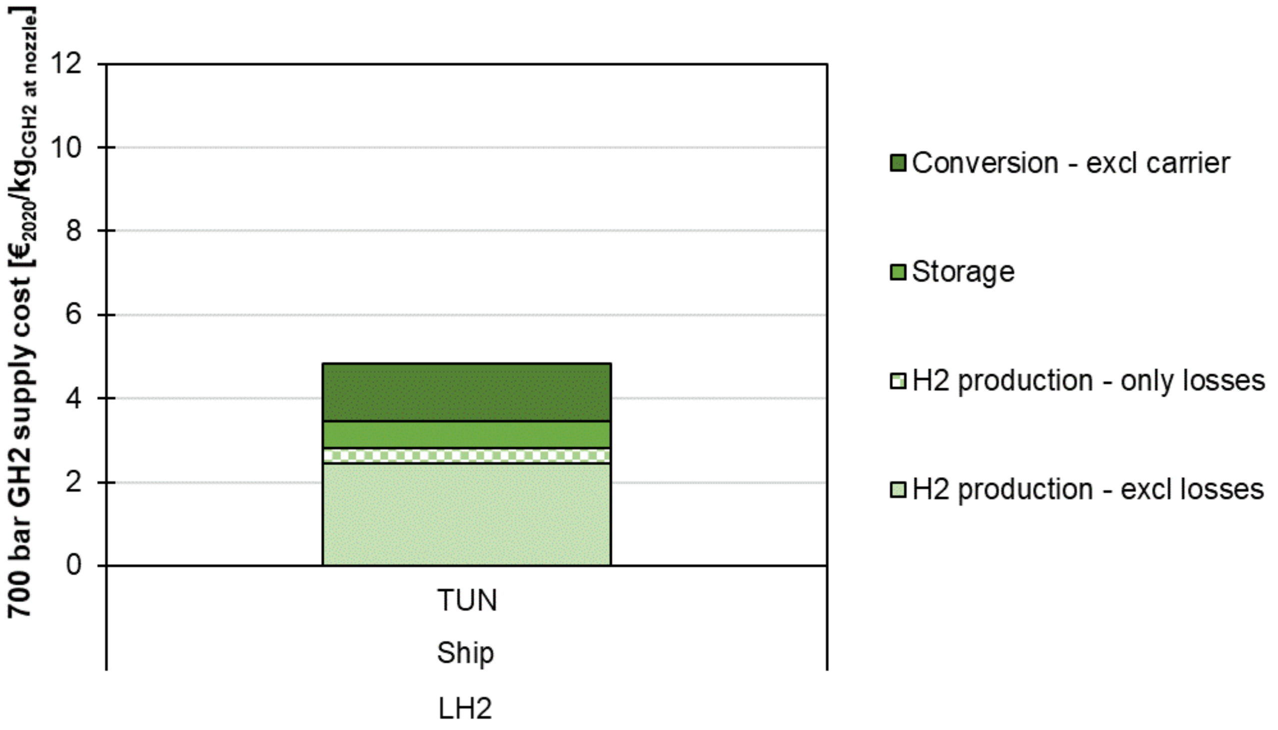
Gaseous Hydrogen Supply Cost in 2030



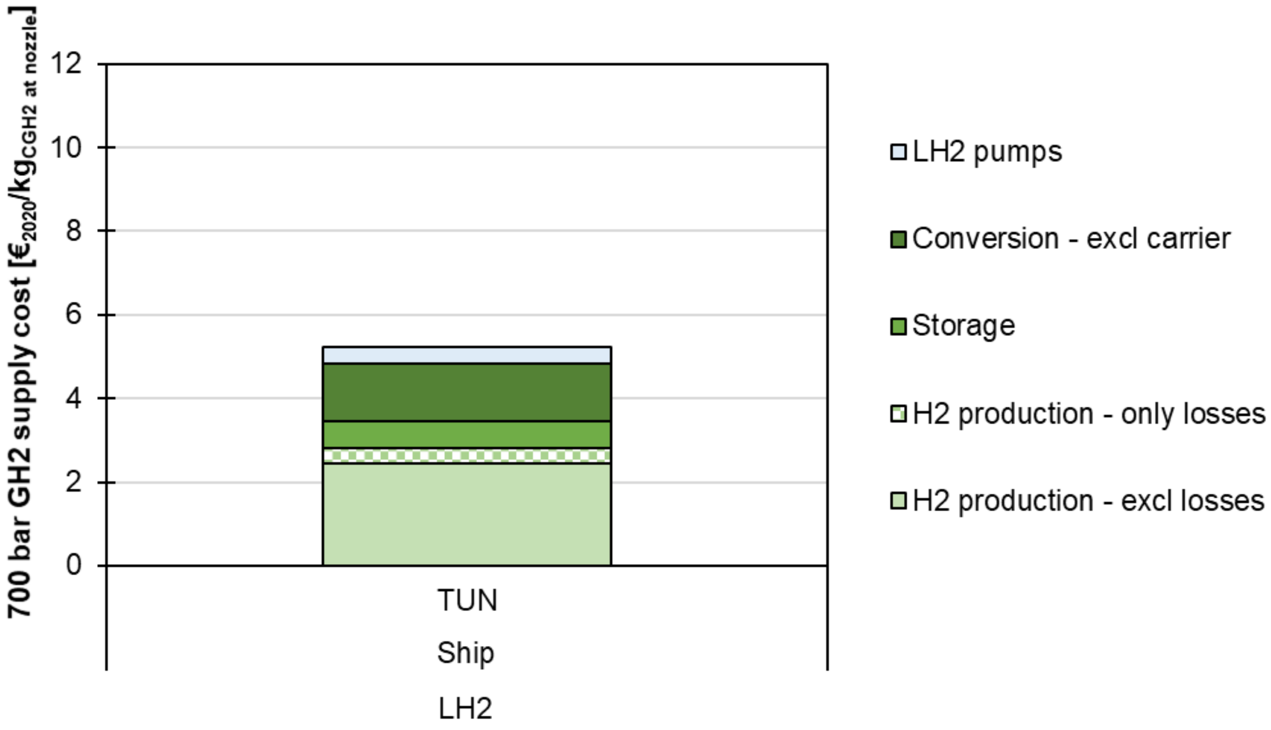
Gaseous Hydrogen Supply Cost in 2030



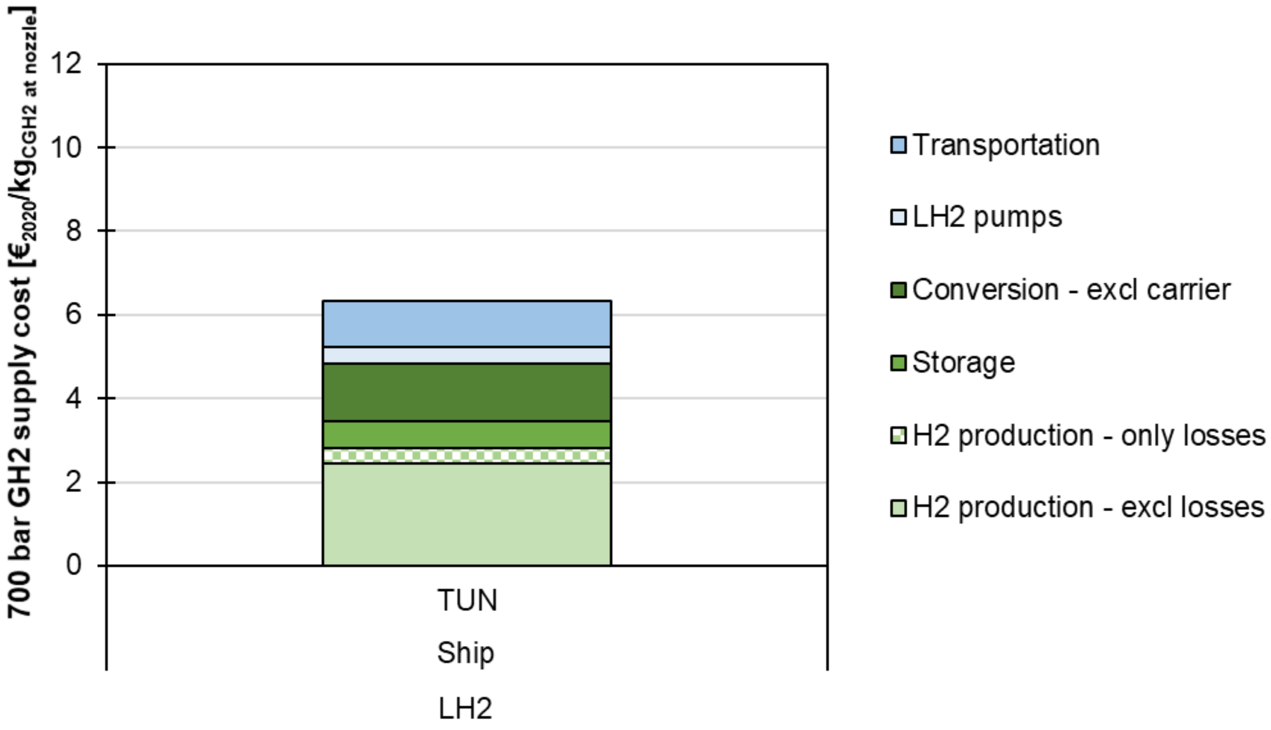
Gaseous Hydrogen Supply Cost in 2030



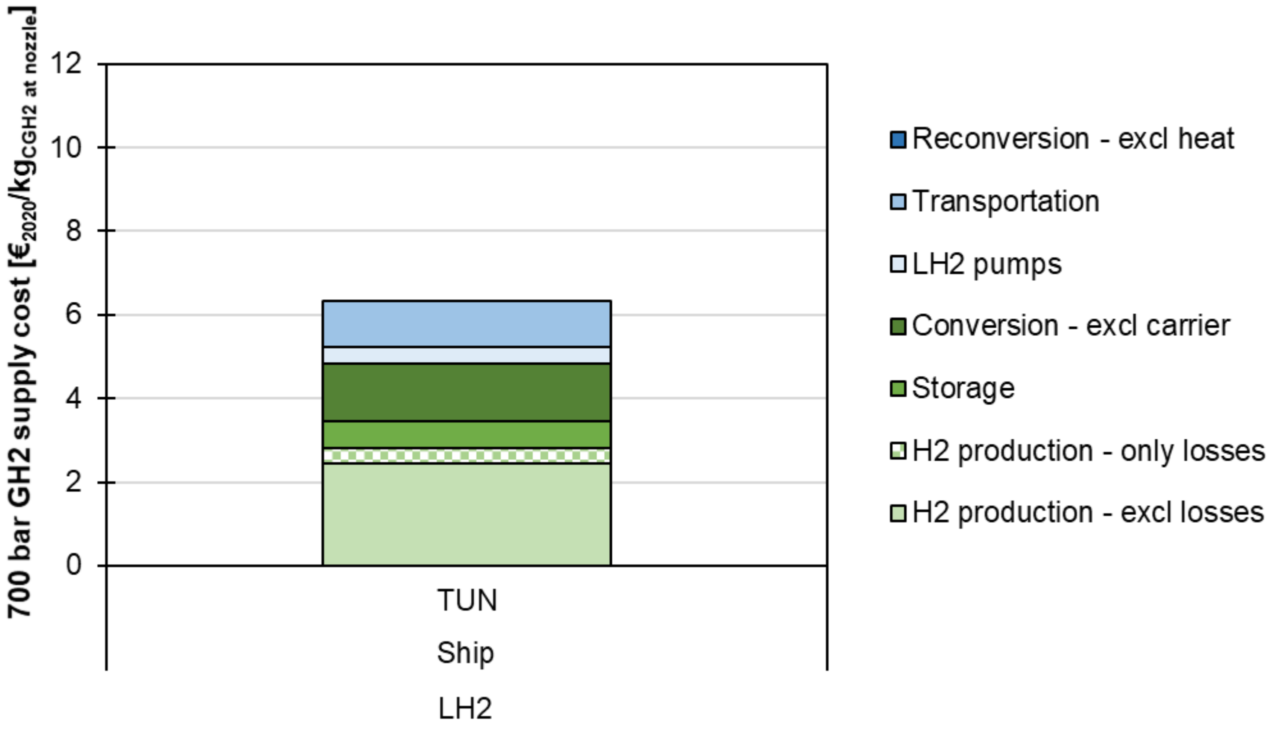
Gaseous Hydrogen Supply Cost in 2030



