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Green Liquid Hydrogen Supply Chains for Future Aviation

A techno-economic well to tank assessment

Lucas Sens, Fabian Carels, Ulf Neuling and Martin Kaltschmitt

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

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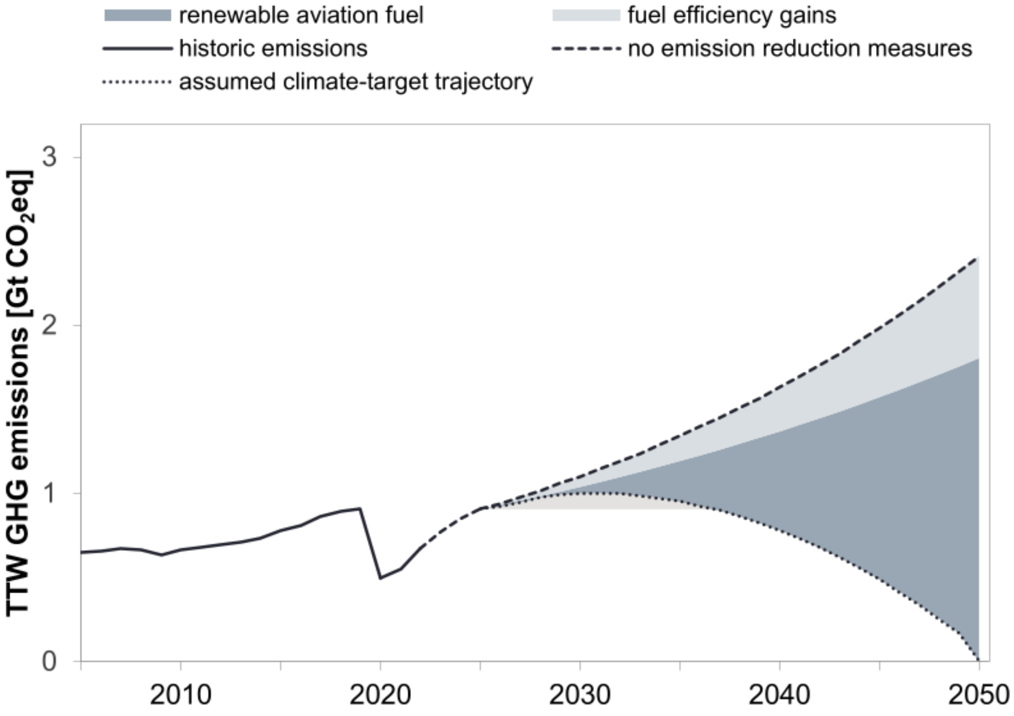
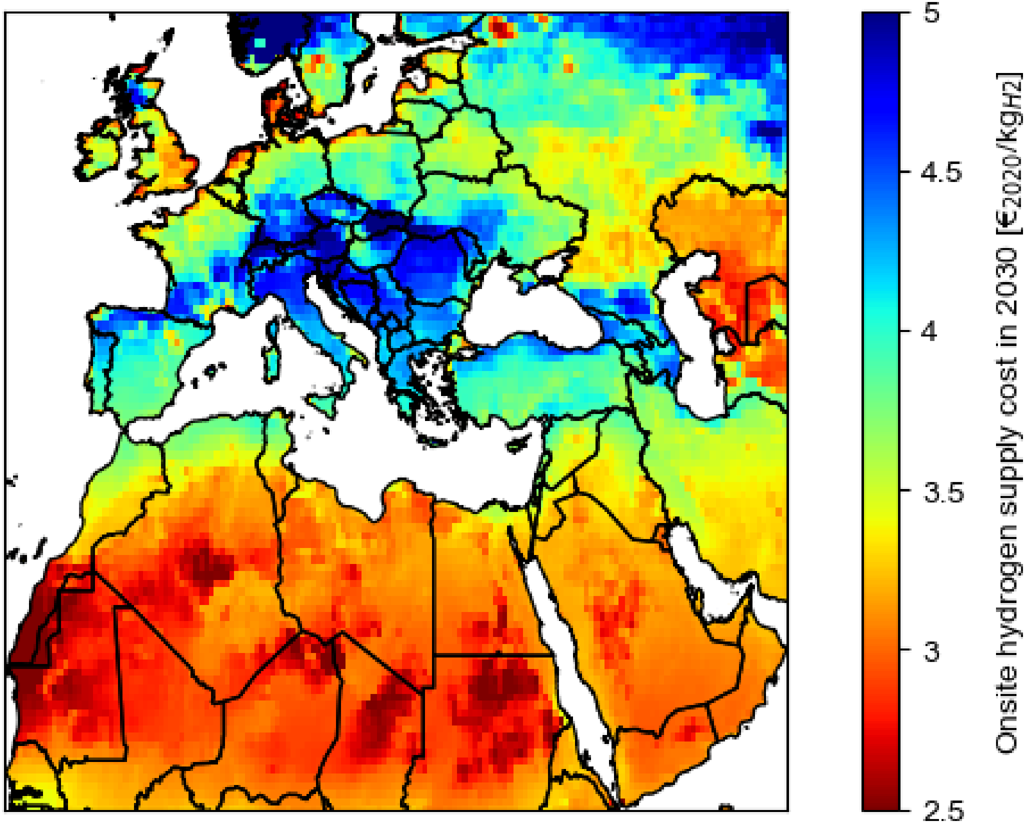
Hydrogen Powered Aviation

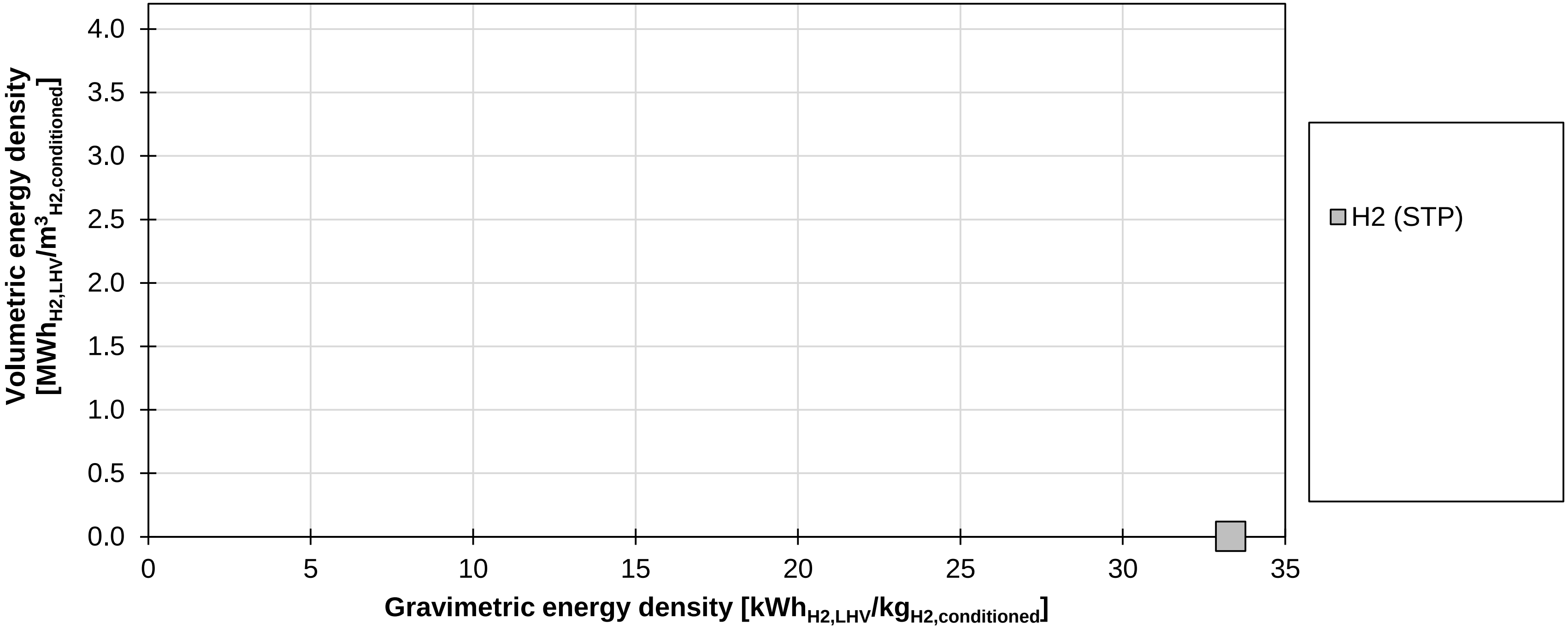


Onsite Hydrogen Supply Cost



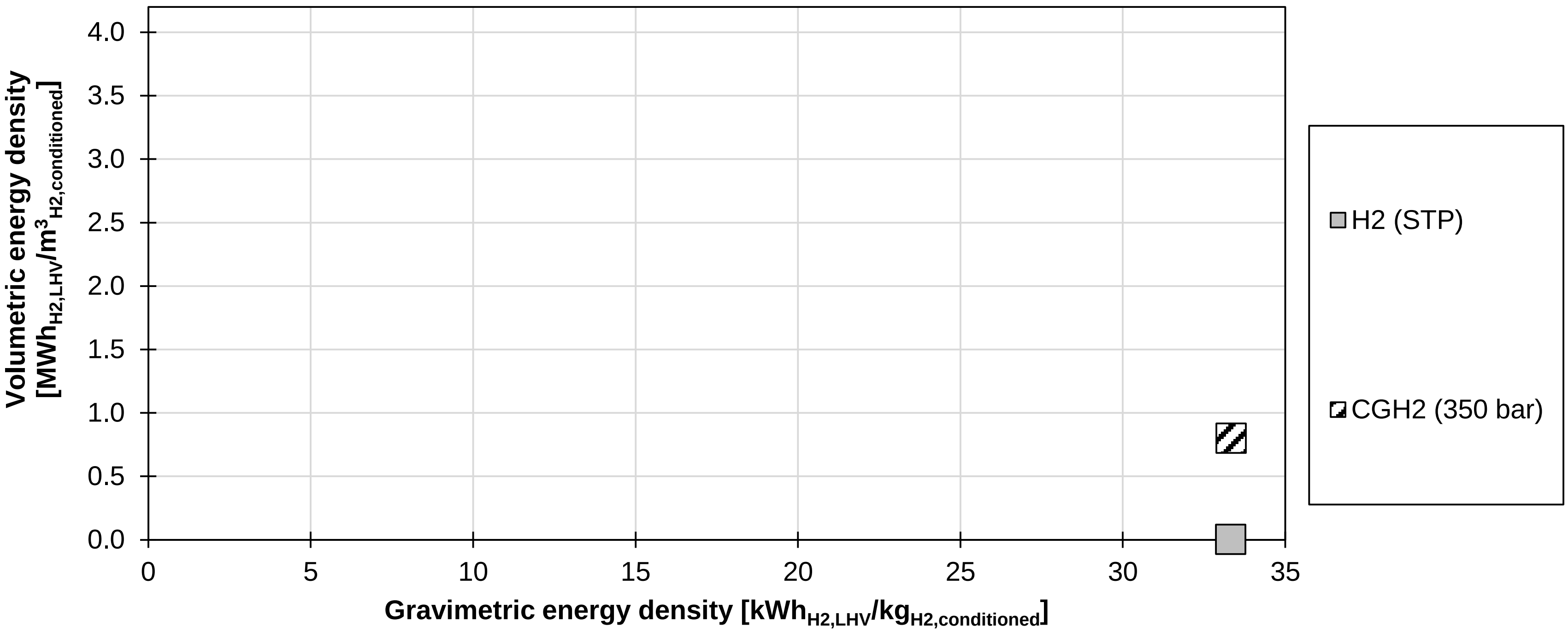
Transportation needed to supply low cost hydrogen to the demand centers

