DOI: https://doi.org/10.15480/882.4387
ORCID: https://orcid.org/0000-0001-6300-4218

Hamburg
23.03.2022

Green Hydrogen Supply Chains

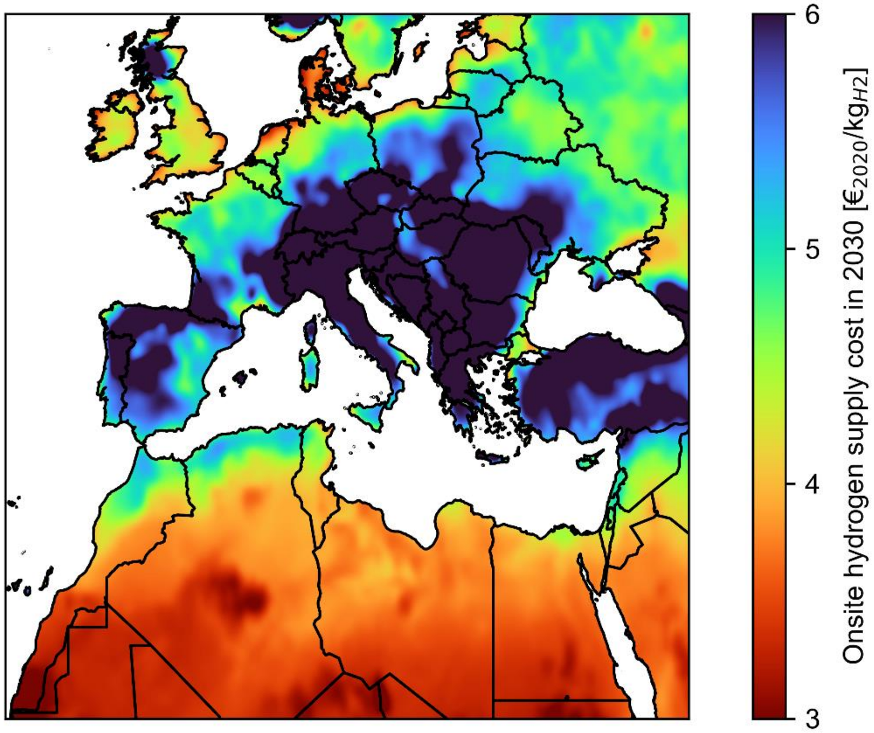
A Techno-economic Assessment

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

Background



Low cost transportation needed to supply hydrogen to the consumption hubs

Compression (CGH_2)

[7]

Liquefaction (LH_2)

[8]

Methanol (CH_3OH)

[10]

Ammonia (NH_3)

[11]

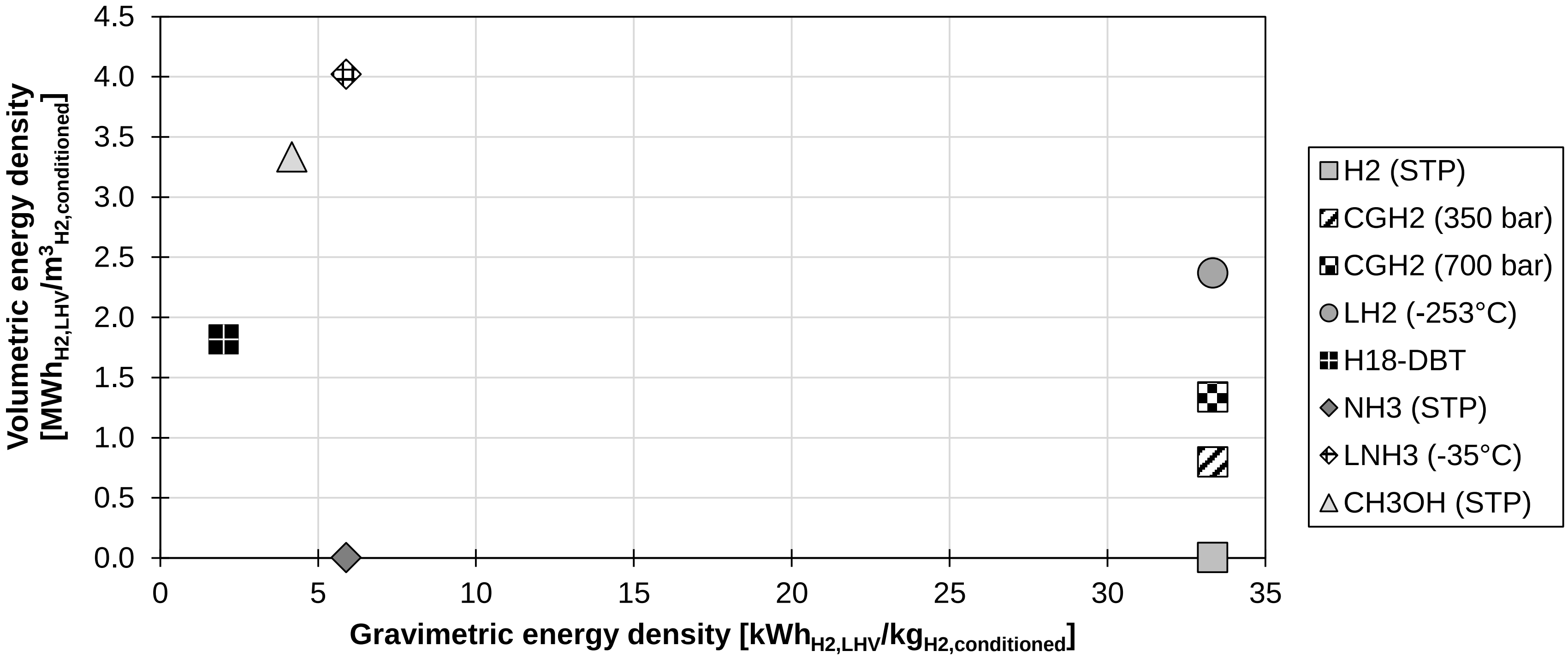
Liquid Organic Hydrogen Carriers (LOHC)

[9]

Outline

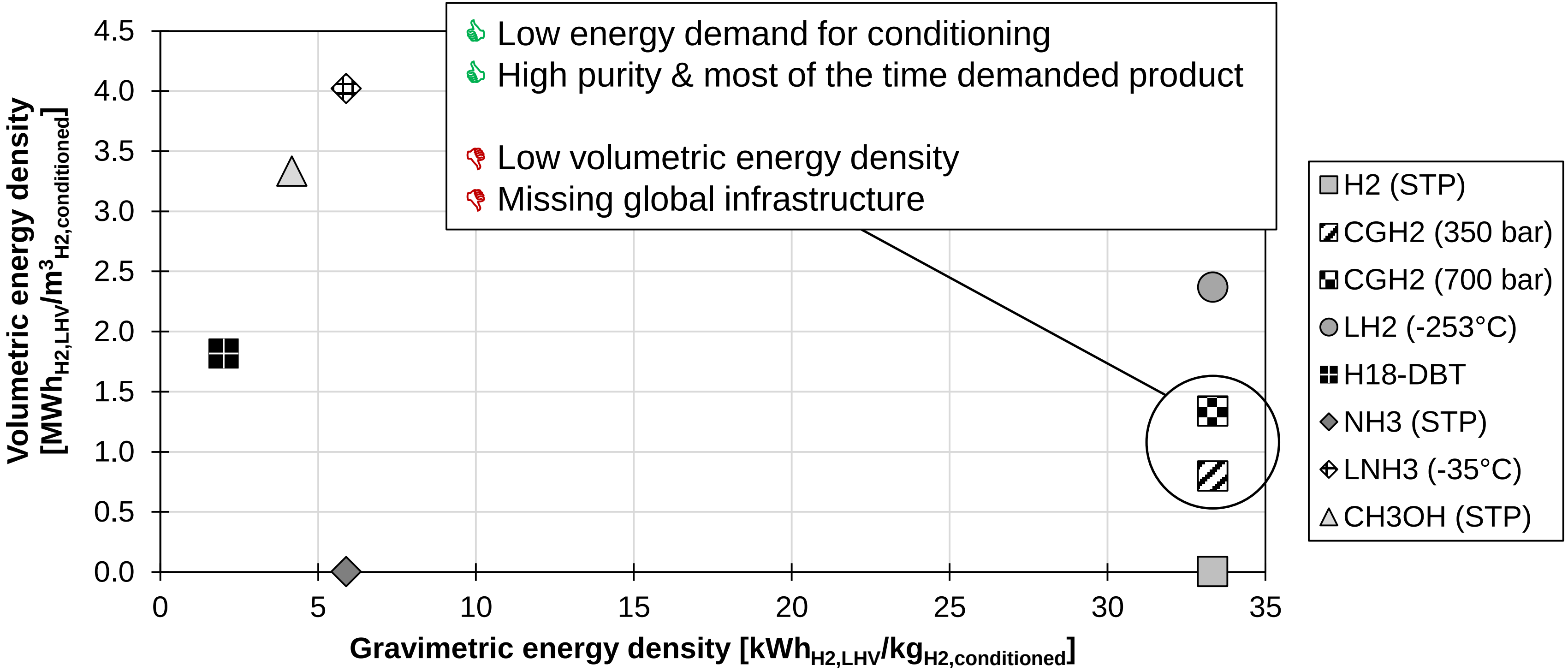
1. Conditioning Options
2. Supply Chains
3. Assessment
4. Conclusion

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)