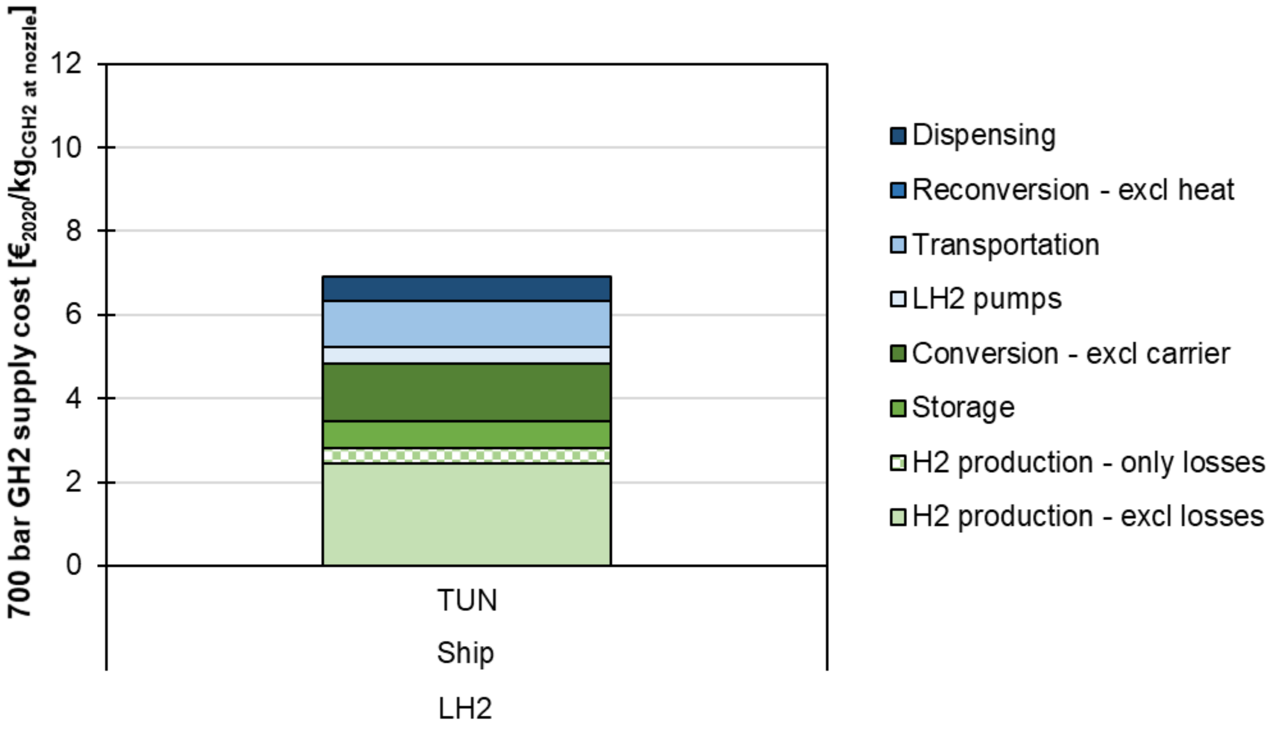
Gaseous Hydrogen Supply Cost in 2030



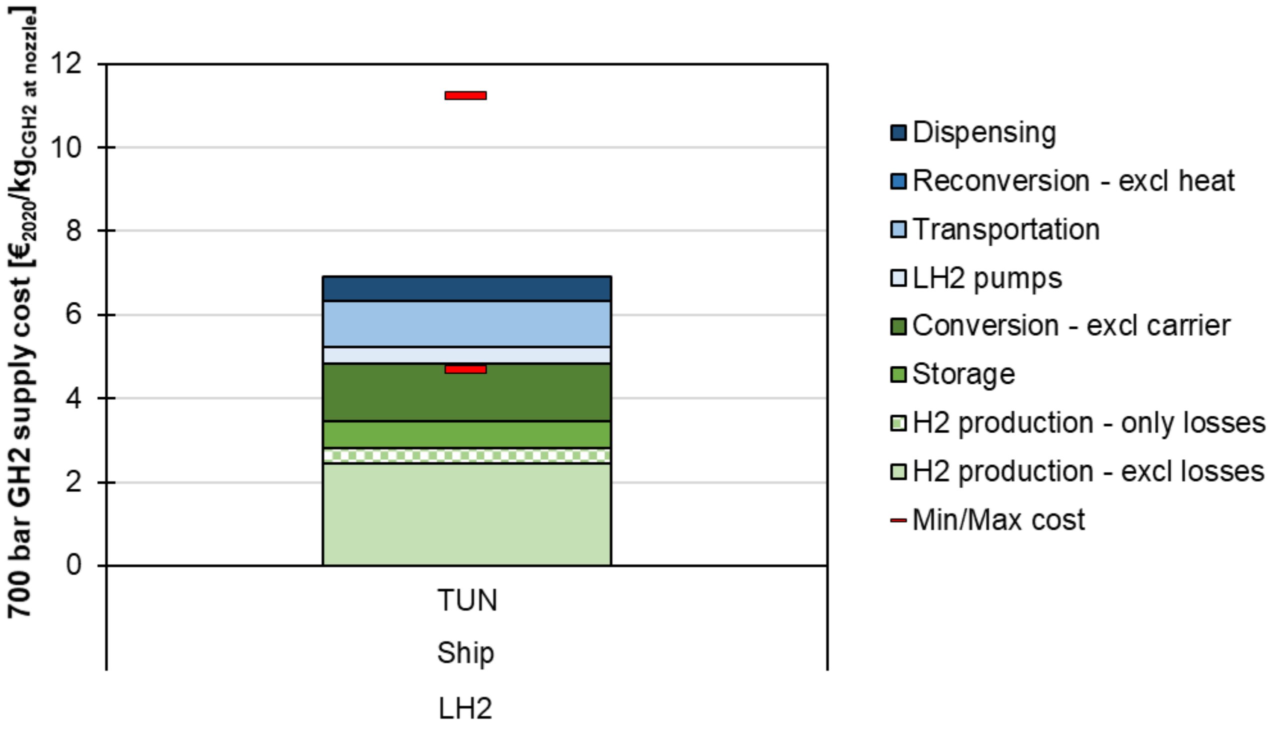
Gaseous Hydrogen Supply Cost in 2030



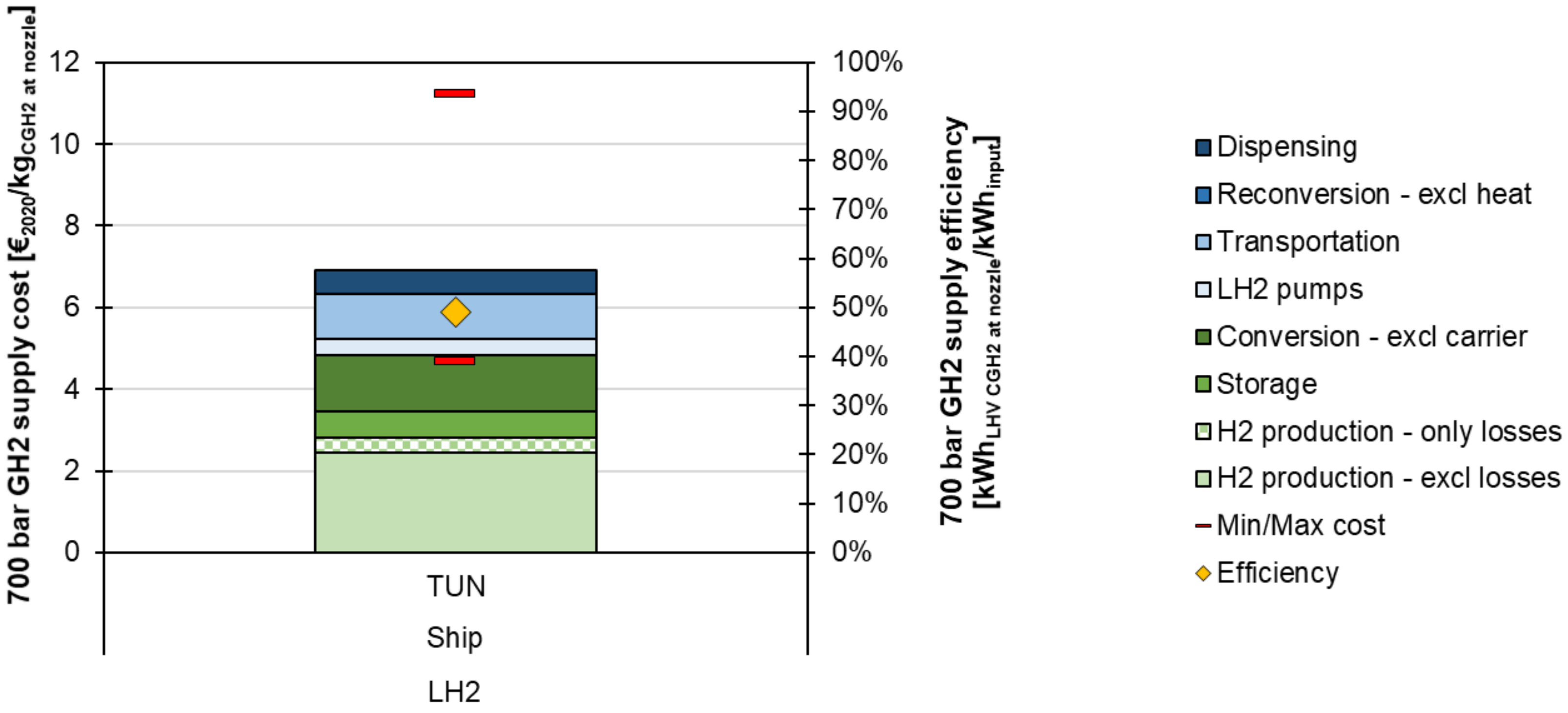
Gaseous Hydrogen Supply Cost in 2030



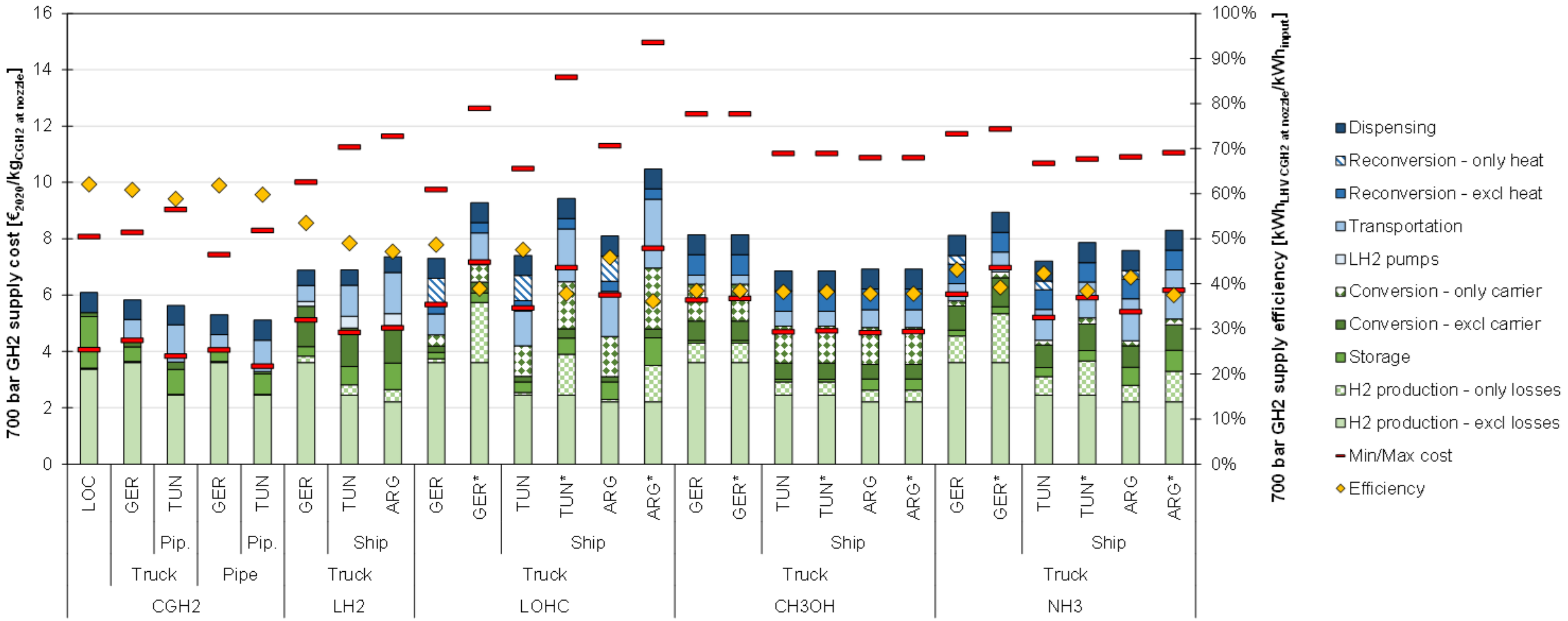
Gaseous Hydrogen Supply Cost in 2030