Hydrogen at Standard Temperature and Pressure



STP = standard temperature and pressure

Compressed Gaseous Hydrogen (CGH_2)



CGH2 = compressed gaseous hydrogen, STP = standard temperature and pressure

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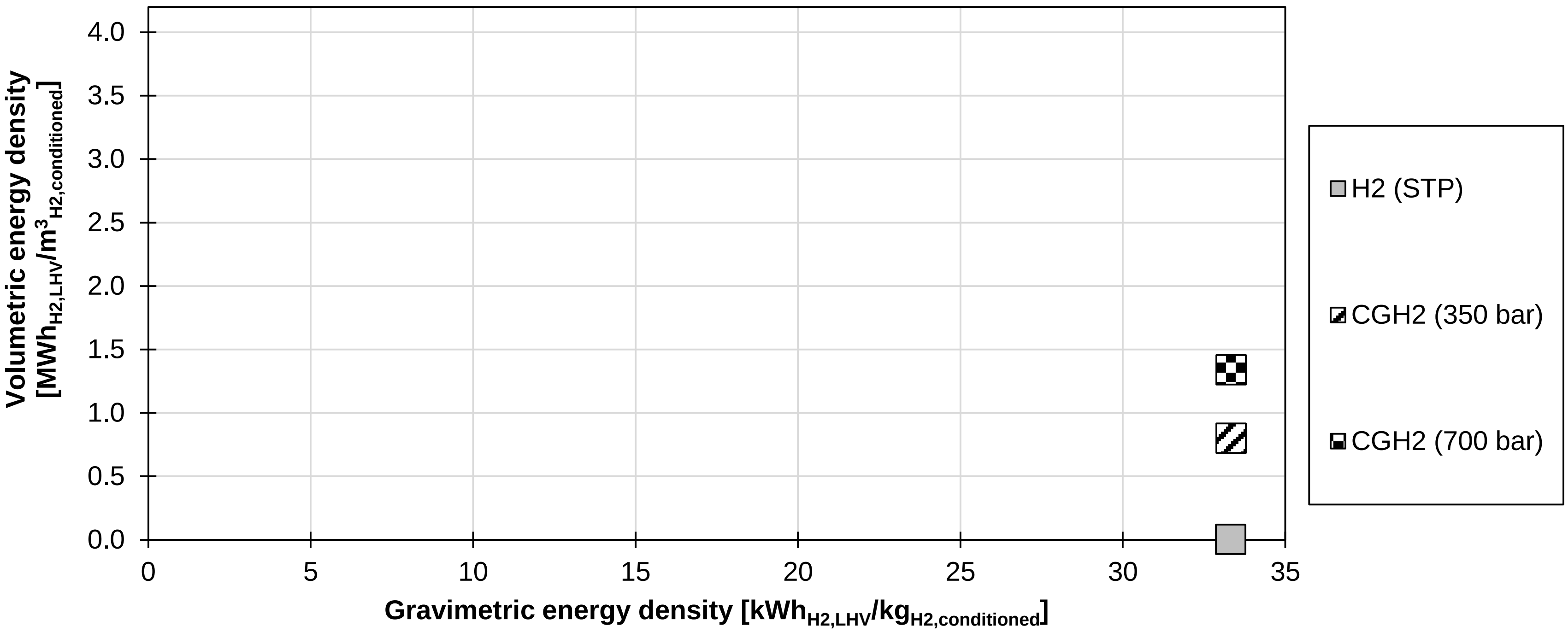

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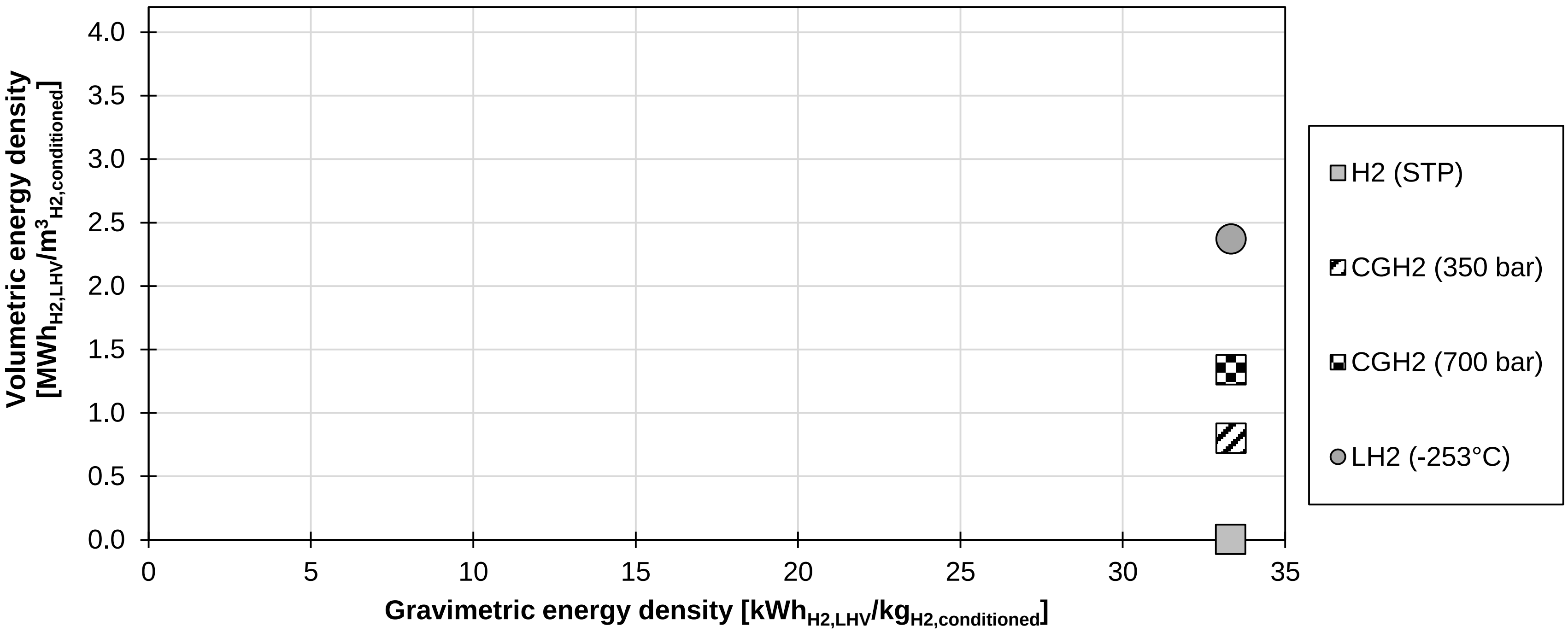
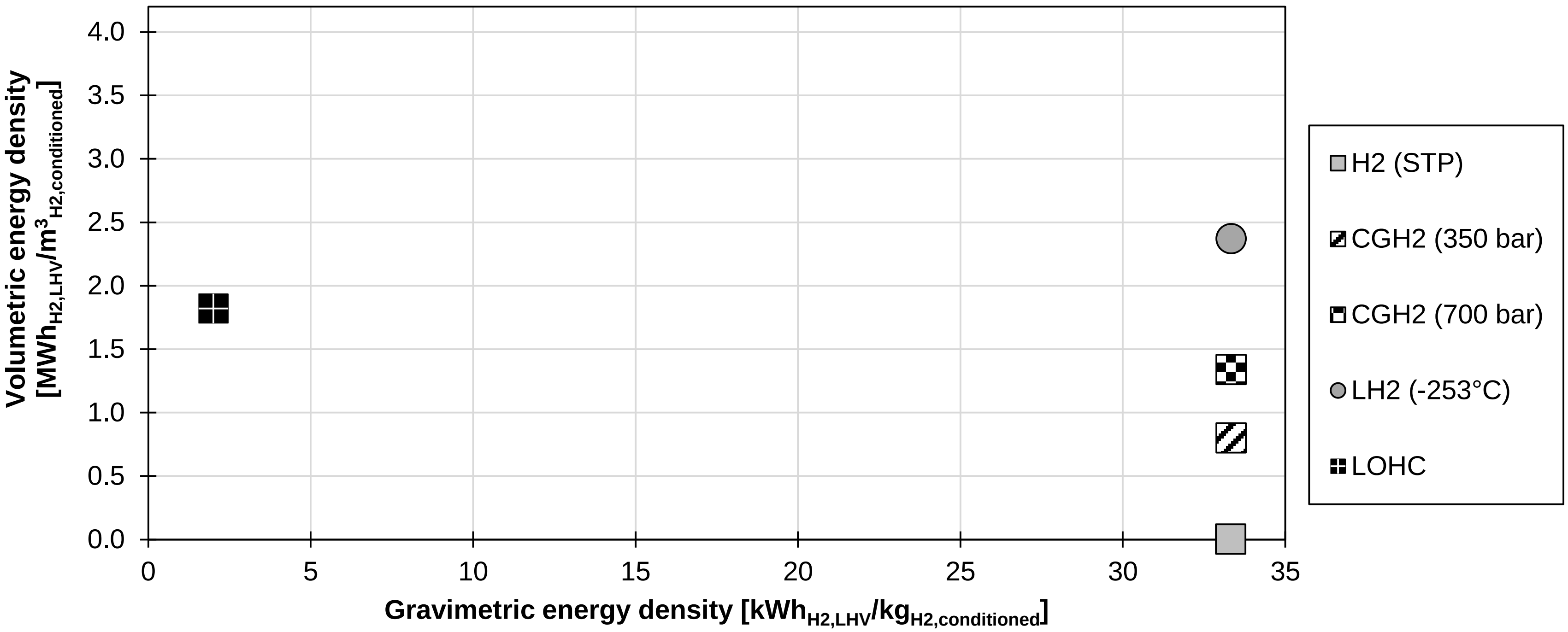
Liquid Hydrogen (LH_2)