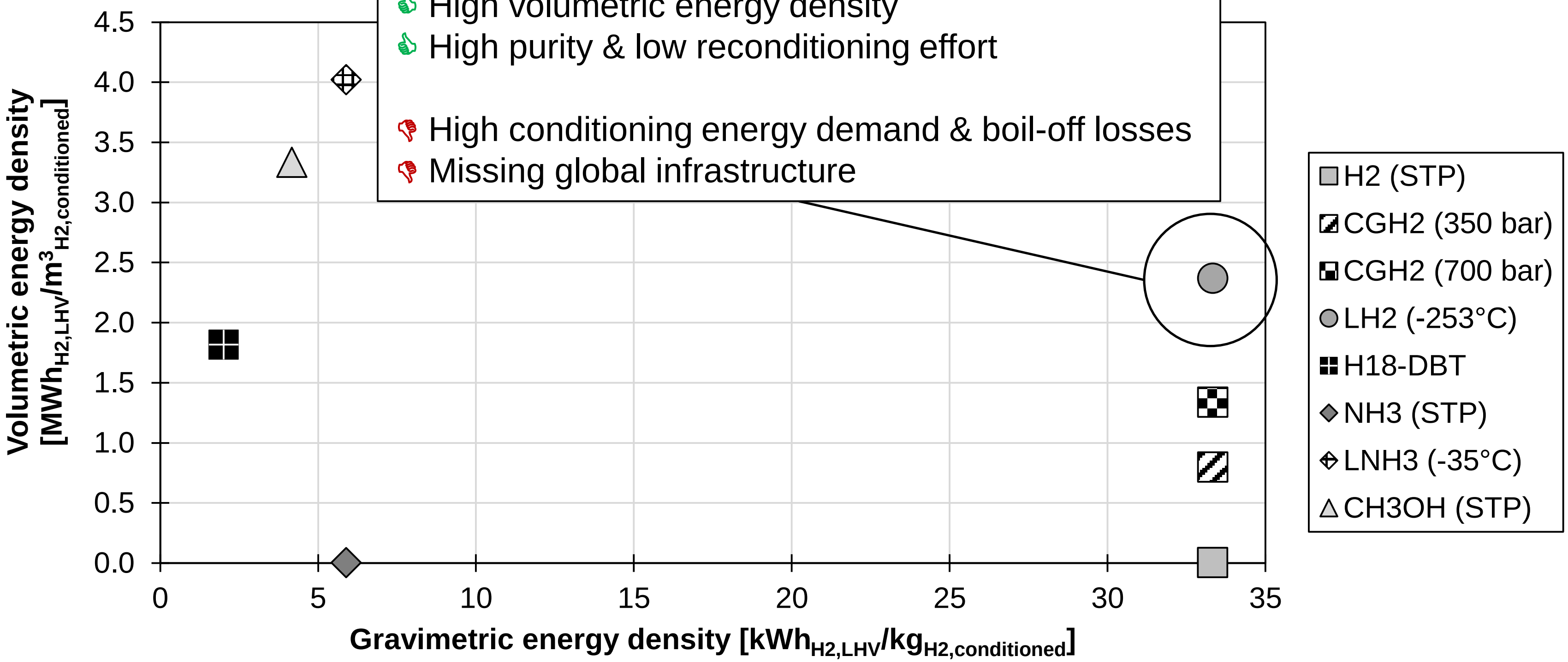


CGH2 = compressed gaseous hydrogen, CH3OH = methanol, H18-DBT = perhydro-dibenzyltoluene (LOHC), LH2 = liquid hydrogen, LNH3 = liquid ammonia, NH3 = ammonia, STP = standard temperature and pressure

Liquid Hydrogen (LH_2)

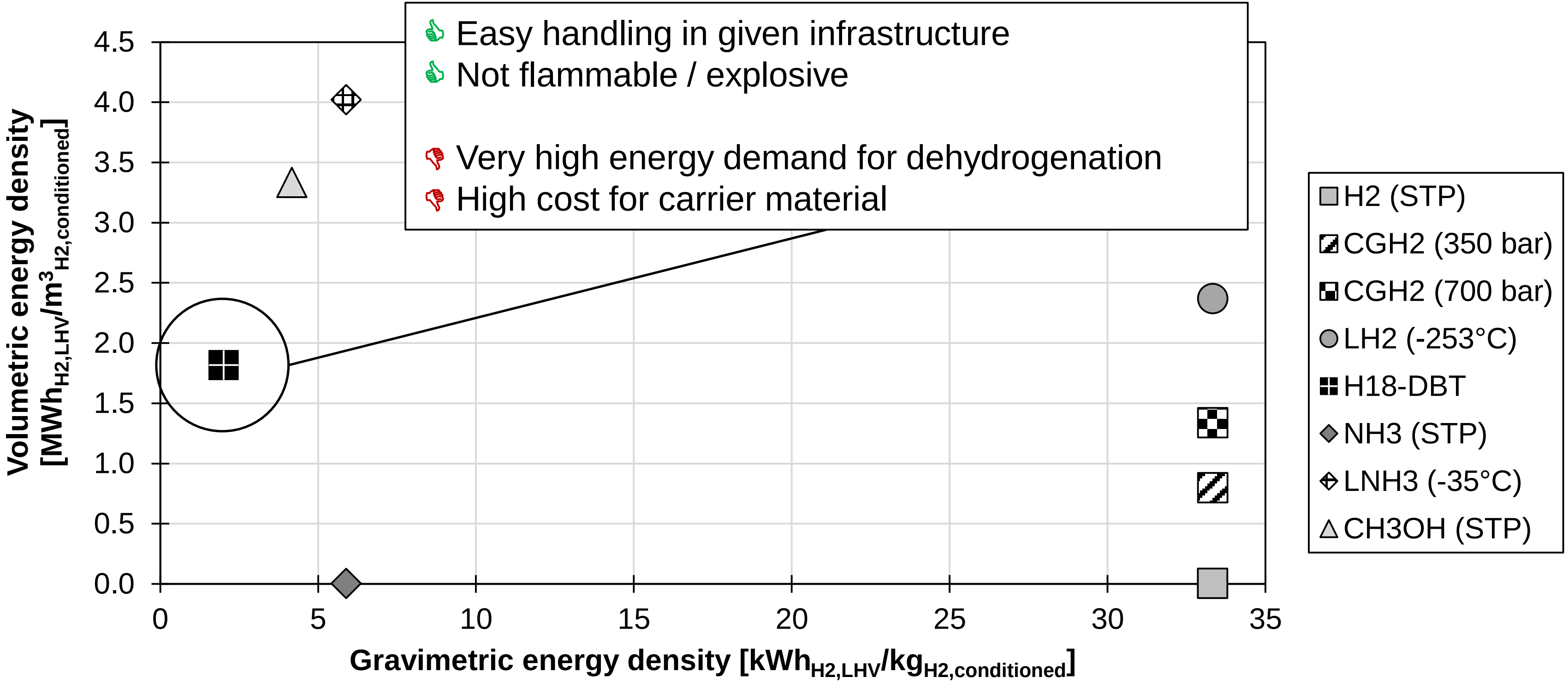
- High volumetric energy density
- High purity & low reconditioning effort

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



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

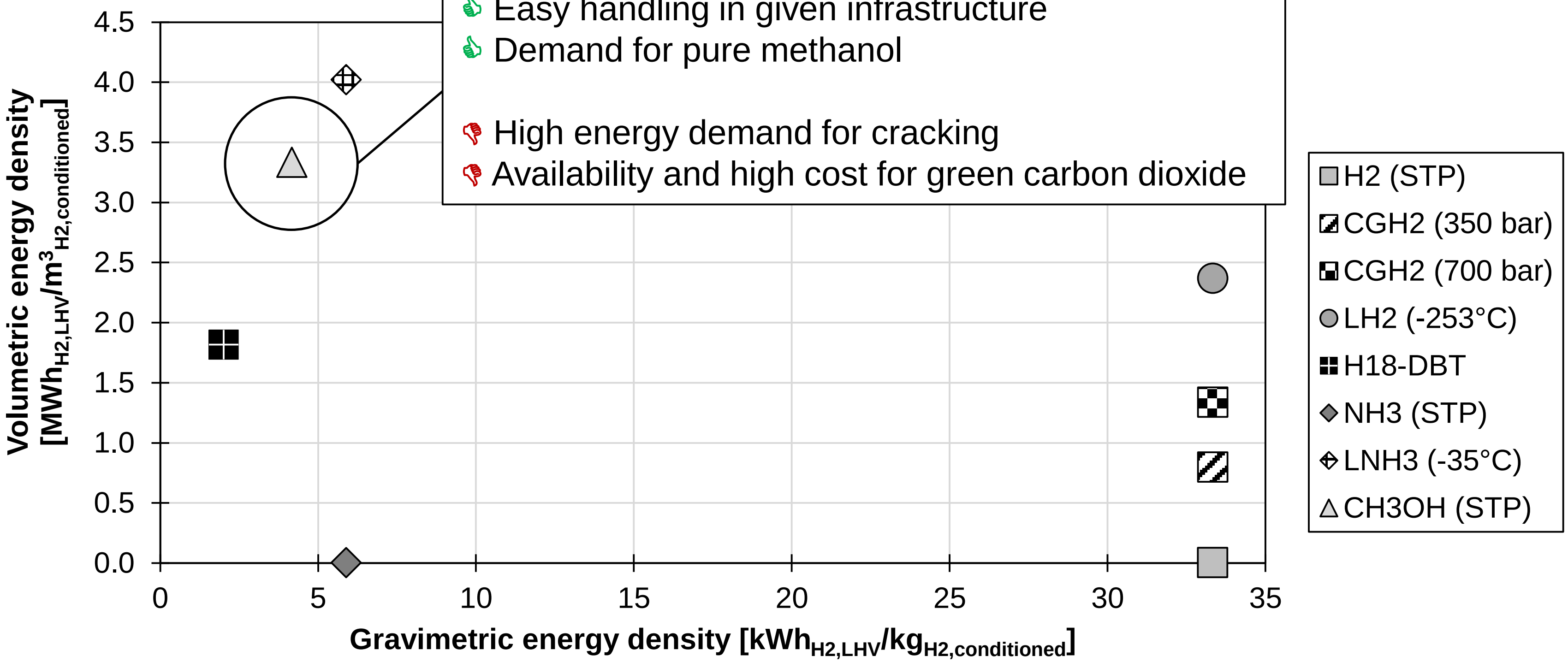
Liquid Organic Hydrogen Carrier (LOHC)



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)

