DOI: https://doi.org/10.15480/882.5026
ORCID: https://orcid.org/0000-0001-6300-4218

Springschool Hydrogen Technology 2023
Lauenburg
29.03.2023

Green Hydrogen Seaborne Supply Chains

A Techno-Economic Assessment

Lucas Sens, 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

Outline

1. Background

2. Hydrogen Supply Chains

3. Methodology and Data

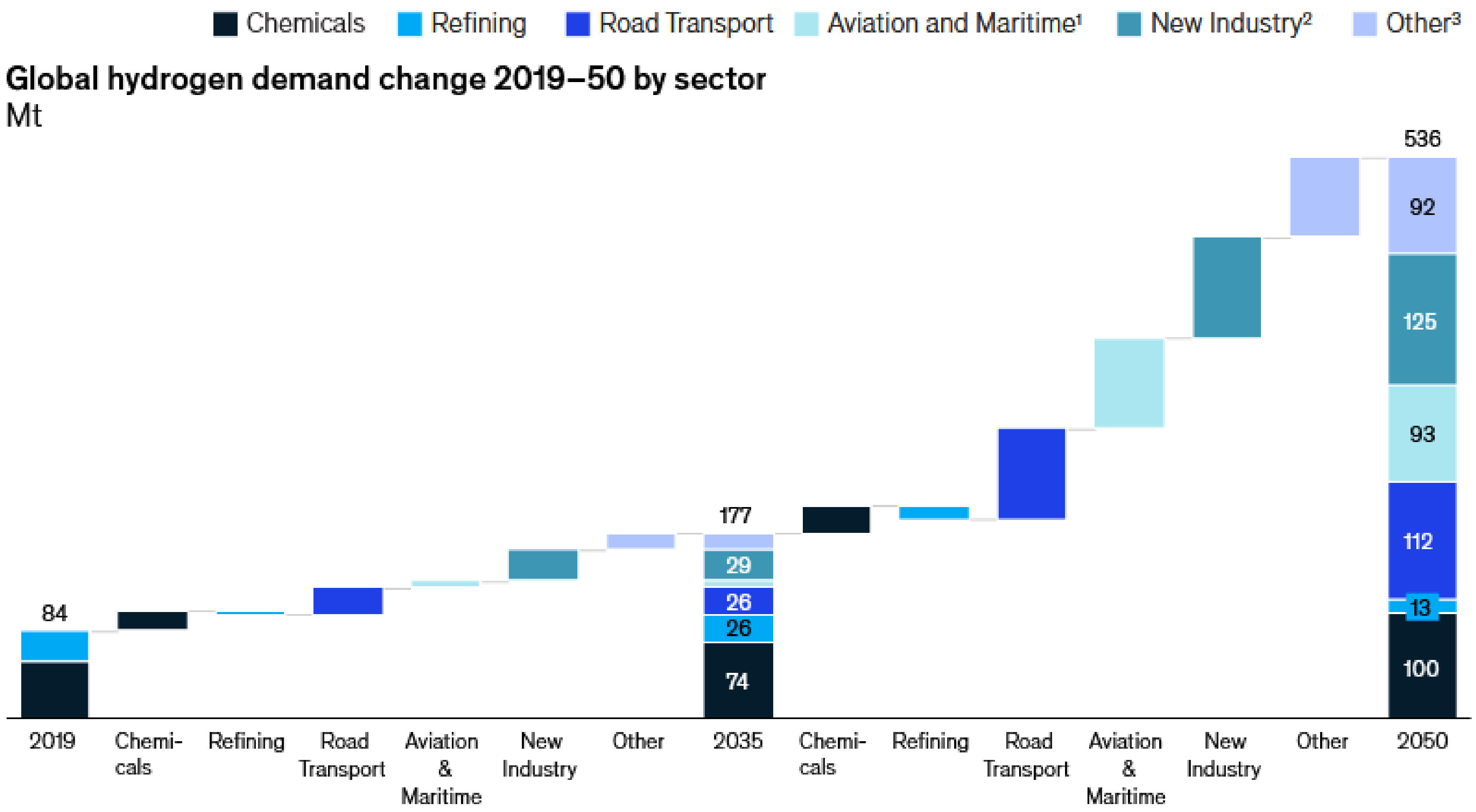
4. Results

5. Final Assessment and Key Conclusions

Green hydrogen in a future energy system

1. Background

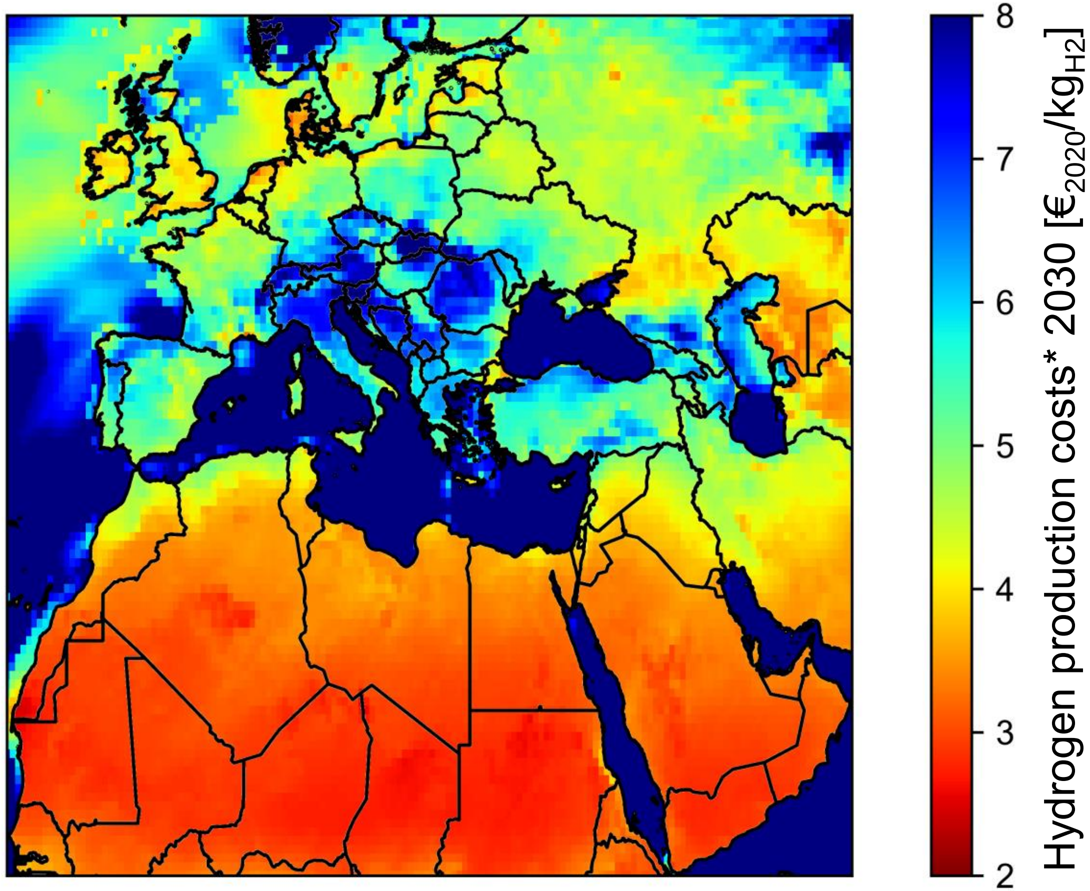
Hydrogen Demand Projections



1. Aviation and maritime include direct use of hydrogen and hydrogen-derived synfuels including kerosene, diesel, methanol, gasoline, and ammonia. The category also includes some hydrogen-derived synfuels in road transport
2. New industry includes all new uses of hydrogen in Industrial processes, eg, iron and steel production, whereas chemicals and refining are traditional hydrogen uses
3. Other includes buildings and electricity generation

Source: McKinsey 2022

Hydrogen Production Costs*



- Hydrogen productions costs are partly significantly higher in regions with a high demand
- Space availability is often high in regions with low hydrogen production costs

