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Liquid Hydrogen Supply for Aviation

A techno-economic assessment

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

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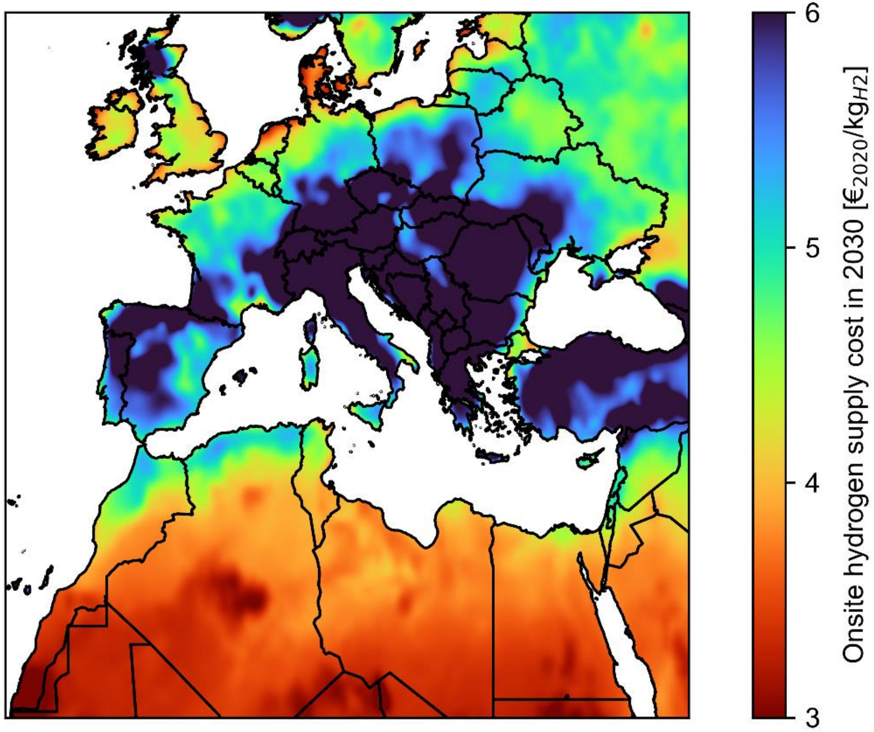
Background



Low cost transportation needed to supply hydrogen to the consumption hubs

Background

Methanol (CH_3OH)

Liquefaction (LH_2)

Compression (CGH_2)

[7]

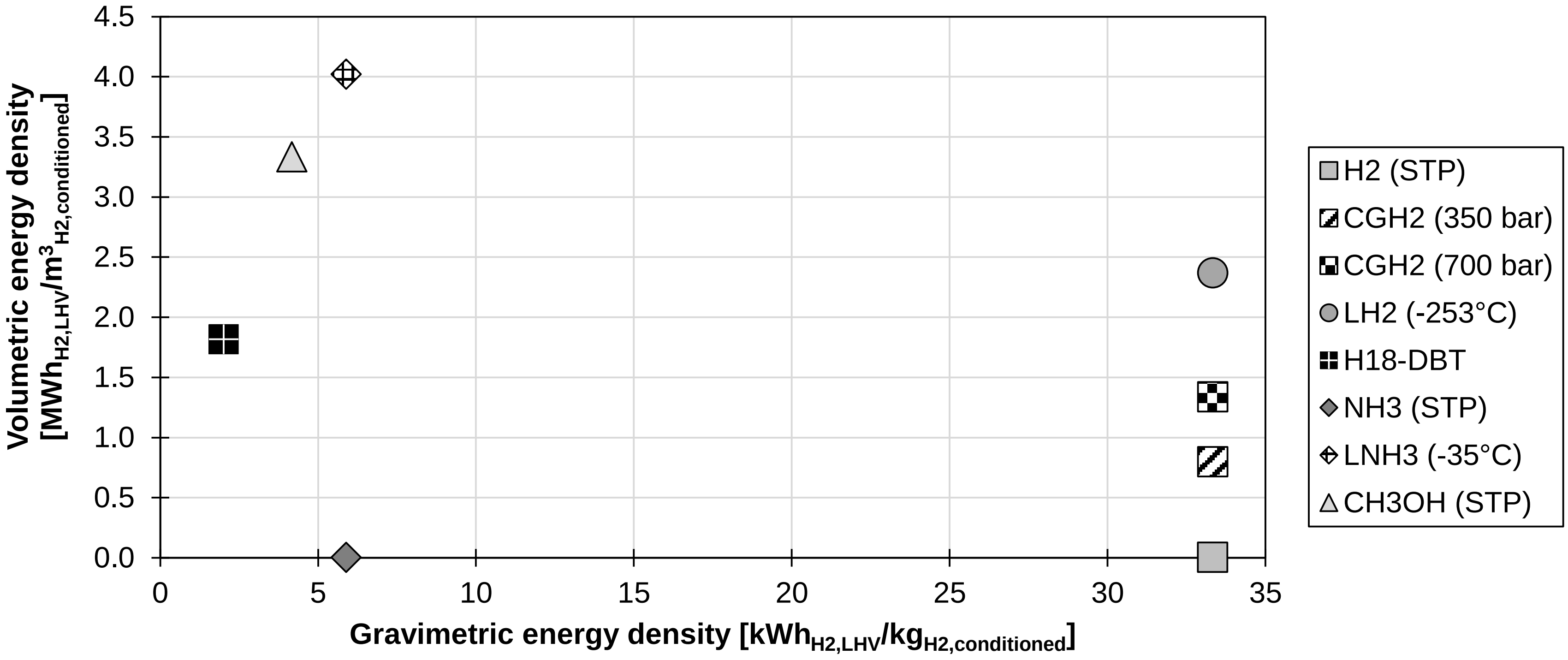
Ammonia (NH_3)

Liquid Organic Hydrogen Carriers (LOHC)

Outline

1. Conditioning Options
2. Supply Chains
3. Economic Assessment
4. Conclusion

Conditioned Hydrogen Options

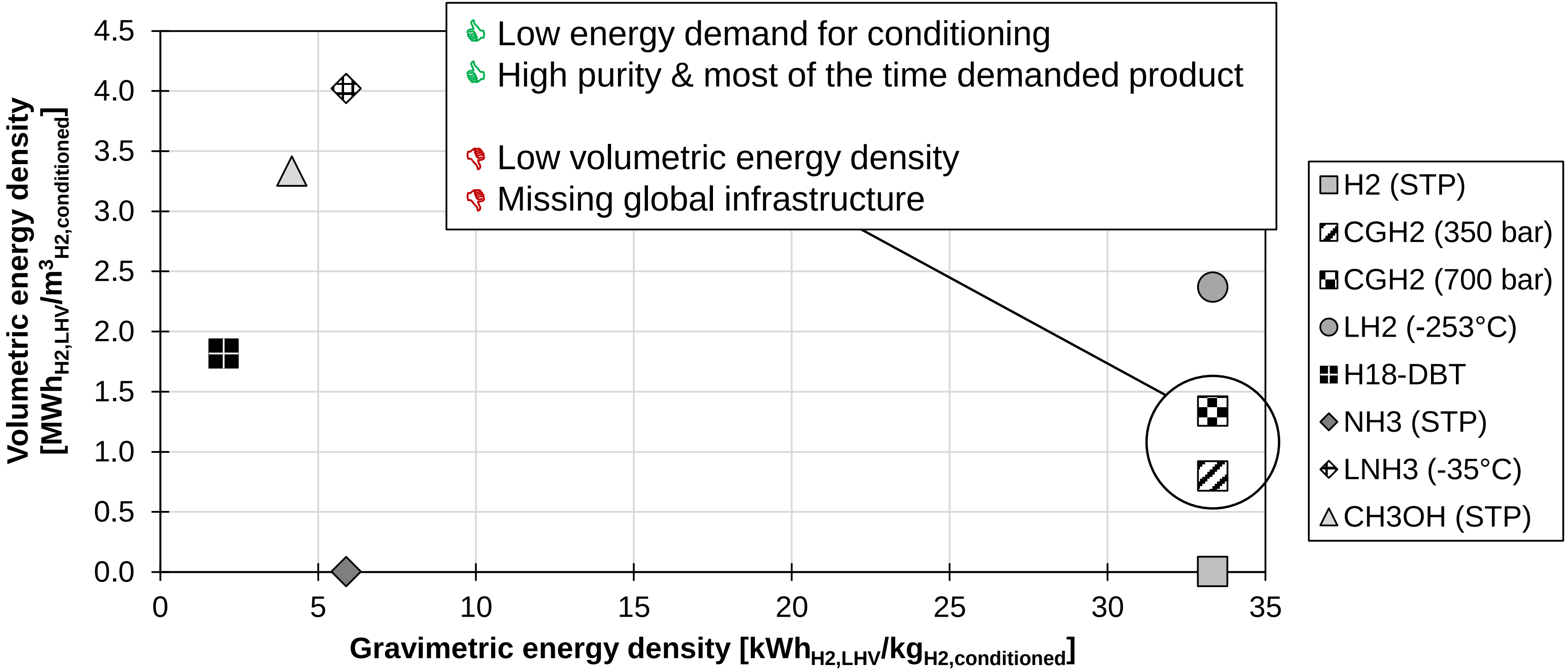


CGH2 = compressed gaseous hydrogen, CH3OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

Compressed Gaseous Hydrogen (CGH_2)