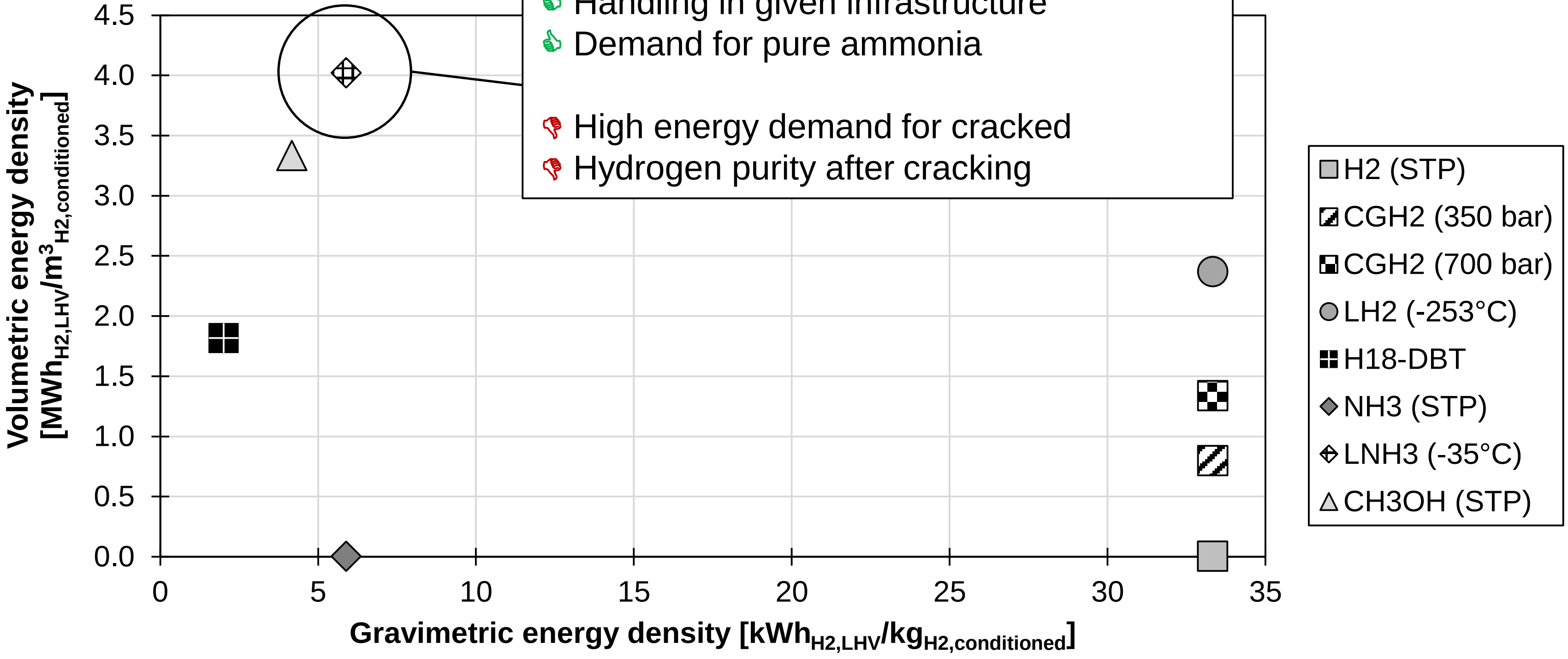
- 👍 Easy handling in given infrastructure
- 👍 Demand for pure methanol
- 👎 High energy demand for cracking
- 👎 Availability and high cost for green carbon dioxide



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

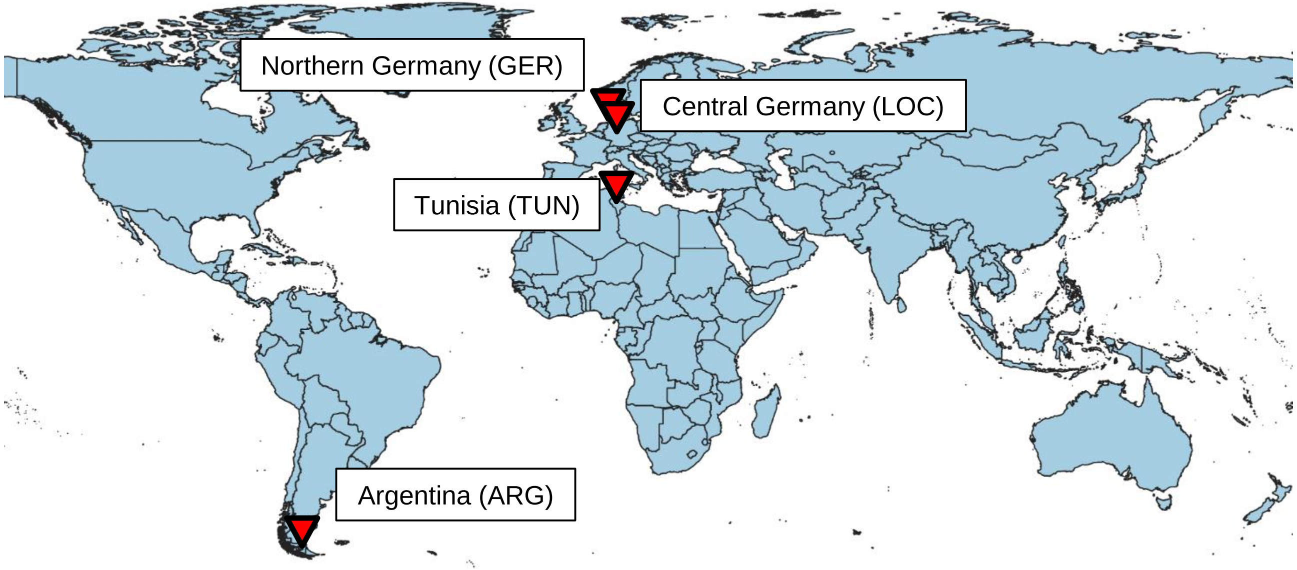
Ammonia (NH_3)

- 👍 Handling in given infrastructure
- 👍 Demand for pure ammonia
- 👎 High energy demand for cracked
- 👎 Hydrogen purity after cracking



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

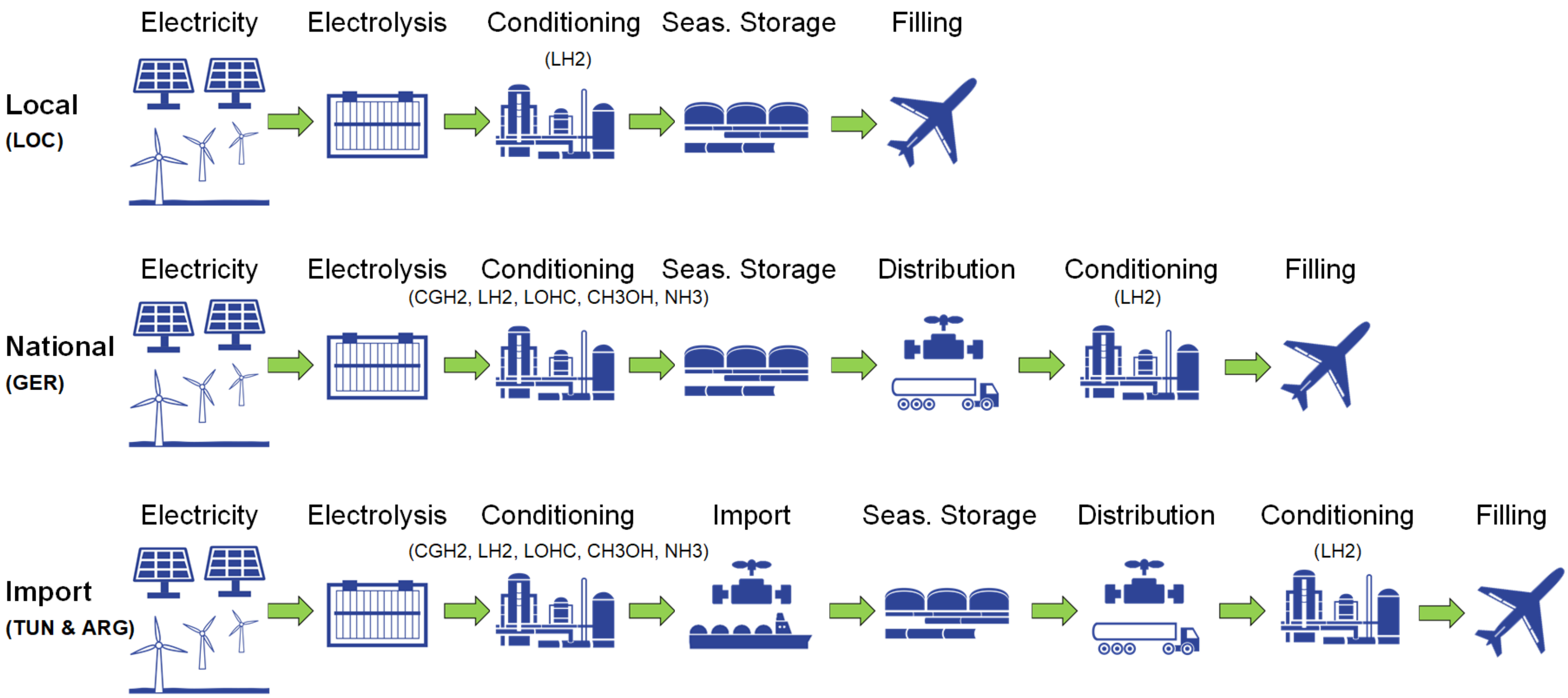
Production Locations



- **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

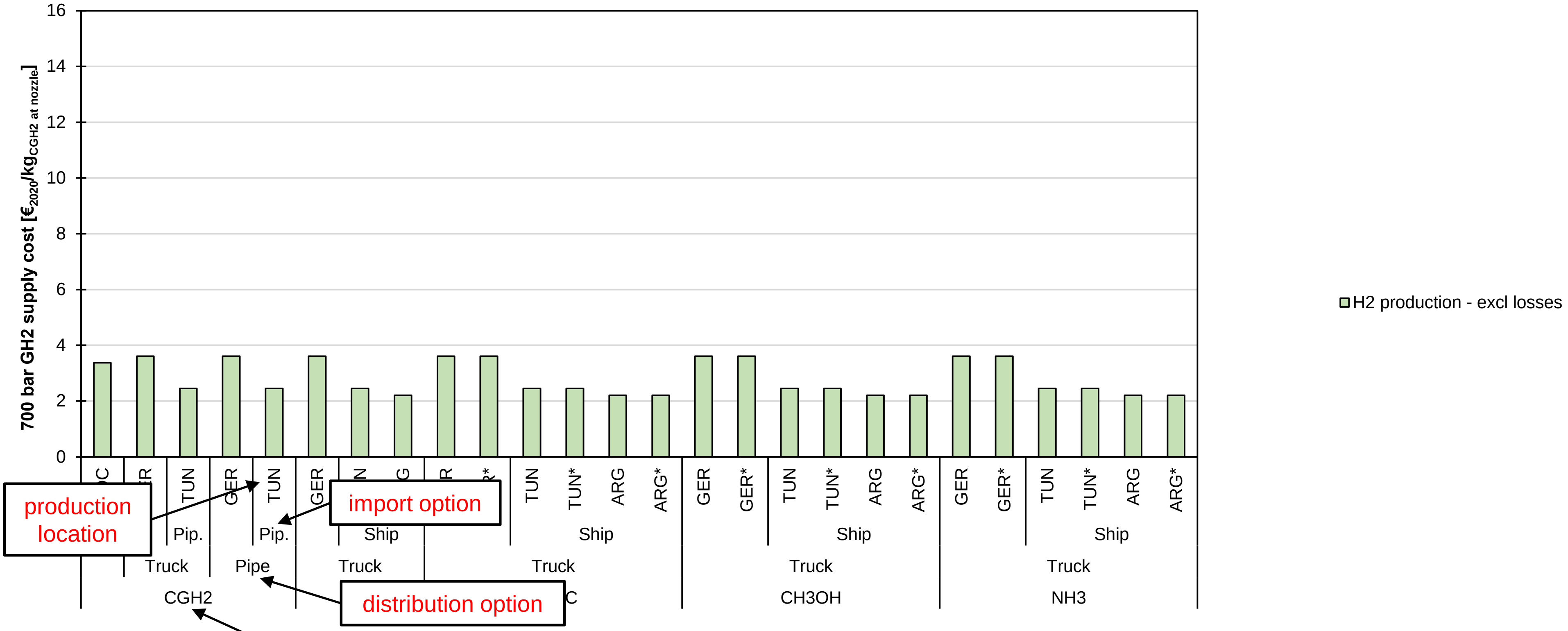
- Supply efficiency based on hydrogen (LHV) filled in tank divided by the overall chain energy input from well to tank