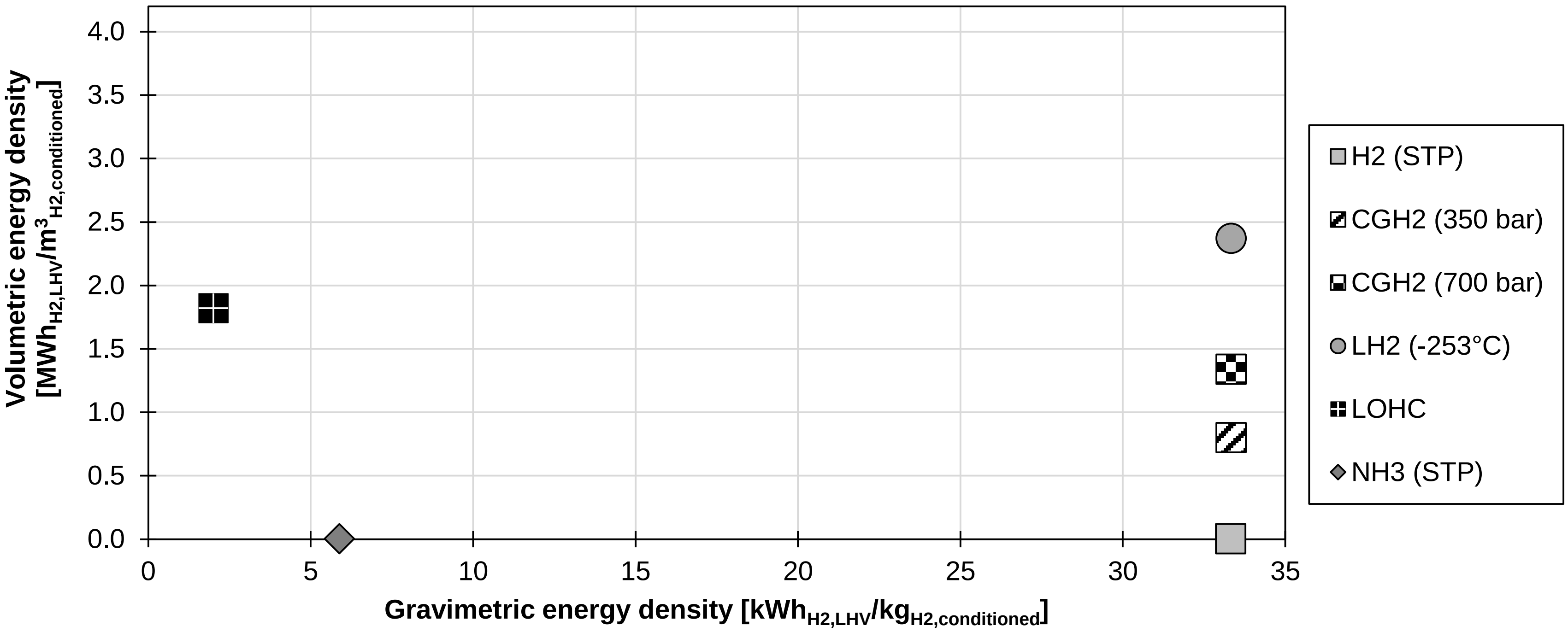
CGH2 = compressed gaseous hydrogen, LH2 = liquid hydrogen, STP = standard temperature and pressure

Liquid Organic Hydrogen Carriers (LOHC)



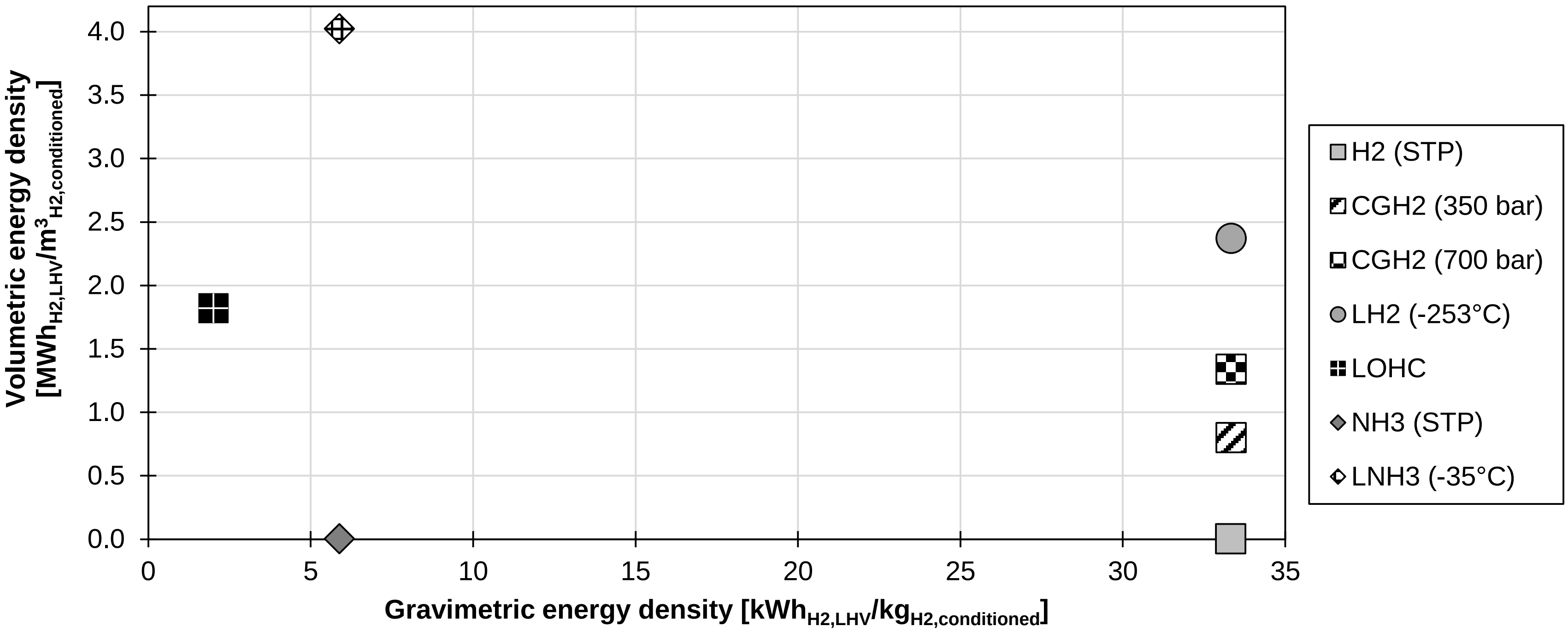
CGH2 = compressed gaseous hydrogen, LOHC = liquid organic hydrogen carrier (here Dibenzyltoluene), LH2 = liquid hydrogen, STP = standard temperature and pressure

Ammonia (NH_3)



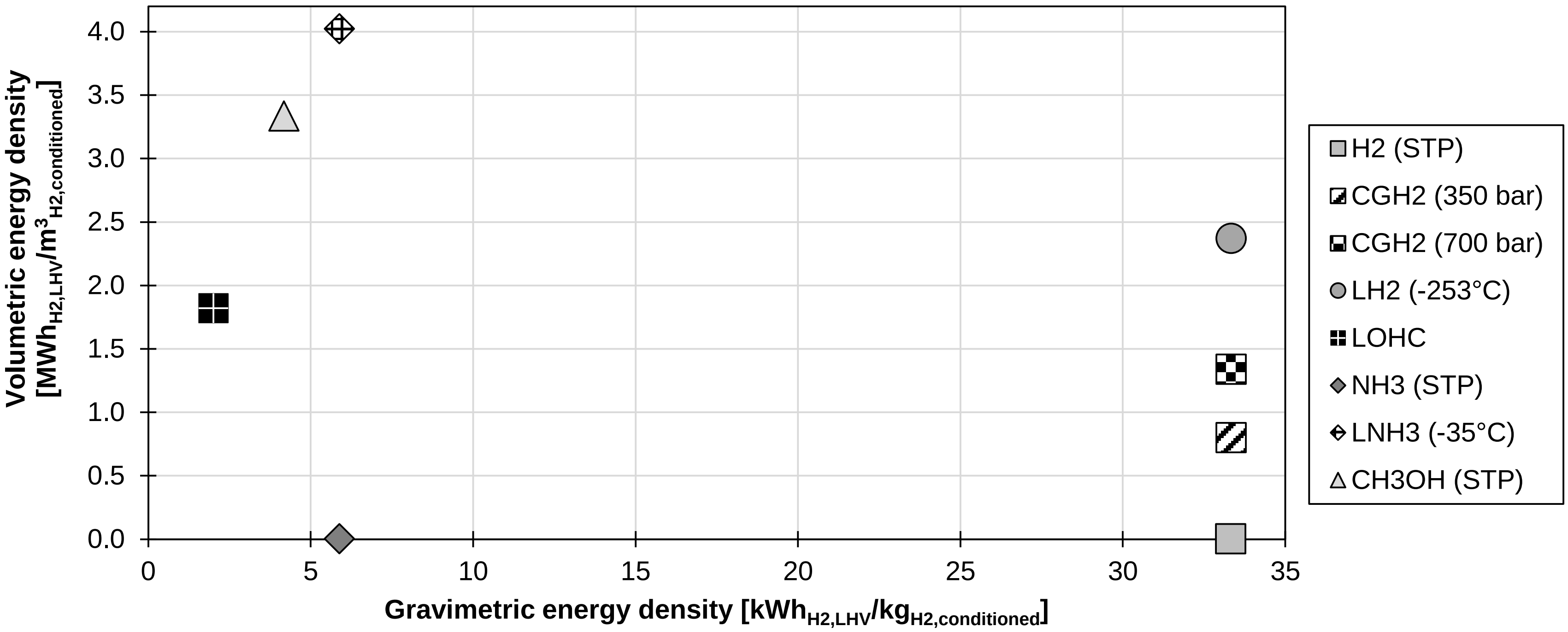
CGH2 = compressed gaseous hydrogen, LOHC = liquid organic hydrogen carrier (here Dibenzyltoluene), LH2 = liquid hydrogen, NH3 = ammonia, STP = standard temperature and pressure

