



Hamburg  
24.02.2022

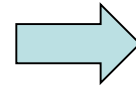
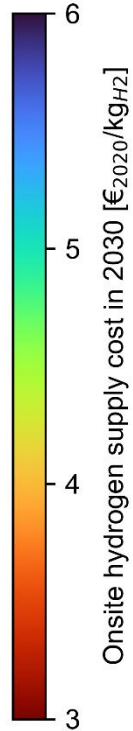
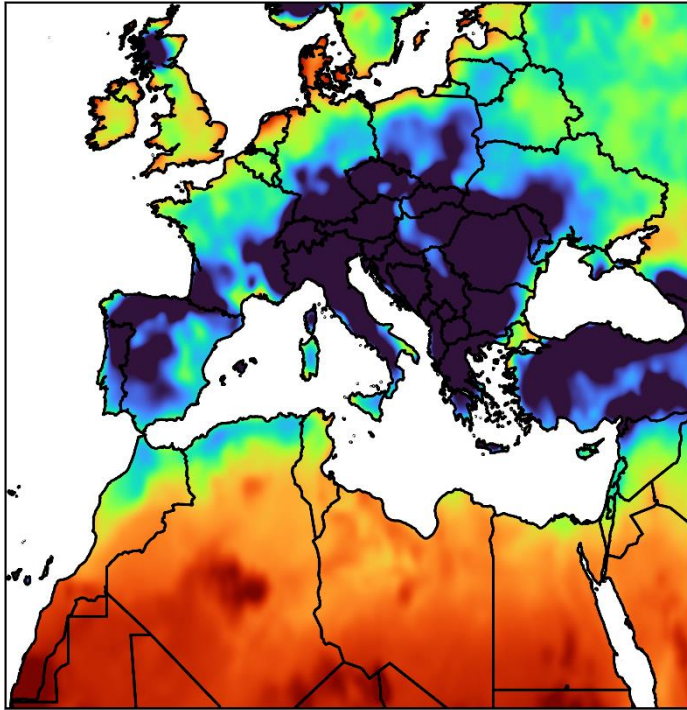
# Liquid Hydrogen Supply for Aviation

## A techno-economic assessment

Lucas Sens, Ulf Neuling, Martin Kaltschmitt

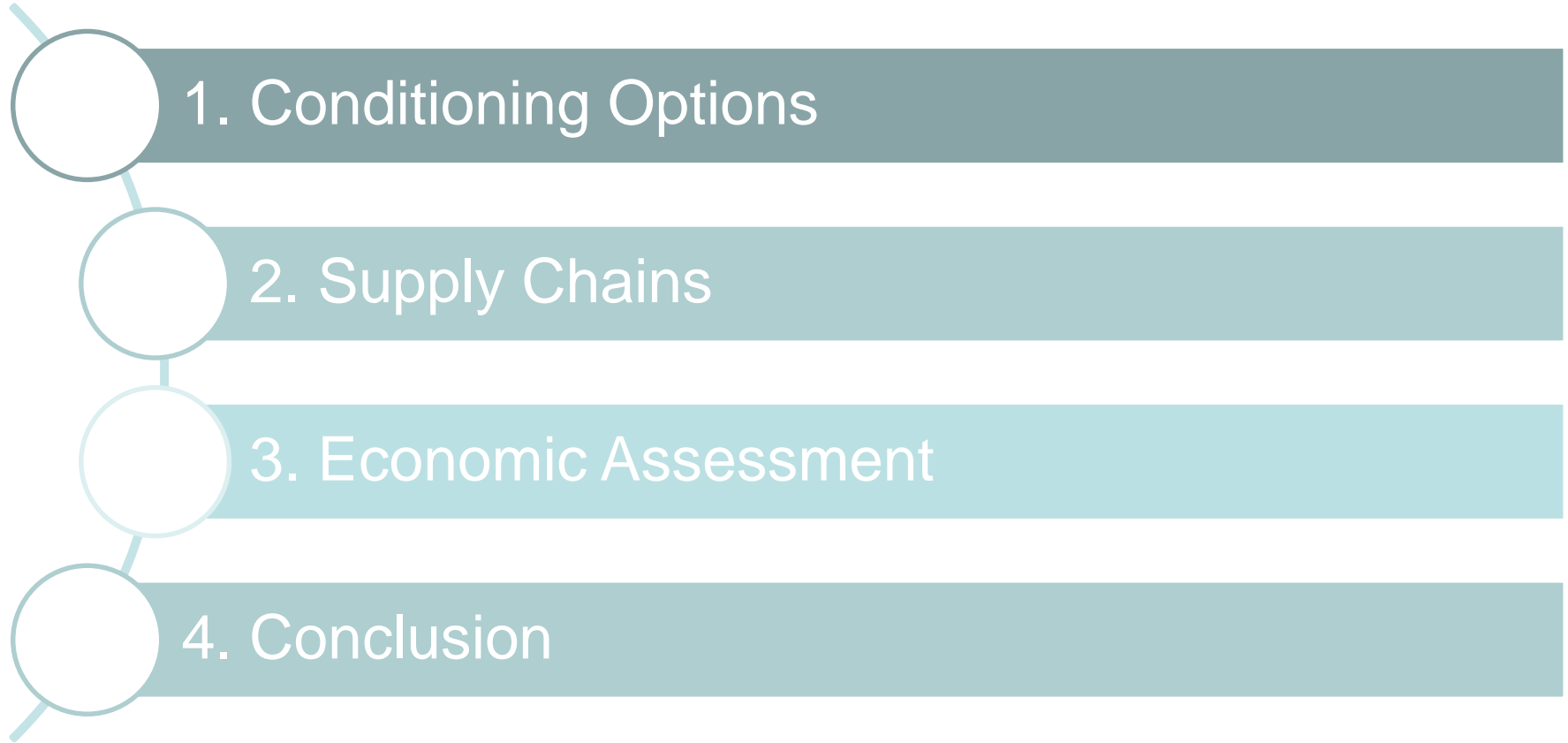


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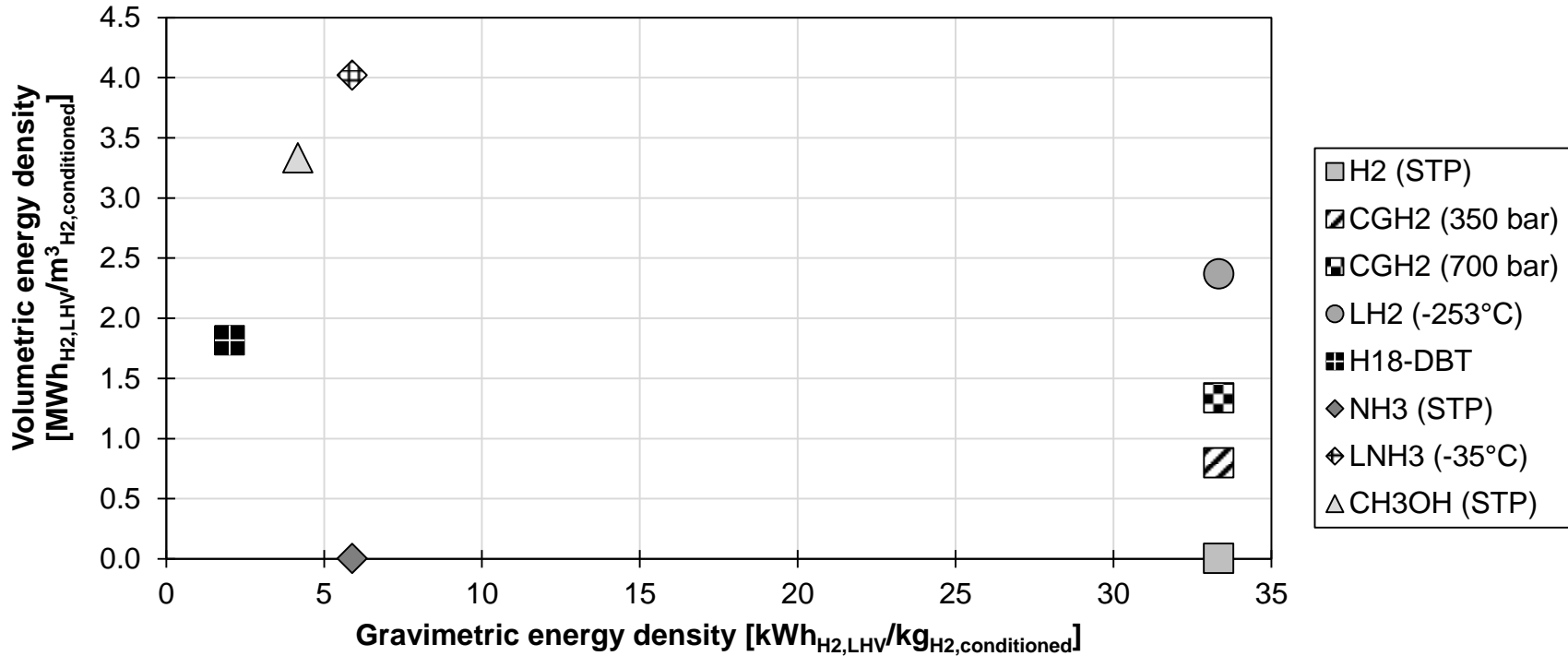


Low cost transportation  
needed to supply hydrogen  
to the consumption hubs



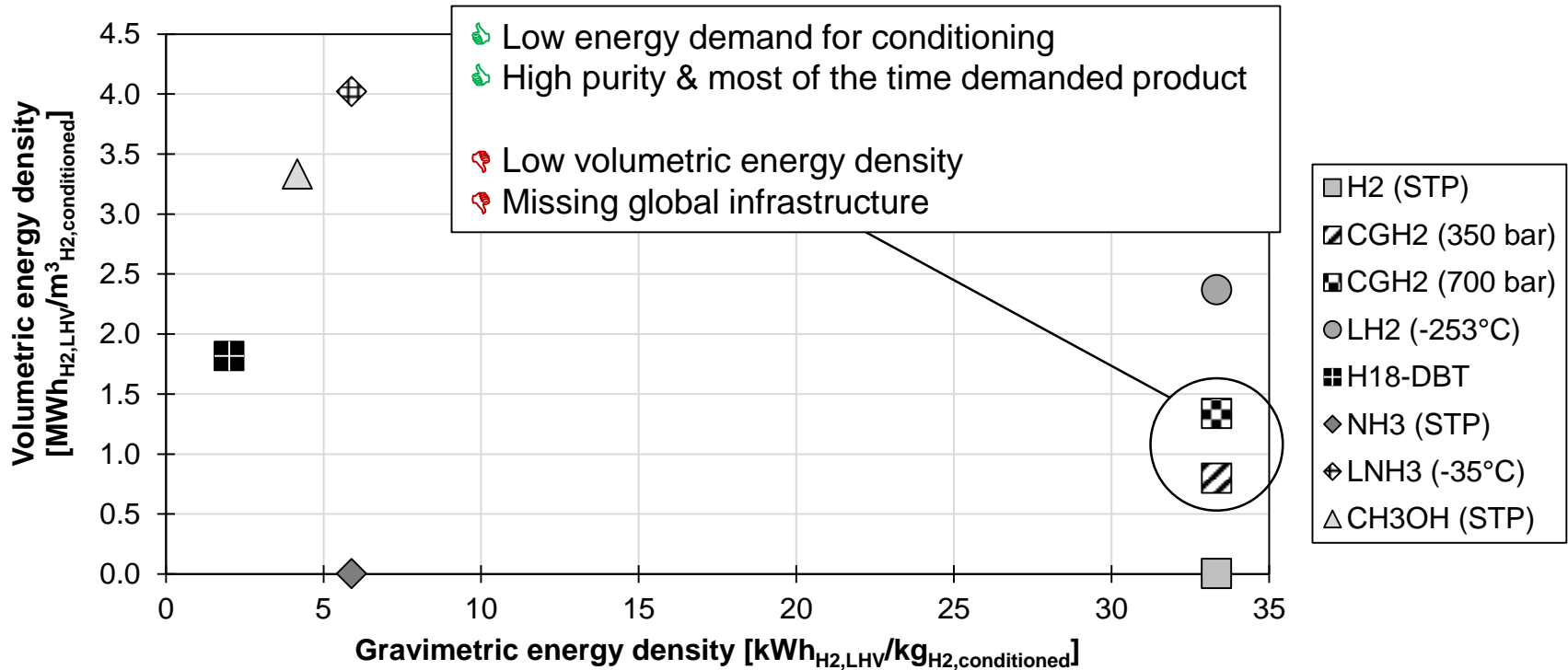
- 
- A vertical list of four items, each preceded by a white circle with a light blue outline. The circles are connected by a thin light blue line that starts at the top left and ends at the bottom left. Each circle is positioned to the left of a horizontal bar of a different shade of blue, containing the text of the item.
1. Conditioning Options
  2. Supply Chains
  3. Economic Assessment
  4. Conclusion