- Hydrogen supply cost considers the well to tank costs and is calculated with the annuity method

- Depreciation equals the technology lifetime

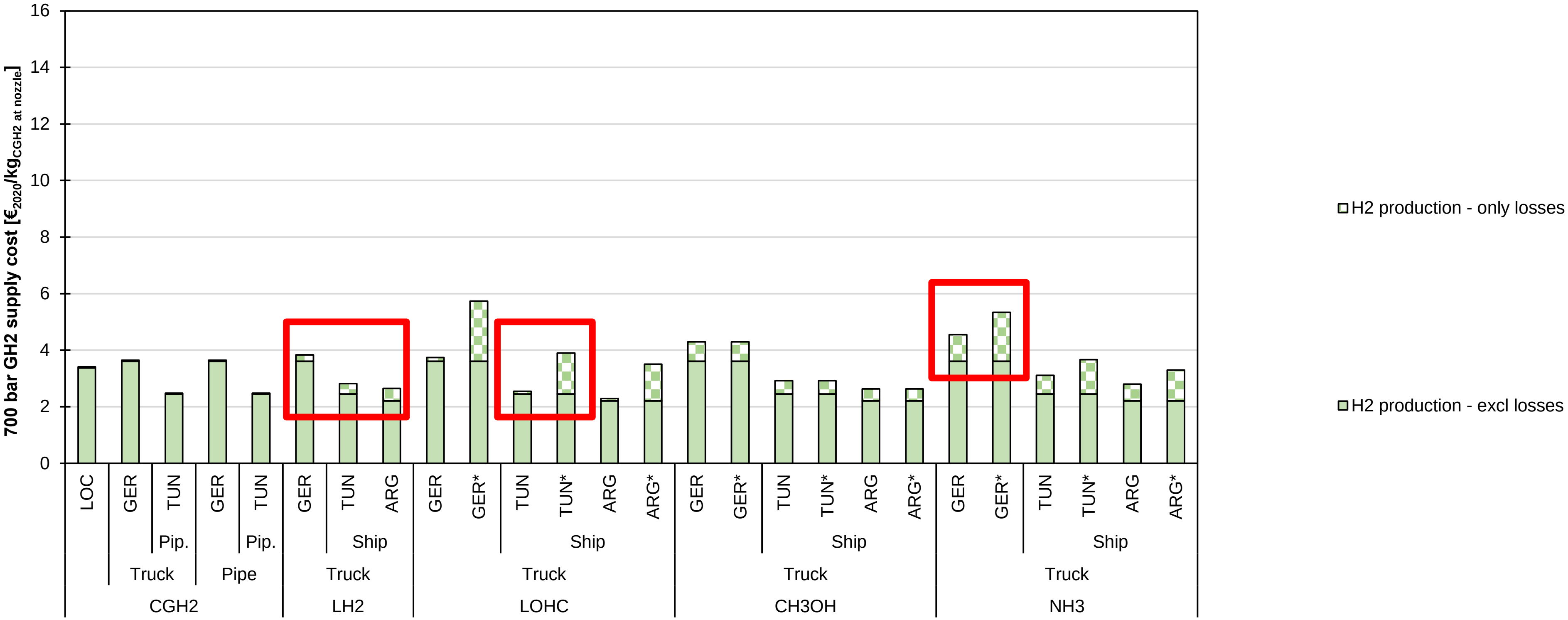
- Real weighted average cost of capital set to 6%

CGH_2 Filling – 2030



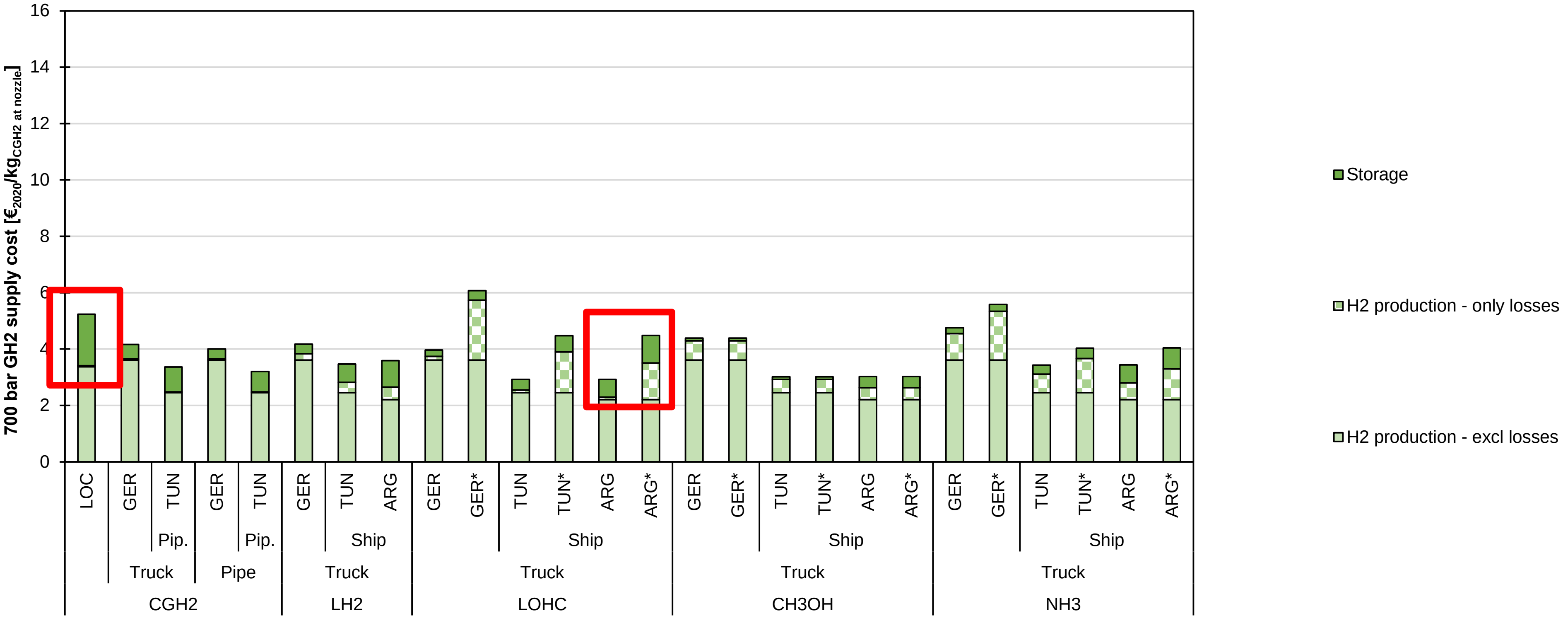
(* = ... needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply cha... North Germany; LH2 = liquid hydrogen supply chain; LOC = local production directly at the airport in Central Germany; LOHC = liquid organic hydrogen carrier supply chain; NH3 = ammonia supply chain; Pip. = pipeline import; Pipe = pipeline distribution to filling station; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to filling station

CGH$_2$ Filling – 2030



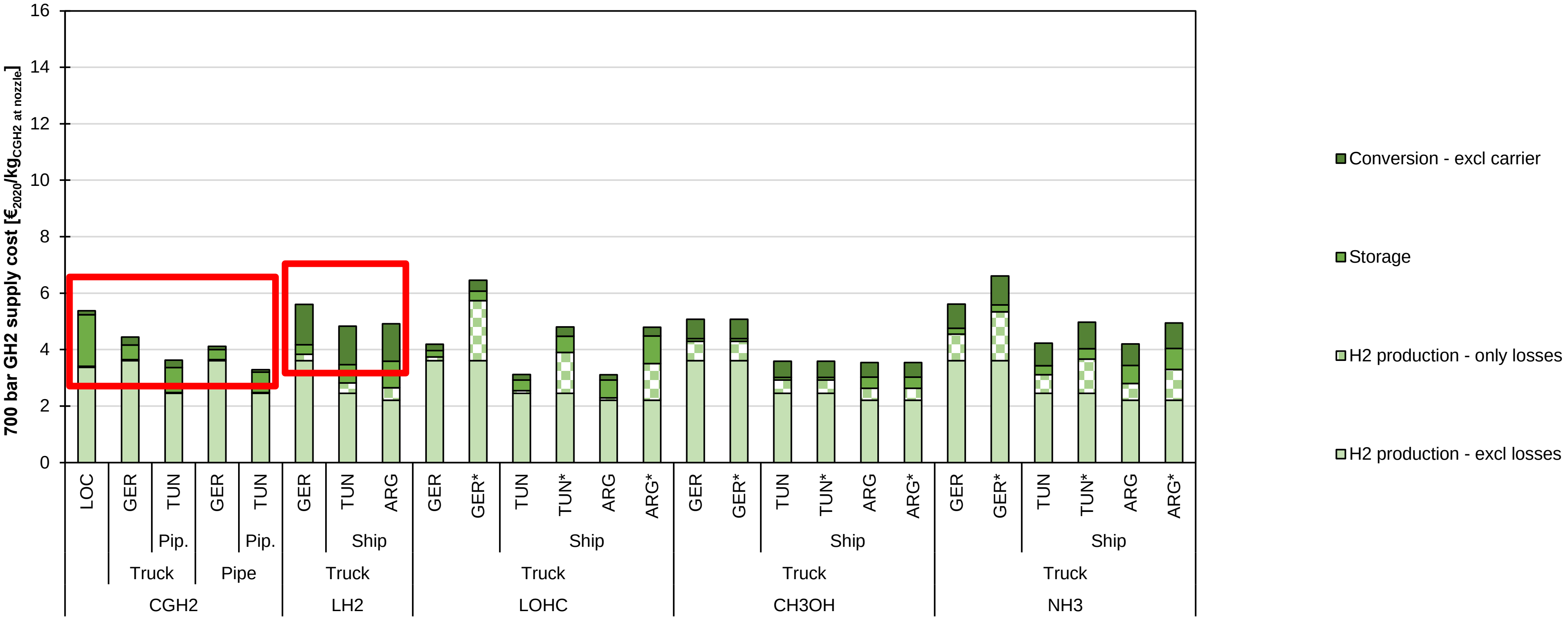
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH$_2$ Filling – 2030