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

- 👎 Low volumetric energy density
- 👎 Missing global infrastructure



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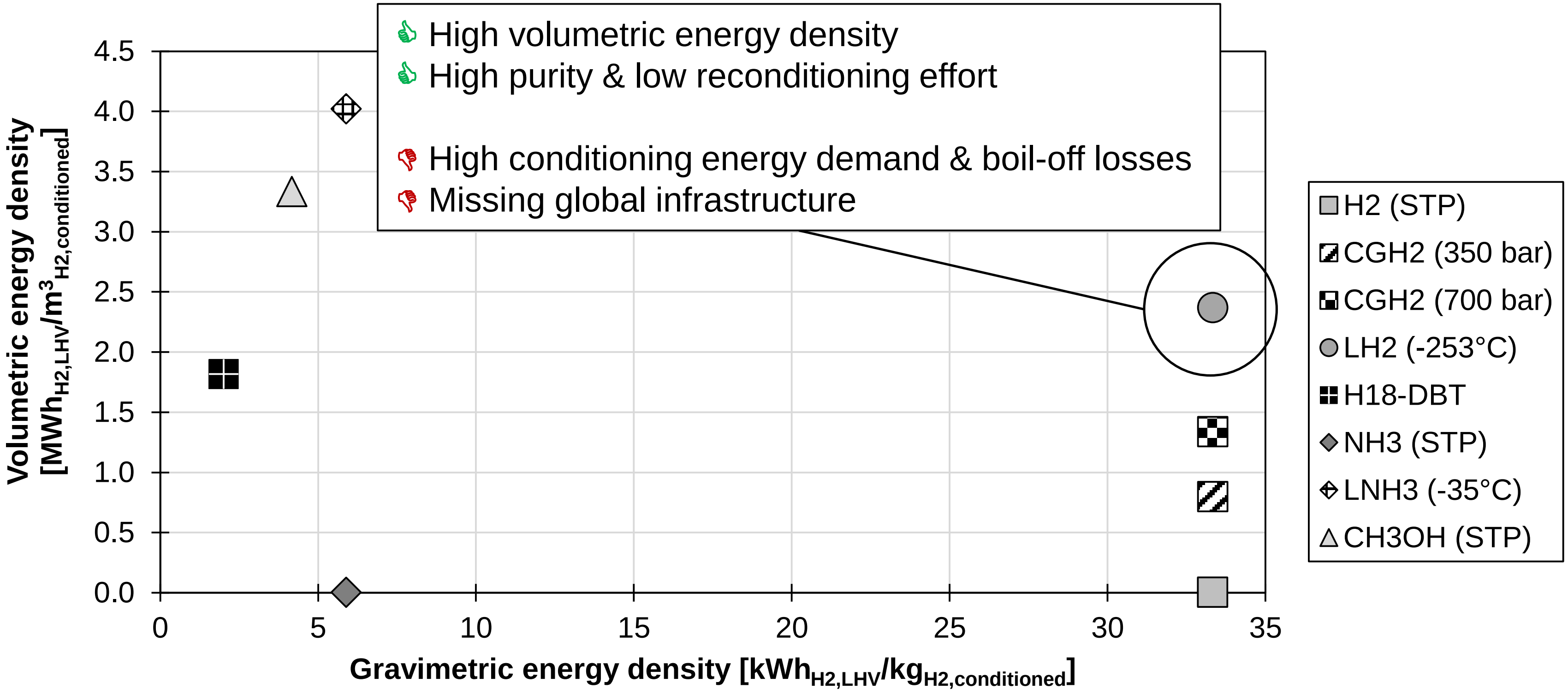
Liquid Hydrogen (LH_2)



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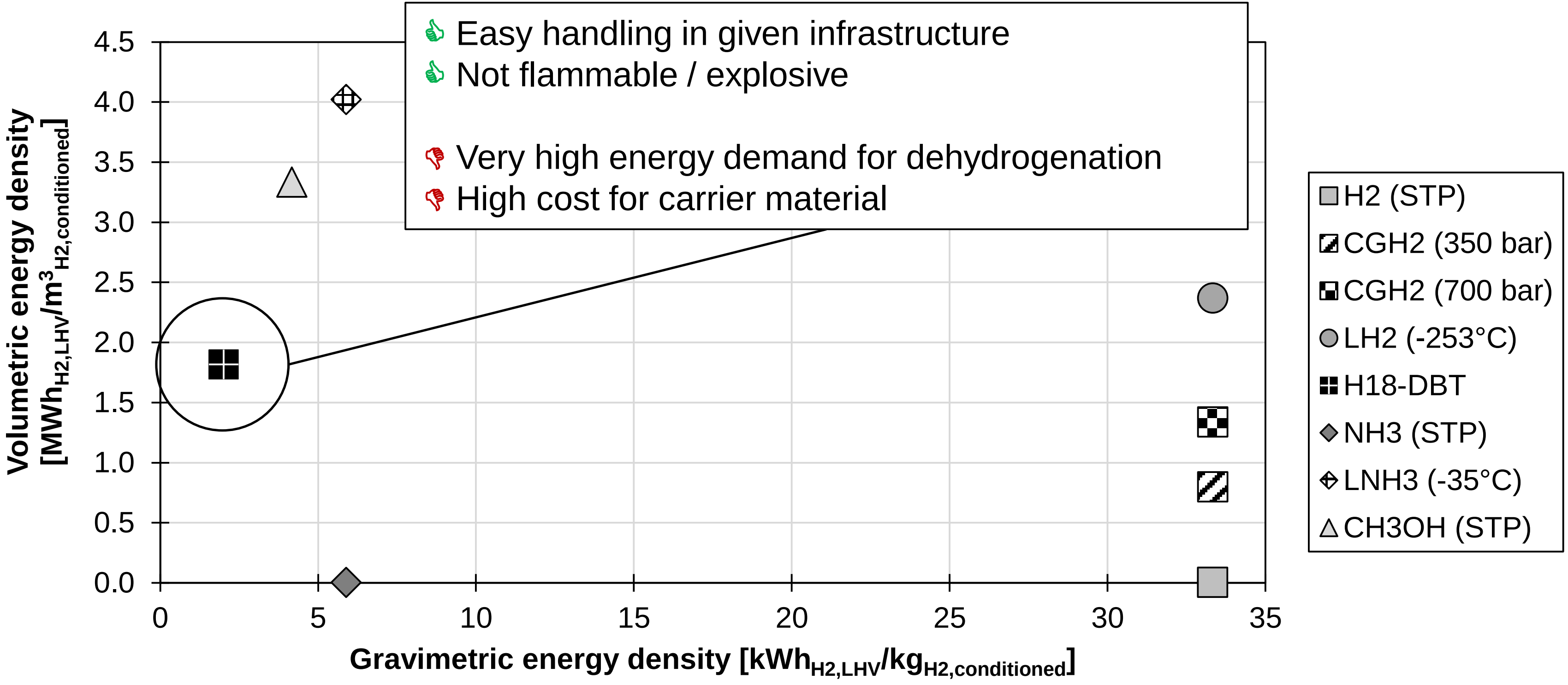
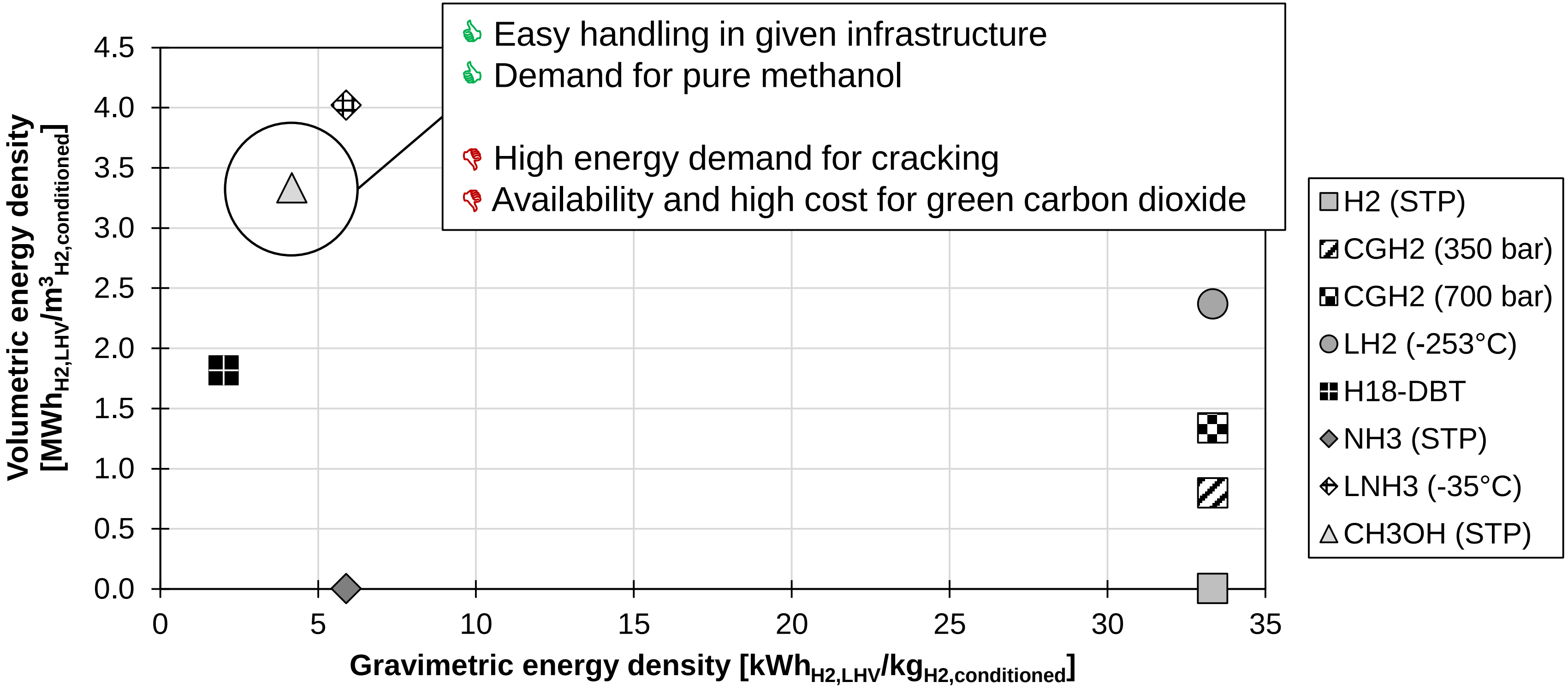
Liquid Organic Hydrogen Carrier (LOHC)



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

Methanol (CH_3OH)