# Conditioned Hydrogen Options



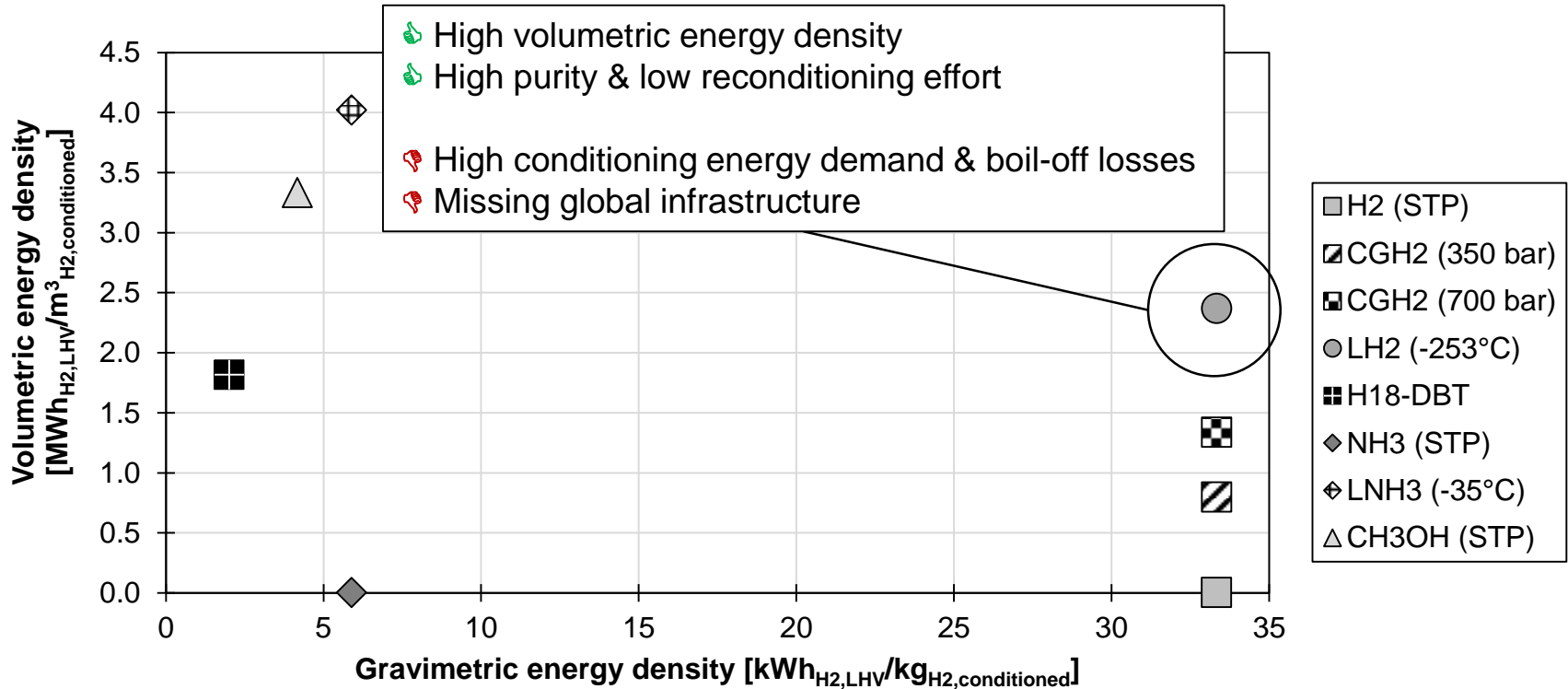
CGH2 = compressed gaseous hydrogen, CH3OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

# Compressed Gaseous Hydrogen (CGH<sub>2</sub>)



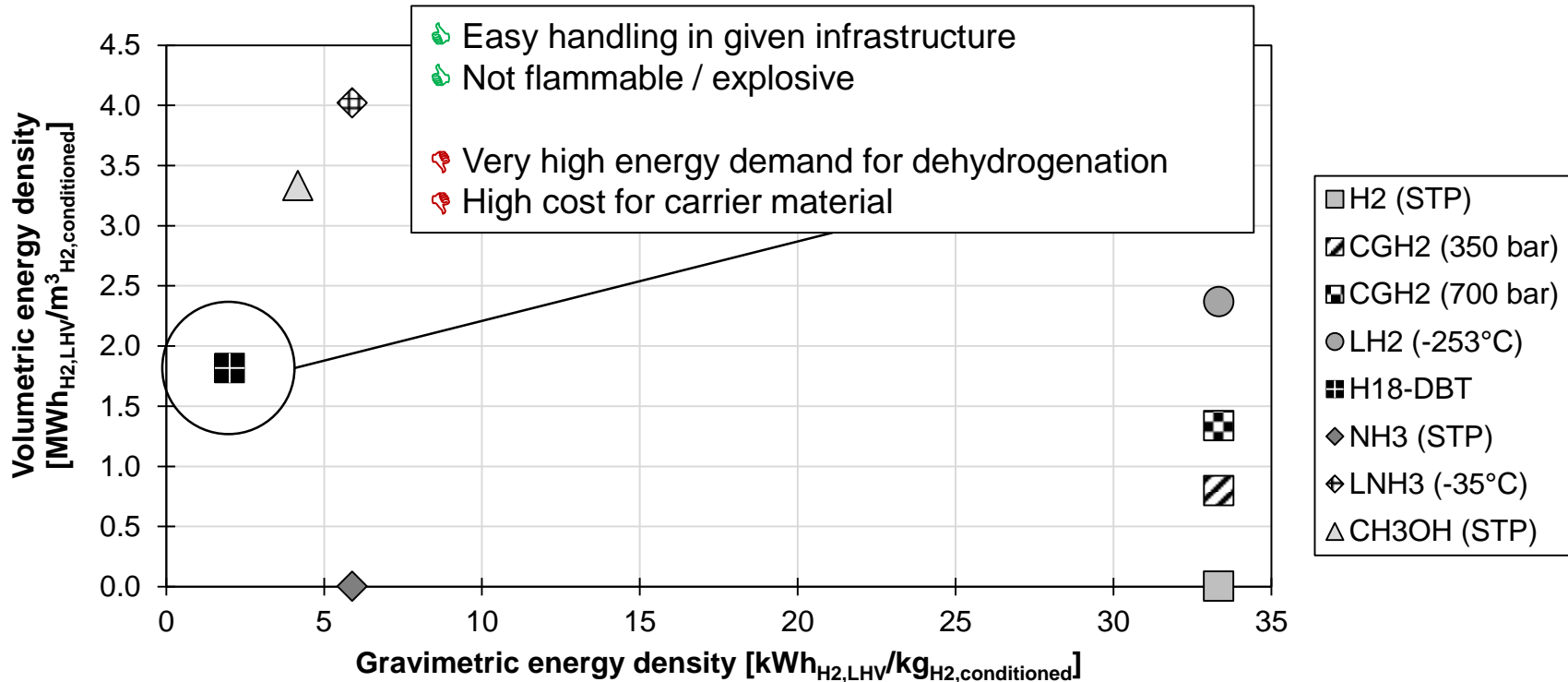
CGH<sub>2</sub> = compressed gaseous hydrogen, CH<sub>3</sub>OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH<sub>2</sub> = liquid hydrogen, LNH<sub>3</sub> = liquid ammonia, NH<sub>3</sub> = ammonia, STP = standard temperature and pressure

# Liquid Hydrogen (LH<sub>2</sub>)



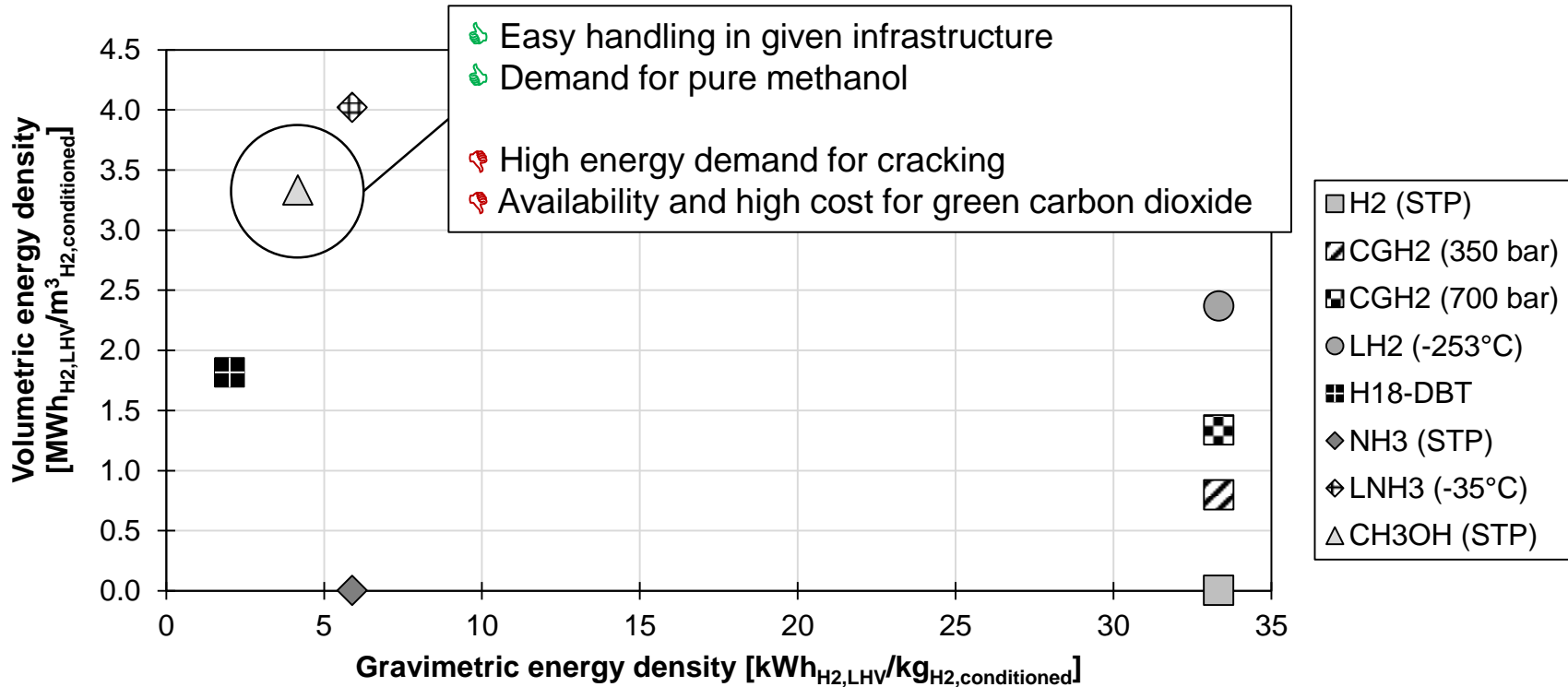
CGH2 = compressed gaseous hydrogen, CH3OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