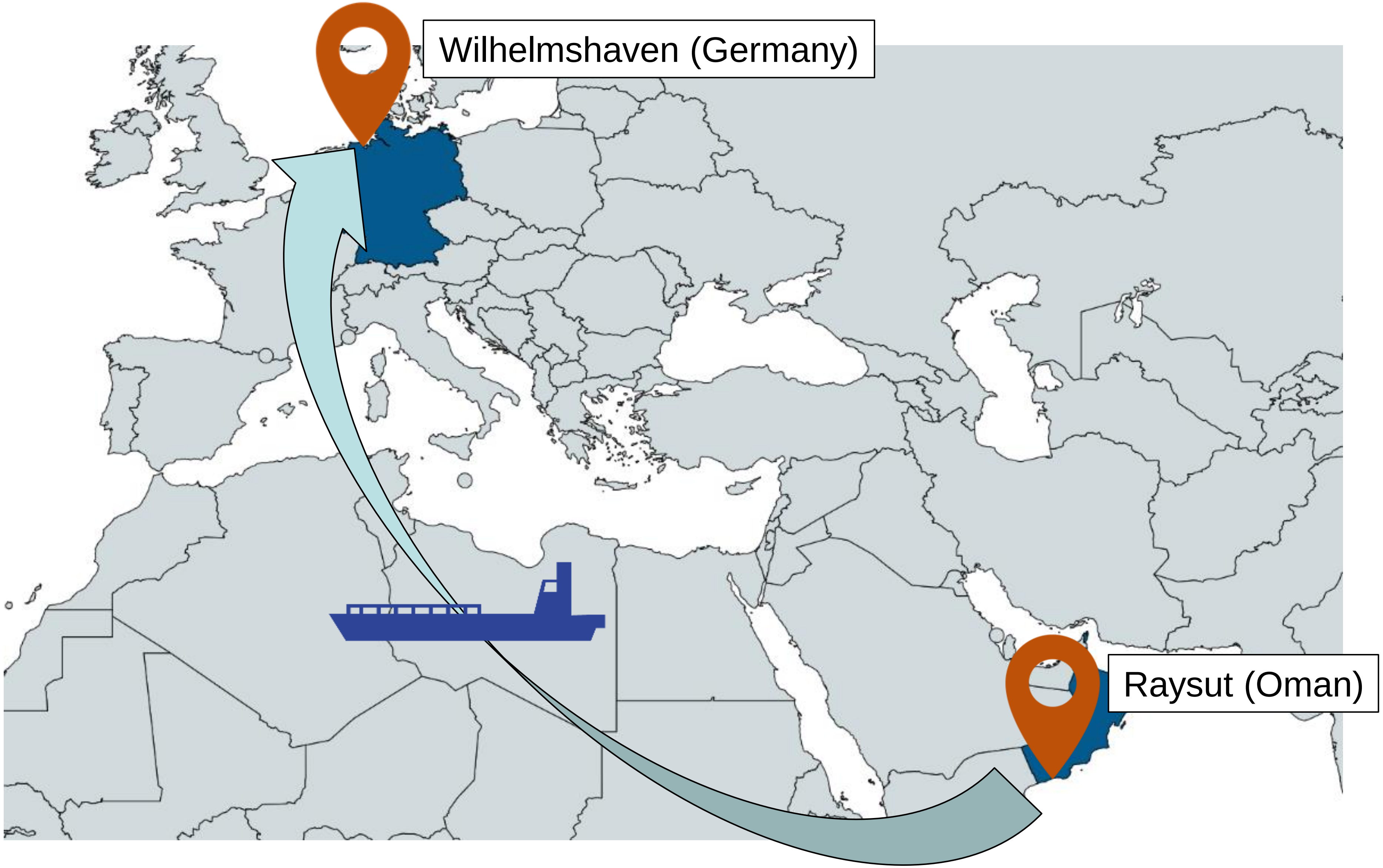
→ A hydrogen import from the MENA-Region to Europe is likely to establish in the future

Source: Sens et al. 2022; *includes the costs for the electricity generation, electrolyzer, compressor and storage capacities for a constant onsite hydrogen supply

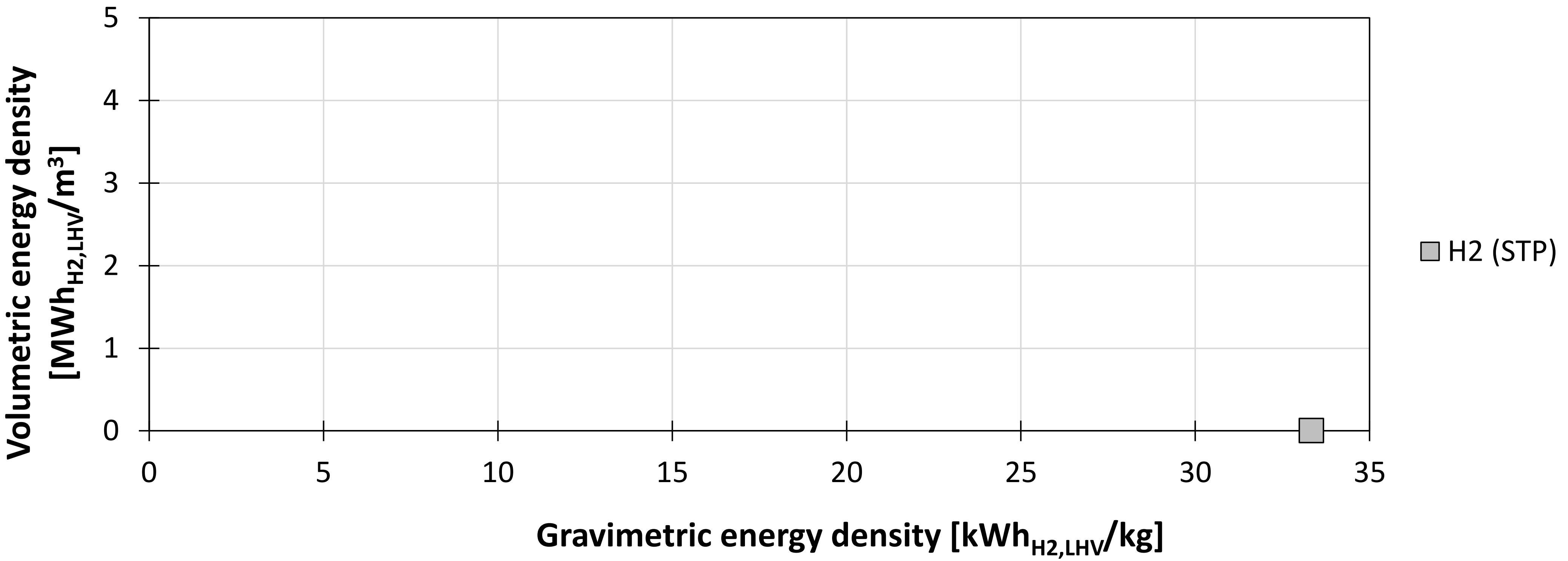
Conditioned hydrogen options and case study

2. Hydrogen Supply Chain

Hydrogen Delivery Route

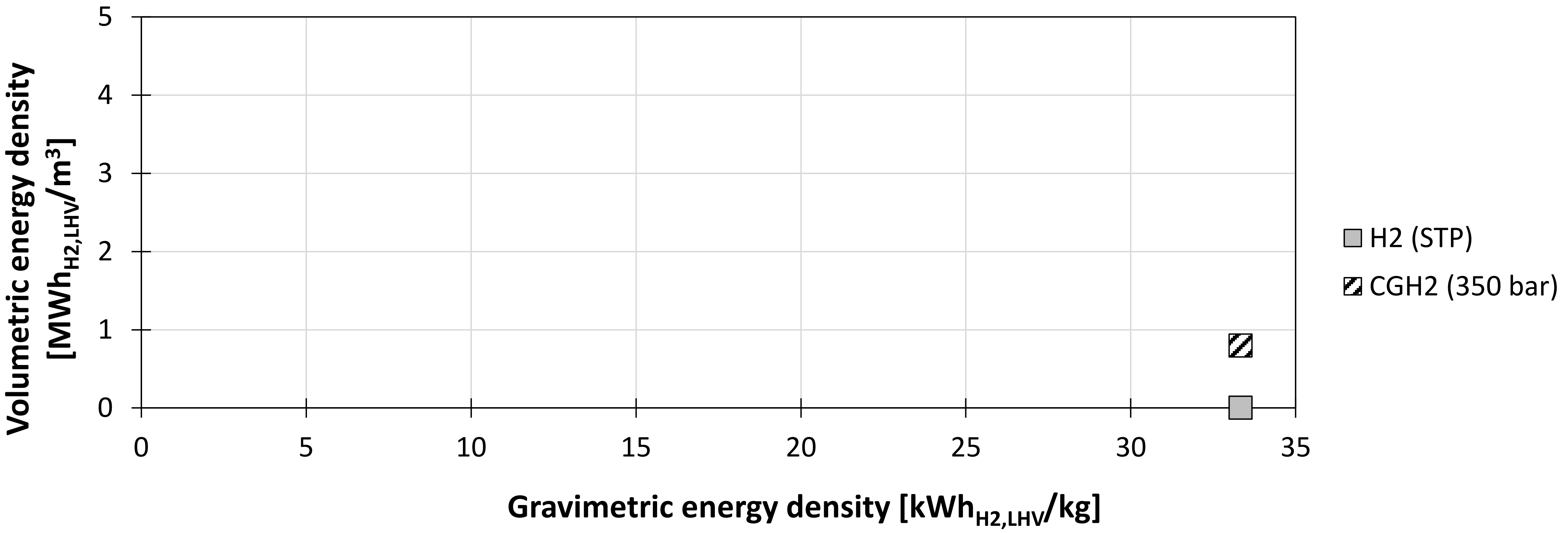


Conditioned Hydrogen – Gaseous Hydrogen



STP = standard temperature and pressure

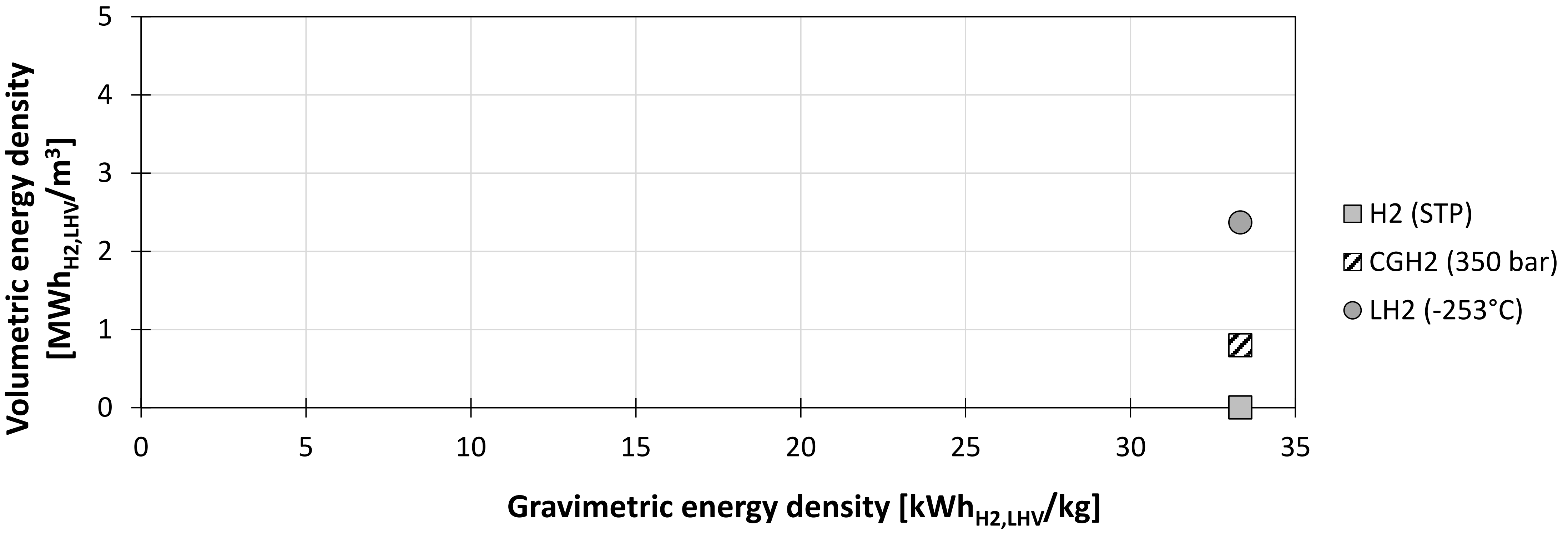
Conditioned Hydrogen – Compressed Gaseous Hydrogen