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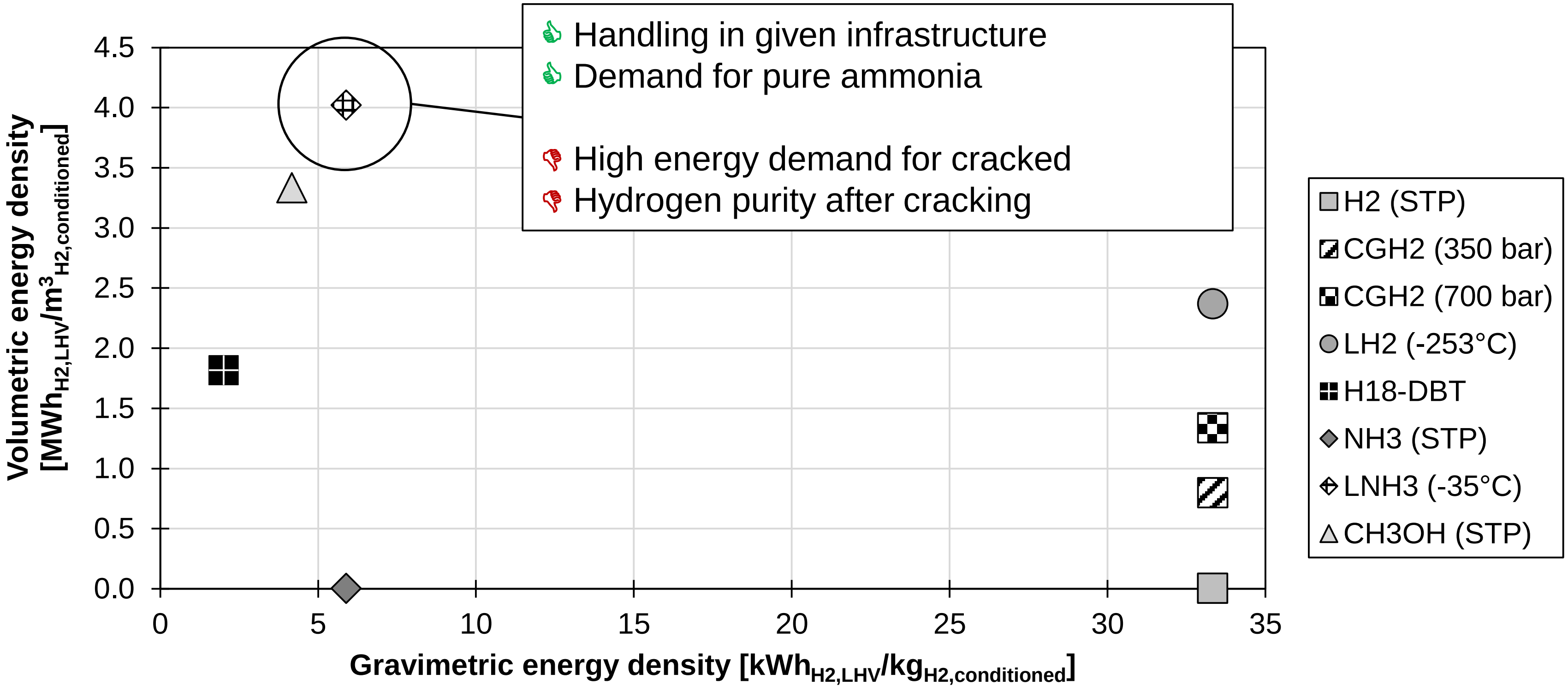
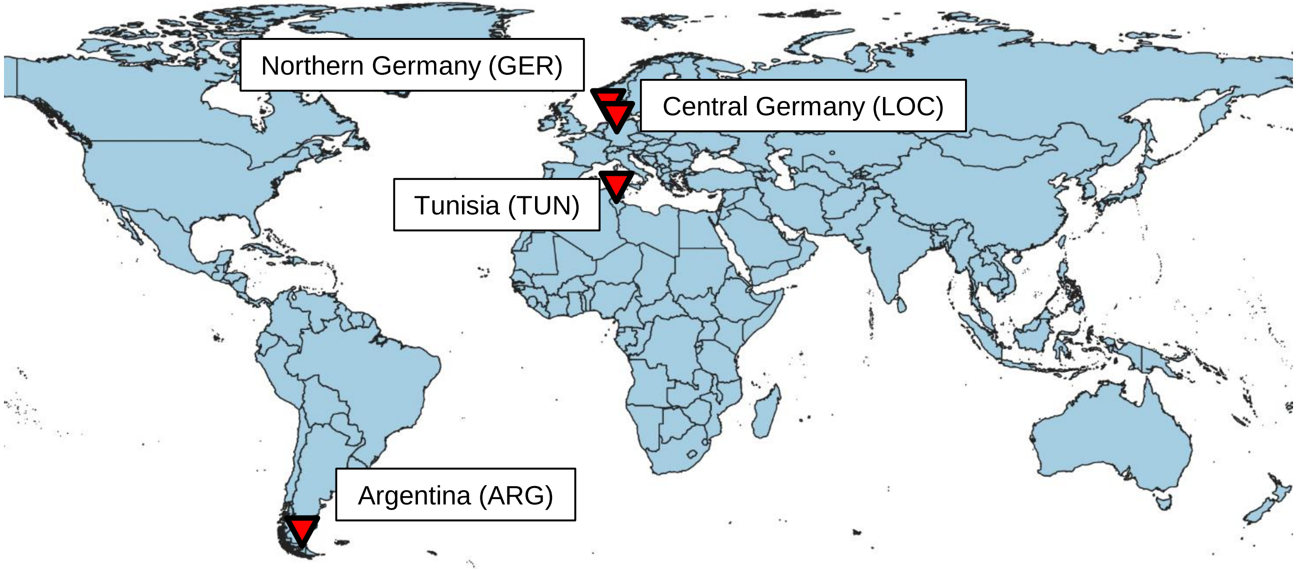
Ammonia (NH_3)