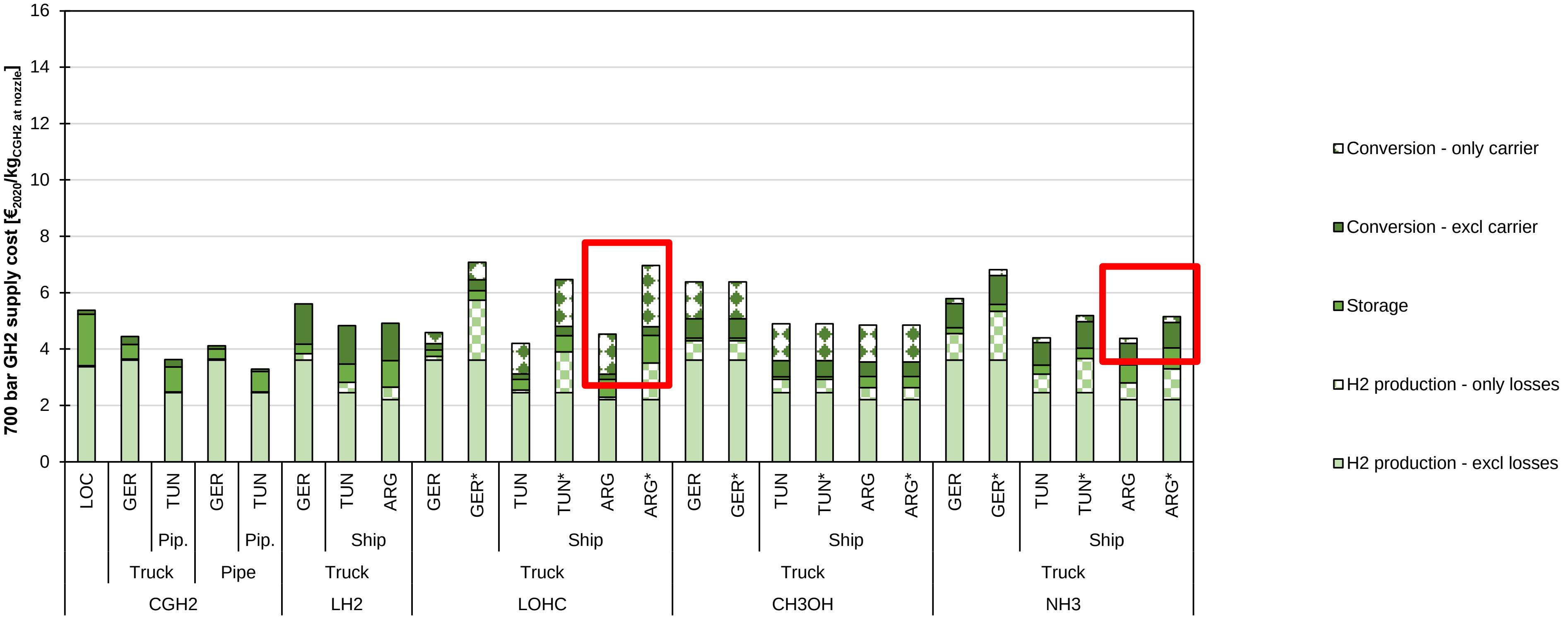
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH_2 Filling – 2030



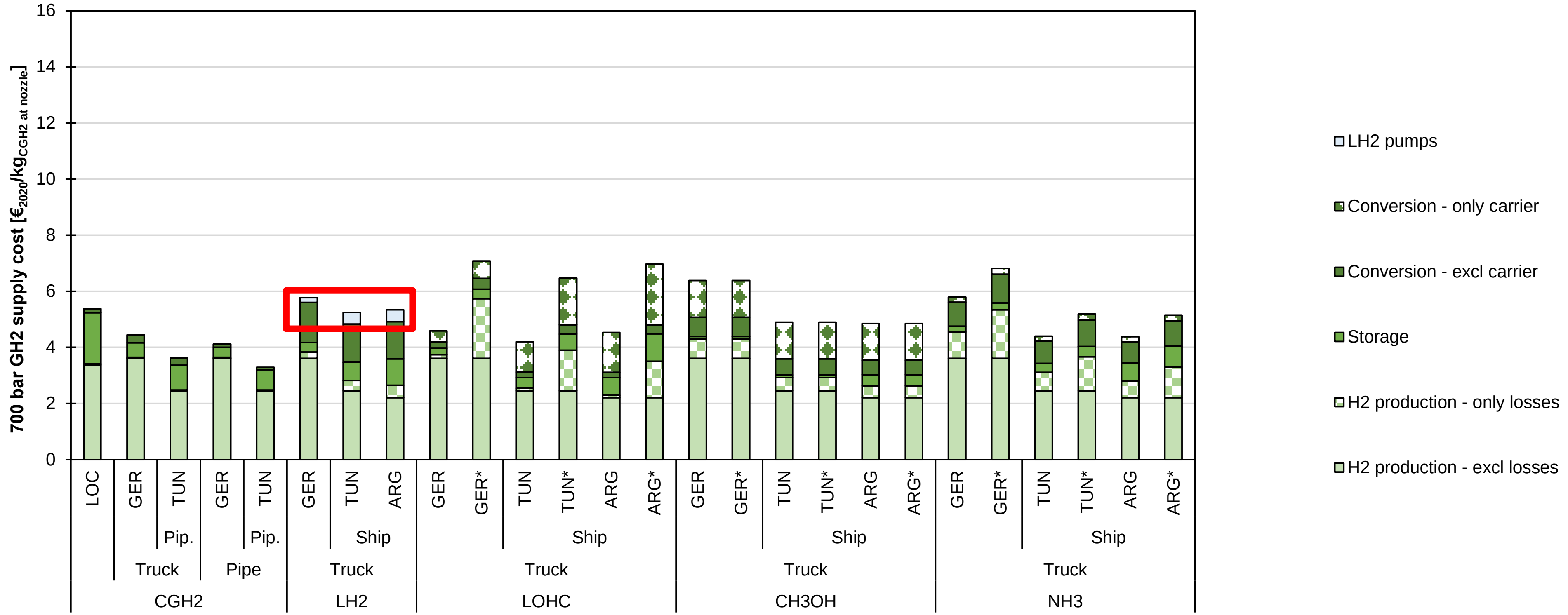
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH_2 Filling – 2030



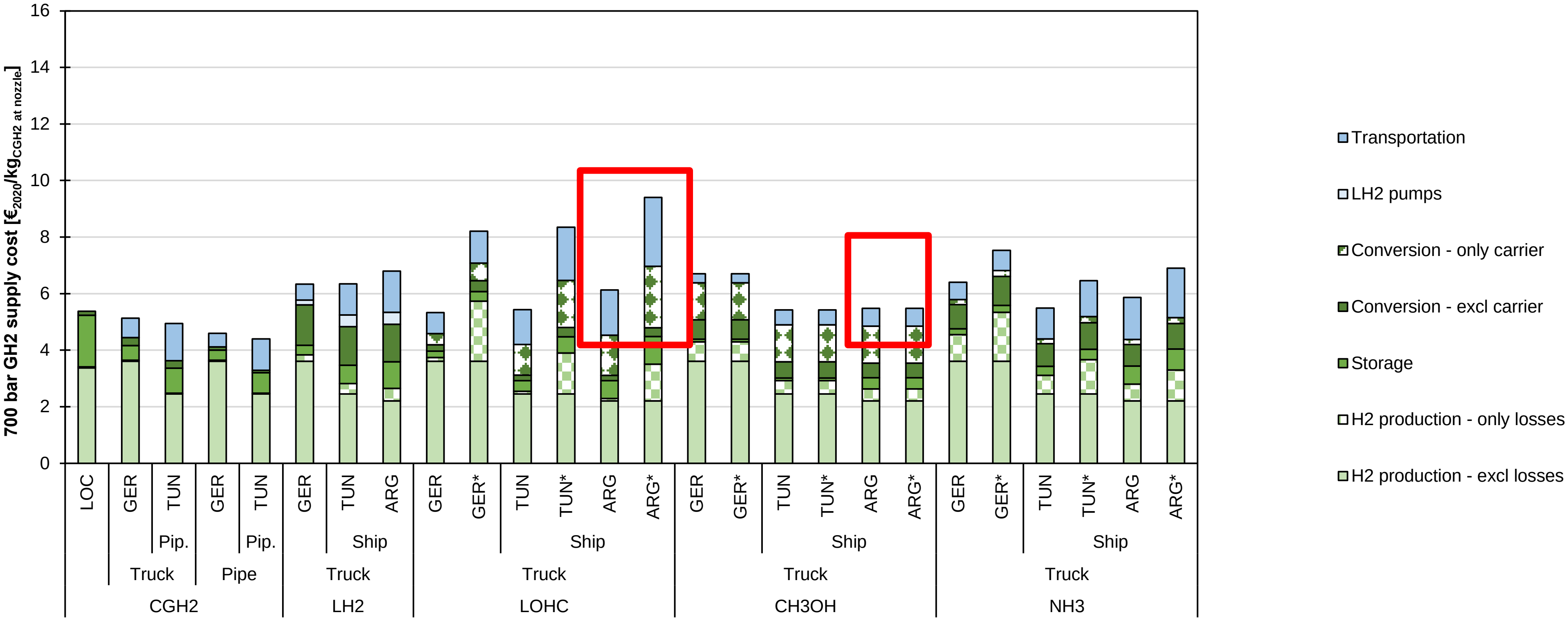
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH$_2$ Filling – 2030