Energy density of compressed gaseous hydrogen is too low for longer distance shipping

CGH_2 = compressed gaseous hydrogen; STP = standard temperature and pressure

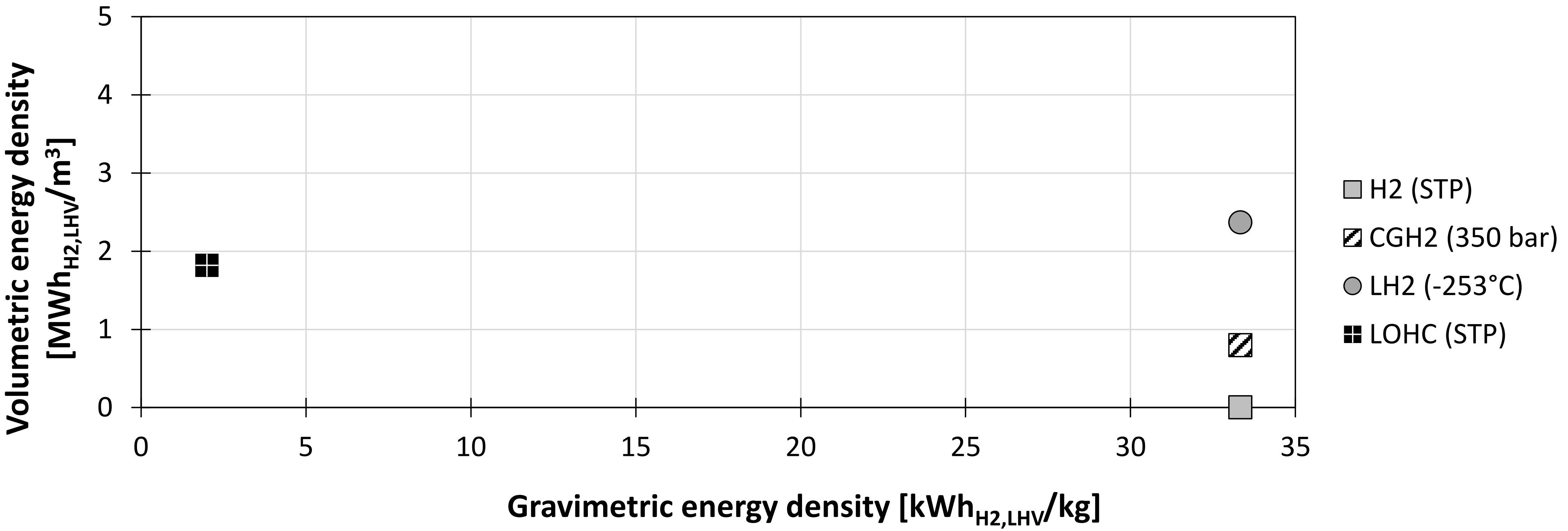
Conditioned Hydrogen – Liquid Hydrogen



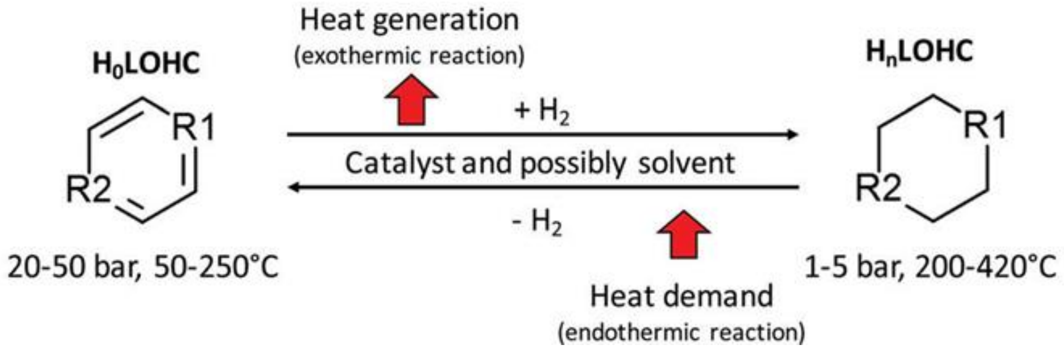
Liquid hydrogen (LH_2): $H_2(gaseous) + electricity \rightleftharpoons H_2(liquid, -253°C)$

CGH_2 = compressed gaseous hydrogen; LH_2 = liquid hydrogen; STP = standard temperature and pressure

Conditioned Hydrogen – Liquid Organic Hydrogen Carrier

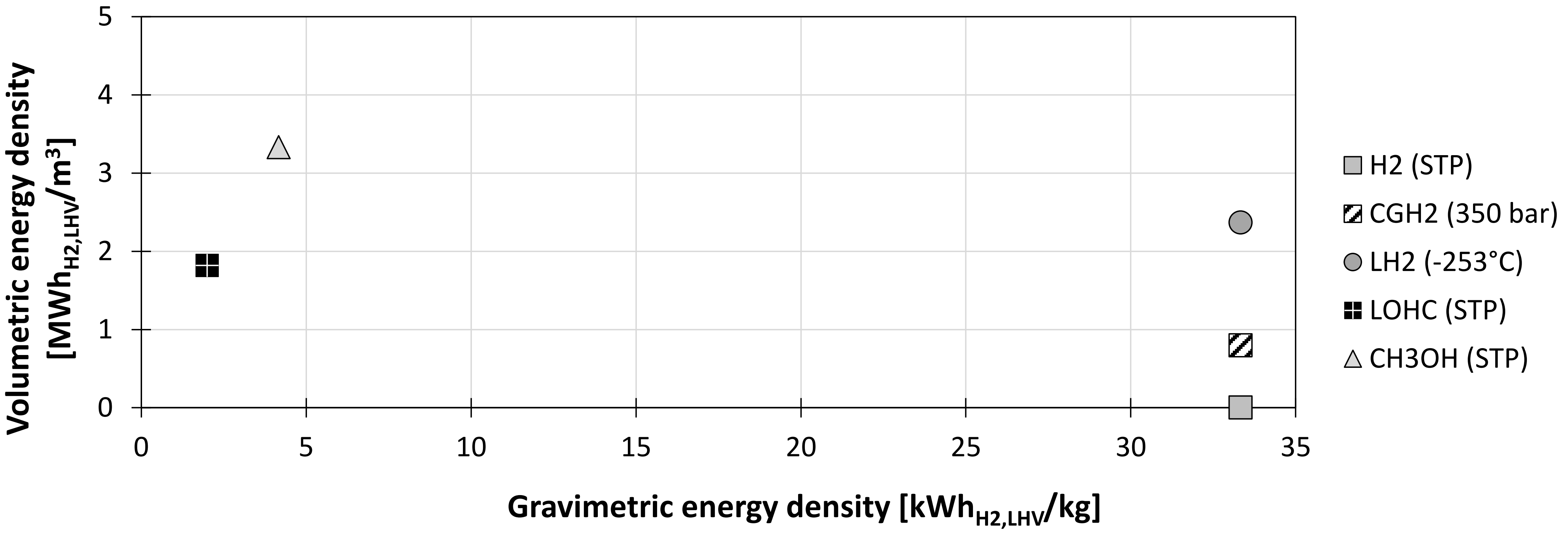


Liquid Organic Hydrogen Carriers (LOHC):



CGH_2 = compressed gaseous hydrogen; LH_2 = liquid hydrogen; LOHC = liquid organic hydrogen carrier; STP = standard temperature and pressure