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

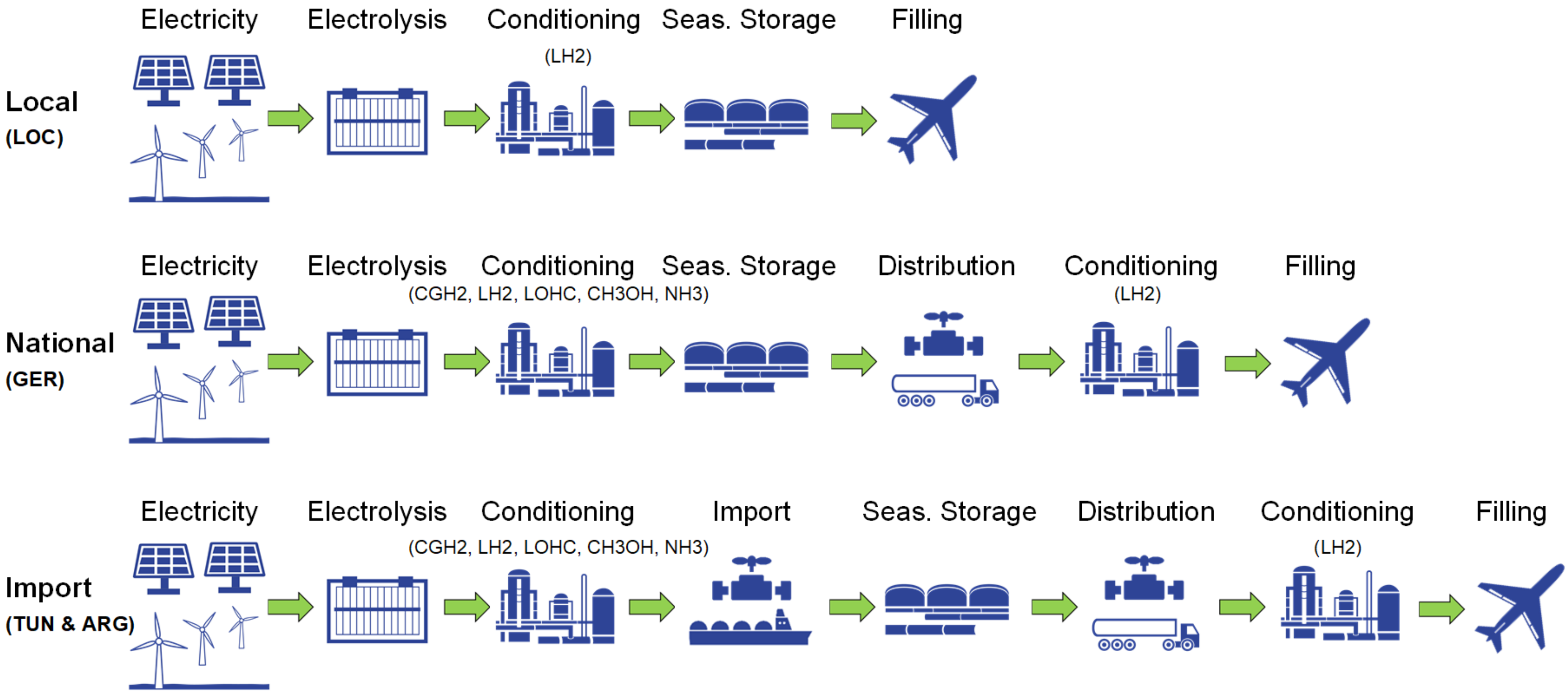
Production Locations



- **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

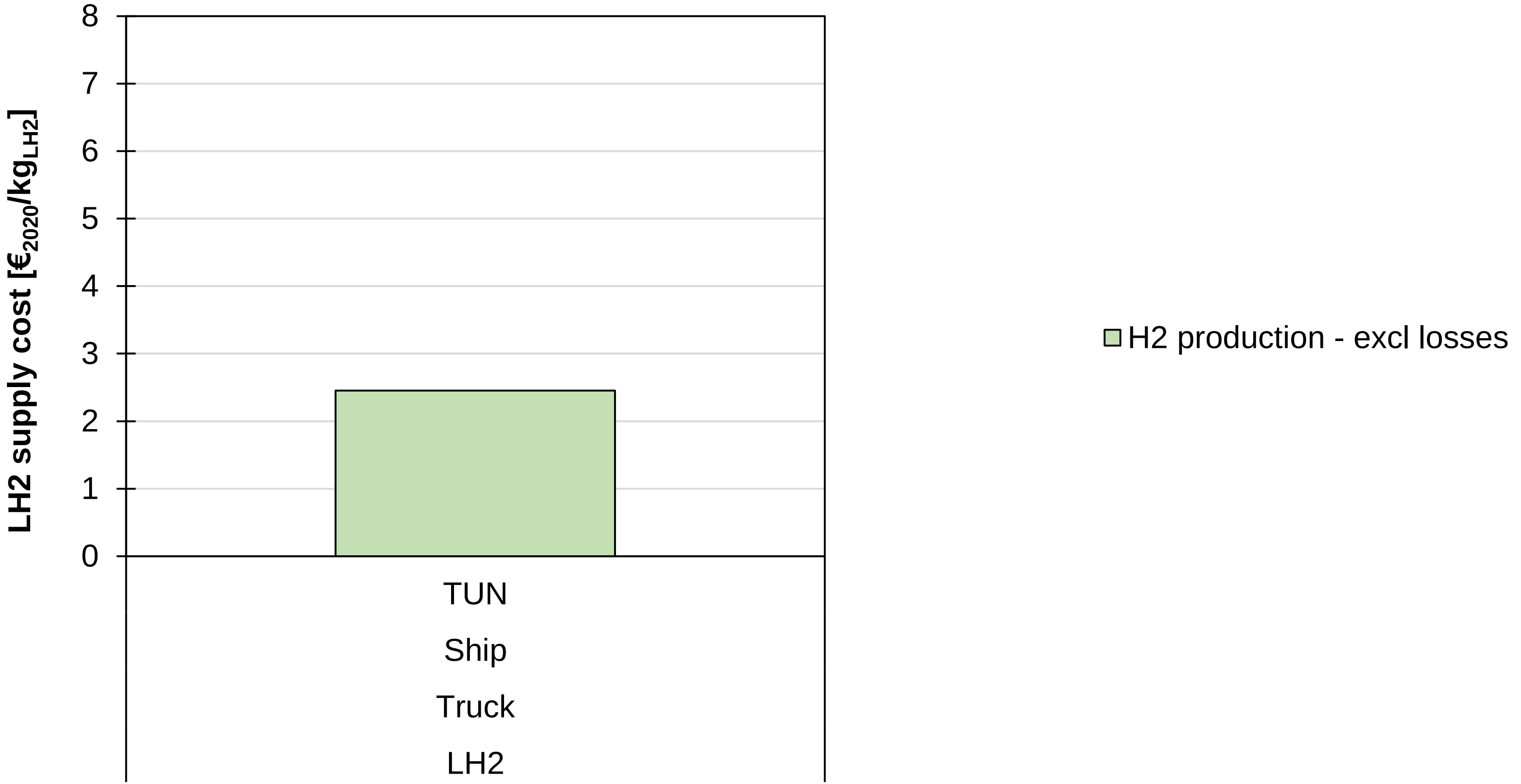
Supply Chains



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%

Liquid Hydrogen Supply Cost in 2030



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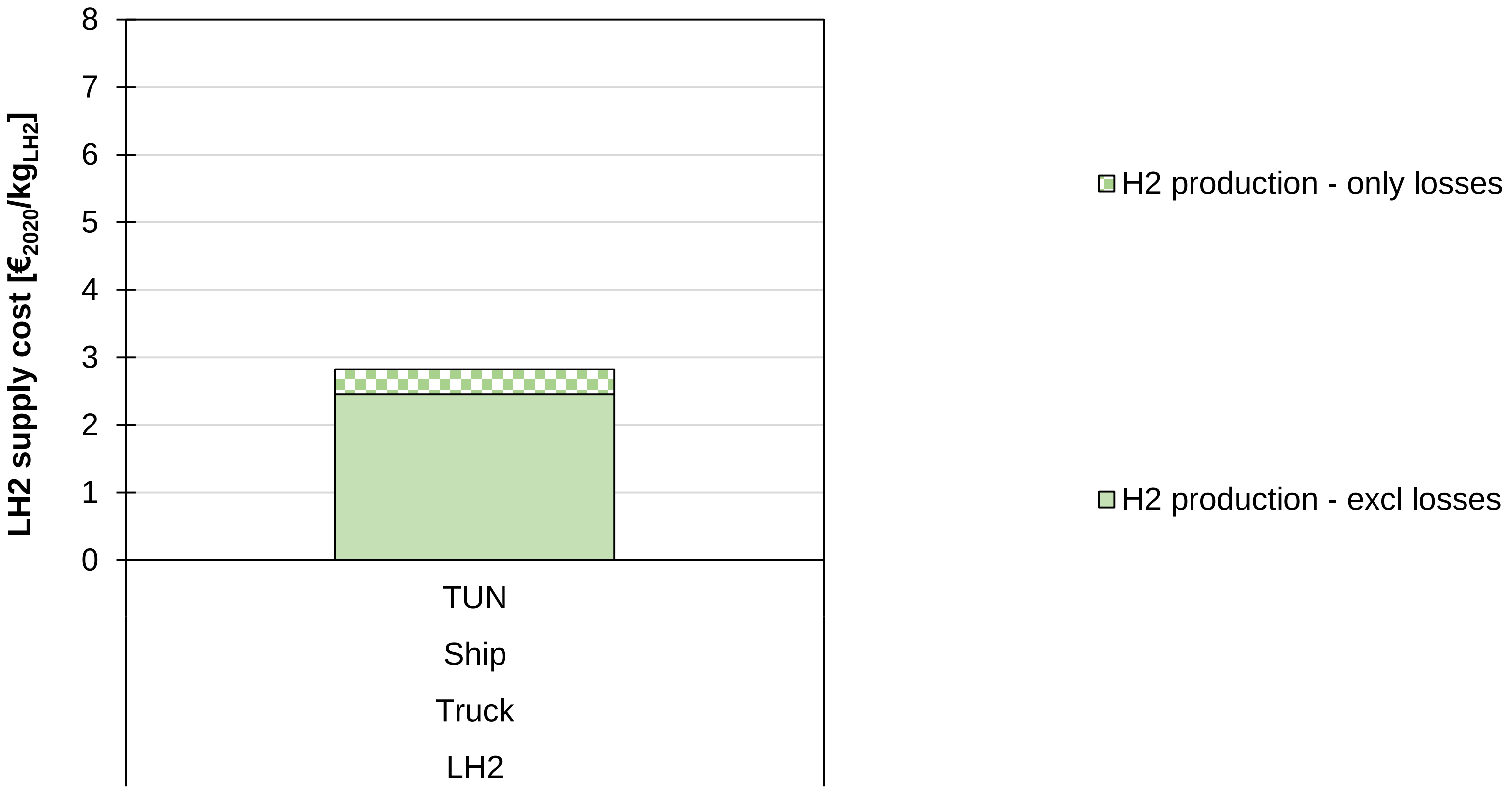

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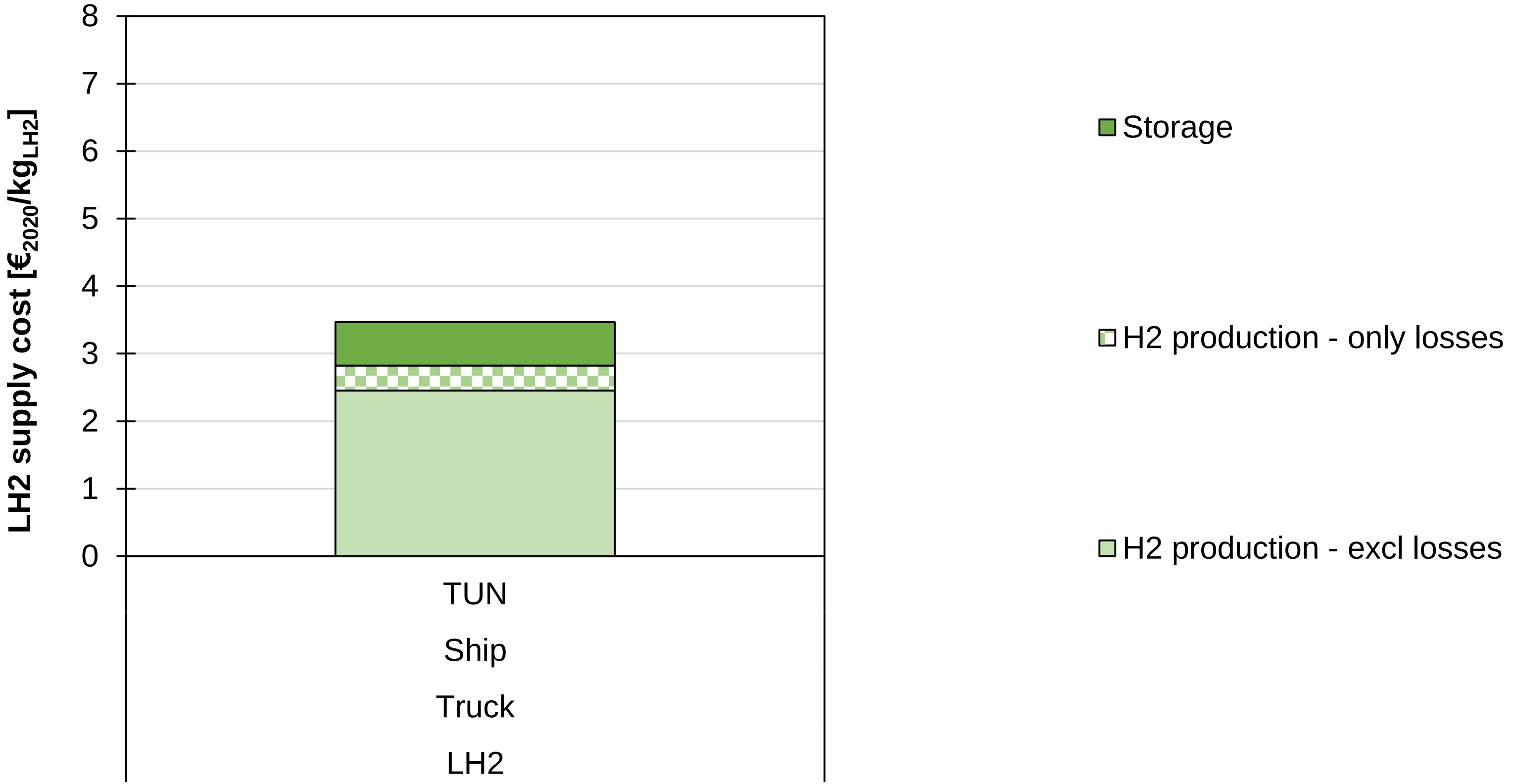