Gaseous Hydrogen Supply Cost in 2030

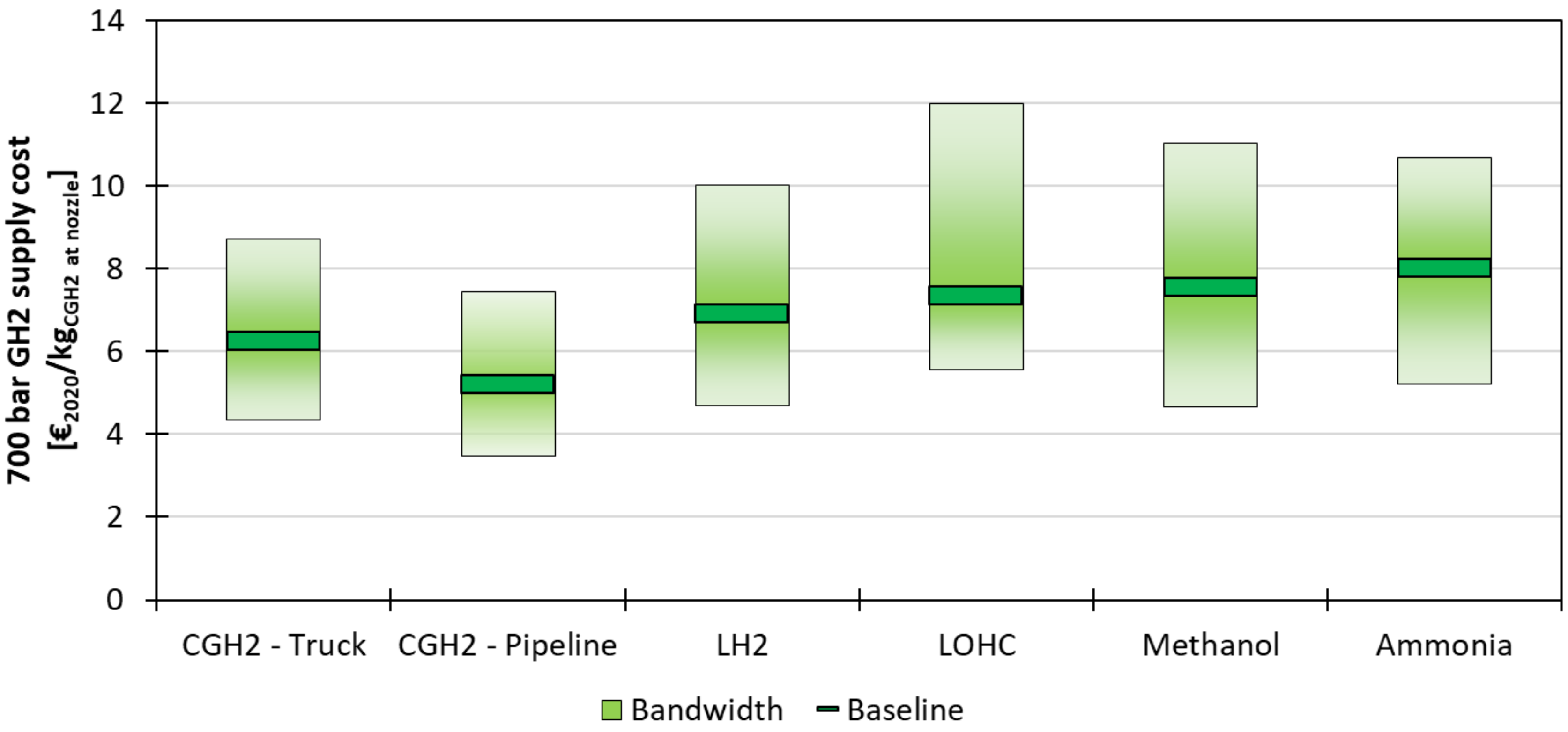


Gaseous Hydrogen Supply Cost in 2030

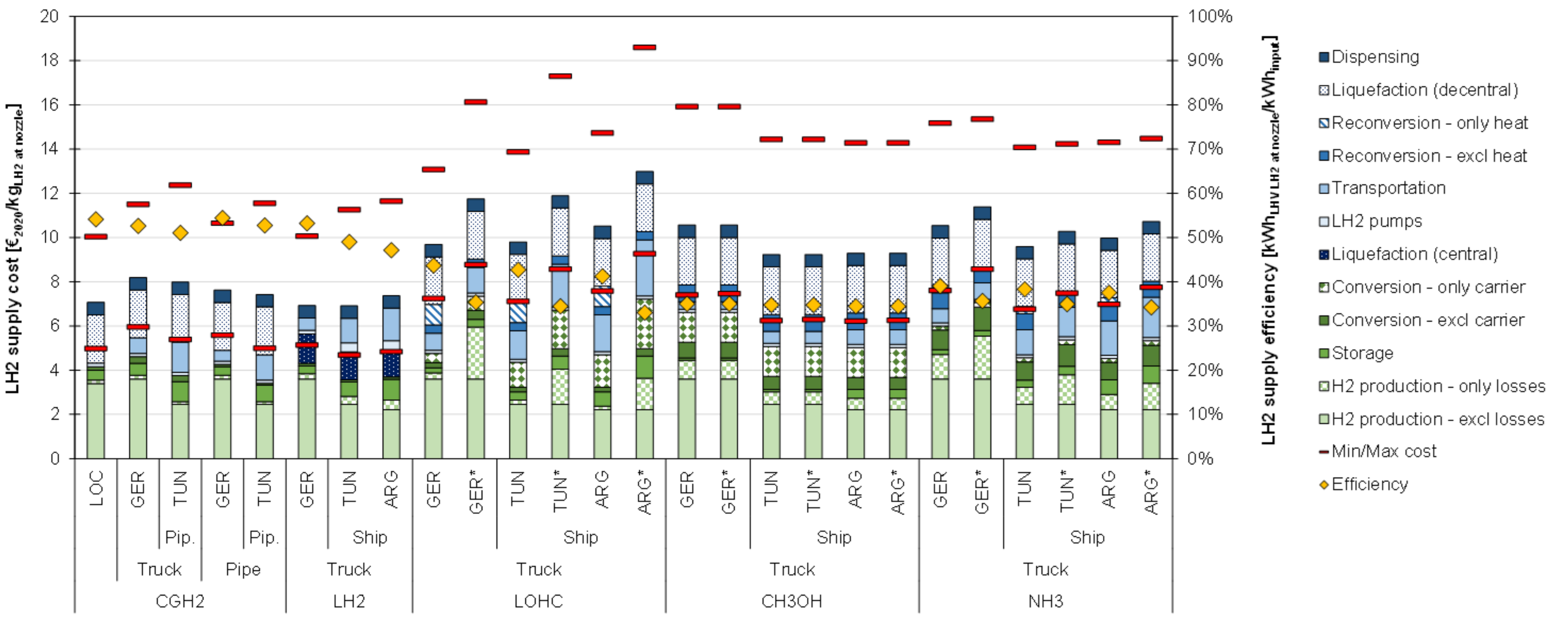


* Hydrogen is used for the dehydrogenation heat supply

Gaseous Hydrogen Supply Cost in 2030

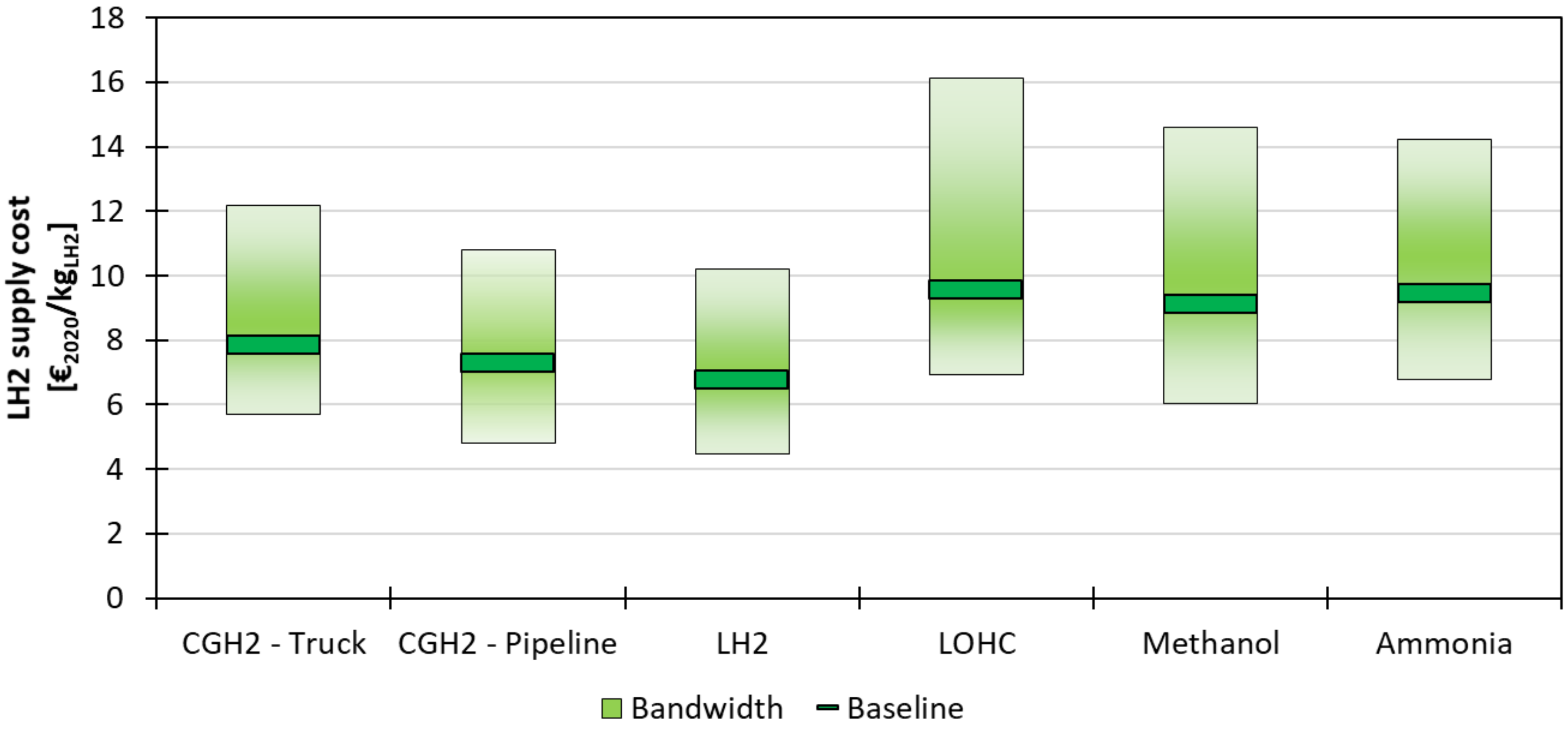


Liquid Hydrogen Supply Cost in 2030