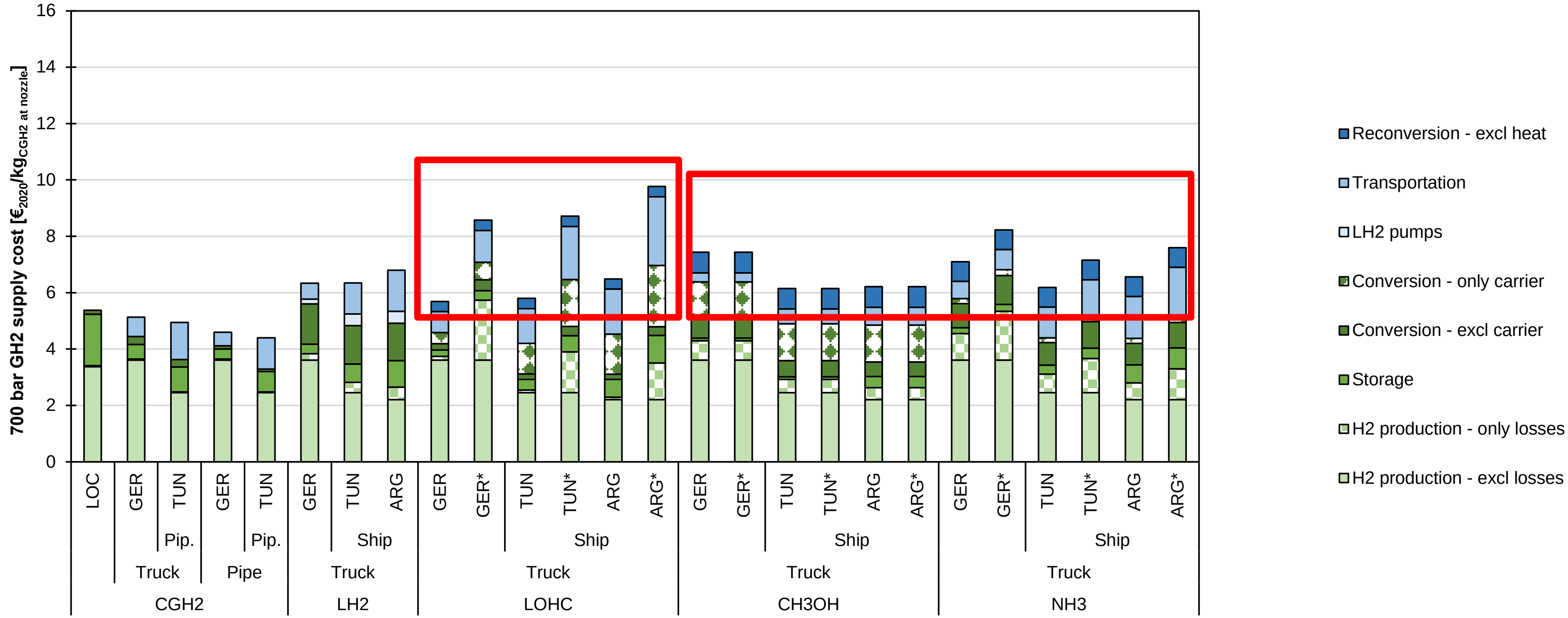
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH_2 Filling – 2030



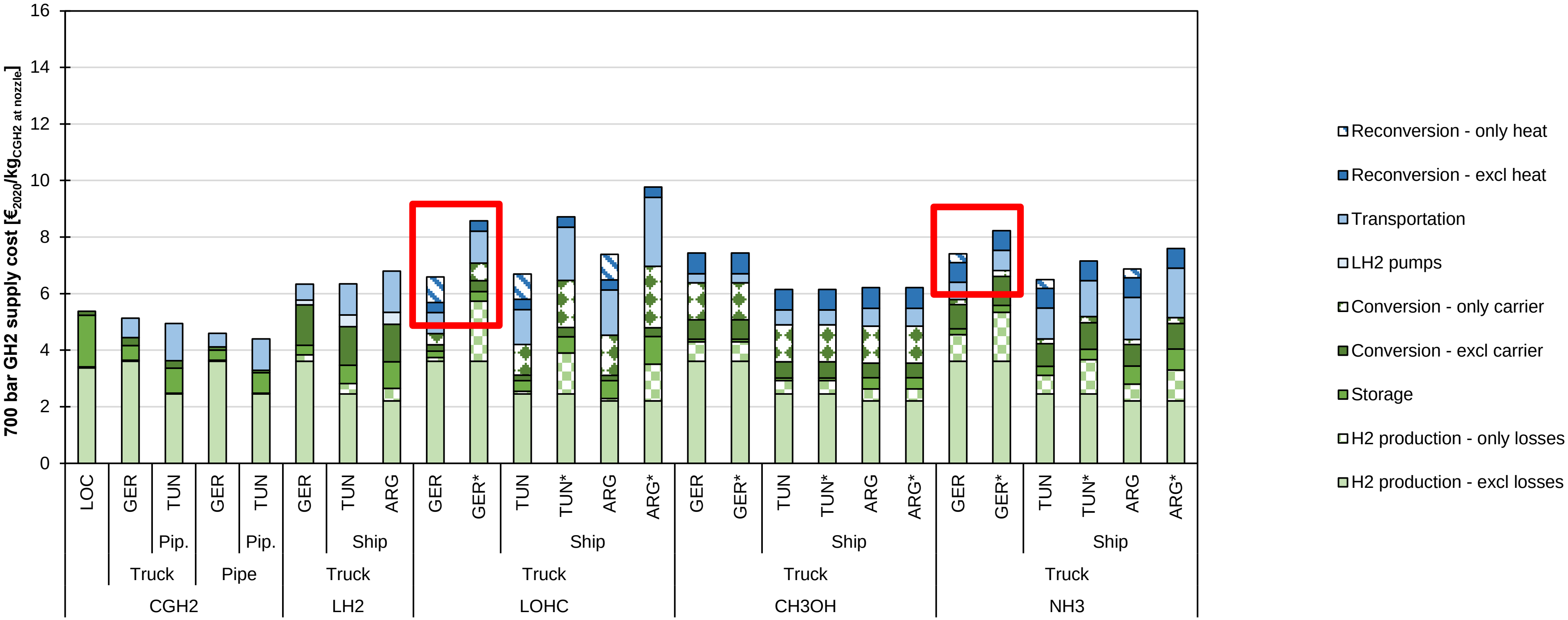
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH_2 Filling – 2030



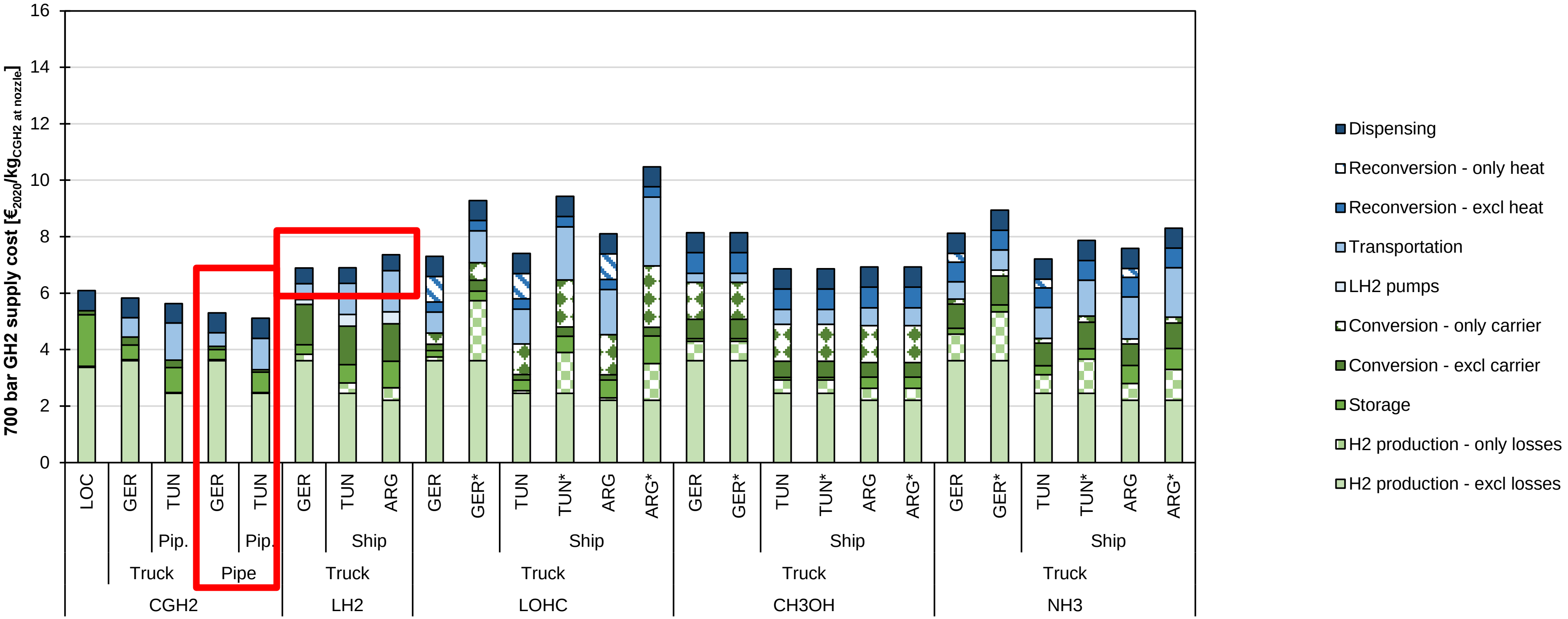
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH$_2$ Filling – 2030