Liquid Ammonia (LNH_3)



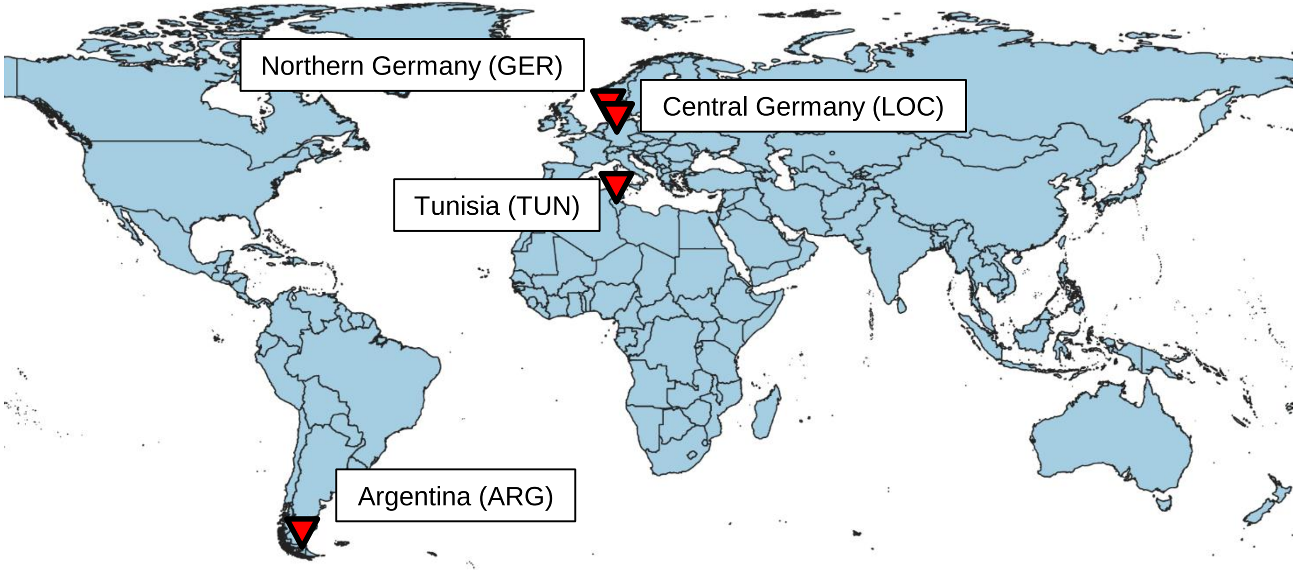
CGH2 = compressed gaseous hydrogen, LOHC = liquid organic hydrogen carrier (here Dibenzyltoluene), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

Methanol (CH_3OH)



CGH2 = compressed gaseous hydrogen, CH3OH = methanol, LOHC = liquid organic hydrogen carrier (here Dibenzyltoluene), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

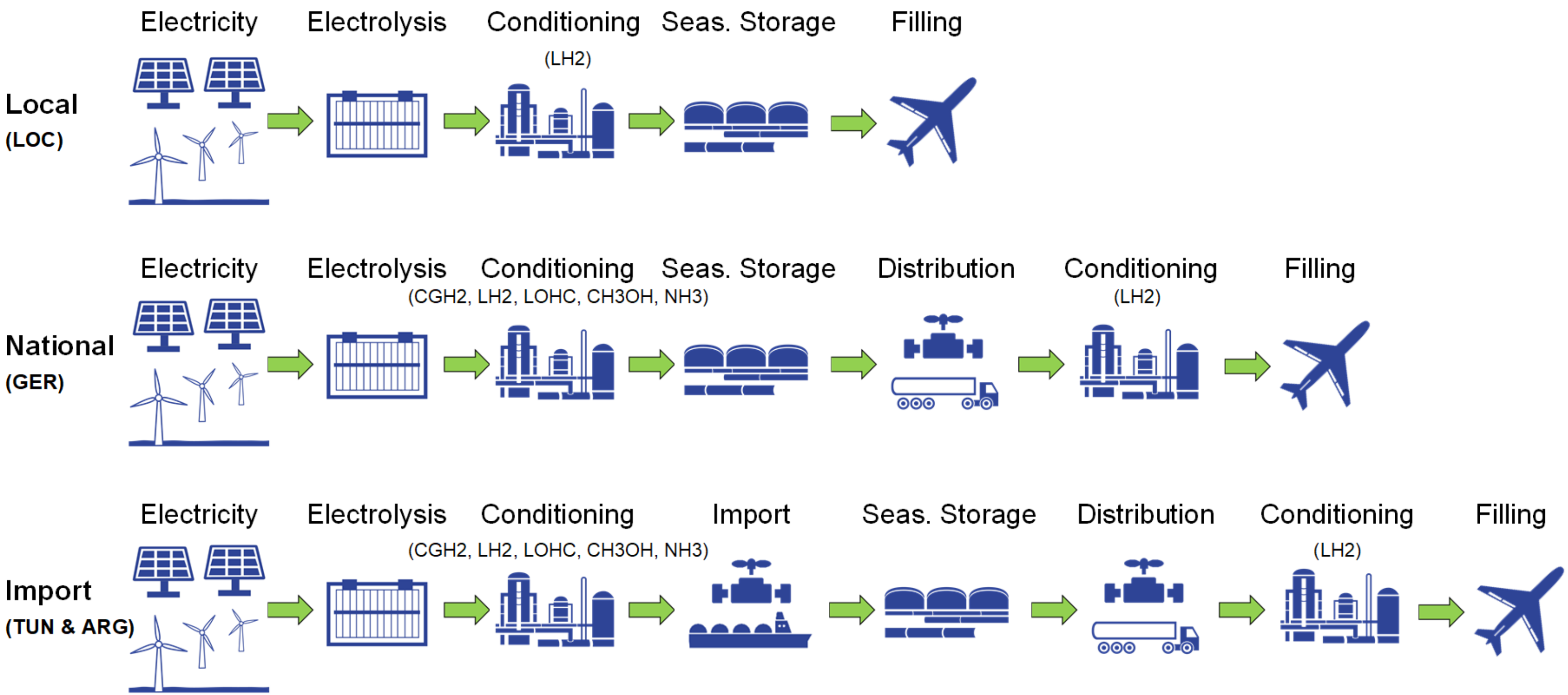
Exemplified Hydrogen Production Locations



- **Central Germany (LOC):** PV ≈ 1,100 AFLH; Onshore Wind ≈ 2,600 AFLH
- **North 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

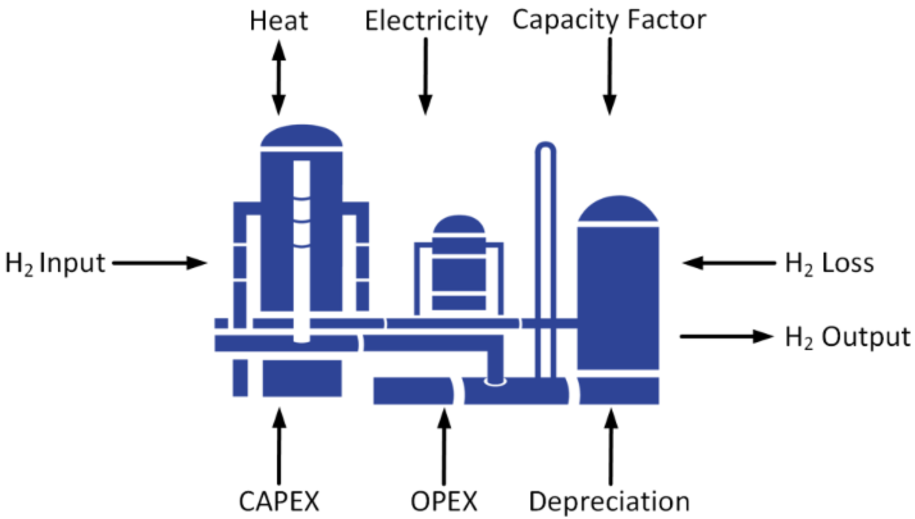
Supply Chains



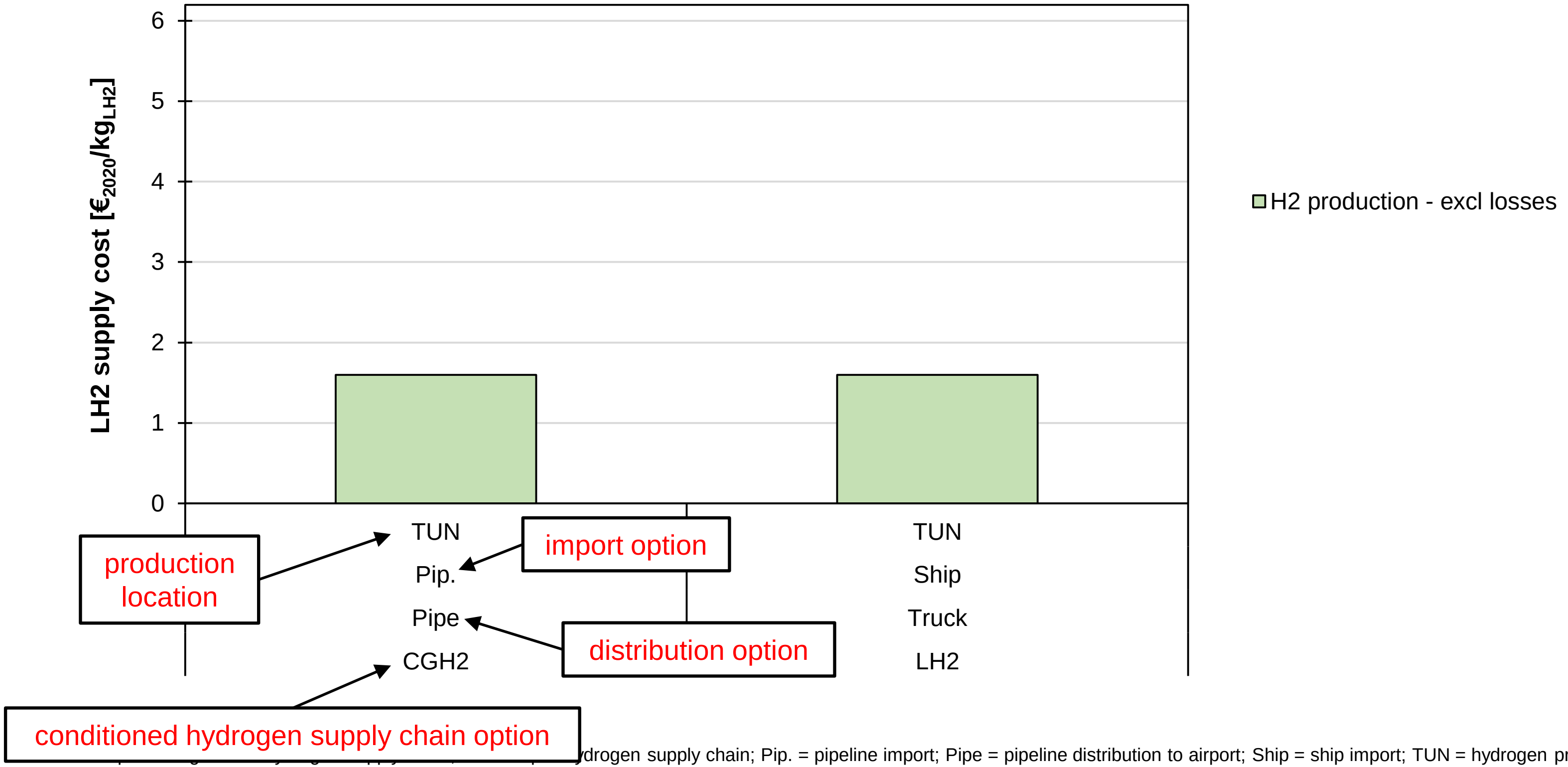
CGH2 = compressed gaseous hydrogen, CH3OH = methanol, LOHC = liquid organic hydrogen carrier (here Dibenzyltoluene), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