# Liquid Organic Hydrogen Carrier (LOHC)



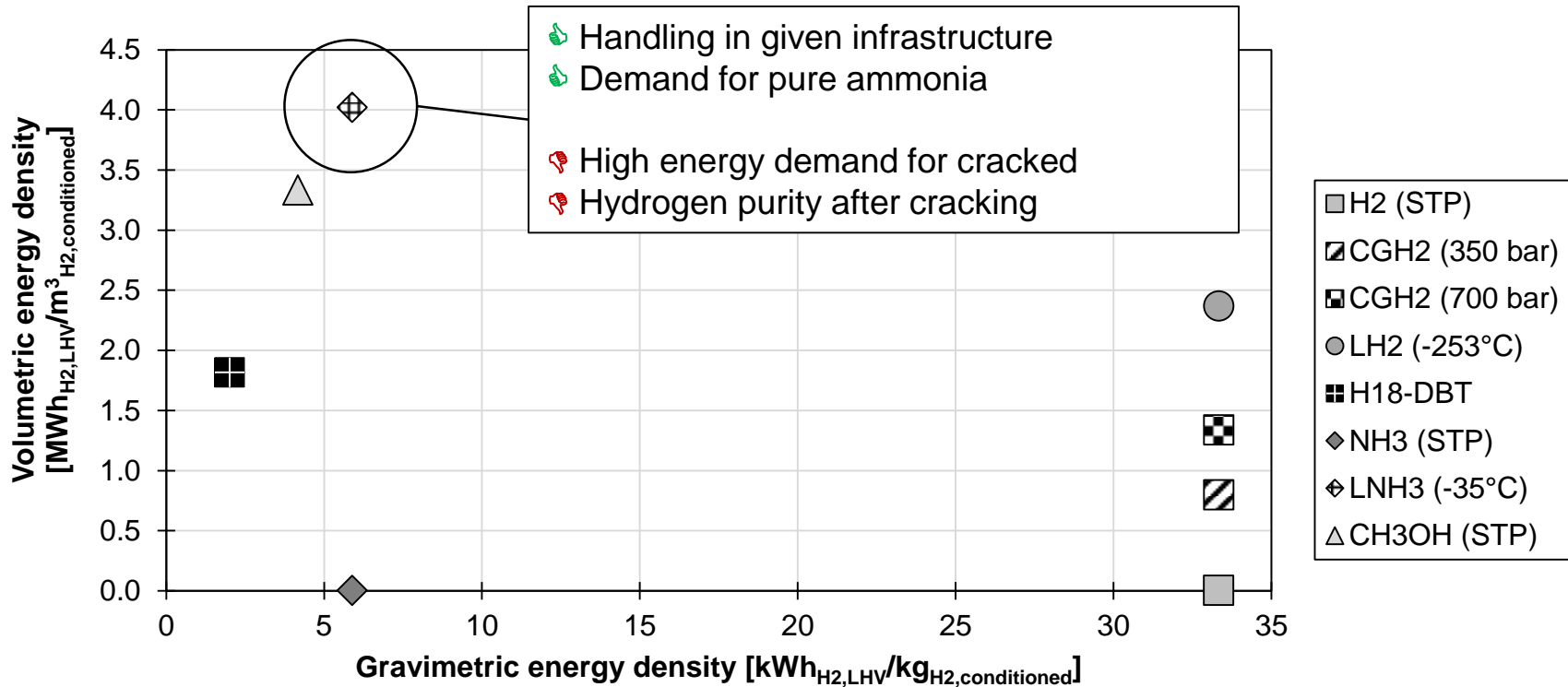
CGH<sub>2</sub> = compressed gaseous hydrogen, CH<sub>3</sub>OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH<sub>2</sub> = liquid hydrogen, LNH<sub>3</sub> = liquid ammonia, NH<sub>3</sub> = ammonia, STP = standard temperature and pressure

# Methanol (CH<sub>3</sub>OH)

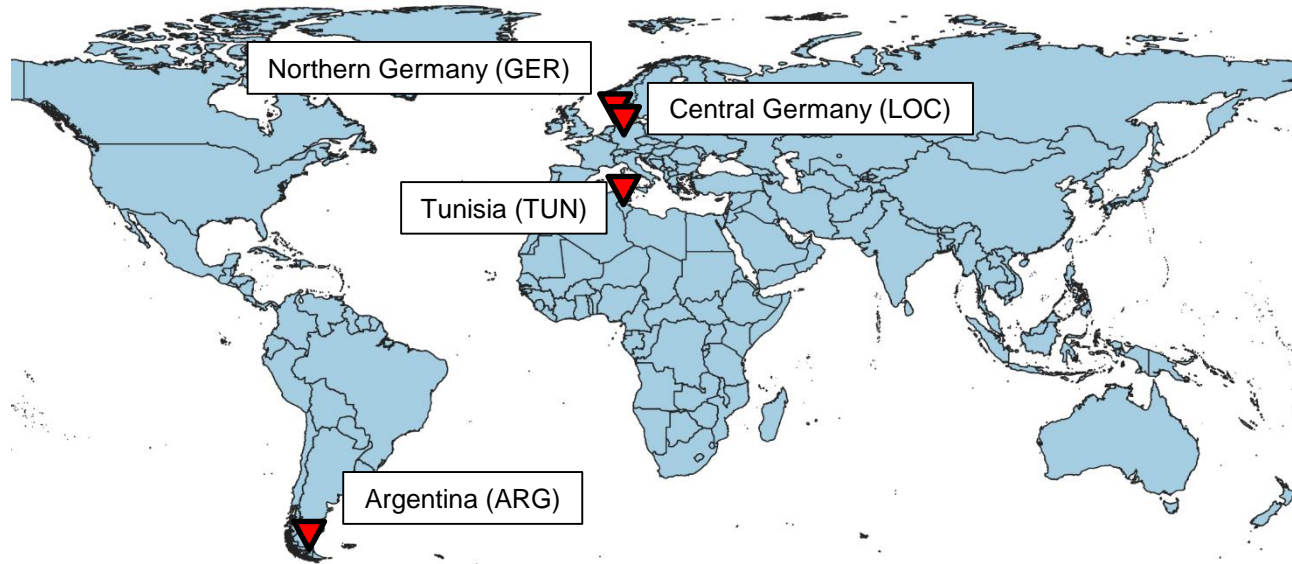


CGH<sub>2</sub> = compressed gaseous hydrogen, CH<sub>3</sub>OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH<sub>2</sub> = liquid hydrogen, LNH<sub>3</sub> = liquid ammonia, NH<sub>3</sub> = ammonia, STP = standard temperature and pressure

# Ammonia (NH<sub>3</sub>)



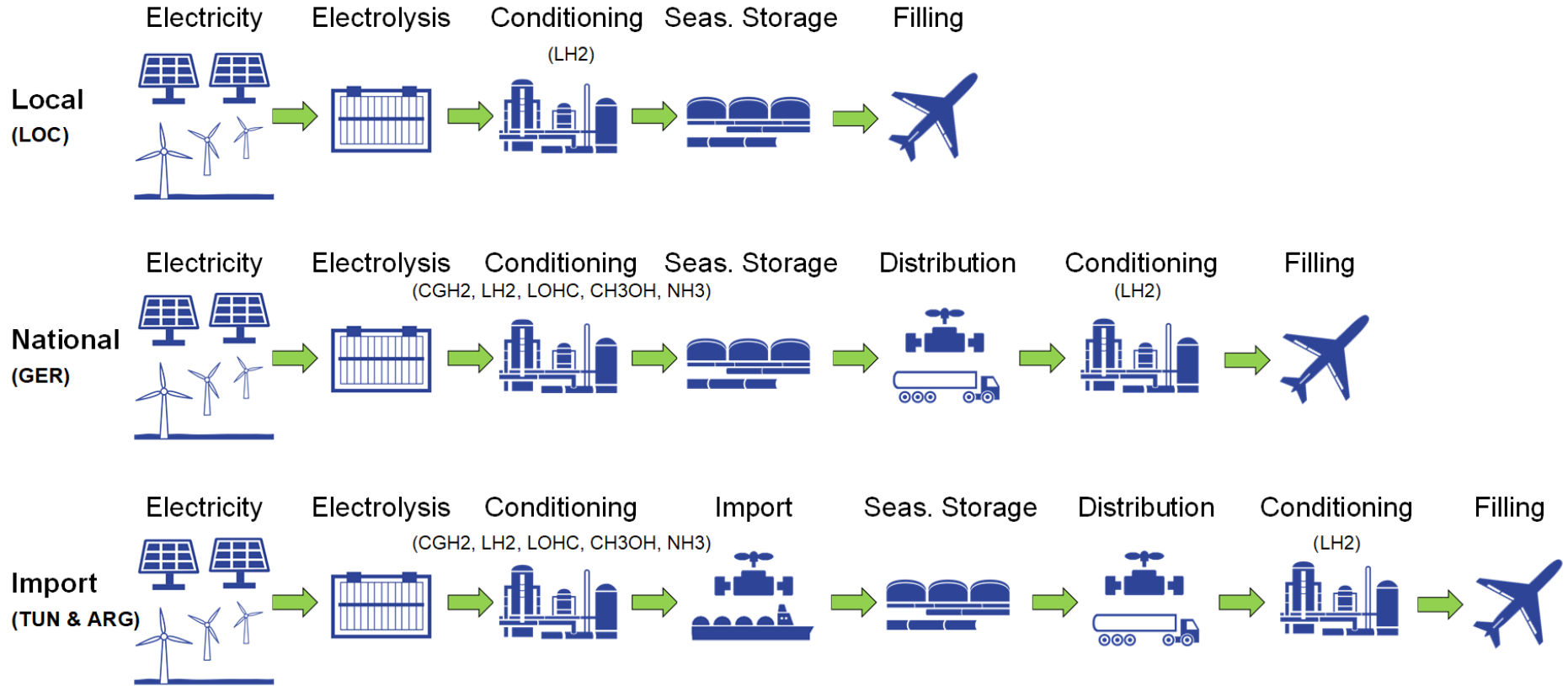
CGH<sub>2</sub> = compressed gaseous hydrogen, CH<sub>3</sub>OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH<sub>2</sub> = liquid hydrogen, LNH<sub>3</sub> = liquid ammonia, NH<sub>3</sub> = ammonia, STP = standard temperature and pressure