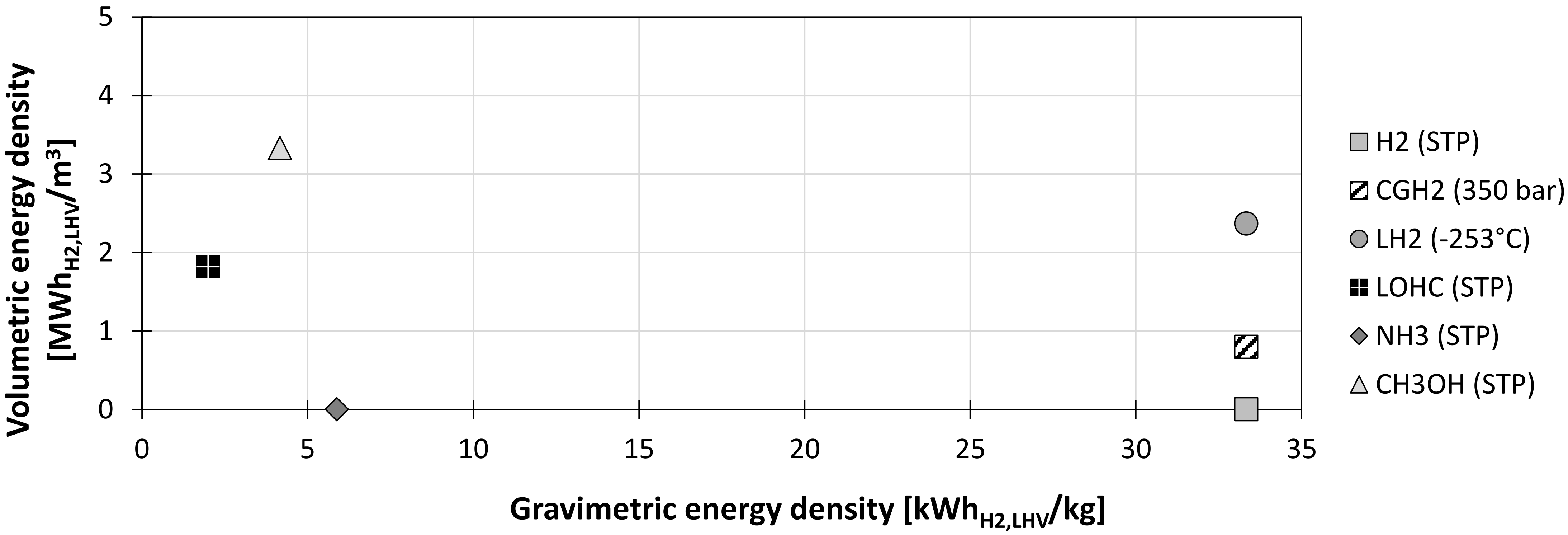
Conditioned Hydrogen – Methanol



Methanol (CH_3OH): $3H_2 + CO_2 \rightleftharpoons CH_3OH + H_2O + heat$

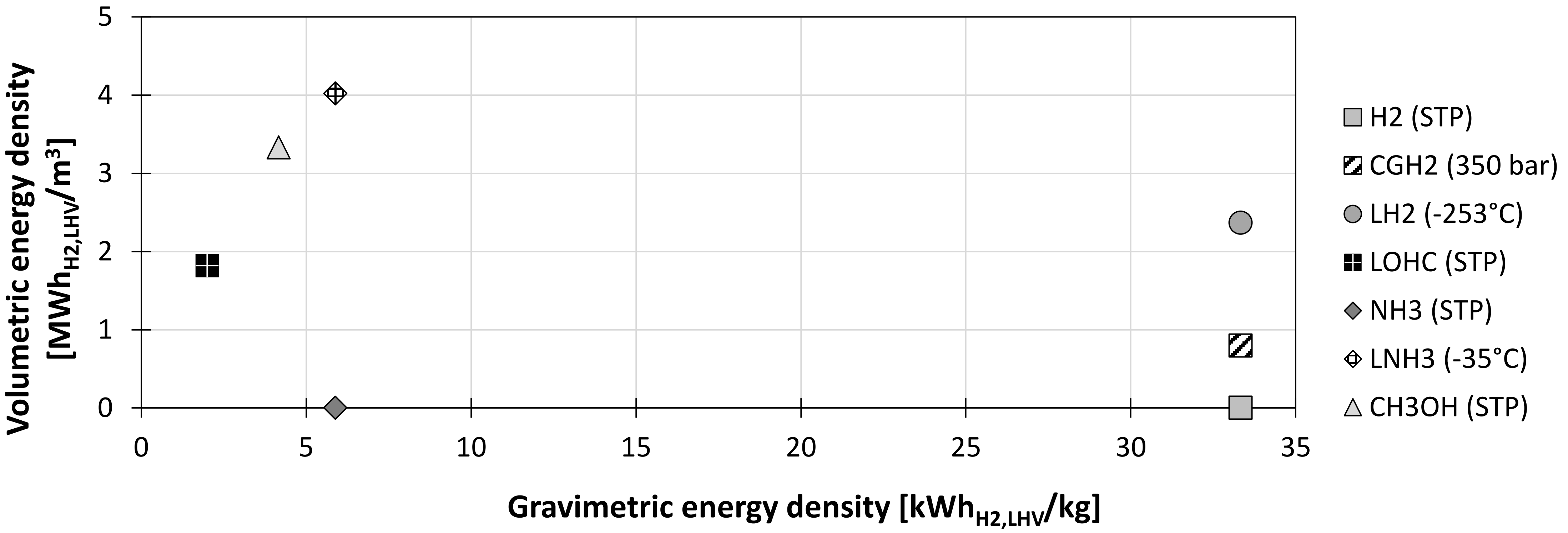
CGH_2 = compressed gaseous hydrogen; CH_3OH = methanol; LH_2 = liquid hydrogen; LOHC = liquid organic hydrogen carrier; STP = standard temperature and pressure

Conditioned Hydrogen – Ammonia



CGH_2 = compressed gaseous hydrogen; CH_3OH = methanol; LH_2 = liquid hydrogen; LOHC = liquid organic hydrogen carrier; NH_3 = ammonia;
STP = standard temperature and pressure

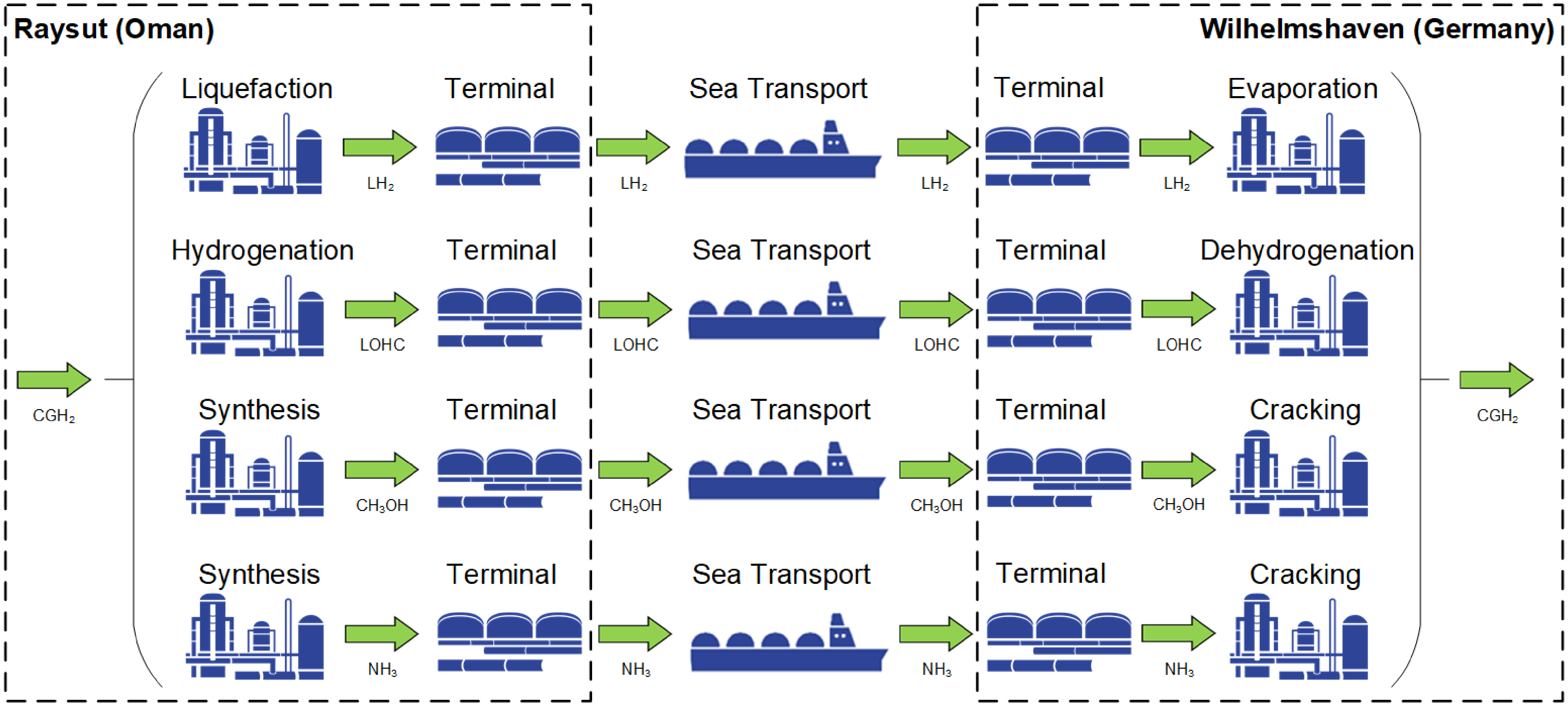
Conditioned Hydrogen – Ammonia



Ammonia (NH_3): $$3H_2 + N_2 \rightleftharpoons 2NH_3 + heat$$

CGH_2 = compressed gaseous hydrogen; CH_3OH = methanol; LH_2 = liquid hydrogen; LNH_3 = liquid ammonia; LOHC = liquid organic hydrogen carrier; NH_3 = ammonia;
STP = standard temperature and pressure