Methodology

- Annuity methodology for cost quantification
- Depreciation period equals technical lifetime
- Economic scaling functions considering the plant size
- Techno-economic parameters based on literature and cross check with industry

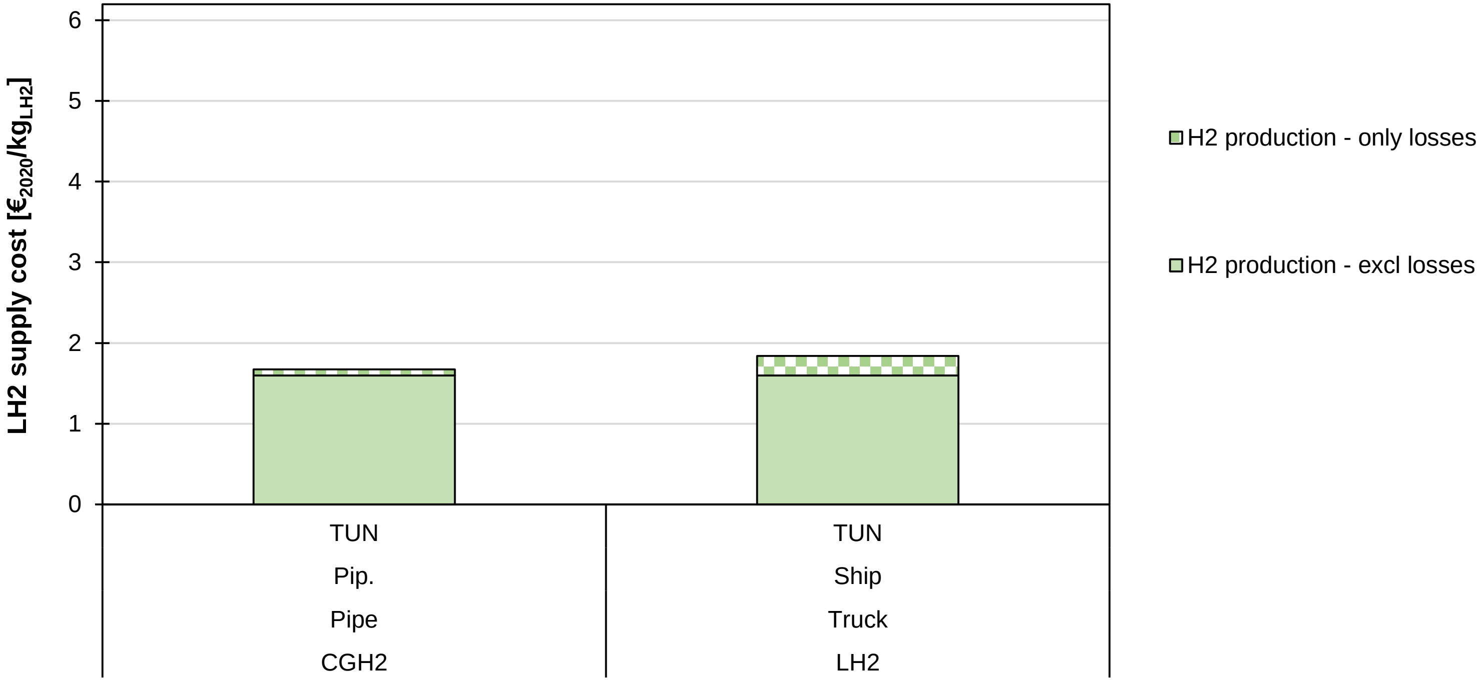


Liquid Hydrogen Supply Cost in 2050



…ydrogen supply chain; Pip. = pipeline import; Pipe = pipeline distribution to airport; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to airport

Liquid Hydrogen Supply Cost in 2050



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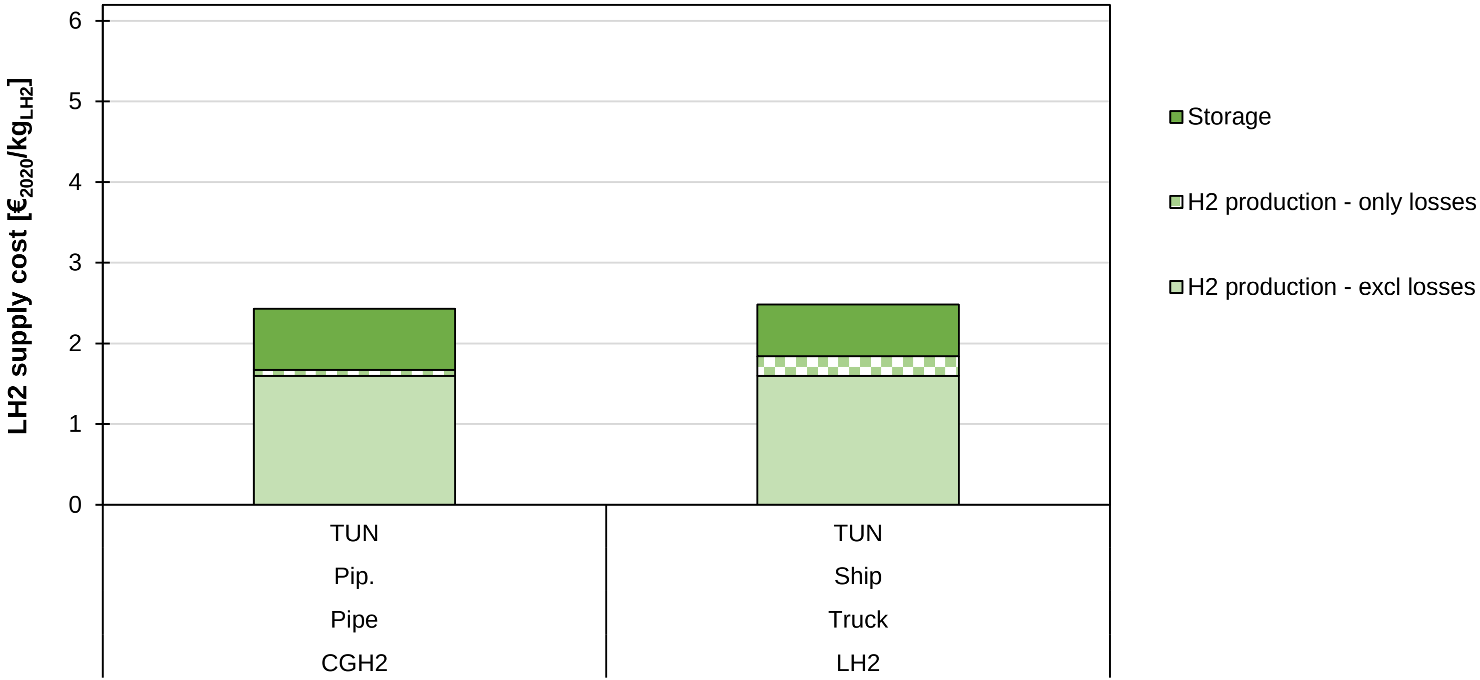

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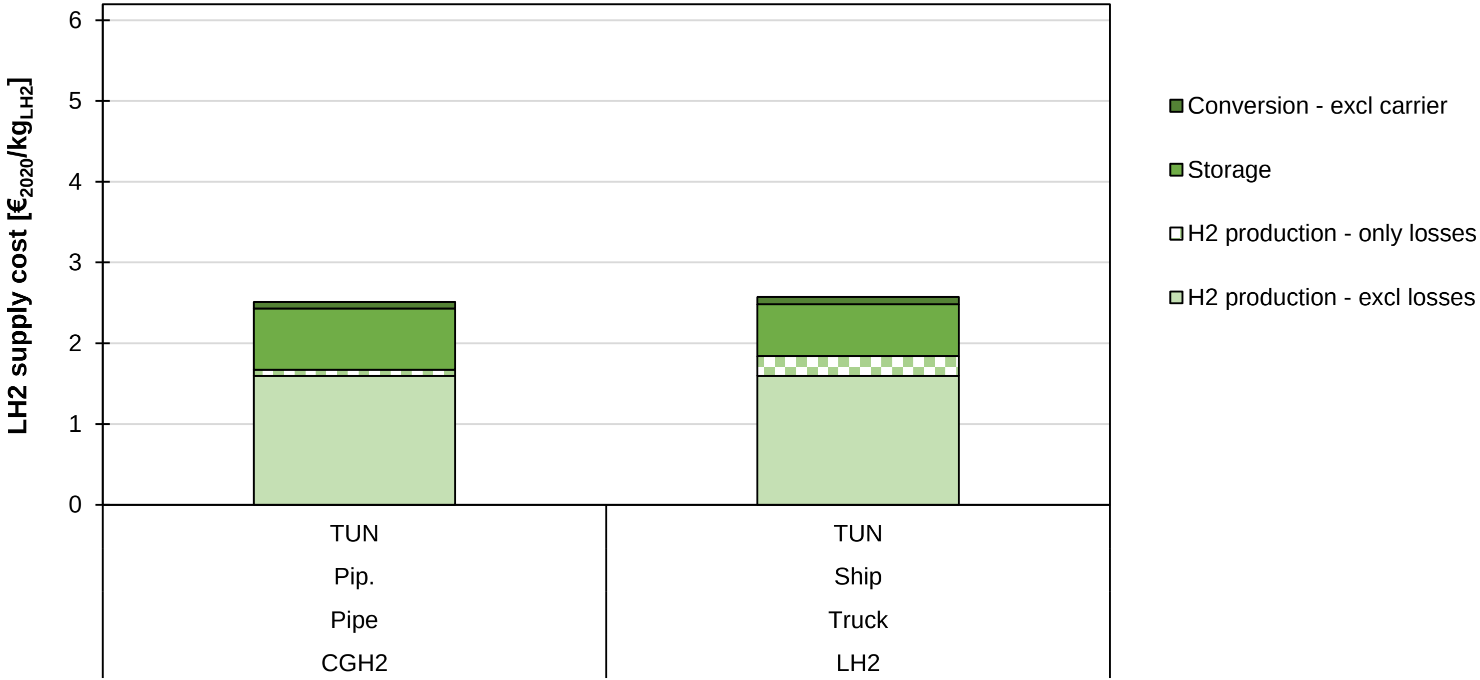