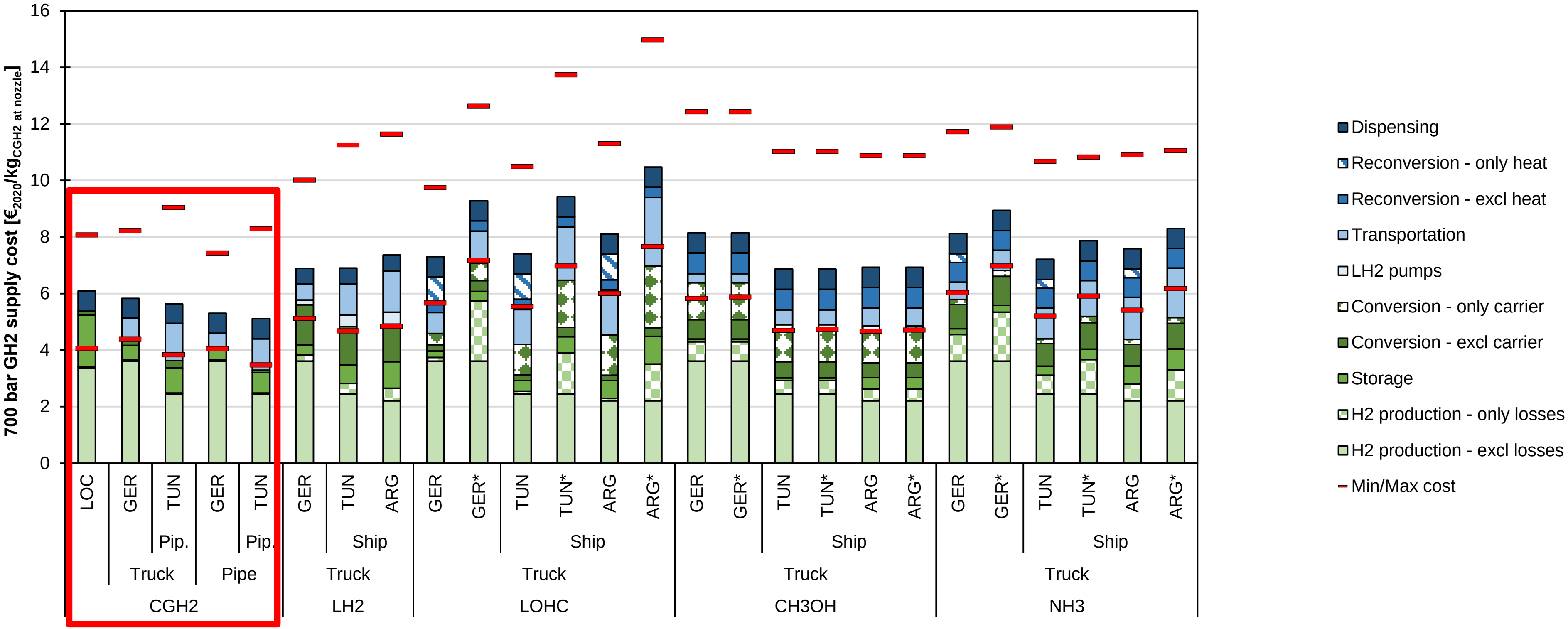
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH_2 Filling – 2030



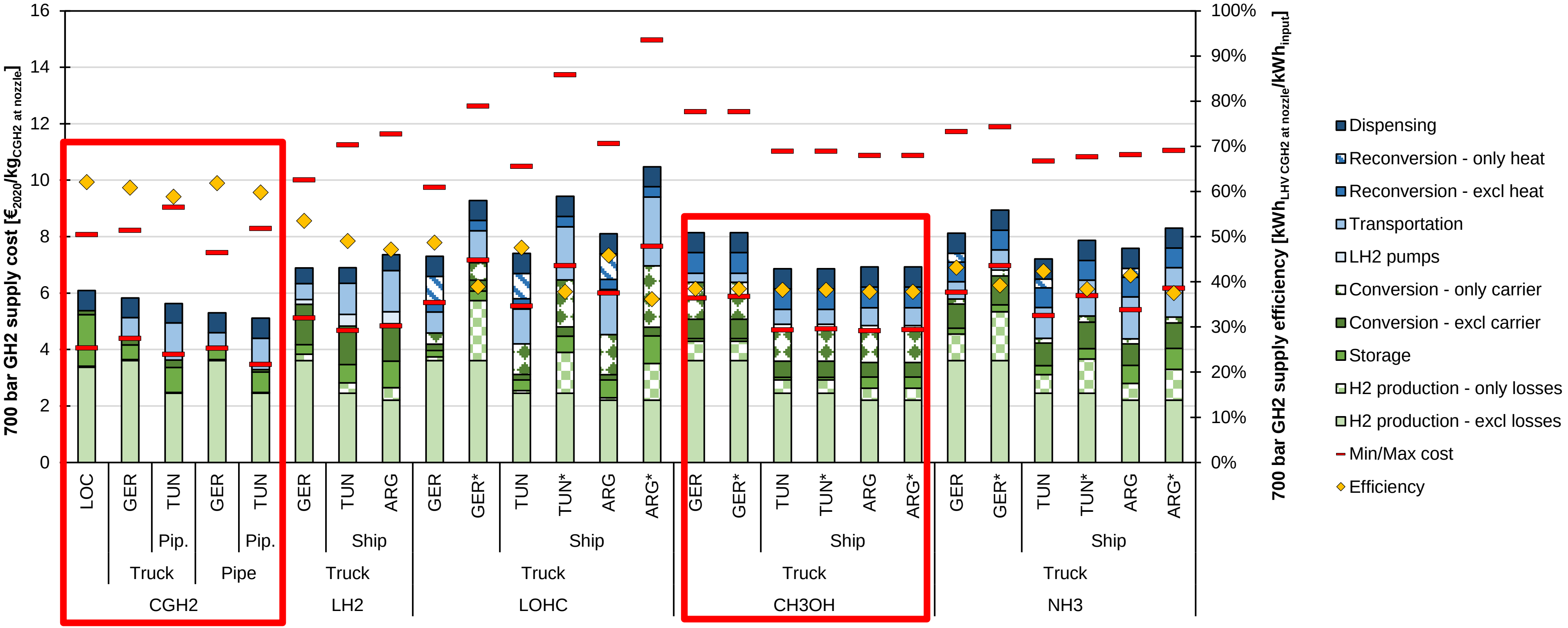
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH_2 Filling – 2030



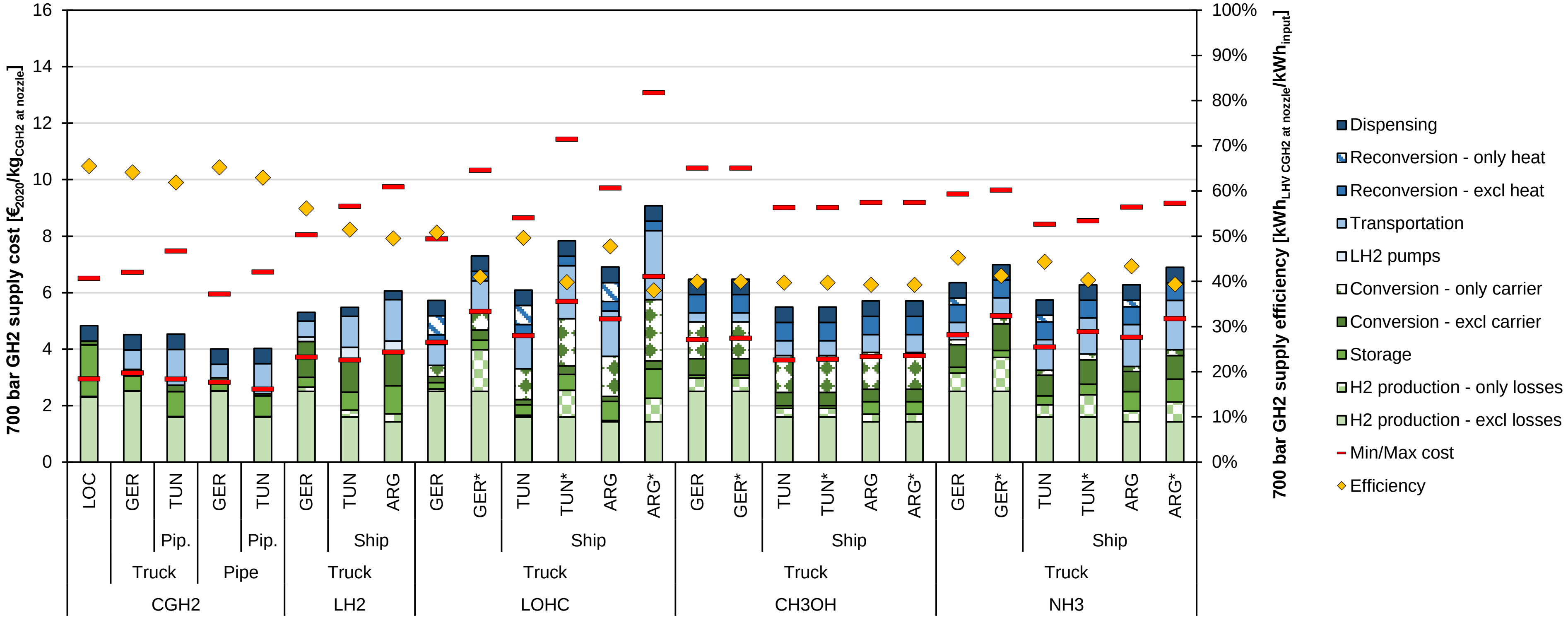
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH$_2$ Filling – 2030



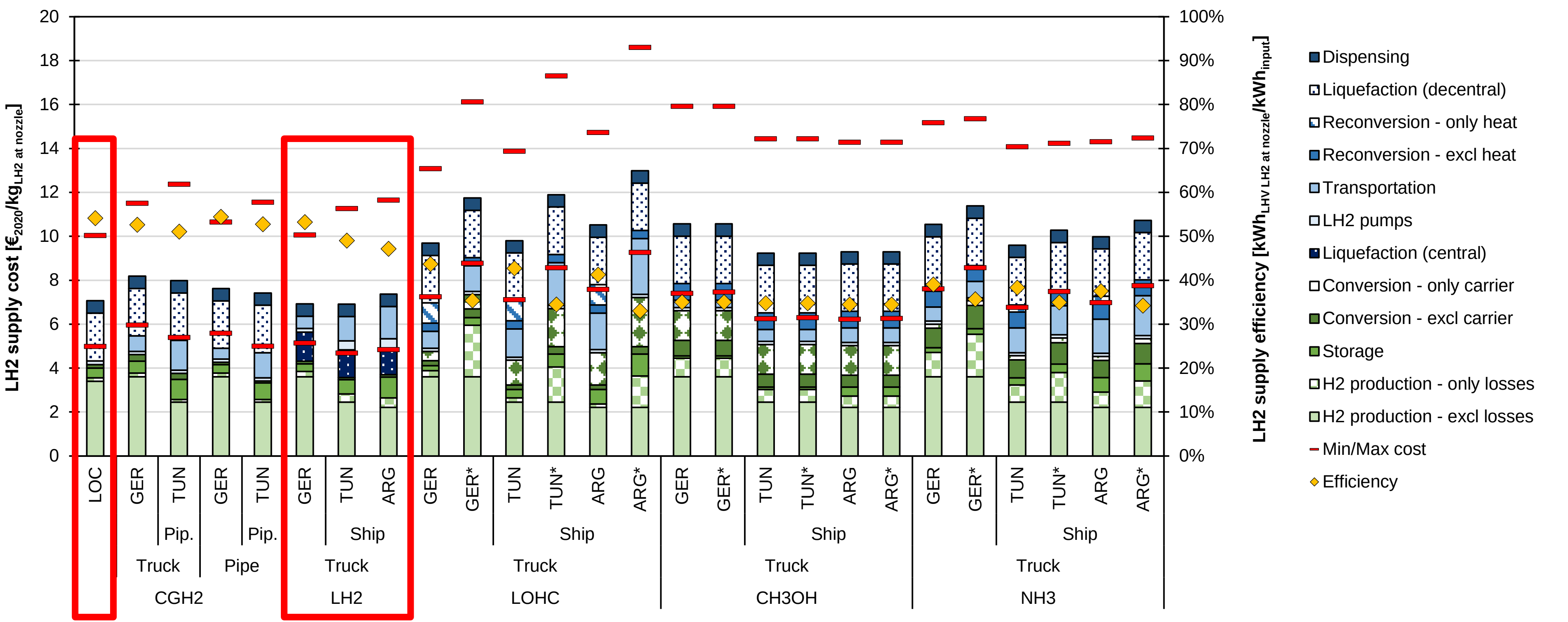
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