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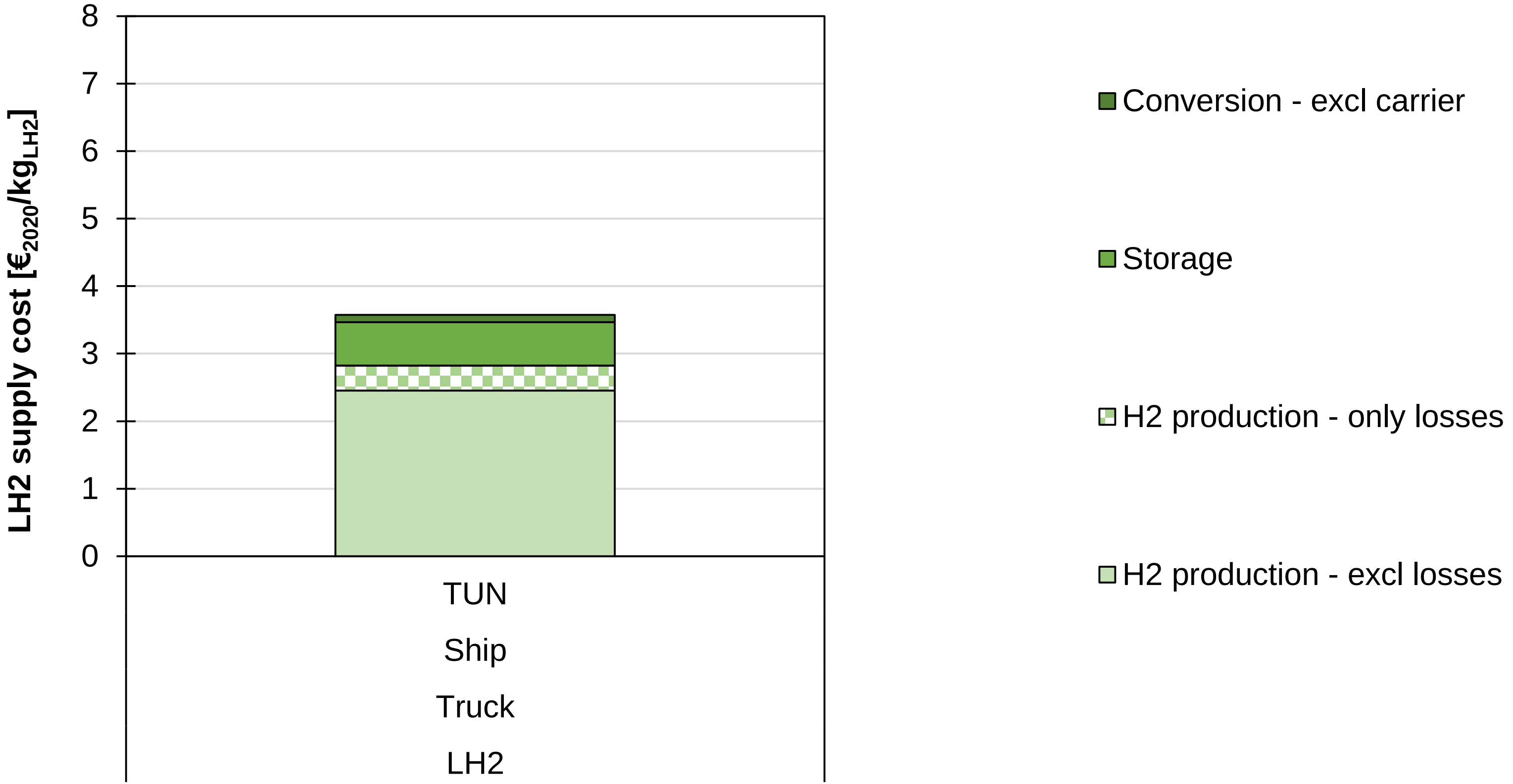

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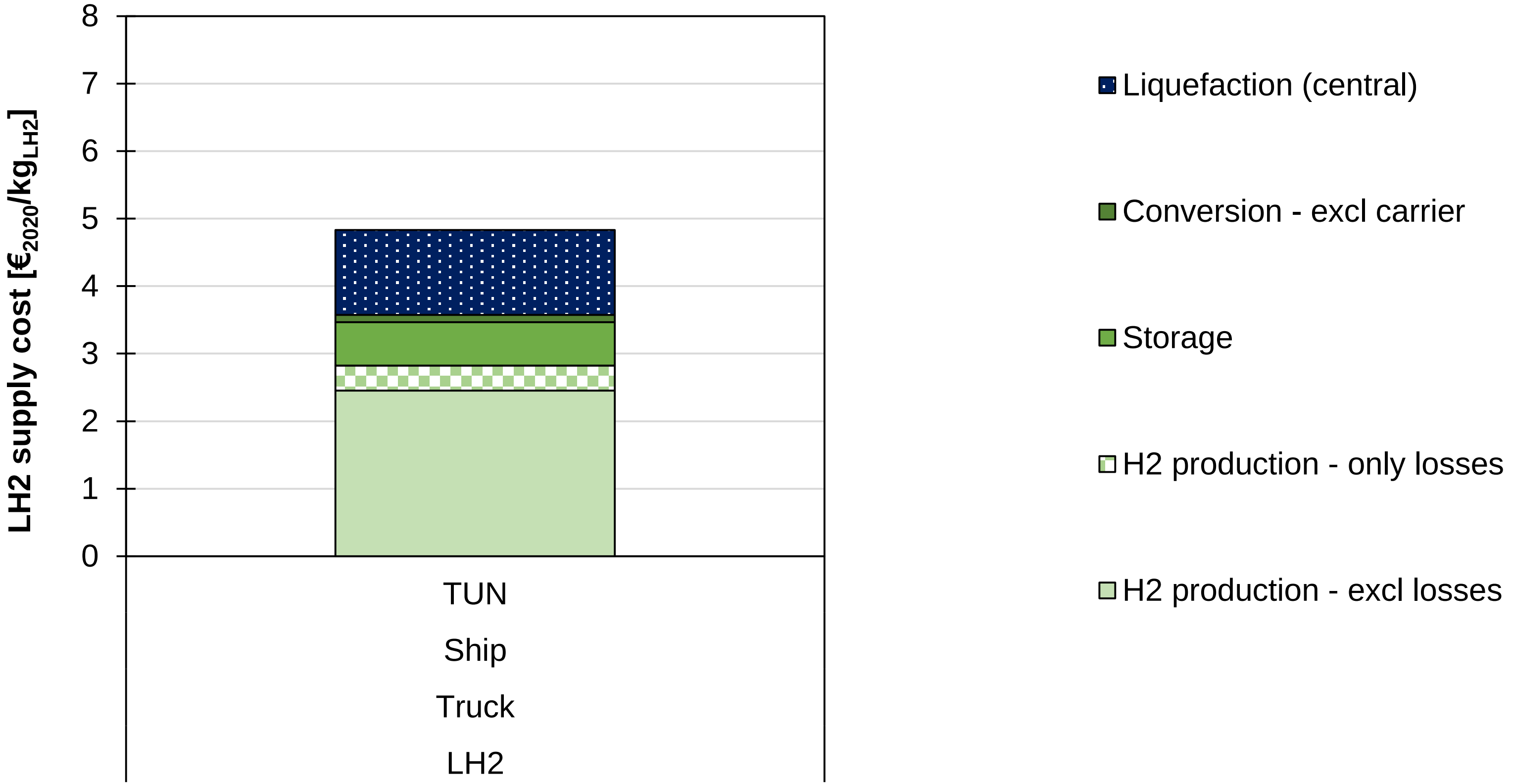