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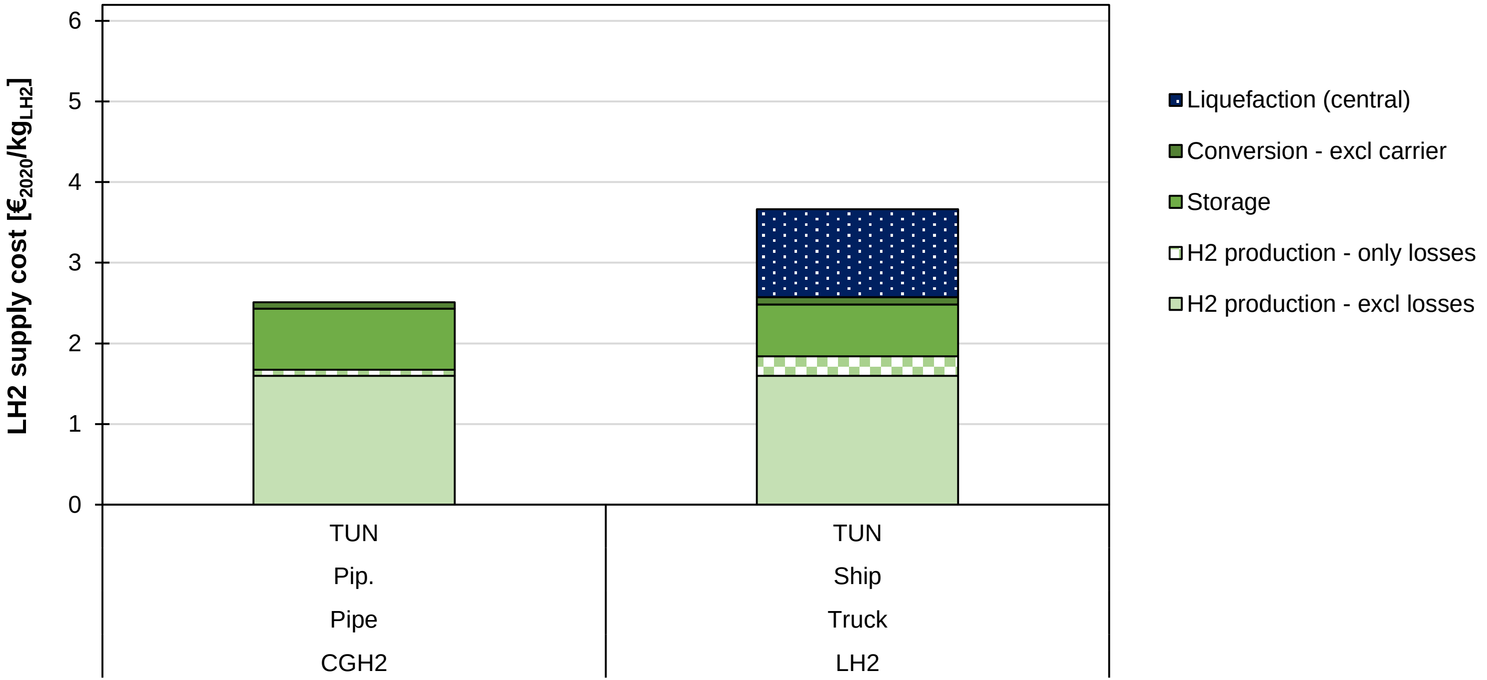

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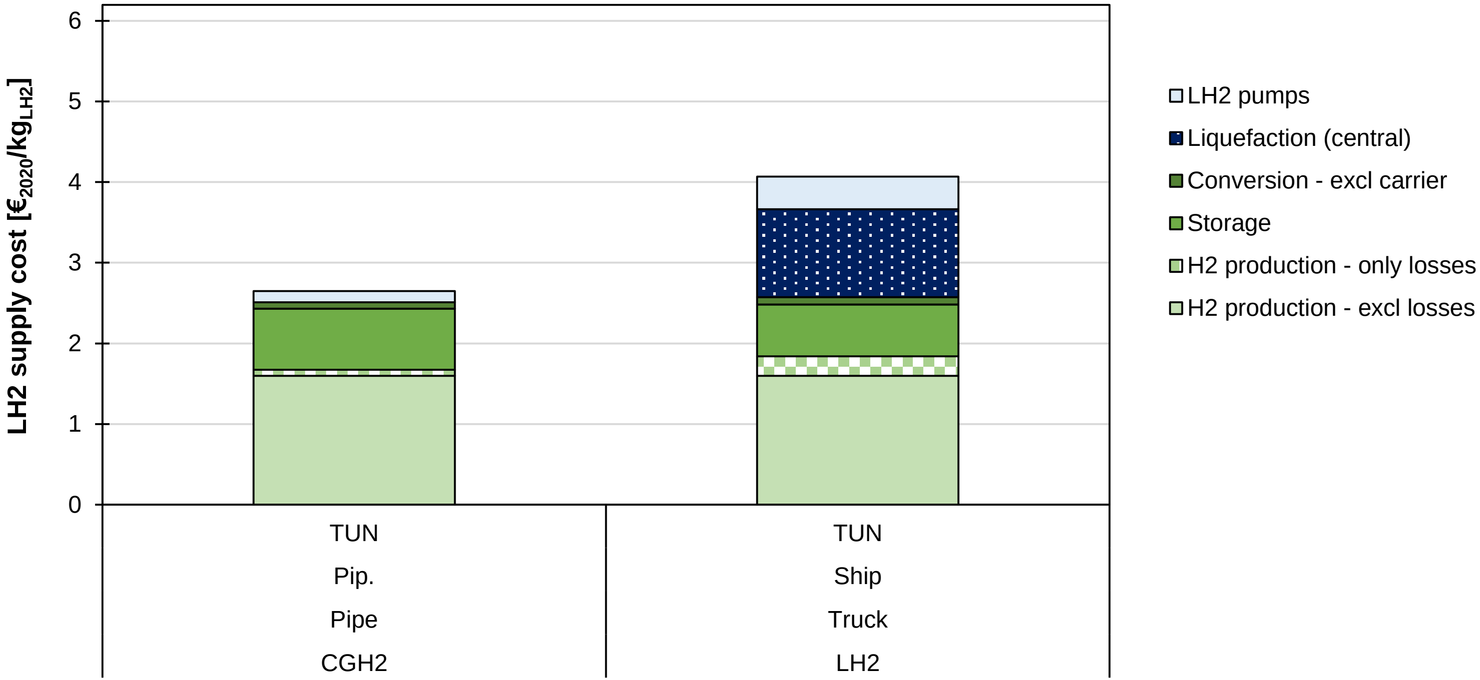

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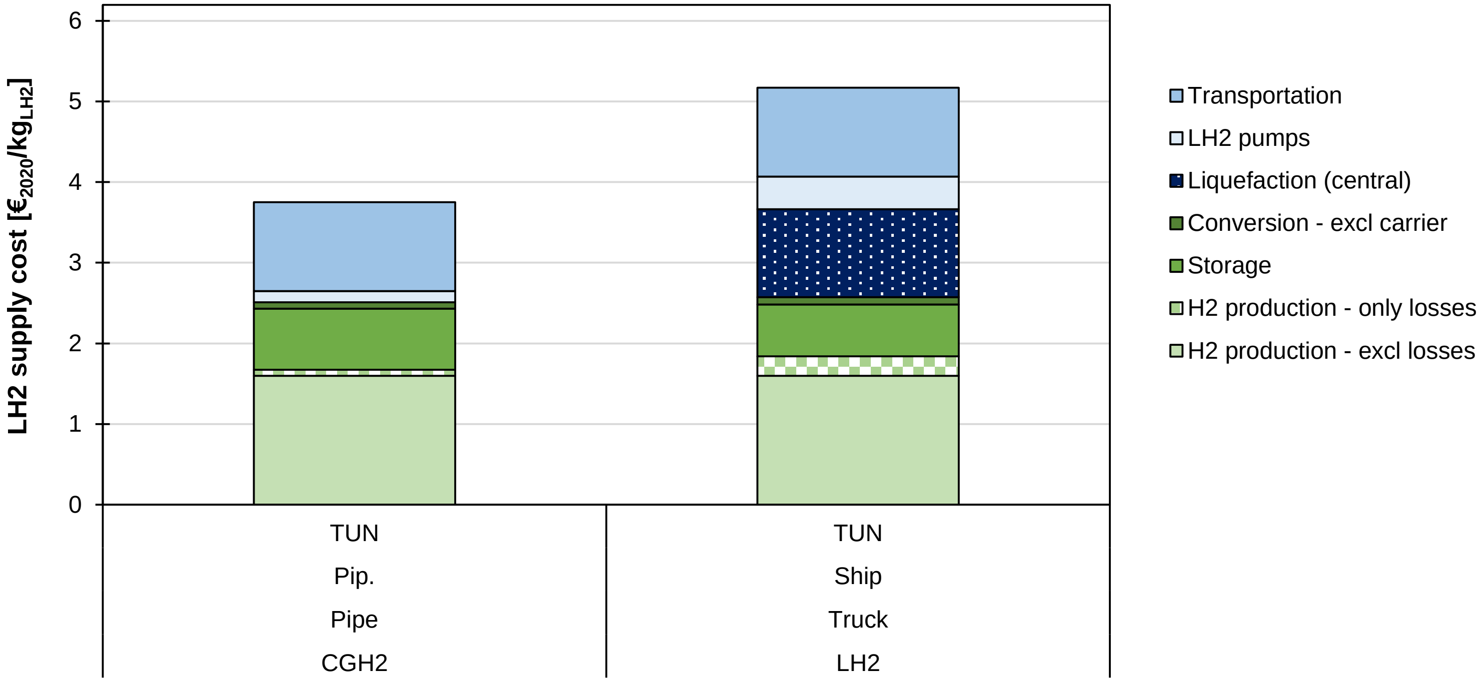