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

AFLH = annual full load hours

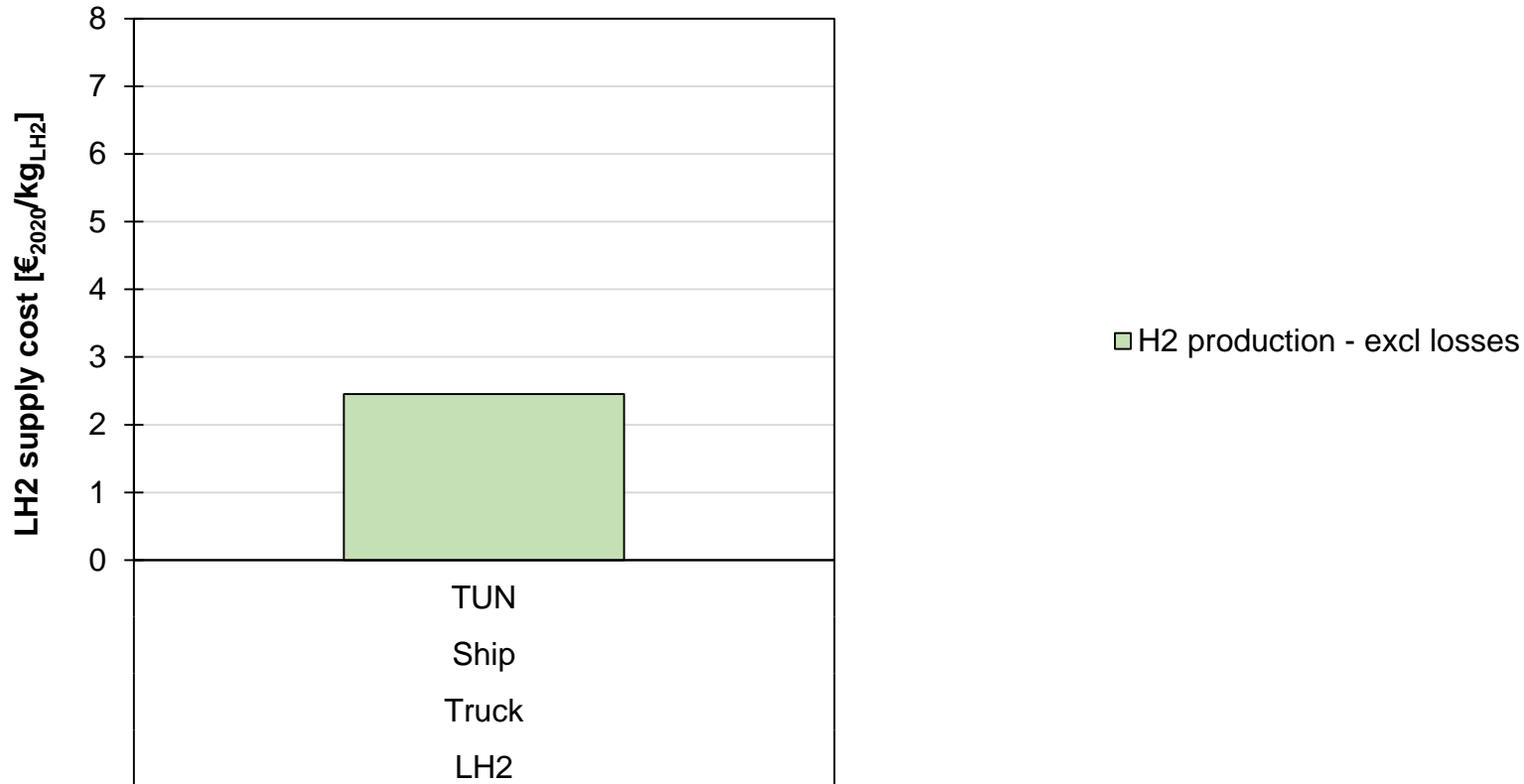
# Supply Chains



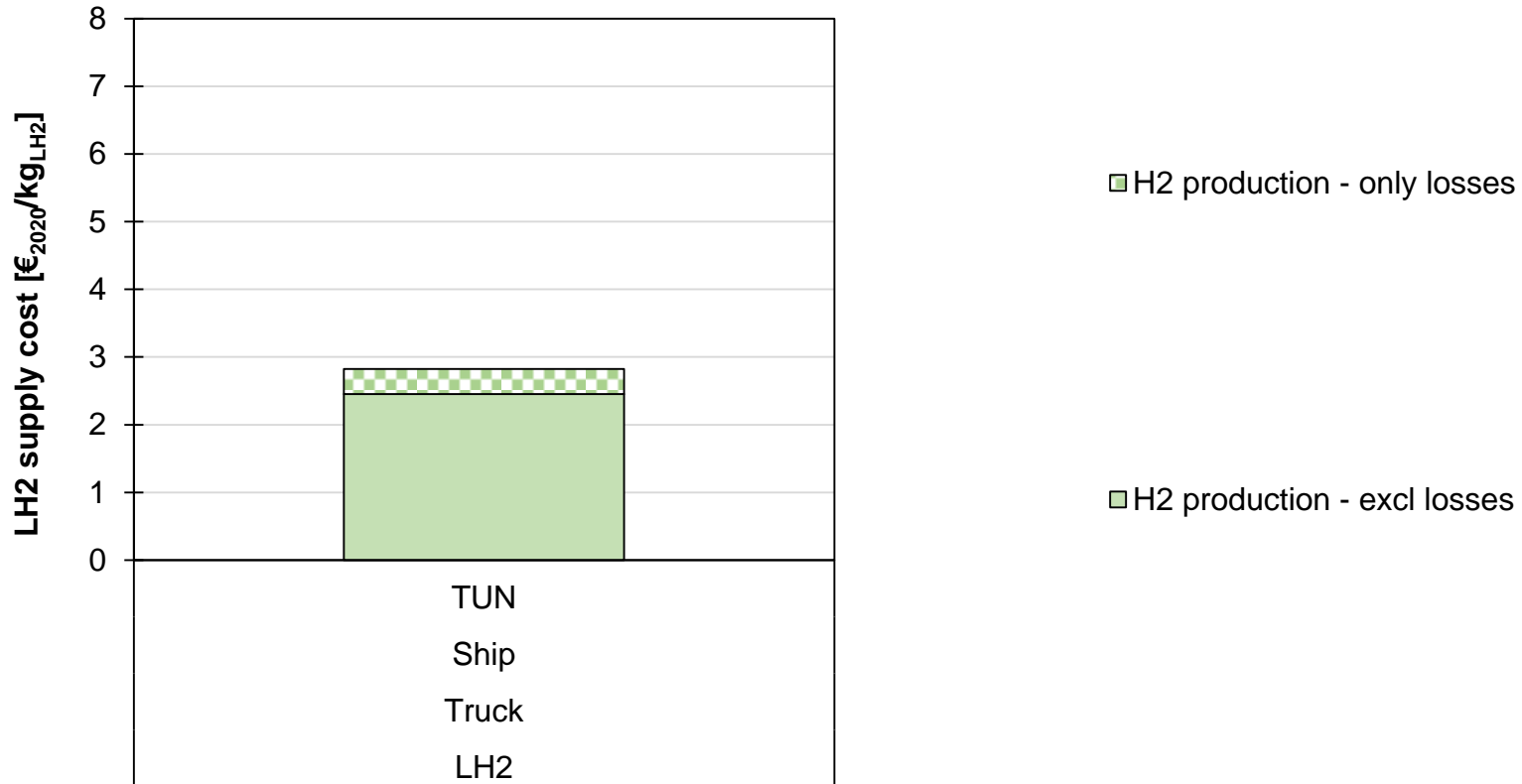
- Supply efficiency based on hydrogen (LHV) filled in tank divided by the overall chain energy input from well to tank
- Hydrogen supply cost considers the well to tank costs and is calculated with the annuity method
- Depreciation equals the technology lifetime
- Real weighted average cost of capital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