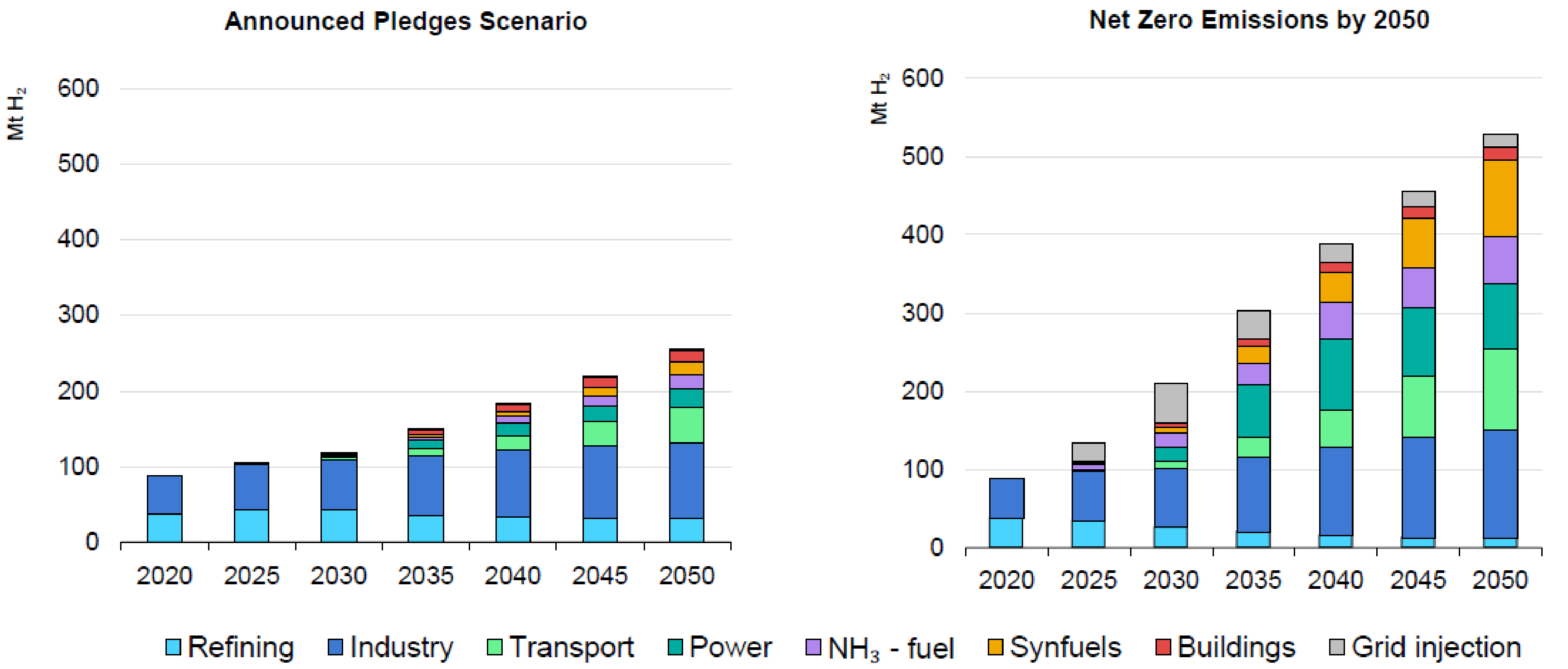


* Hydrogen is used for the dehydrogenation heat supply

Liquid Hydrogen Supply Cost in 2030



Overview Hydrogen Utilization



[12]

Heavy Duty Vehicles

- Faster refueling times reduces downtimes
- Lighter energy storage enables higher payloads
- Higher energy density offers longer ranges

⇨ Promising for multi-day, difficult-to-plan long-haul transport

Aviation and Shipping

- Energy efficient green fuel
- Lower supply cost than PtL fuels
- Enables stronger reduction of the global warming potential

⇨ Promising for short to midrange airplanes and vessels

Steel and Electricity Generation

- Direct iron reduction using hydrogen is seen as the most promising defossilization option for steel
- Salt cavern enables long time storage of renewable energy and with a subsequent electricity generation an uninterruptible power supply

Hamburg University of Technology (TUHH)

Institute of Environmental Technology and Energy Economics (IUE)