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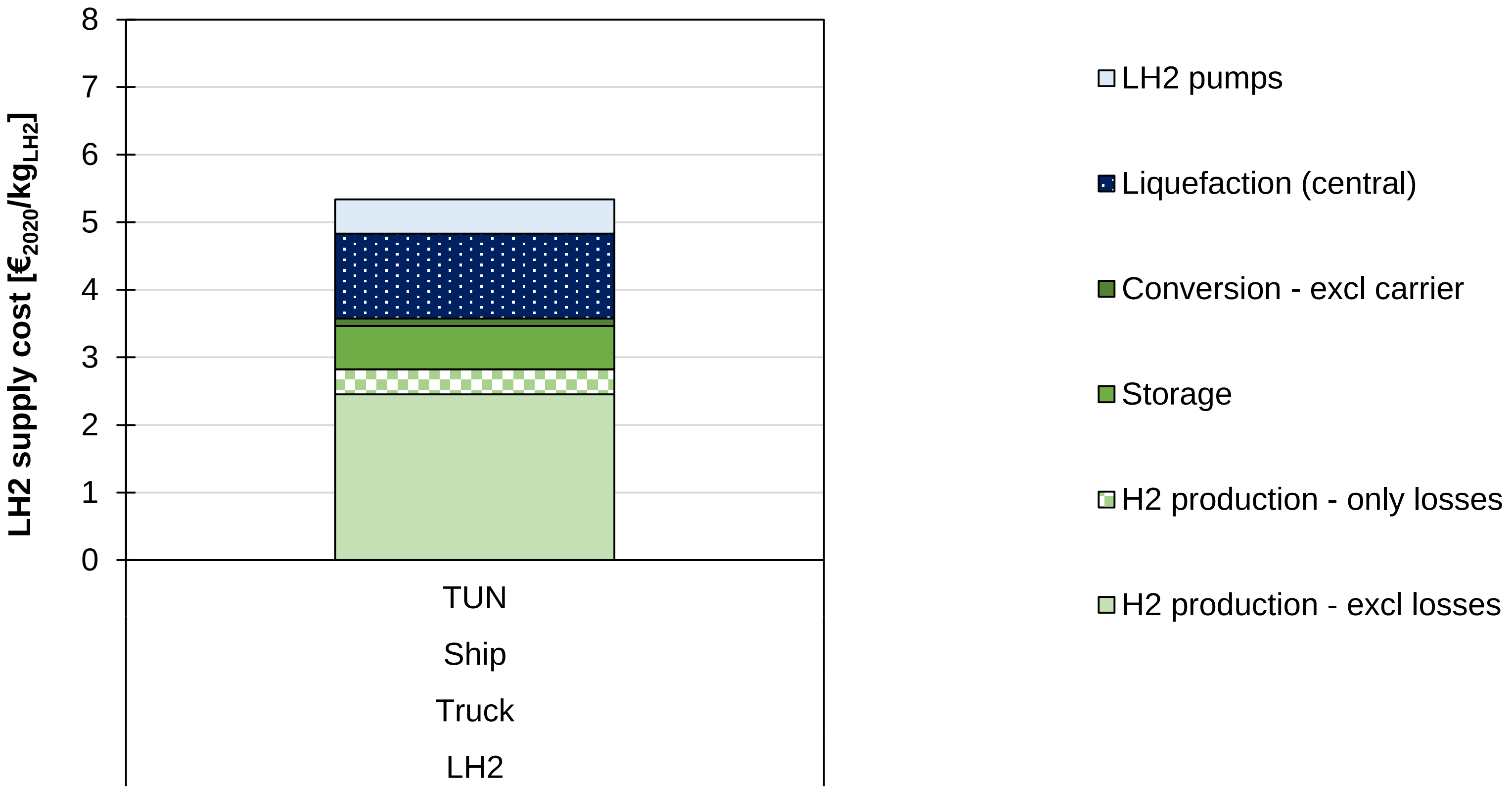

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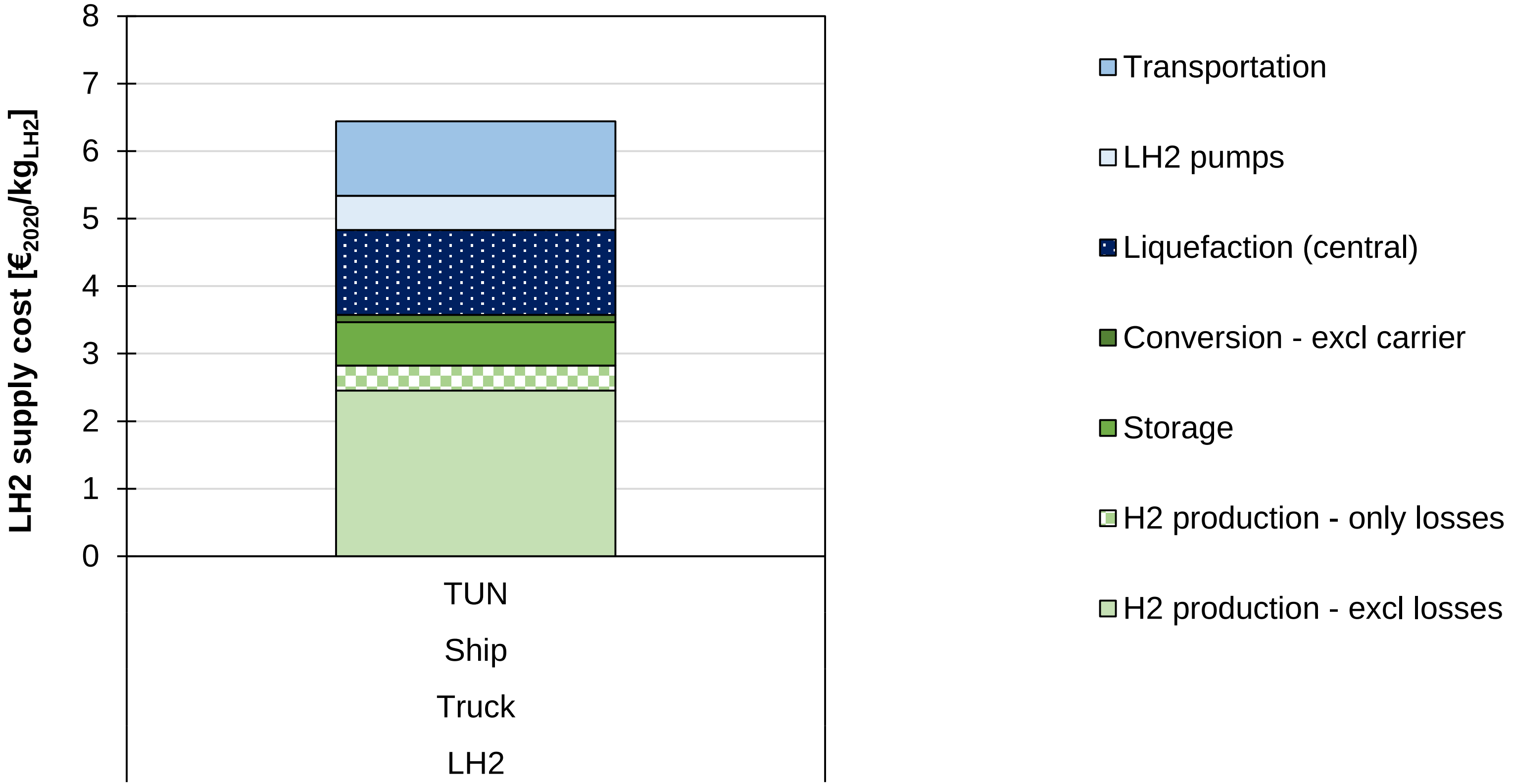

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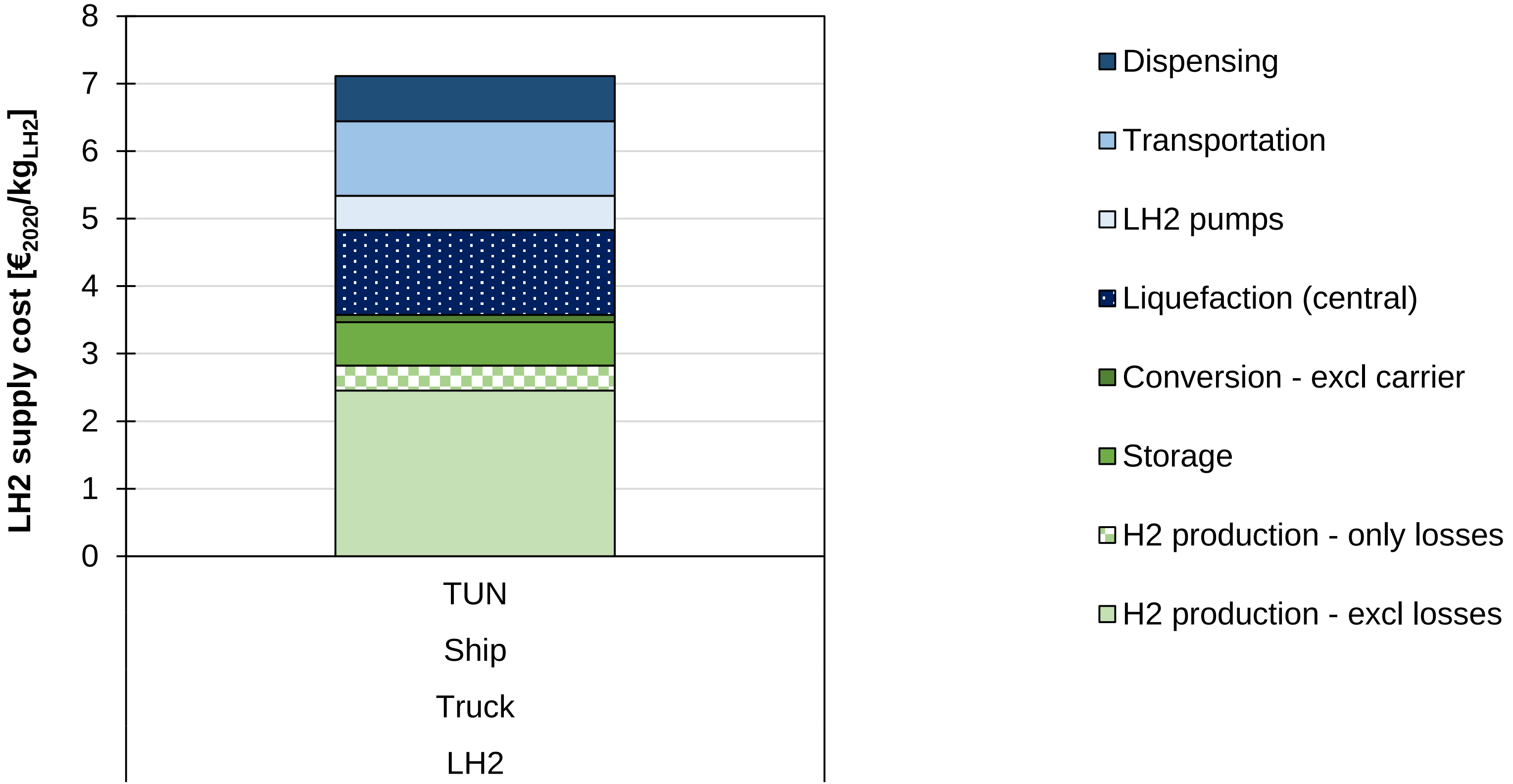