CGH$_2$ Filling – 2050



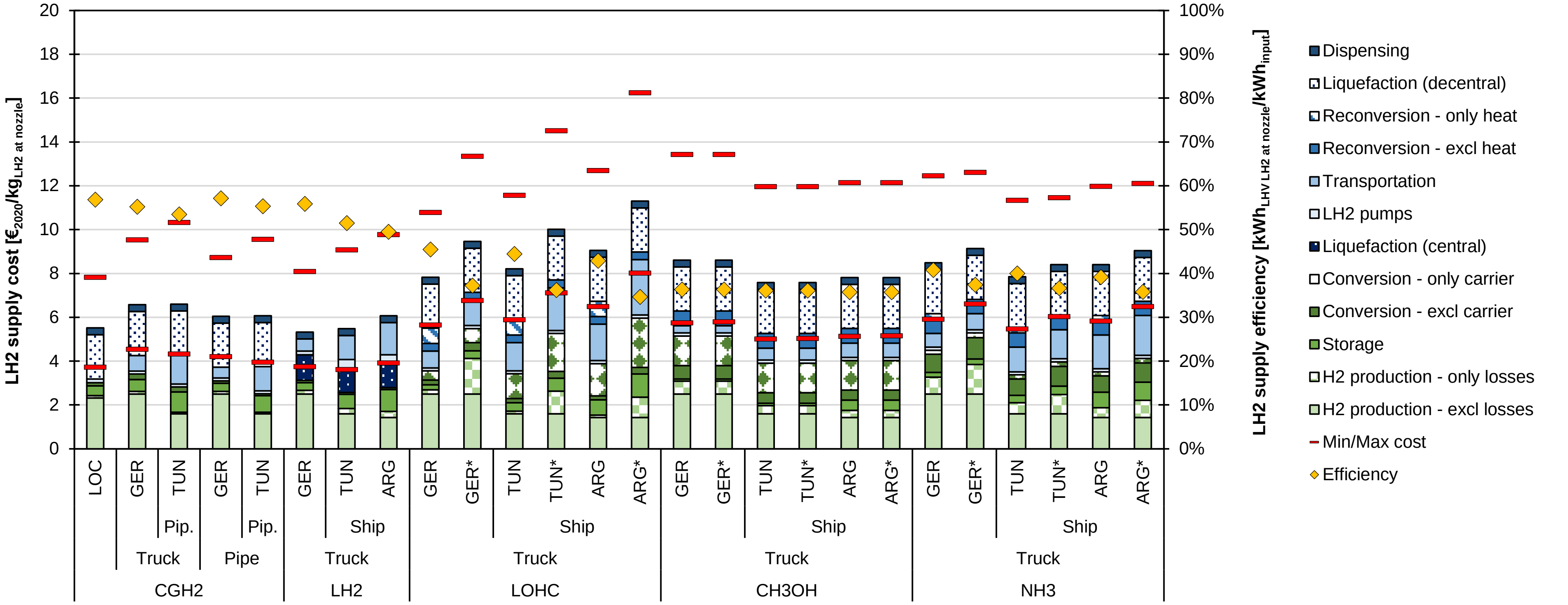
(* = heat demand for the reconversion is supplied internally by using the needed energy fraction from the released hydrogen; ARG = hydrogen production in Argentina (Patagonia); CGH2 = compressed gaseous hydrogen supply chain; CH3OH = methanol supply chain; GER = centralized production in North Germany;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

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; Pip. = pipeline import; Pipe = pipeline distribution to filling station; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to filling station

LH$_2$ 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); 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; Pip. = pipeline import; Pipe = pipeline distribution to filling station; Ship = ship import; TUN = hydrogen production in Tunisia; Truck = truck distribution to filling station

Conclusion

- **Gaseous hydrogen** supply chain is the **lowest cost option** for a supply of **gaseous hydrogen filling** stations
  ≈ 5 $€_{2020}/kg_{CGH2}$ & 60 % (2030)
  ≈ 4 $€_{2020}/kg_{CGH2}$ & 65 % (2050)

- **Liquid hydrogen and gaseous hydrogen** supply chains are the **lowest cost options** for a supply of **liquid hydrogen filling** stations
  ≈ 7 $€_{2020}/kg_{LH2}$ & 50 % (2030)
  ≈ 6 $€_{2020}/kg_{LH2}$ & 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 only **slightly higher cost** than the **import** from North Africa (e.g., Tunisia), while the average **local** hydrogen production for gaseous filling shows partly **significant higher cost**

Hamburg University of Technology (TUHH)

Institute of Environmental Technology and Energy Economics (IUE)

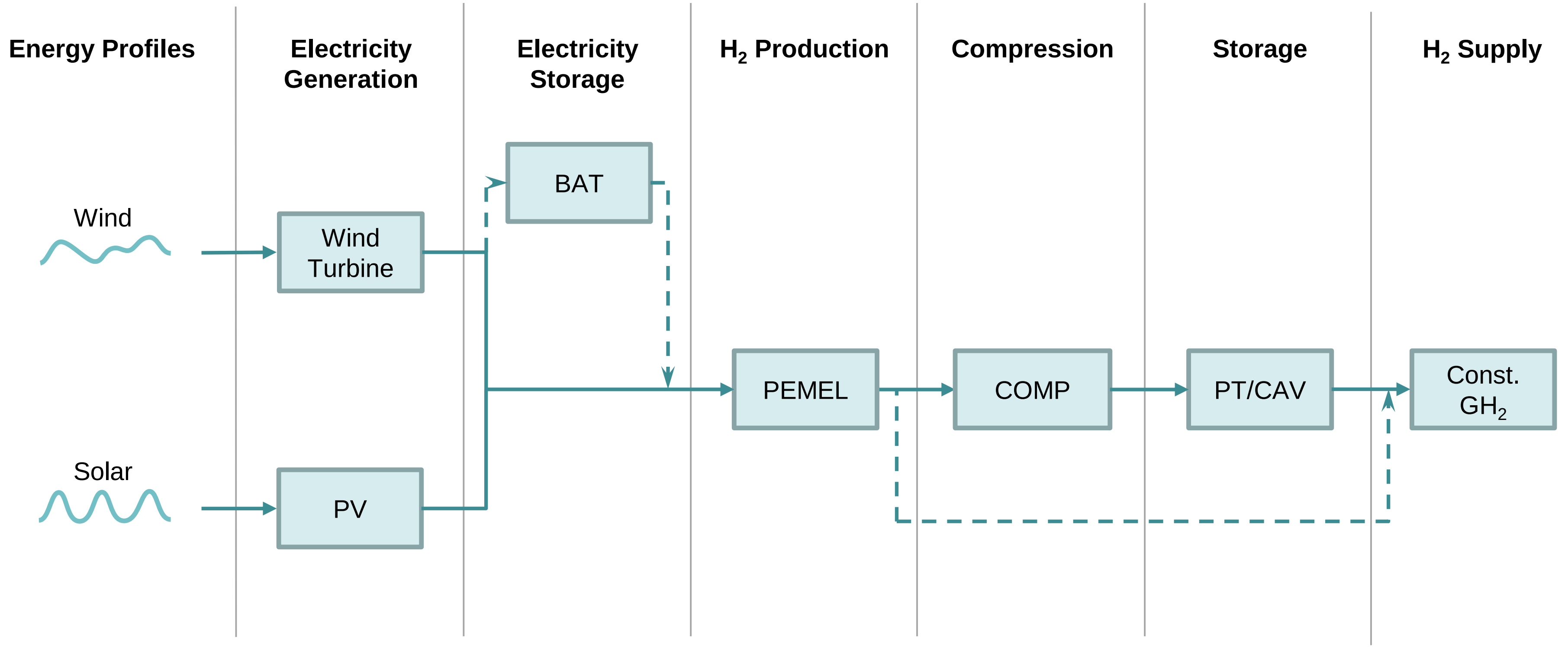
Eissendorfer Str. 40; D-21073 Hamburg

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 3, 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

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

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

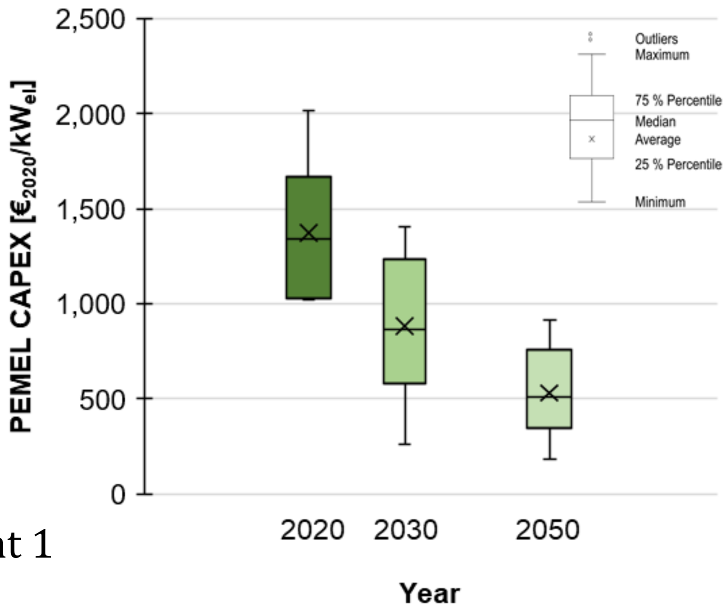
$$c_{section,i} = \frac{ACAPEX_i + OPEX_i}{m_{H2,fill,annual}}$$

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

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

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)

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

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

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