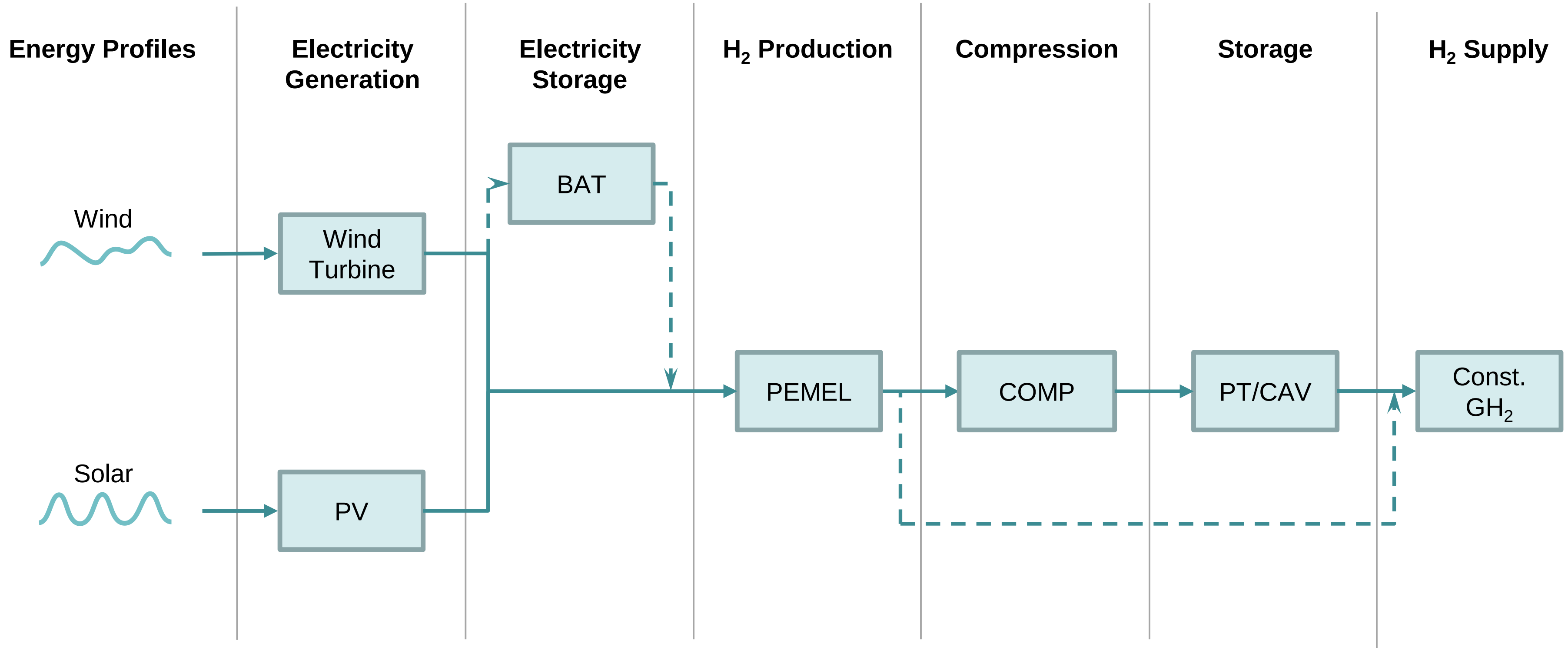
Eissendorfer Str. 40; D-21073 Hamburg

References

- Images slide 1, from left to right:
  - [1] https://images.app.goo.gl/q2W7NAgYantkJjKZ9
  - [2] https://images.app.goo.gl/tgVUA1EQwqGEsxhm8
  - [3] https://images.app.goo.gl/emZiwi4GPQbrGvHu6
  - [4] https://images.app.goo.gl/wpf5beDJPAXoCJxF6
  - [5] https://images.app.goo.gl/bD24v1L26ANsmx4n8
  - [6] https://images.app.goo.gl/58YNgjNLviaWJ1rZA
- Images slide 2, from left to right:
  - [7] https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/
  - [8] http://www.hystra.or.jp/en/gallery/article.html
  - [9] https://www.hydrogenious.net/index.php/en/2020/07/21/lohc-global-hydrogen-opportunity/
  - [10] https://vision-mobility.de/news/gumpert-will-methanol-brennstoffzelle-weiterentwickeln-58015.html
  - [11] https://www.wasserstoff-leitprojekte.de/leitprojekte/transhyde
- Images slide 26, from left to right:
  - [12] https://www.iea.org/reports/global-hydrogen-review-2021
- Images slide 27, from left to right:
  - [13] https://www.daimler.com/innovation/drive-systems/hydrogen/start-of-testing-genh2-truck-prototype.html
  - [14] https://totallyev.net/hyundais-xcient-hydrogen-fuel-cell-powered-truck-heads-to-europe/
- Images slide 28, from left to right:
  - [15] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe
  - [16] https://www.rechargenews.com/technology/worlds-first-hydrogen-powered-ferry-in-norway-to-run-on-green-gas-from-germany/2-1-976939
- Images slide 29, from left to right:
  - [17] https://www.faz.net/aktuell/technik-motor/technik/sauberer-stahl-wasserstoff-als-alternative-zum-koksen-15456145.html
  - [18] https://www.offshorewind.biz/2021/12/17/worlds-first-offshore-hydrogen-storage-concept-unveiled/
  - [19] https://www.envisioninteligence.com/blog/gas-turbine-manufacturers-market-share/

Detailed Supply Chains

Optimized Hydrogen Production



BAT = Battery; CAV = Cavern; COMP = Compressor; GH_2 = Gaseous Hydrogen; PT = Pressure Tank

Key Assumptions

	Year	PV	Onshore Wind	Offshore Wind	PEMEL