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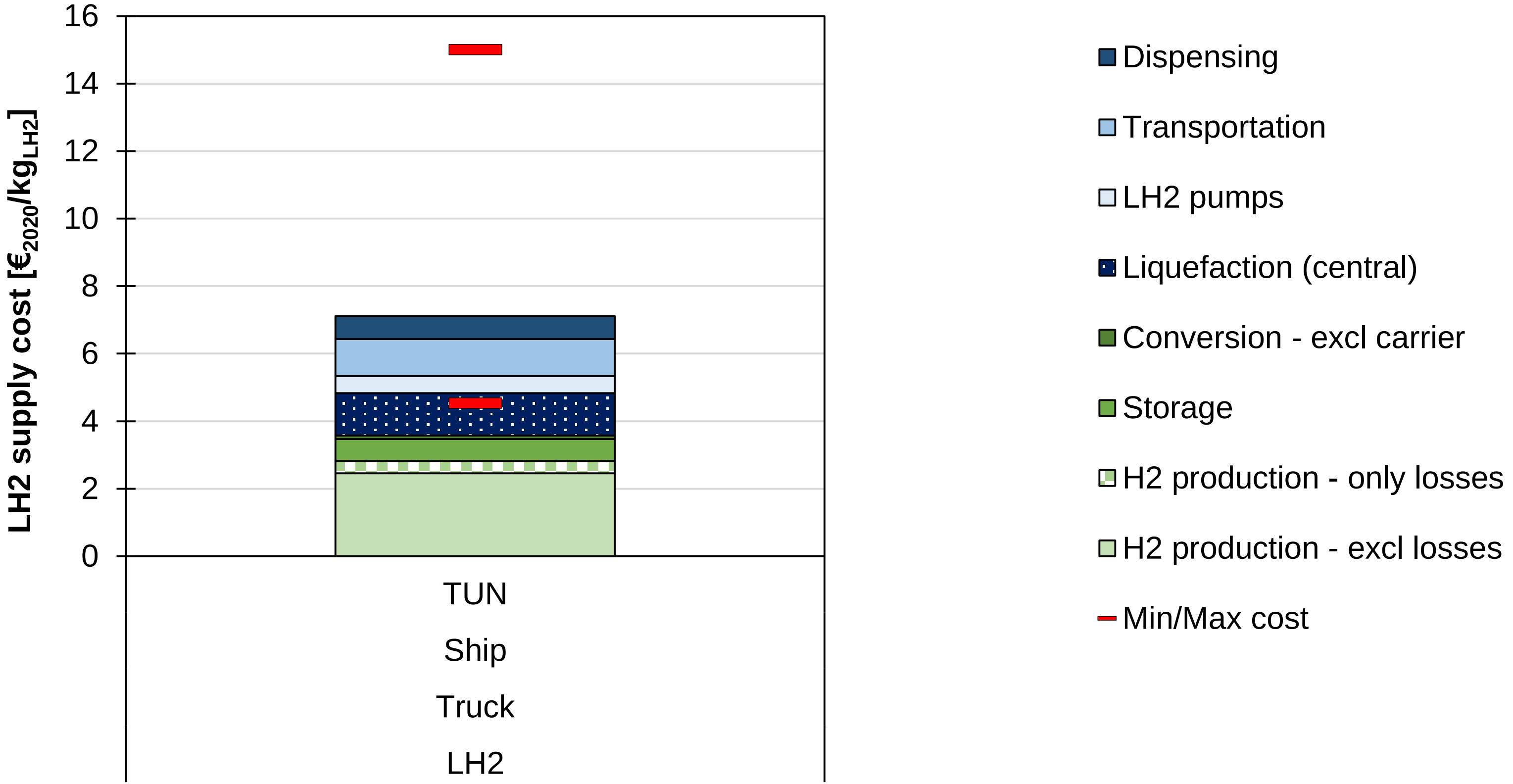

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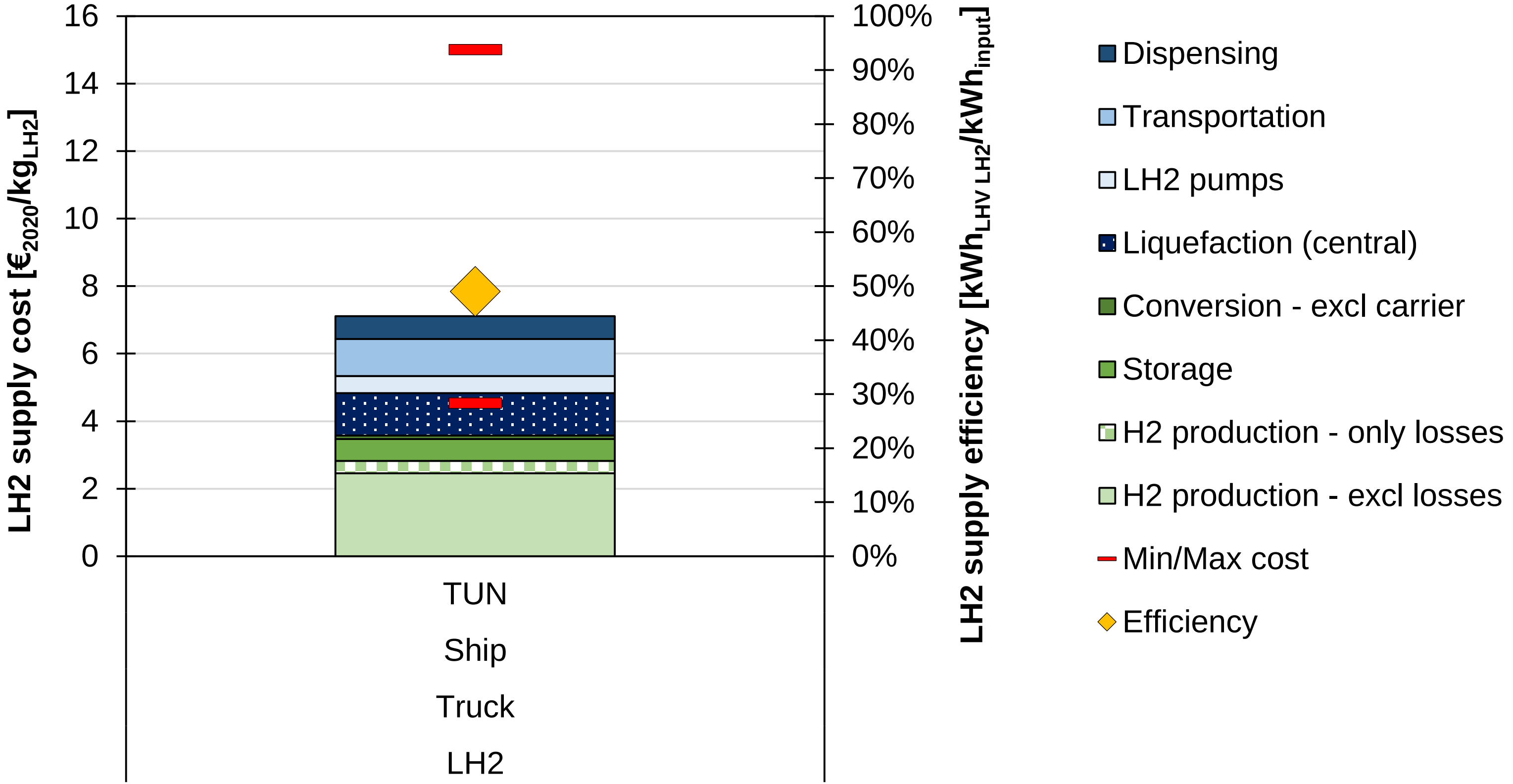
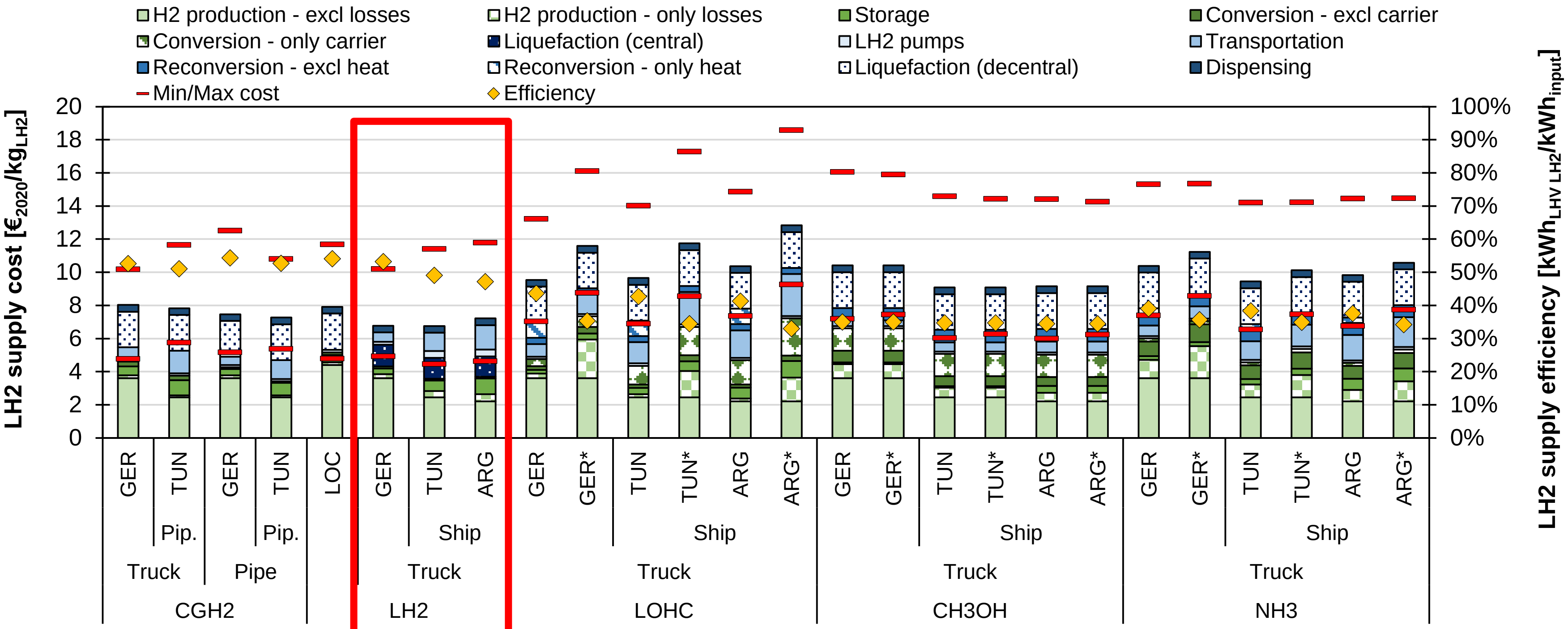
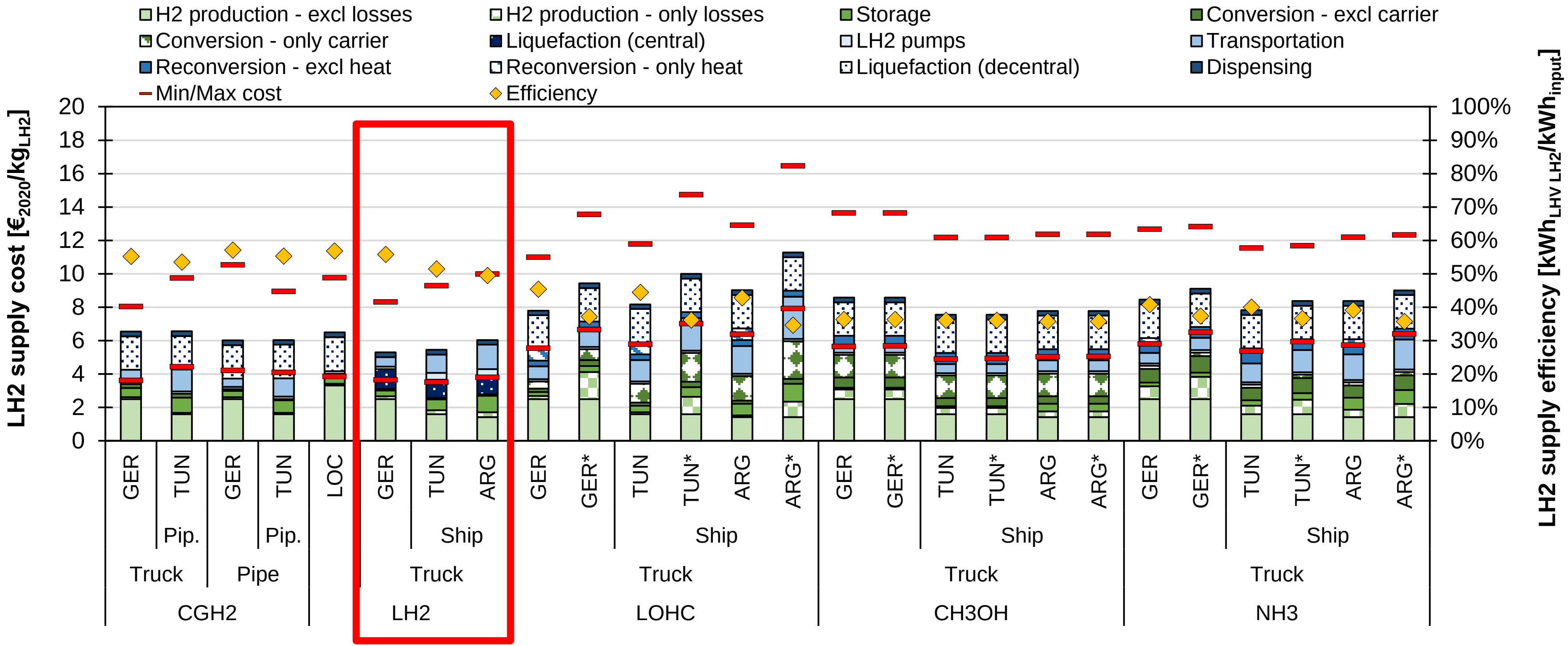