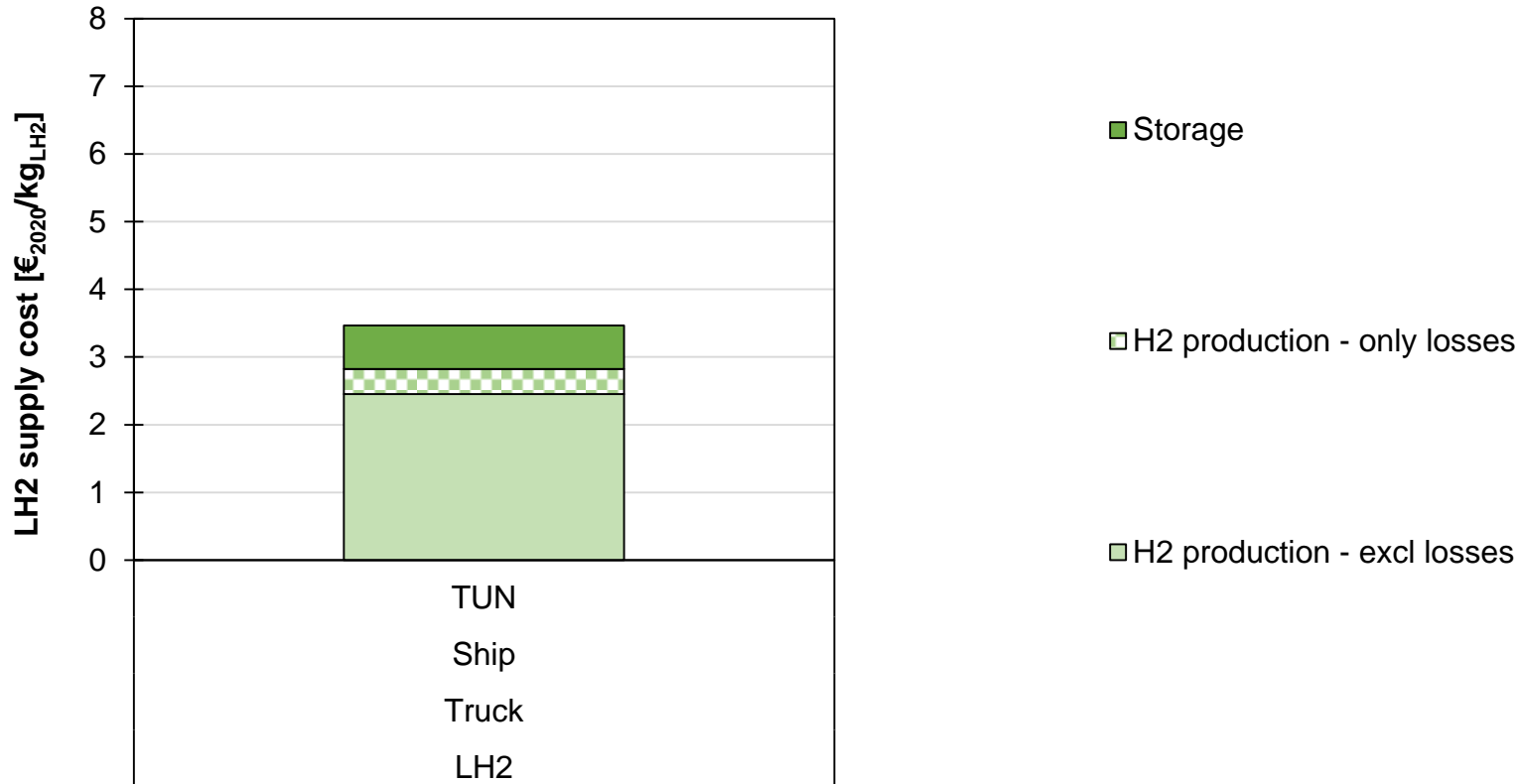
# Liquid Hydrogen Supply Cost in 2030



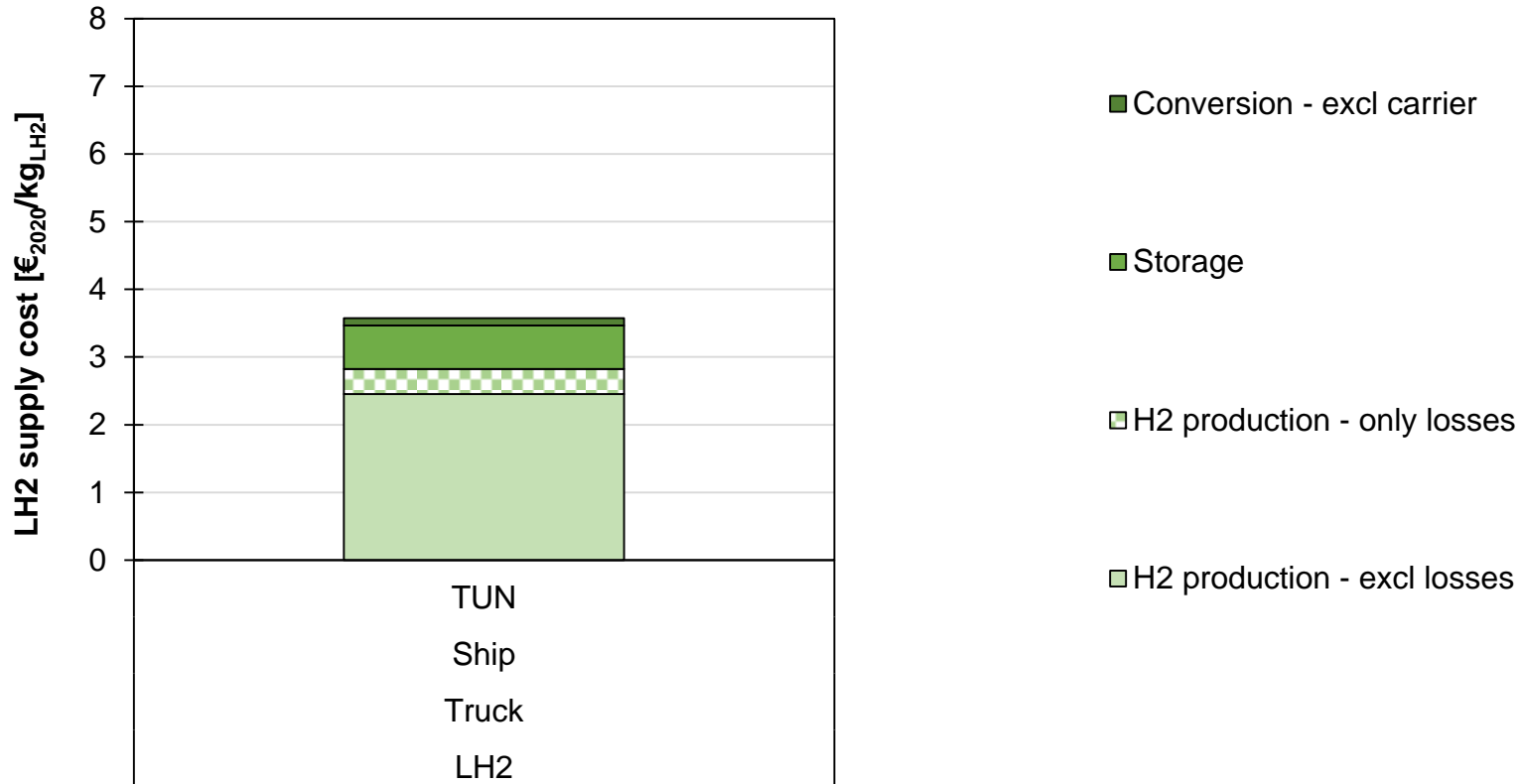
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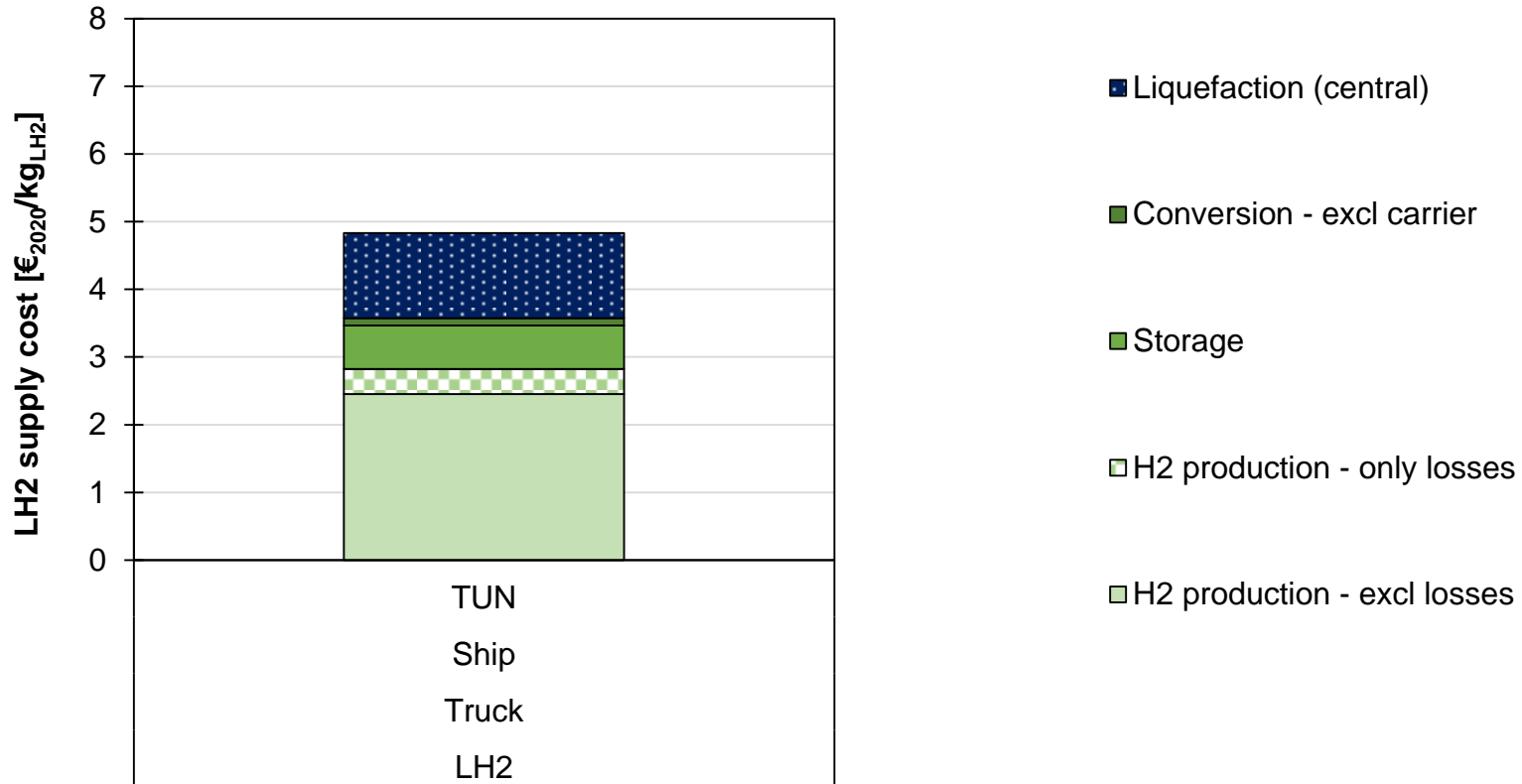
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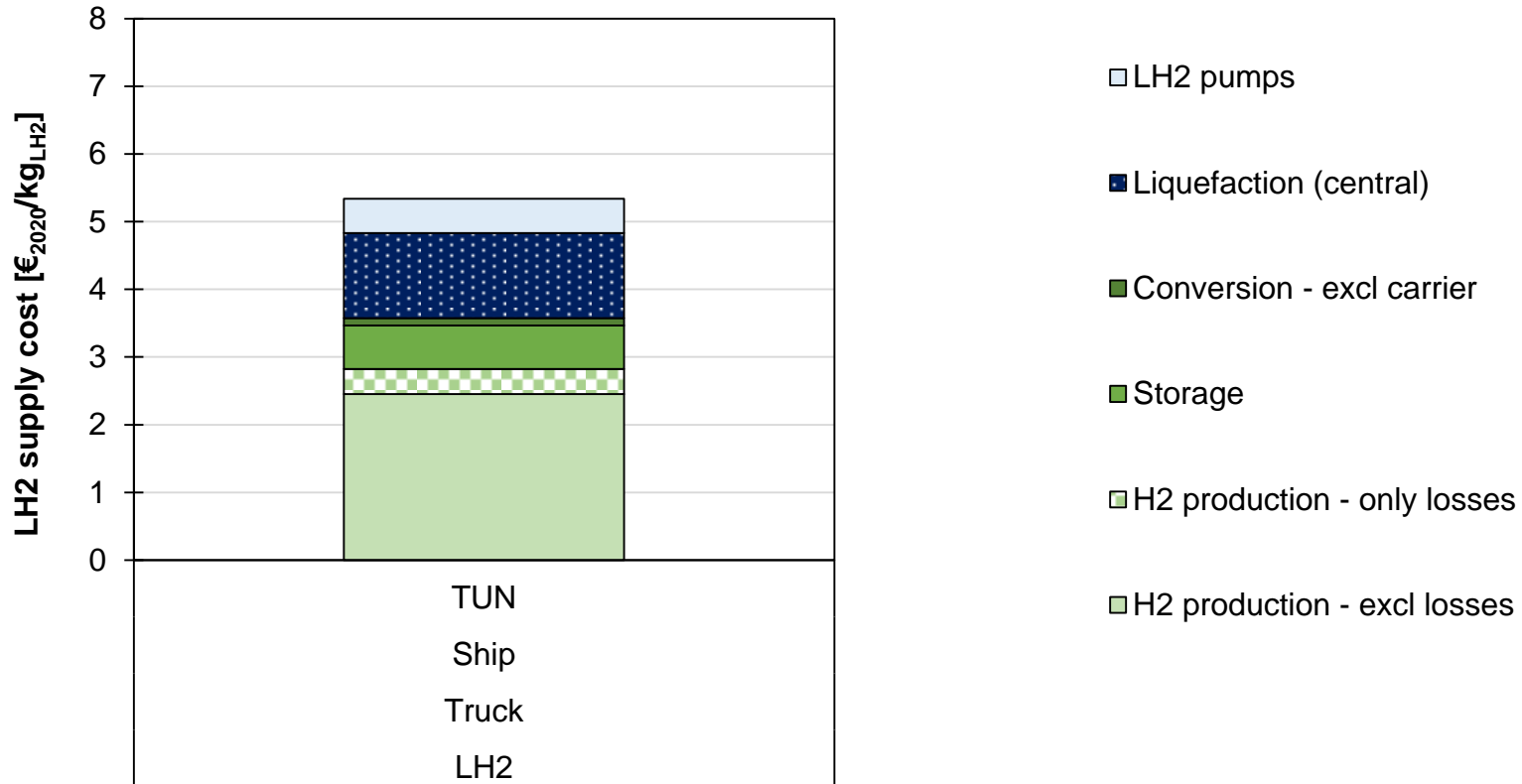
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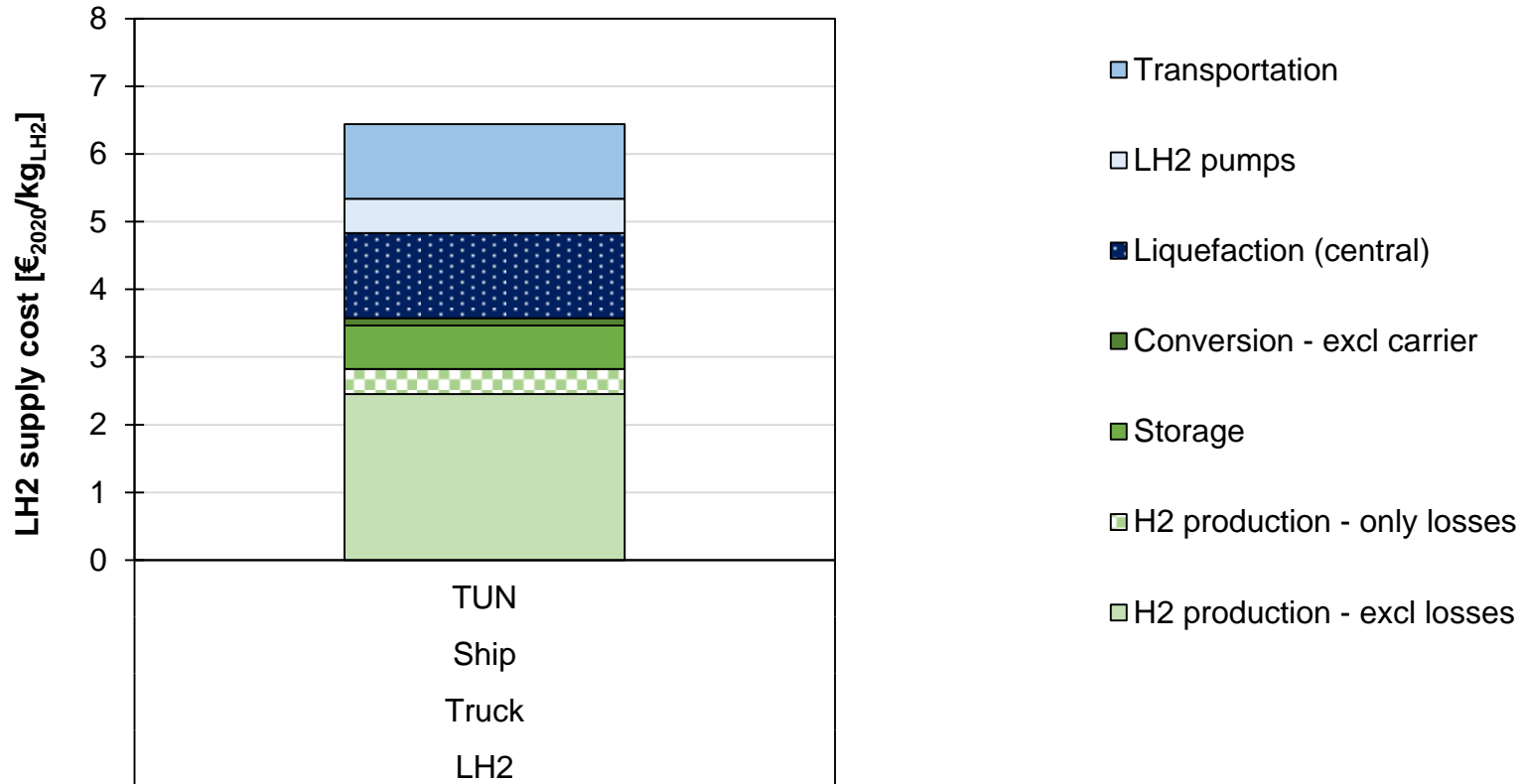