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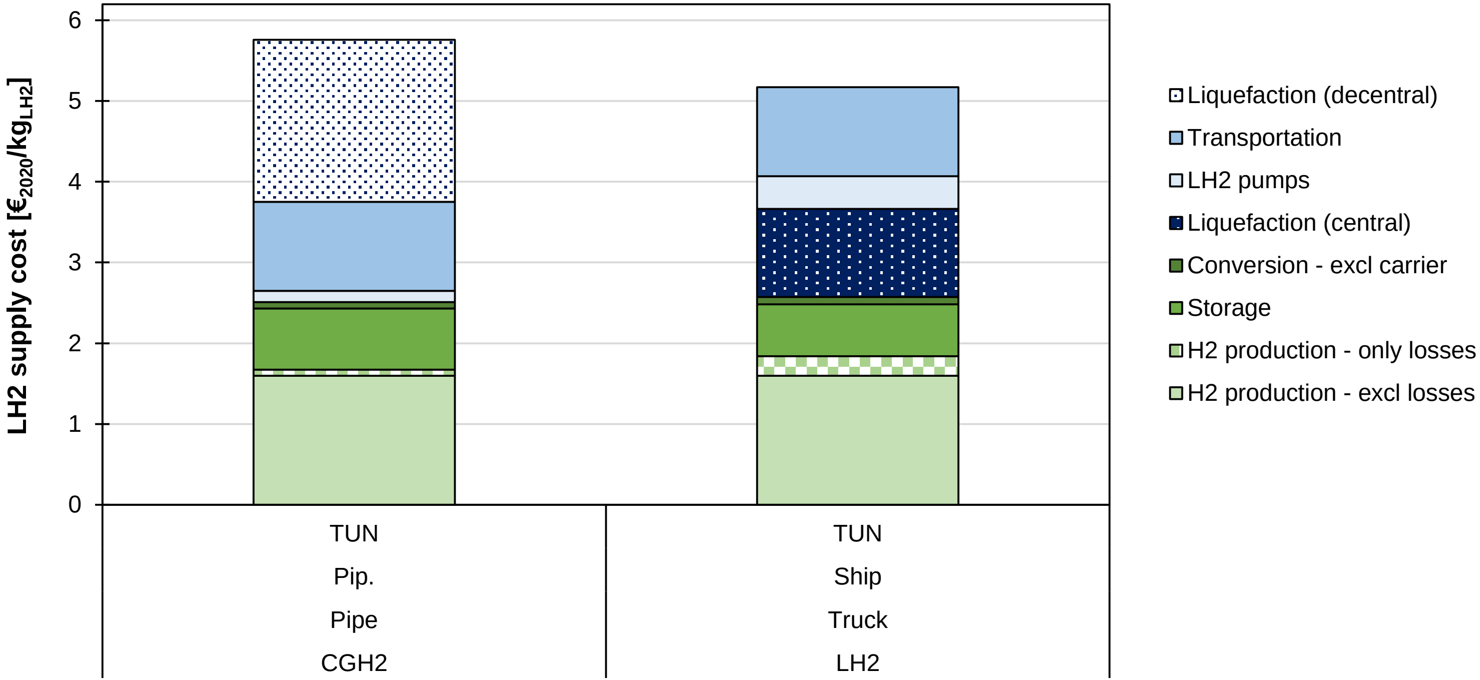

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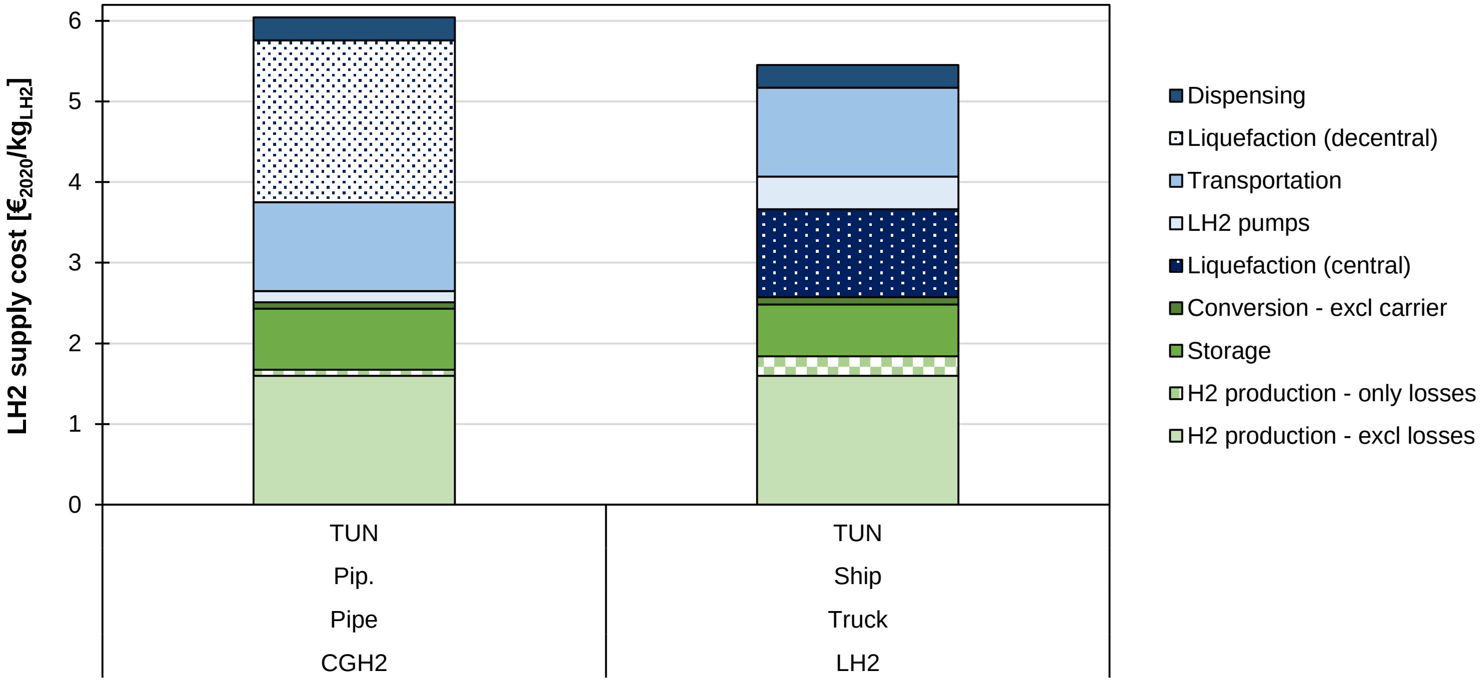

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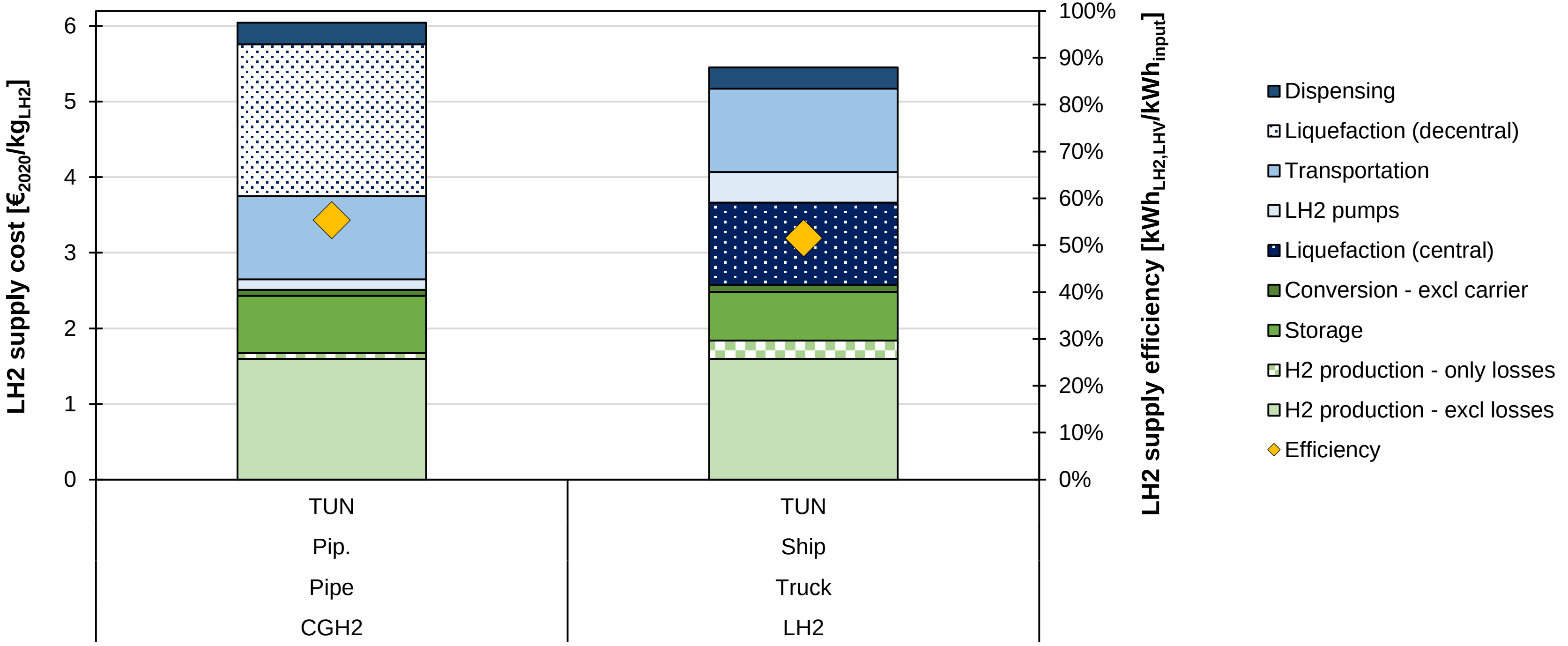