Case Study

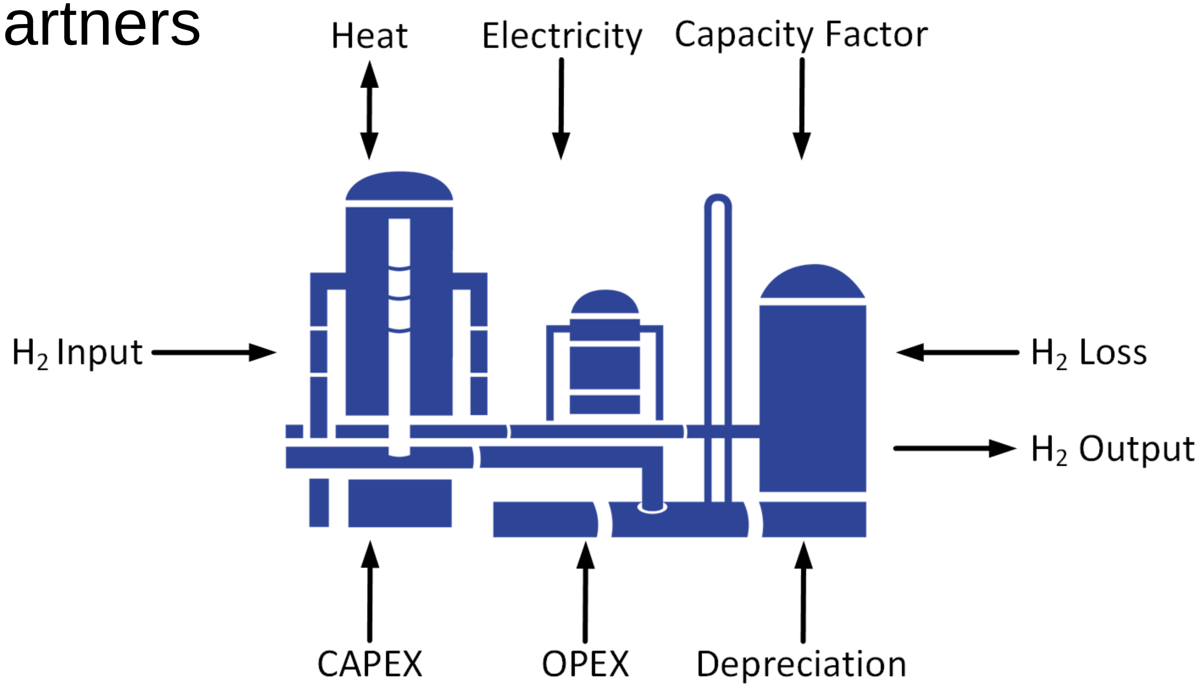


Raysut (Oman)
Wilhelmshaven (Germany)
CGH₂
Liquefaction
Terminal
Sea Transport
Terminal
Evaporation
LH₂
LH₂
LH₂
LH₂
Hydrogenation
Terminal
Sea Transport
Terminal
Dehydrogenation
LOHC
LOHC
LOHC
LOHC
Synthesis
Terminal
Sea Transport
Terminal
Cracking
CH₃OH
CH₃OH
CH₃OH
CH₃OH
Synthesis
Terminal
Sea Transport
Terminal
Cracking
NH₃
NH₃
NH₃
NH₃
CGH₂

Approach and techno-economic parameters

3. Methodology and Data

- 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 by industrial partners



Data

	Specification	Liquid Hydrogen (500 $t_{H2}pd$)	LOHC (500 $t_{H2}pd$)	Ammonia (500 $t_{H2}pd$)	Methanol (500 $t_{H2}pd$)
CAPEX [$€_{2020}/(kg_{H2,cond}/h)$]	Conditioning	32,300 (23,000 – 39,000)	3,200 (2,700 – 3,600)	20,600 (17,600 – 23,500)	7,000 (3,200 – 10,500)
	Reconditioning	610 (510 – 700)	2,800 (2,000 – 3,600)	12,000 (9,000 – 19,700)	4,000 (2,900 – 8,300)
Energy Demand* [$kWh/(kg_{H2,cond}$]	Conditioning	7.4 (6.0 – 9.8)	0.2 (0.1 – 0.4)	1.8 (1.4 – 2.3)	3.7 (3.6 – 3.8)
	Reconditioning	0.5 (0.4 – 0.6)	13.5 (11.6 – 15.5)	11.5 (10.9 – 12.1)	4.2 (3.9 – 4.5)
Carrier Cost [$€_{2020}/kg_{educt}$]	-	-	3.2 (2.2 – 5.4)	0.03 (0.02 – 0.04)	0.15 (0.08 – 0.30)
H_2 Loss [$kg_{H2,loss}/kg_{H2,cond}$]	Conditioning	0.5%	0.5% (0.1 – 1.0%)	0%	0%
	Reconditioning	0%	2% (1 – 3%)	20% (10 – 30%)	15% (10 – 20%)

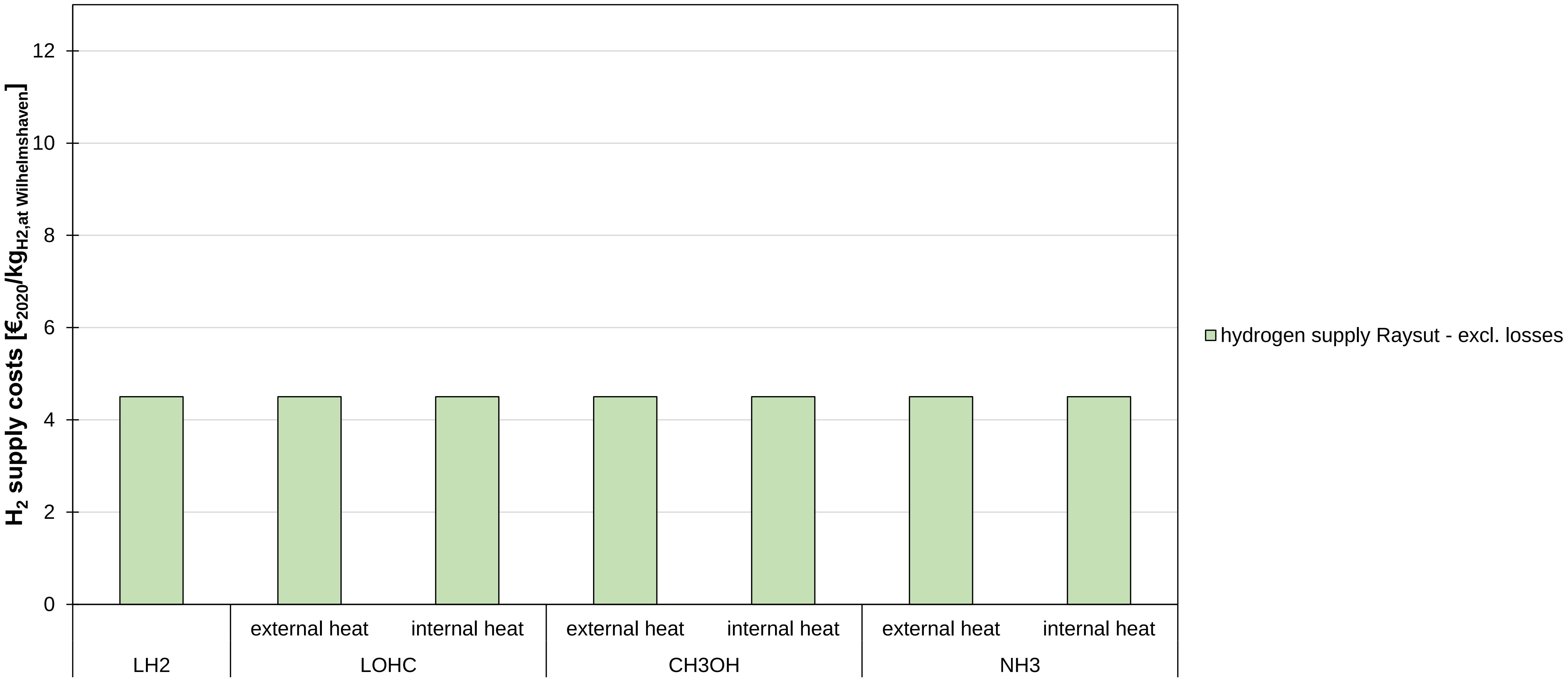
- Gaseous hydrogen costs at the Harbor in Raysut (Oman): 4.5 $€_{2020}$/kg (bandwidth: 3.0 to 6.0 $€_{2020}$/kg)
- Time horizon: 2025
- Real WACC: 6%

*Sum of the heat and electricity demand which can be lowered by using the hydrogen losses in the reconditioning process