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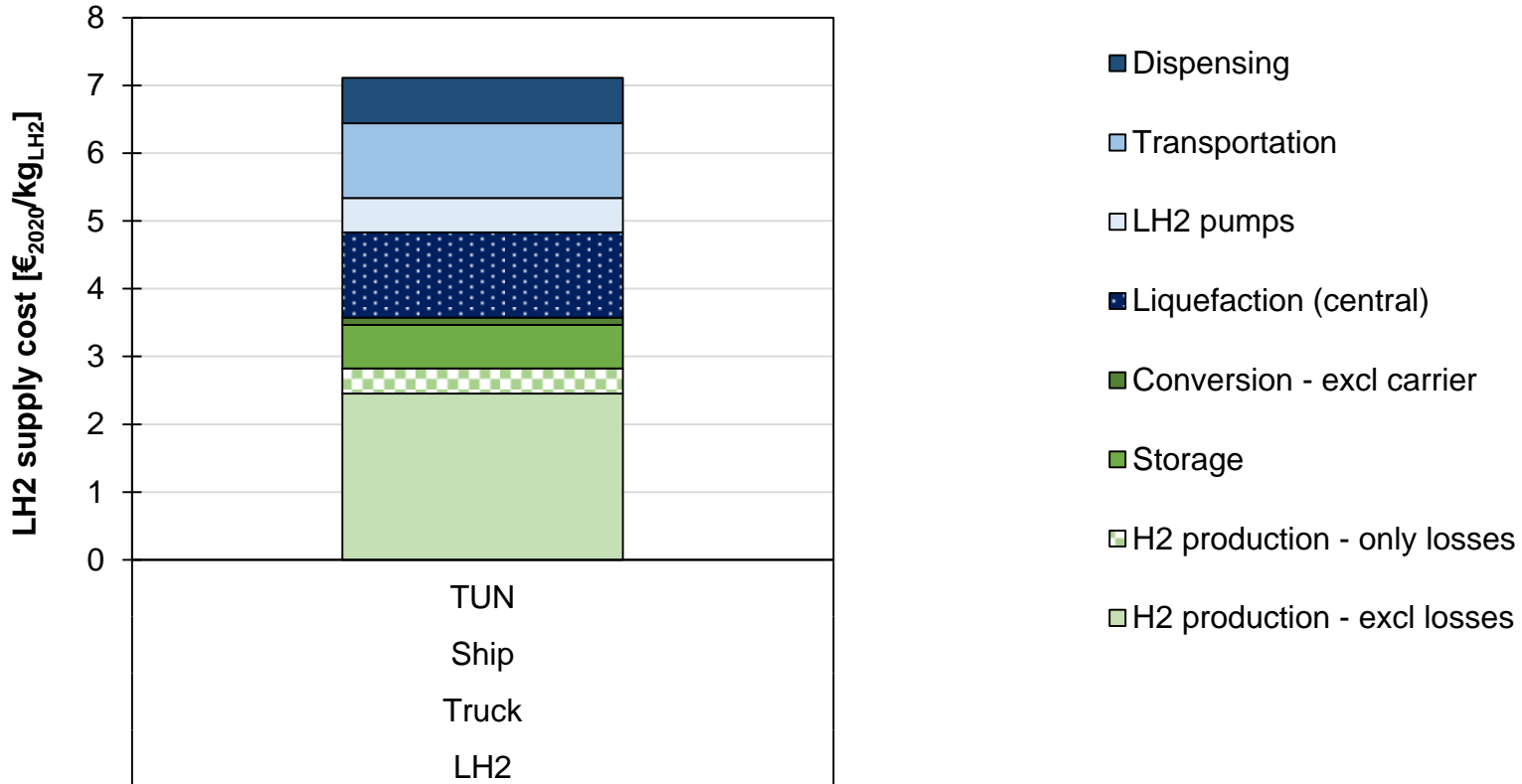
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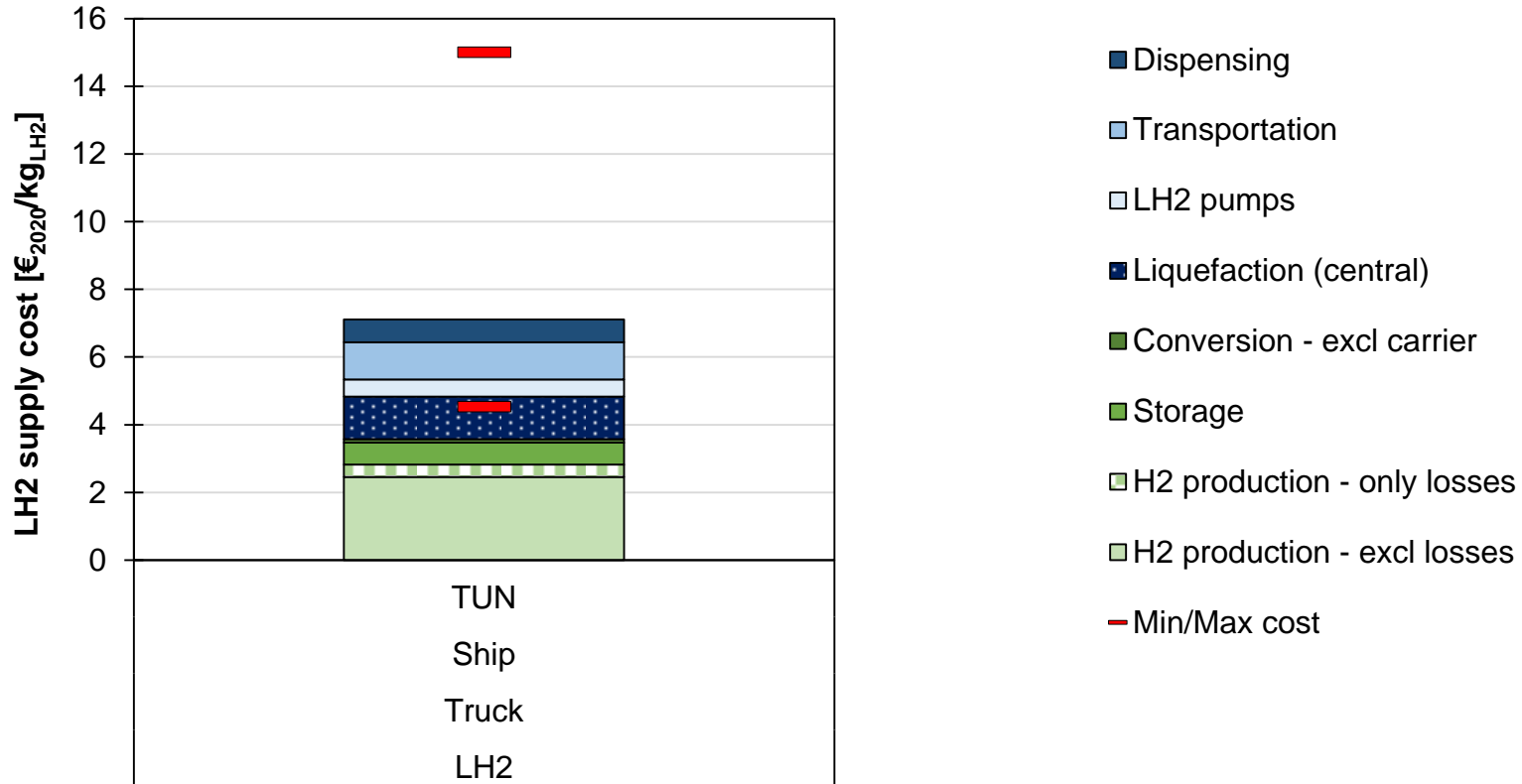
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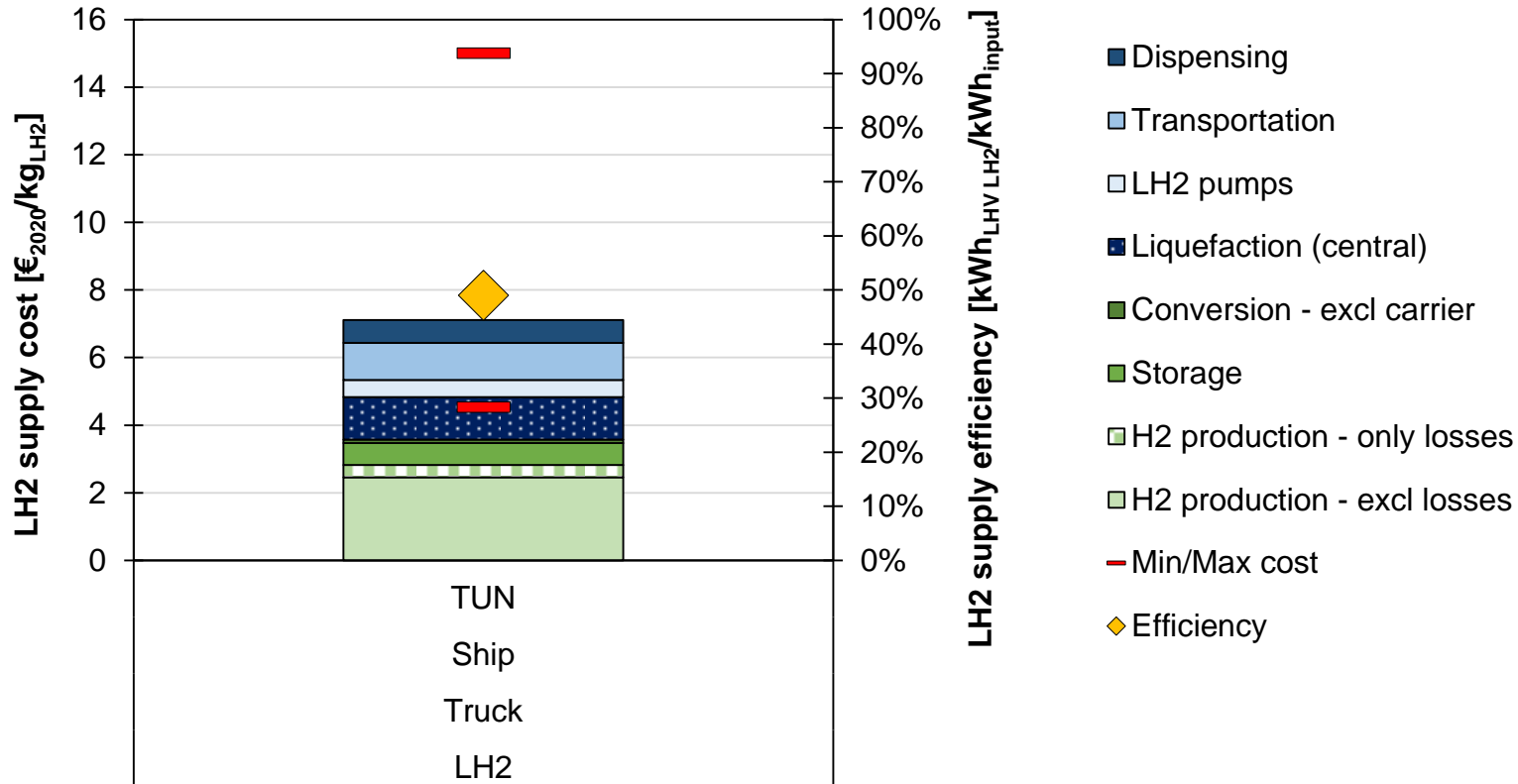
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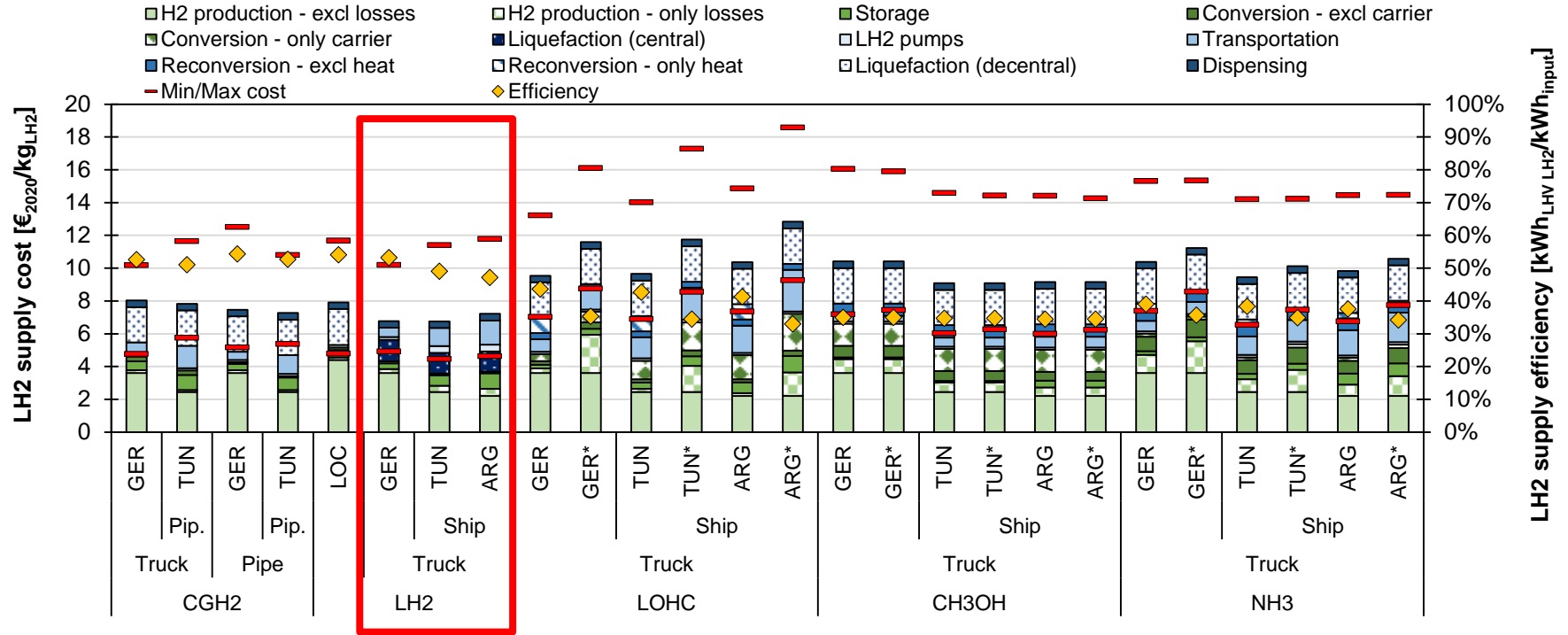
# Liquid Hydrogen Supply Cost in 2030