LH_2 Filling – 2030



(* = 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_2 Filling – 2050



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Conclusion

- **Liquid hydrogen and gaseous hydrogen** supply chains are the **lowest cost options** for a supply of **liquid hydrogen**
  ≈ 7 $€_{2020}/kg_{LH2}$ & 50 % (2030)
  ≈ 5 $€_{2020}/kg_{LH2}$ & 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


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References

- Images slide 1, from left to right:
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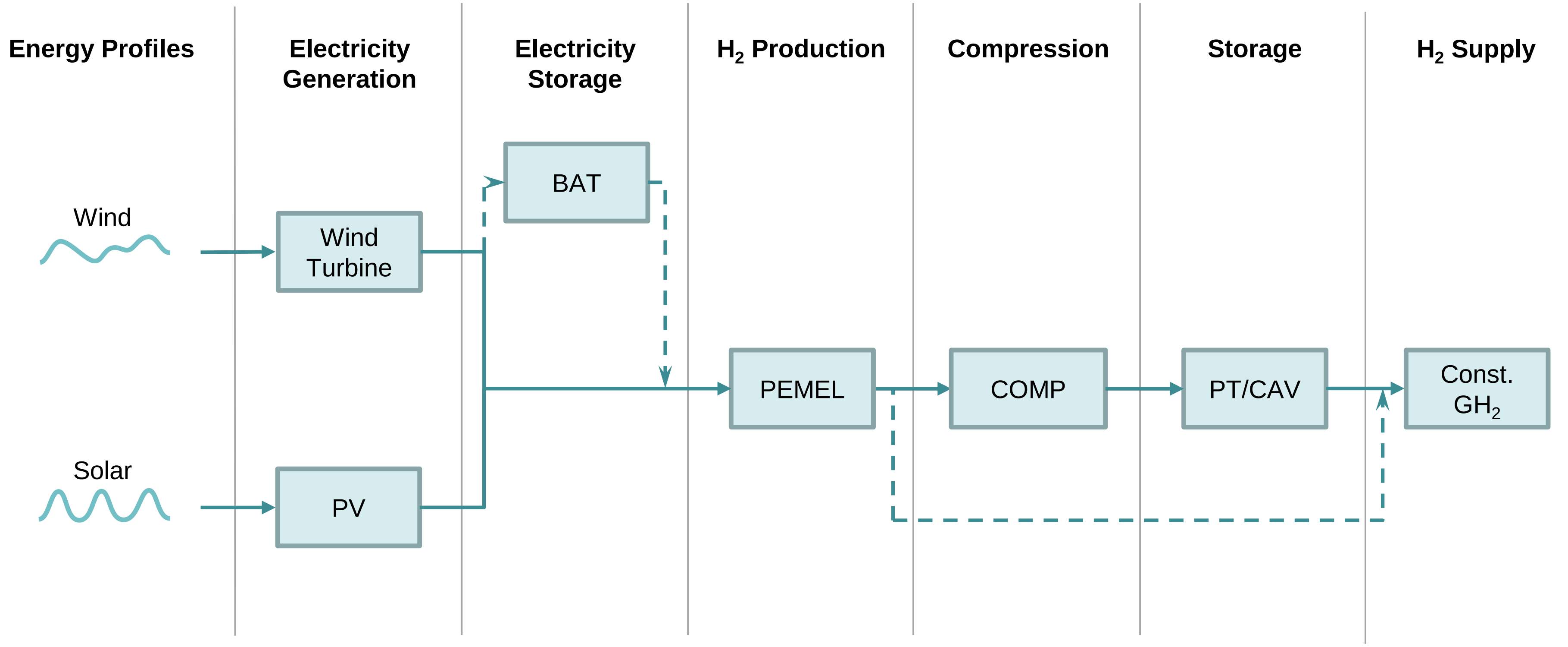
Electricity
CGH2
LH2
DBT
NH3
CH3OH
Local (LOC)
National (GER)
Import (TUN & ARG)
Wind/PV
Storage
Electrolysis
Compres-sion
Pipeline Distribution
Hydr. (DBT)
NH3 Synthesis
CH3OH Synthesis
Lique-faction
Pump
Pipeline Import
Ship Import
Truck Transport
Seasonal Storage
Pipeline Transport
Truck Distribution
Dehydr. (DBT)
NH3 Splitting
CH3OH Splitting
Filling (LwPrDI)
Filling (HgPrDI)
Filling (LH2DI)
Filling
Wind & PV
Buffer Storage (Electricity)
Electrolysis
Conditioning (Compression)
Buffer Storage (CGH2)
Transport (Pipeline)
Conditioning (Conversion)
LH2 Pump
Buffer Storage (Conditioned H2)
LH2 Pump
Import
LH2 Pump
Buffer Storage (Conditioned H2)
LH2 Pump
Transport (Truck)
LH2 Pump
Seasonal Storage (Conditioned H2)
Transport (Pipeline)
Conditioning (Compression)
Buffer Storage (CGH2)
Distribution
Buffer Storage (Conditioned H2)
Conditioning (Reconversion)
Conditioning (Liquefaction)
LH2 Pump
Filling

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

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

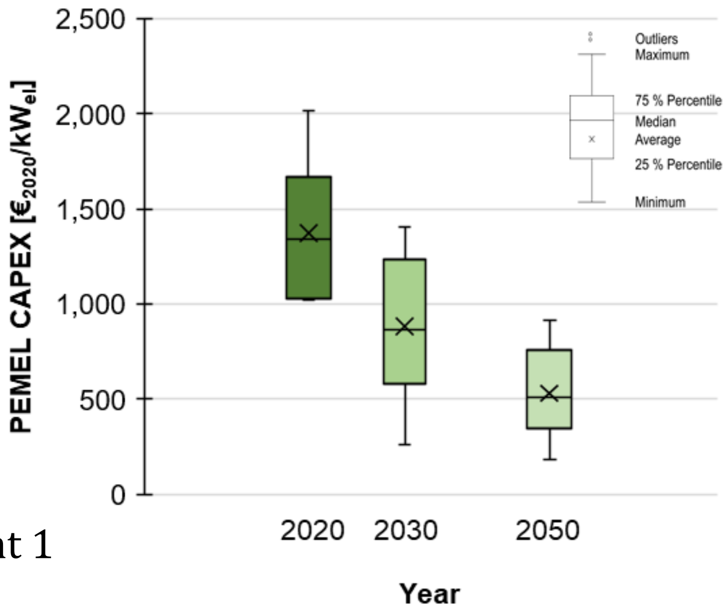
$$c_{section,i} = \frac{ACAPEX_i + OPEX_i}{m_{H2,fill,annual}}$$

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

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

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

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

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

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