CAPEX [$€_{2020}/kW_{el}$]	2030	400 (310 – 570)	1,110 (1,010 – 1240)	1,890 (1,750 – 2,020)	860 (580 – 1,230)
	2050	270 (170 – 350)	990 (860 – 1,140)	1,620 (1,320 – 1,930)	510 (350 – 760)
Efficiency [$kWh_{H2,LHV}/kWh_{el}$]	2030	-	-	-	67% (63 – 69%)
	2050	-	-	-	71% (67 – 74%)

Seasonal storage capacities:

- Local (LOC) scenario: 15 days
- National (GER) scenario: 30 days
- Import (TUN & ARG) scenario: 60 days

Filling station capacity rate:

- Baseline: 50%
- Progressive: 60%
- Conservative: 40%

Technical Assessment

$$\eta_{supply\ chain} = \frac{q_{H2,nozzle}}{q_{overall}}$$

$$q_{overall} = q_{production} + q_{conversion} + q_{storage} + q_{transport} + q_{reconversion} + q_{fill}$$

$$q_{production} = q_{production,ideal} + q_{production,losses}$$

$$q_{compression} = \frac{R_s\, T_{comp}}{\eta_{comp}} \left[z_{out}\ \ln\left(\frac{p_{out}}{1.0135\ bar}\right) - z_{in}\ \ln\left(\frac{p_{in}}{1.0135\ bar}\right) \right]$$

Economic Assessment

$$c_{overall} = c_{production} + c_{conversion} + c_{storage} + c_{transport} + c_{reconversion} + c_{fill}$$

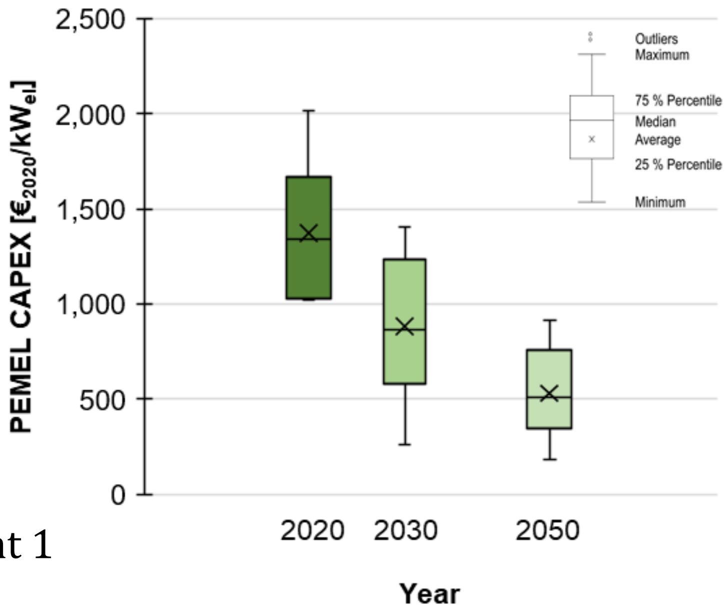
$$c_{section,i} = \frac{ACAPEX_i + OPEX_i}{m_{H2,fill,annual}}$$

$$ACAPEX_i = CAPEX_i \frac{WACC_{real}\,(1+WACC_{real})^{d_i}}{(1+WACC_{real})^{d_i}-1}$$

$$WACC_{real} = \frac{1+WACC_{nom}}{1+INFL} - 1$$

CAPEX Calculation

$$CAPEX_1 = f_{inst}\ f_{infl}\ CAPEX_{ref} \left(\frac{C_1}{C_{ref}}\right)^{\alpha}$$



- α = scaling factor
- C_1 = capacity of plant 1
- C_{ref} = capacity of reference plant
- $CAPEX_{1,inst}$ = installed 2020 € capital expenditure plant 1
- $CAPEX_{ref}$ = capital expenditure for reference plant
- f_{infl} = inflation factor (adjustmend to 2020 €)
- f_{inst} = installation factor (includes equipment, materials, construction and engineering)

LOHC CAPEX

$$c_{LOHC} = \frac{CAPEX_{LOHC}}{Cycle_{LOHC,annual}} \frac{WACC_{real}\,(1+WACC_{real})^{d_{LOHC}}}{(1+WACC_{real})^{d_{LOHC}}-1}$$

$$cycle_{LOHC,annual} = 8760\frac{h}{a} / \; t_{LOHC,cycle}$$

$$t_{LOHC,cycle} = \sum_{i=1}^{n} t_i$$