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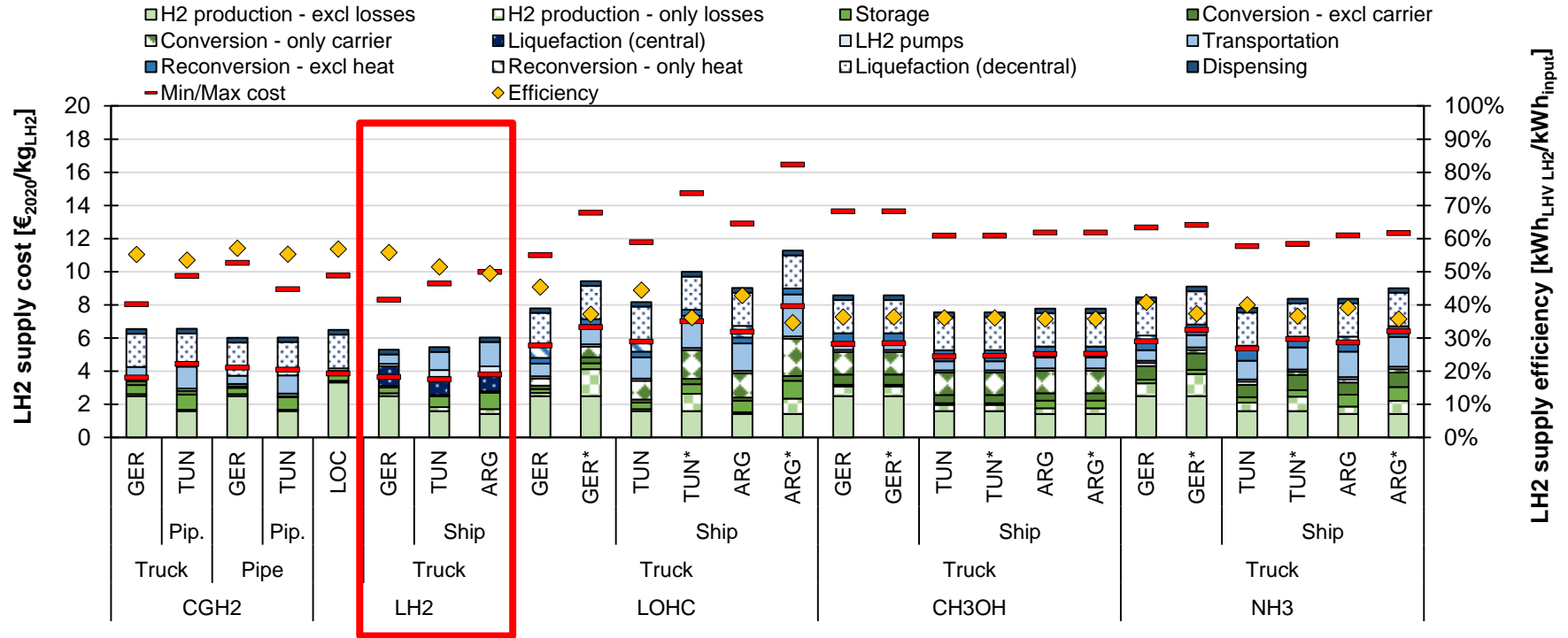


# LH<sub>2</sub> Filling – 2030



(\* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany; LH2 = liquid hydrogen supply chain; LOC = local production directly at the airport in Central Germany; LOHC = liquid organic hydrogen carrier supply chain; NH3 = ammonia supply chain; Pipe = pipeline import; Pip. = pipeline distribution to airport; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to airport