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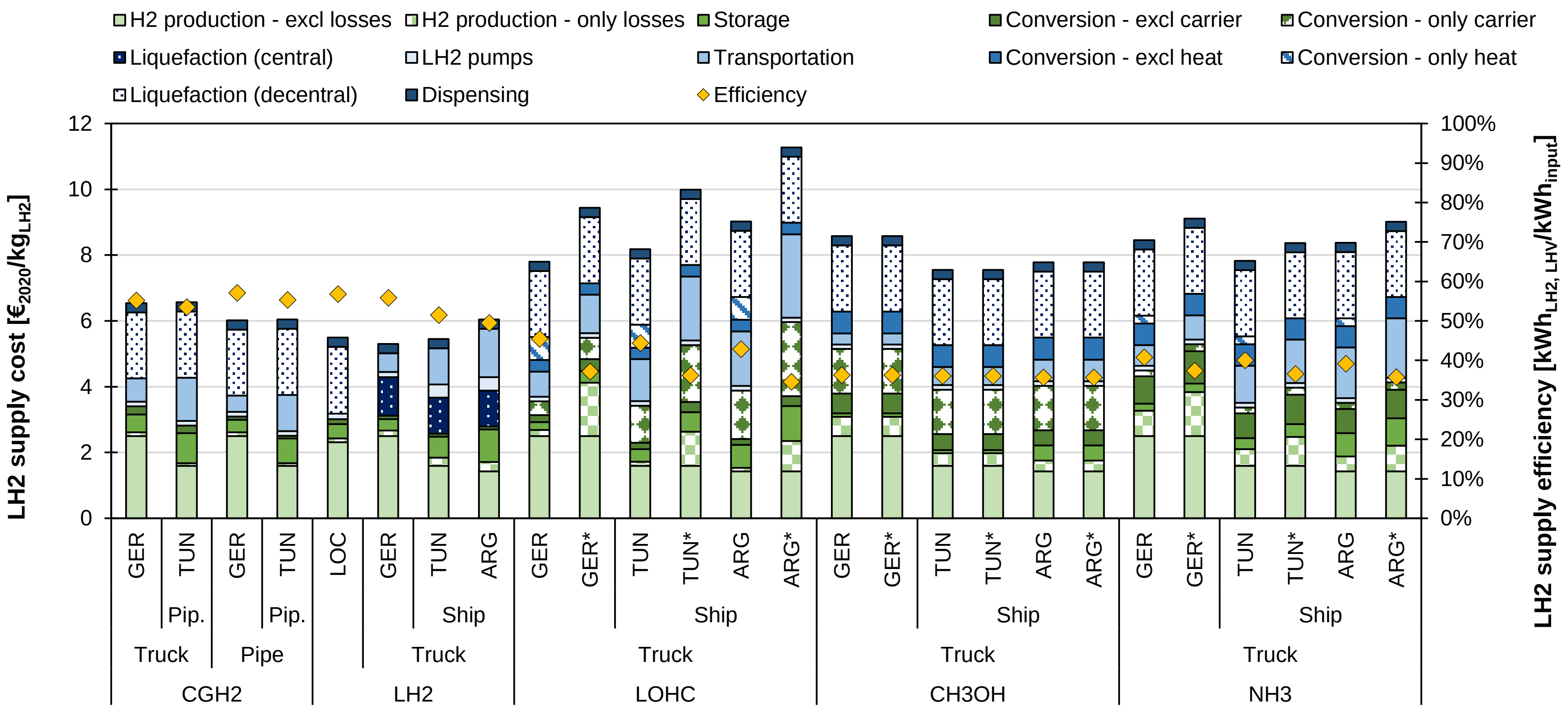

(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany (Offshore); 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; Pip. = pipeline import; Pipe = pipeline distribution to airport; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to airport)

Key Takeaways

1. For a supply of liquid hydrogen at airports liquid and gaseous hydrogen supply chains are the lowest cost options
   - ➢ ≈ 5 to 6 $€_{2020}/kg_{LH2}$
   - ➢ ≈ 0.55 $kWh_{LH2,LHV}/kWh_{input}$

2. LOHCs (dibenzyltoluene), ammonia and methanol as a hydrogen carrier appear to be not a viable option for a liquid hydrogen supply due to:
   - ➢ heat demand for dehydrogenation/cracking
   - ➢ carrier cost (LOHCs and methanol)
   - ➢ purification losses (ammonia and methanol)

3. The liquid hydrogen supply costs are in a same magnitude for a local, national or international hydrogen supply. Hence factors like land availability and security of supply become even more important

Questions & Remarks

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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
  - [7] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

Detailed Supply Chains

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

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

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

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

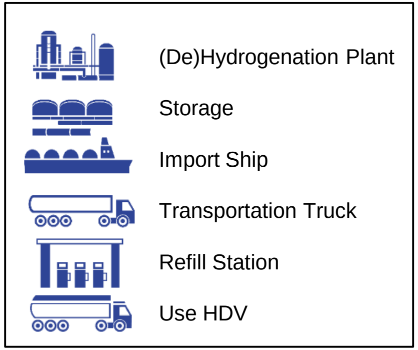
$$WACC_{real} = \frac{1+WACC_{nom}}{1+INFL} - 1$$

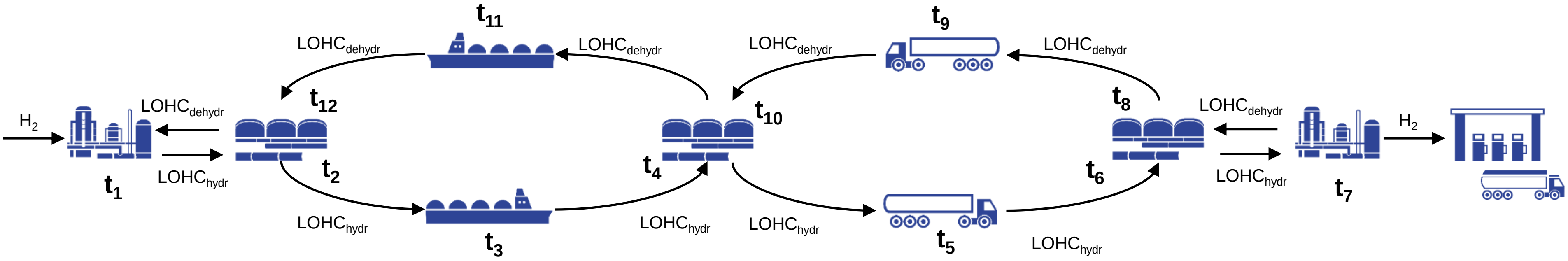
LOHC CAPEX

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

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

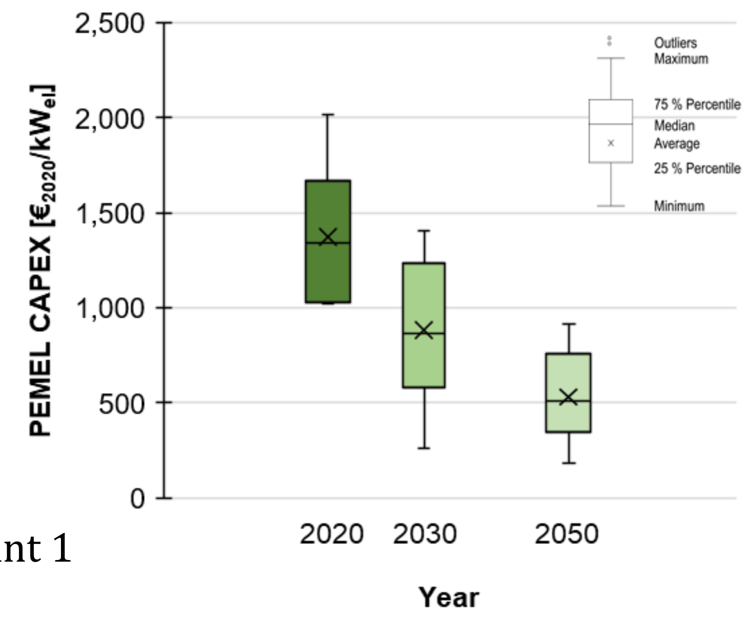
$$t_{LOHC,cycle} = \sum_{i=1}^{n} t_i$$





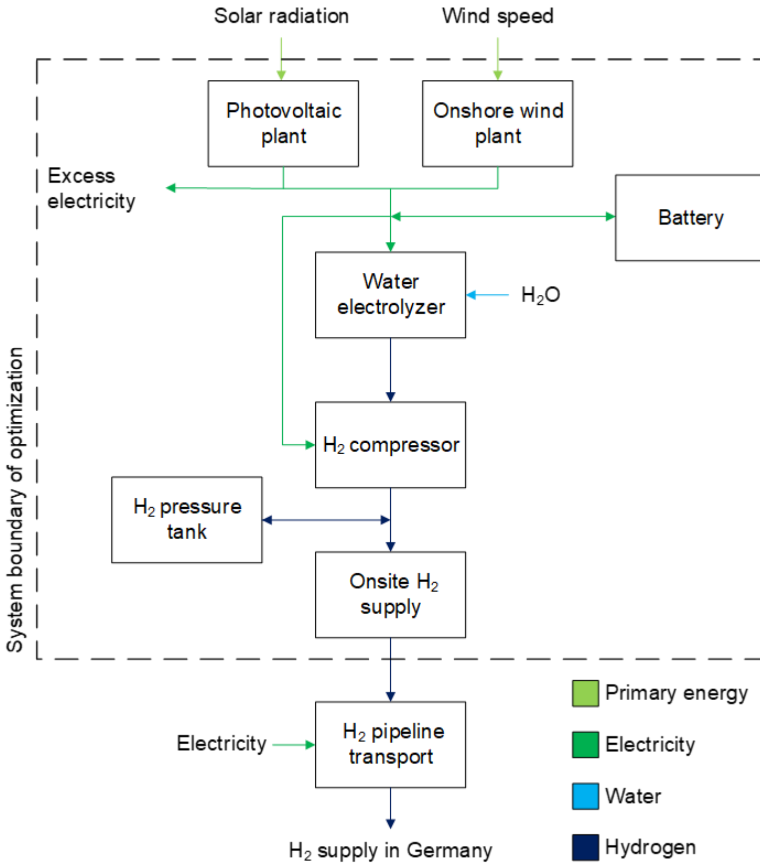
CAPEX Calculation

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



- 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)

Cost Minimized Hydrogen Production



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%