Hydrogen supply costs and efficiencies

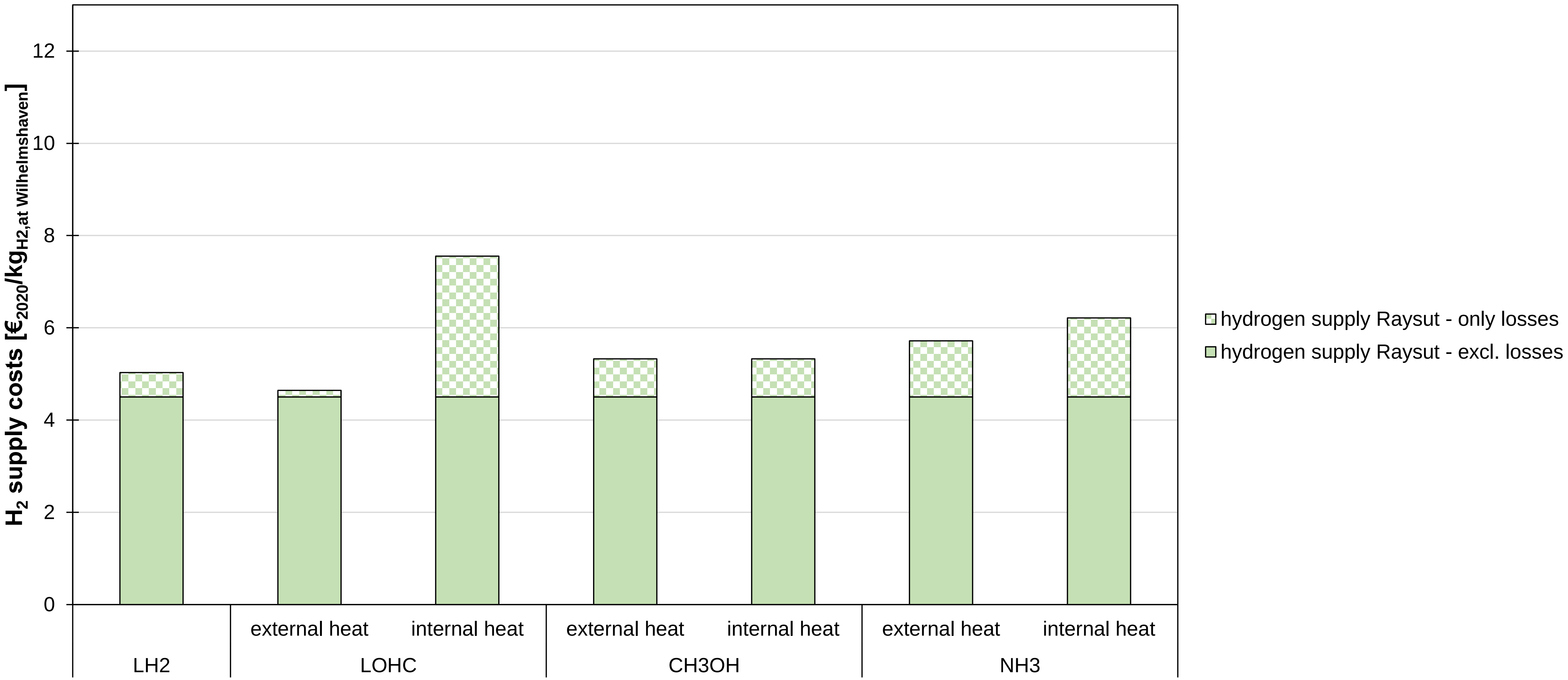
4. Results

Hydrogen Supply Costs



external heat = external heat source used for reconditioning heat; internal heat = imported hydrogen used for the reconditioning heat
CH3OH = methanol; LOHC = liquid organic hydrogen carrier; LH2 = liquid hydrogen; NH3 = ammonia

Hydrogen Supply Costs



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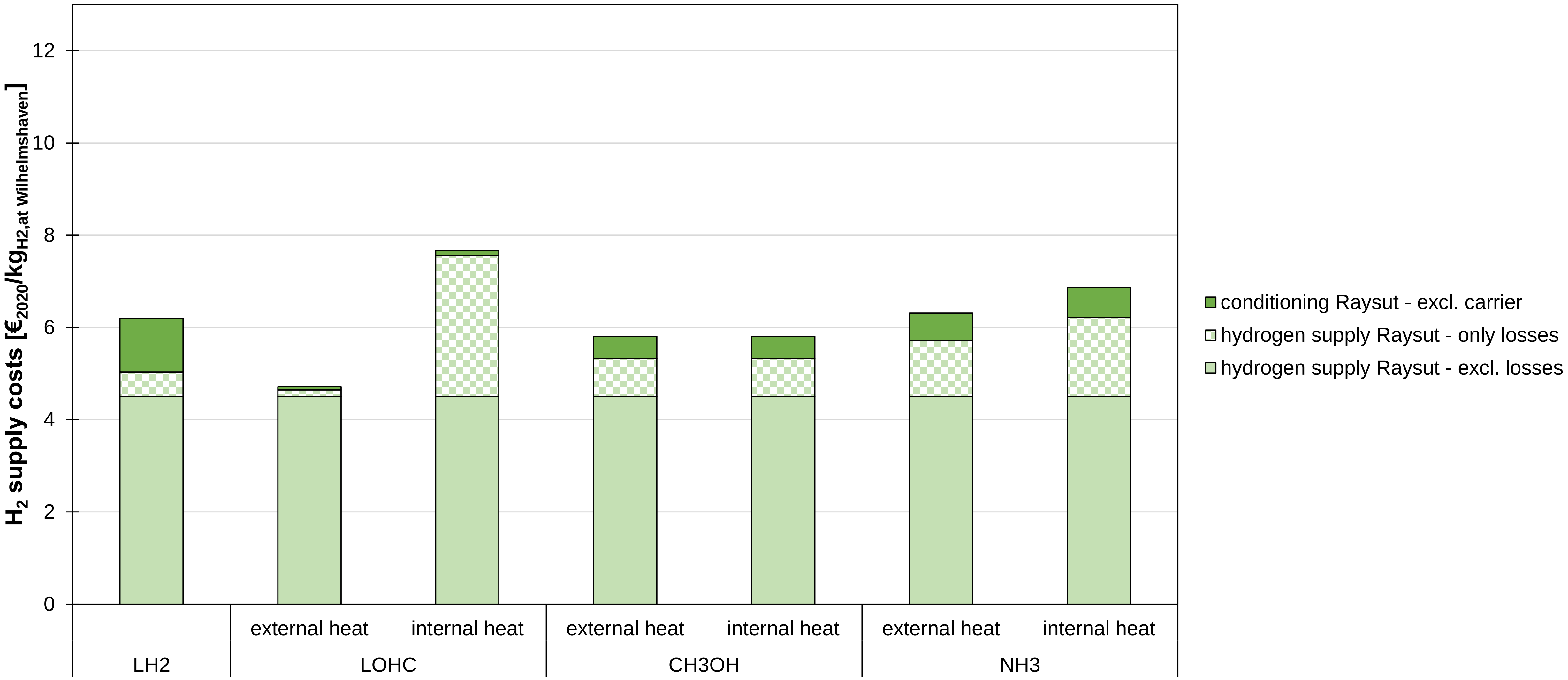

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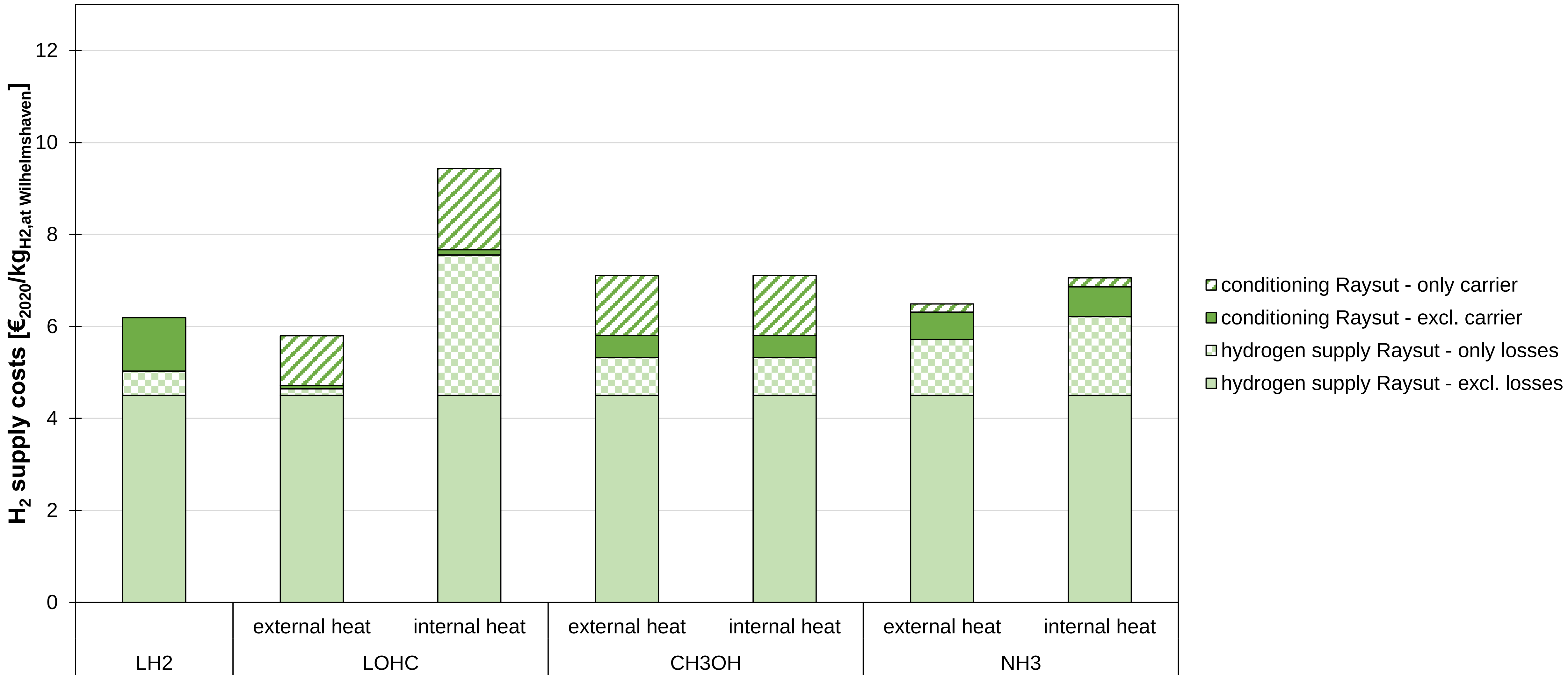