# LH<sub>2</sub> Filling – 2050



(\* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH<sub>2</sub> = compressed gaseous hydrogen supply chain; CH<sub>3</sub>OH = methanol supply chain; GER = centralized production in North Germany; LH<sub>2</sub> = liquid hydrogen supply chain; LOC = local production directly at the airport in Central Germany; LOHC = liquid organic hydrogen carrier supply chain; NH<sub>3</sub> = ammonia supply chain; Pipe = pipeline import; Pip. = pipeline distribution to airport; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to airport

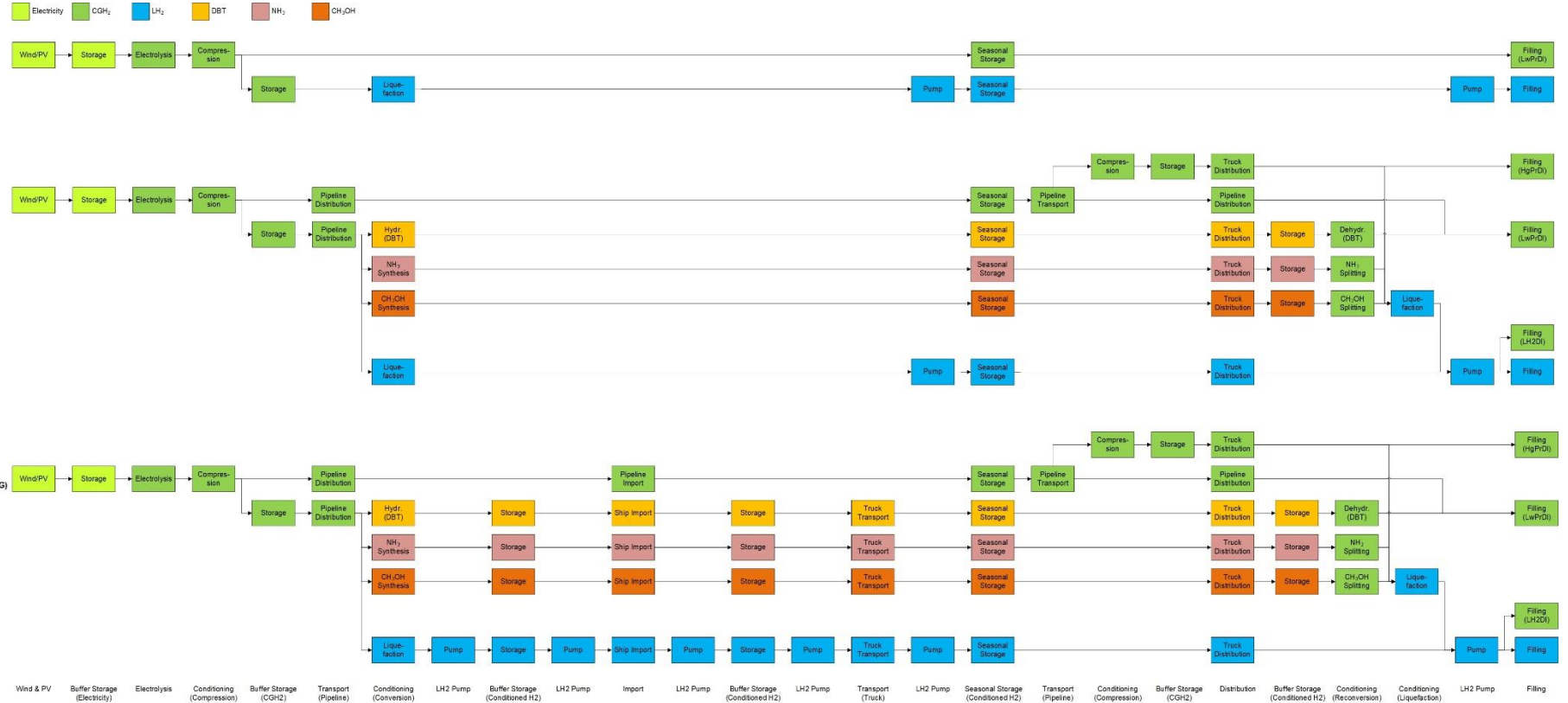
- **Liquid hydrogen and gaseous hydrogen** supply chains are the **lowest cost options** for a supply of **liquid hydrogen**
  - ≈ 7 €<sub>2020</sub>/kg<sub>LH2</sub> & 50 % (2030)
  - ≈ 5 €<sub>2020</sub>/kg<sub>LH2</sub> & 55 % (2050)
- **LOHCs** (dibenzyltoluene), **ammonia** and **methanol** as a hydrogen carrier appear to be **not a viable** option for a hydrogen supply of filling stations caused by the heat demand for dehydrogenation/cracking, the educt cost (LOHCs and methanol) and purification losses (ammonia)
- The hydrogen supply by a **national** production (by offshore wind power) shows **similar cost** than the **import** from Northern Africa (e.g., Tunisia), while the long distance import from Patagonia (e.g., Argentina) is slightly higher



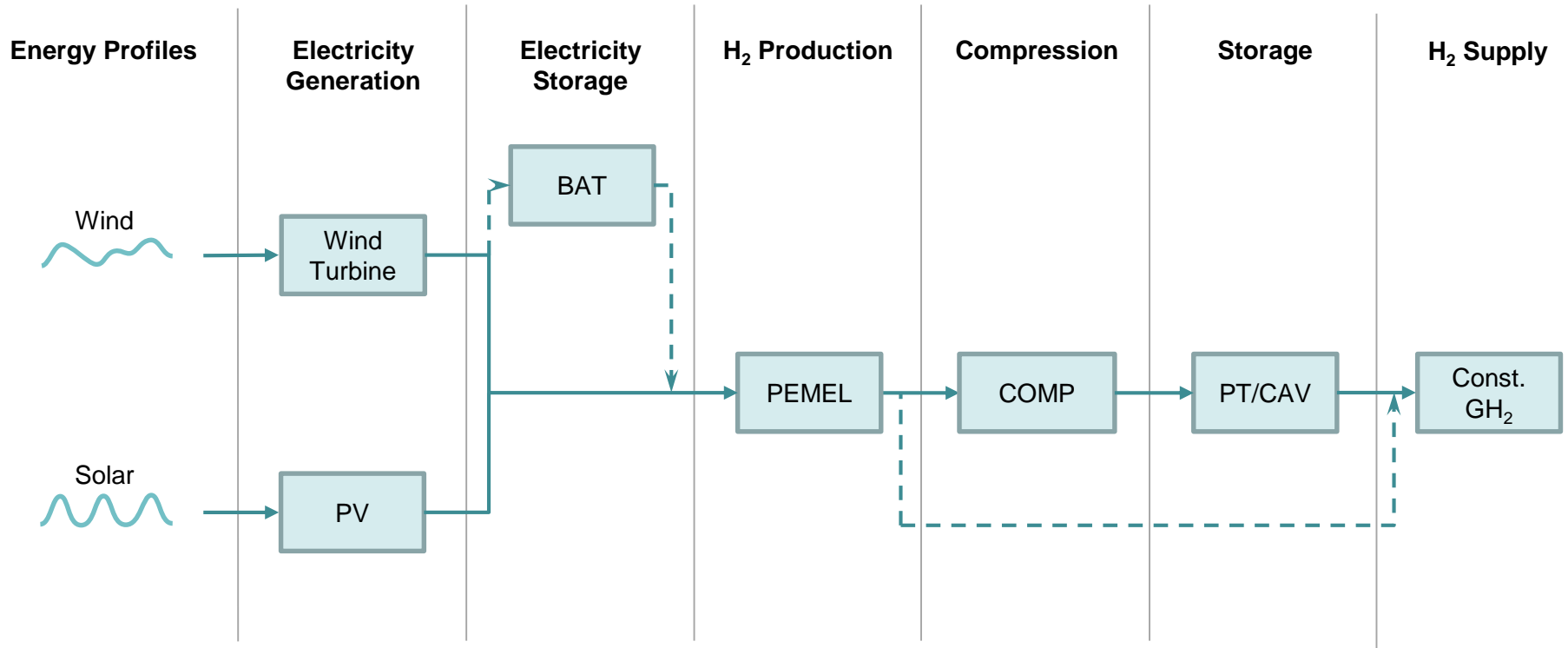
Hamburg University of Technology (TUHH)  
Institute of Environmental Technology and Energy Economics (IUE)  
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- Images slide 1, from left to right:
  - [1] <https://images.app.goo.gl/q2W7NAqYantkJjKZ9>
  - [2] <https://images.app.goo.gl/tgVUA1EQwqGESxhm8>
  - [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/](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.envisionintelligence.com/blog/gas-turbine-manufacturers-market-share/>

# Detailed Supply Chains



# Optimized Hydrogen Production



BAT = Battery; CAV = Cavern; COMP = Compressor; GH<sub>2</sub> = Gaseous Hydrogen; PT = Pressure Tank

	Year	PV	Onshore Wind	Offshore Wind	PEMEL
<b>CAPEX</b> [€ <sub>2020</sub> /kW <sub>el</sub> ]	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)
<b>Efficiency</b> [kWh <sub>H2,LHV</sub> /kWh <sub>el</sub> ]	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%

$$\eta_{supply\ chain} = \frac{q_{H_2, nozzle}}{q_{overall}}$$

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

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

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

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

$$C_{section,i} = \frac{ACAPEX_i + OPEX_i}{m_{H_2,fill,annual}}$$

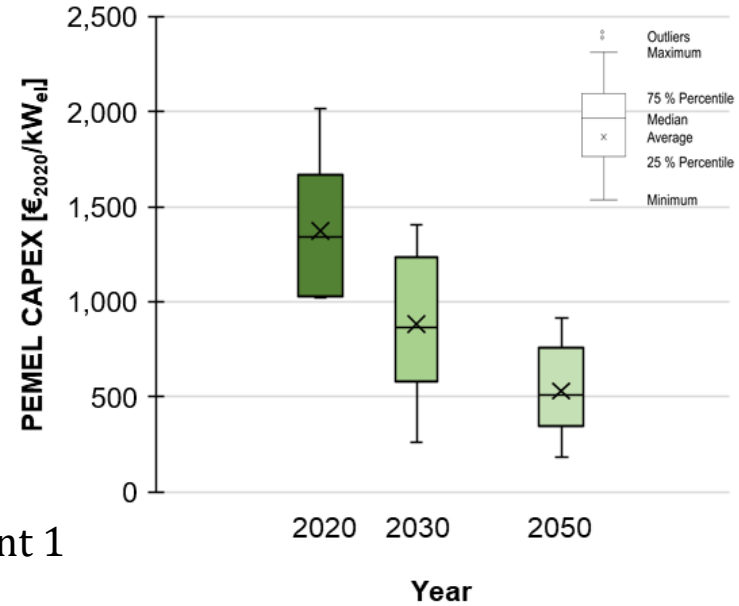
$$ACAPEX_i = CAPEX_i \frac{WACC_{real} (1+WACC_{real})^{d_i}}{(1+WACC_{real})^{d_i} - 1}$$

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

# CAPEX Calculation

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

- $\alpha$  = 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 (adjustment to 2020 €)
- $f_{inst}$  = installation factor (includes equipment, materials, construction and engineering)



# LOHC CAPEX

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

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

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