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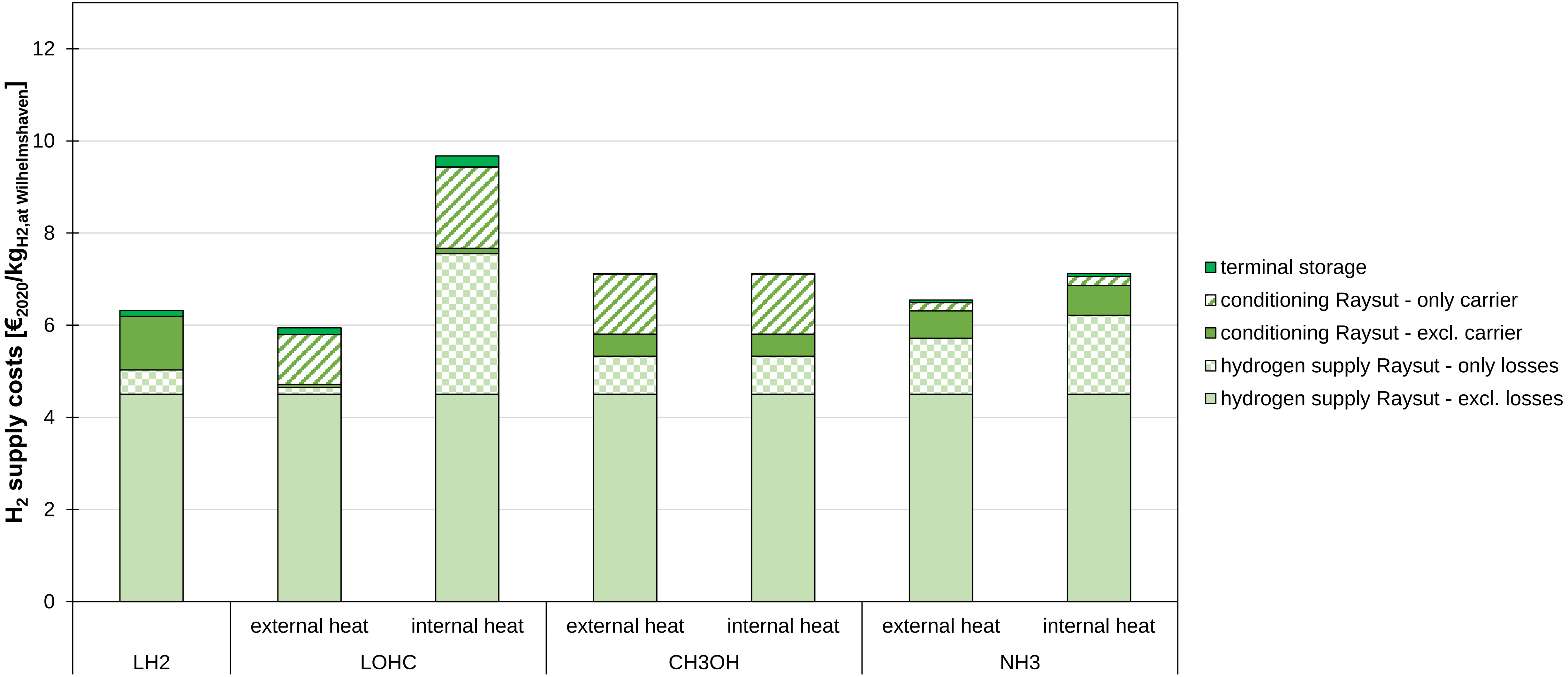

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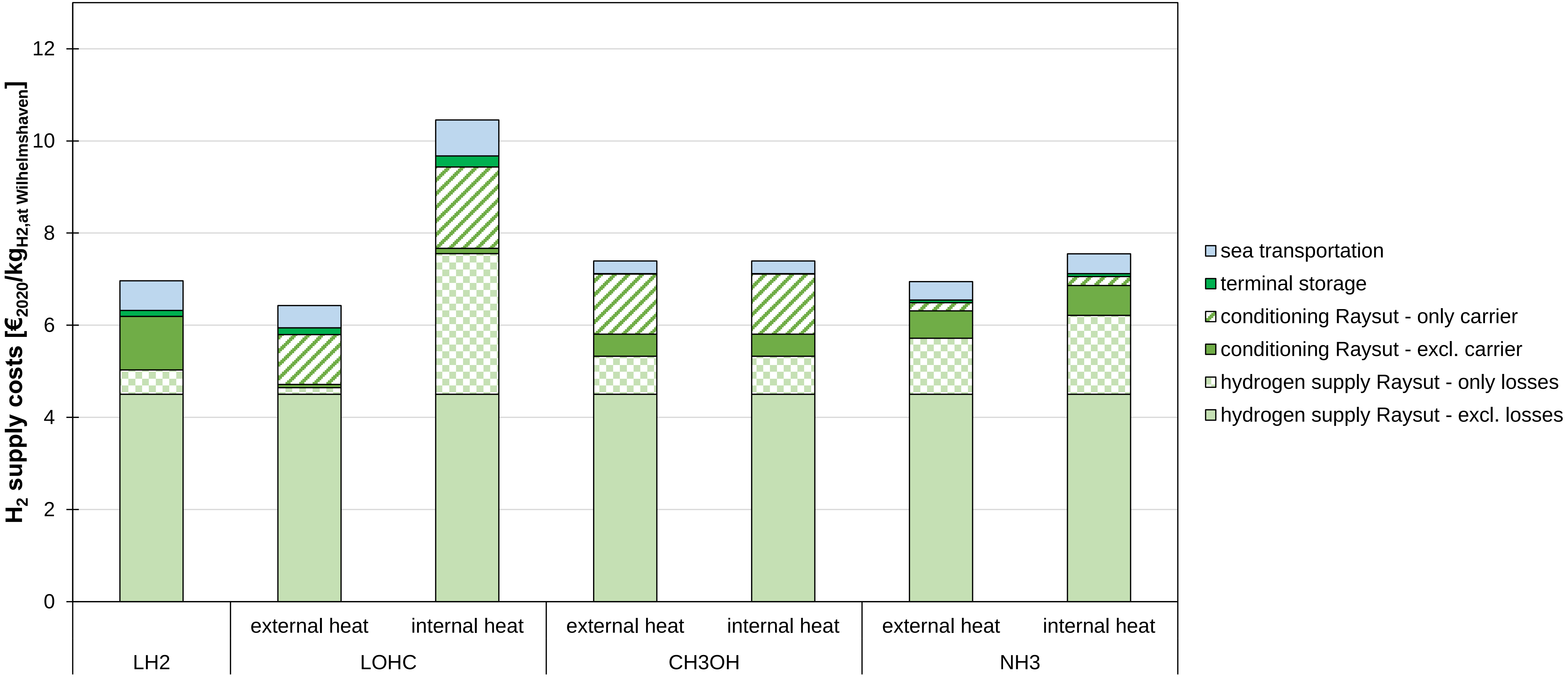

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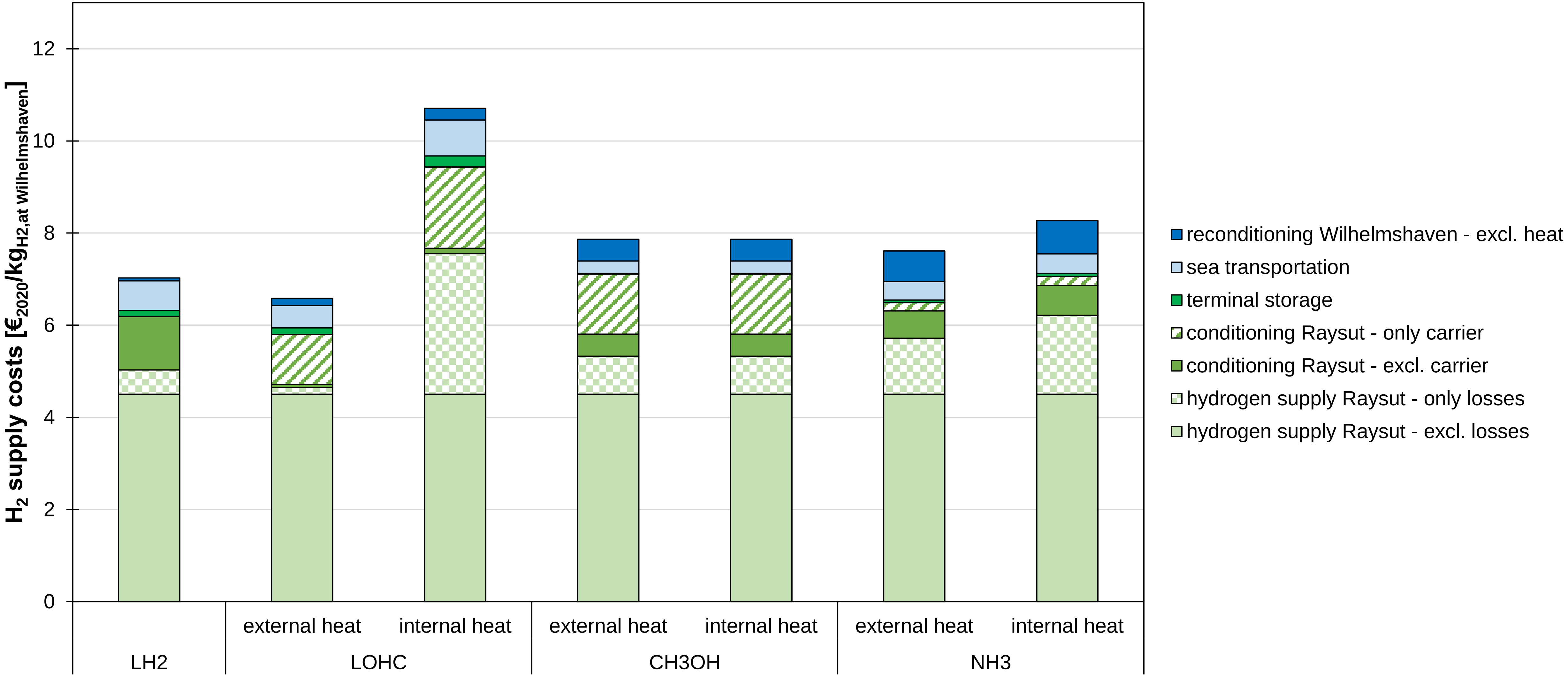

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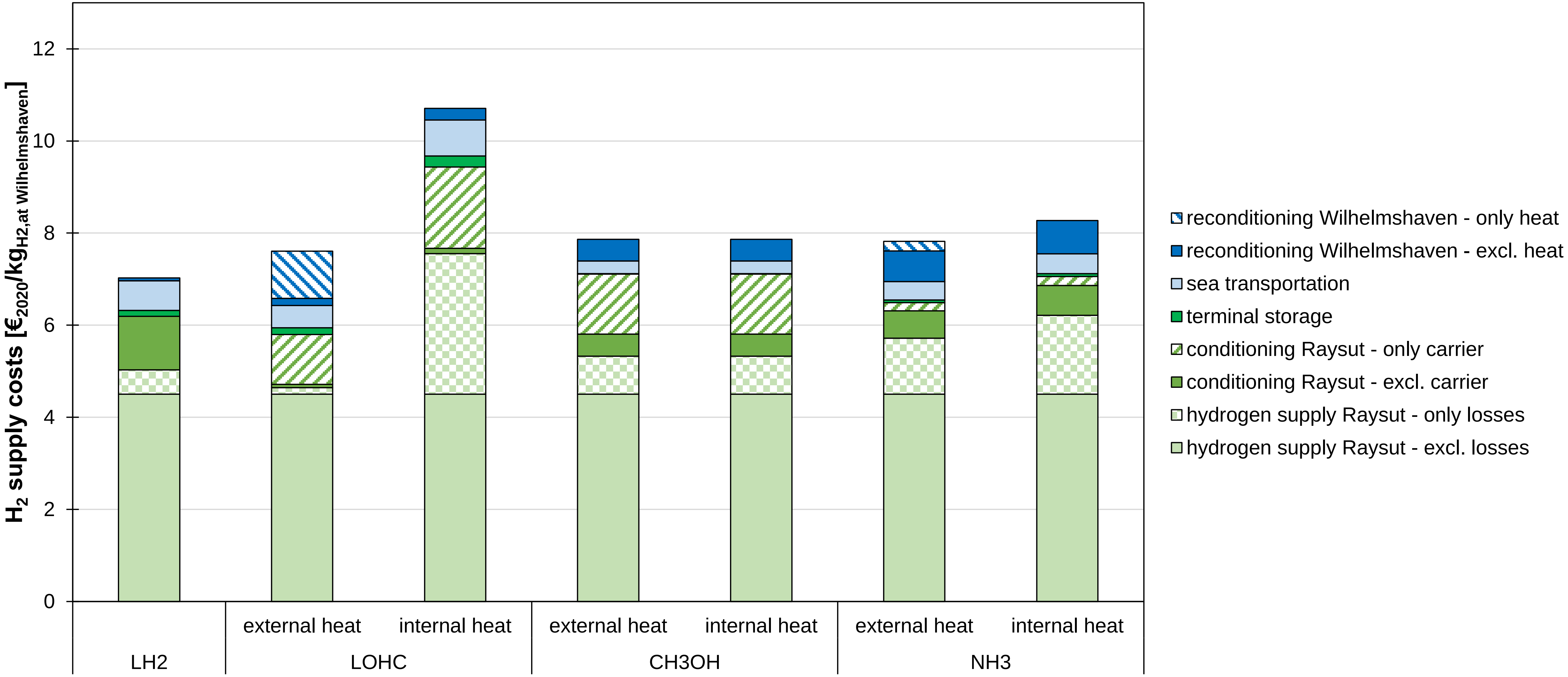

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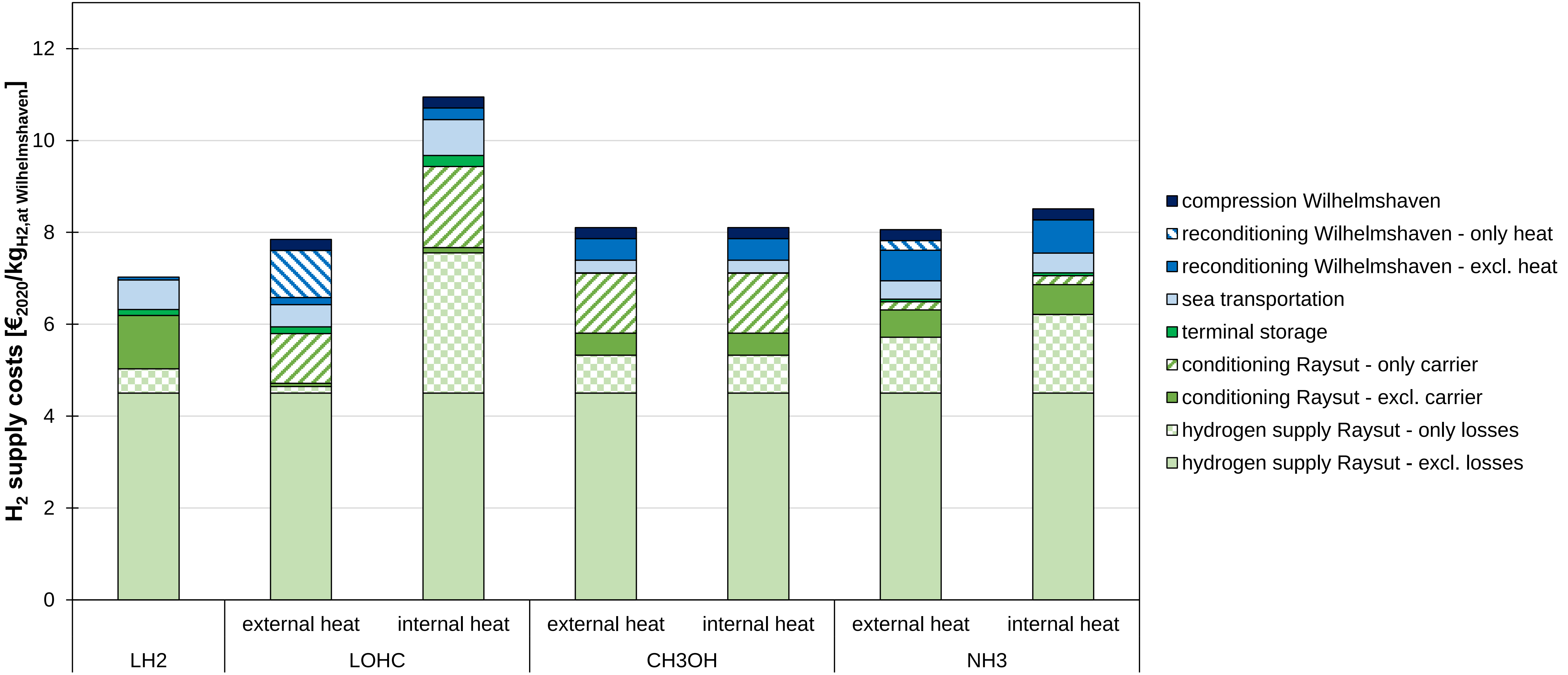

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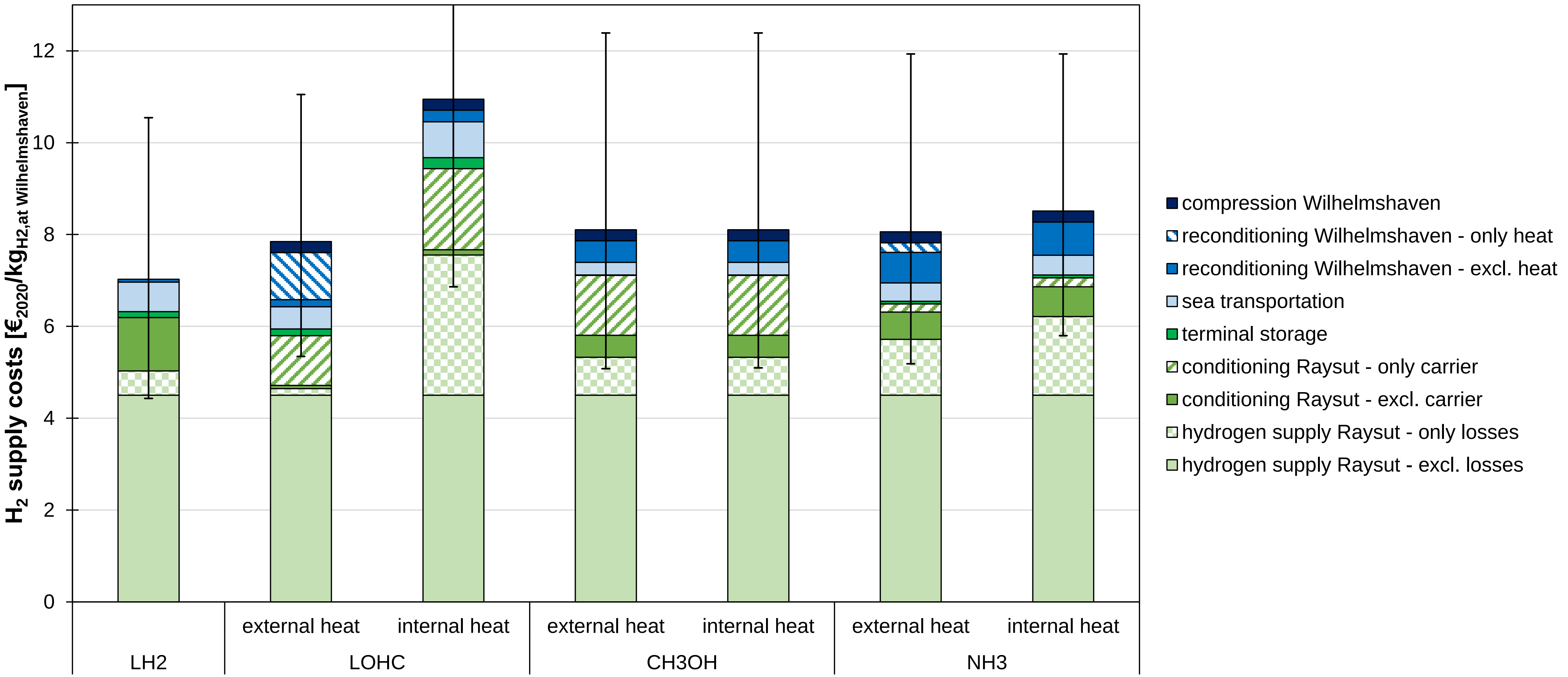

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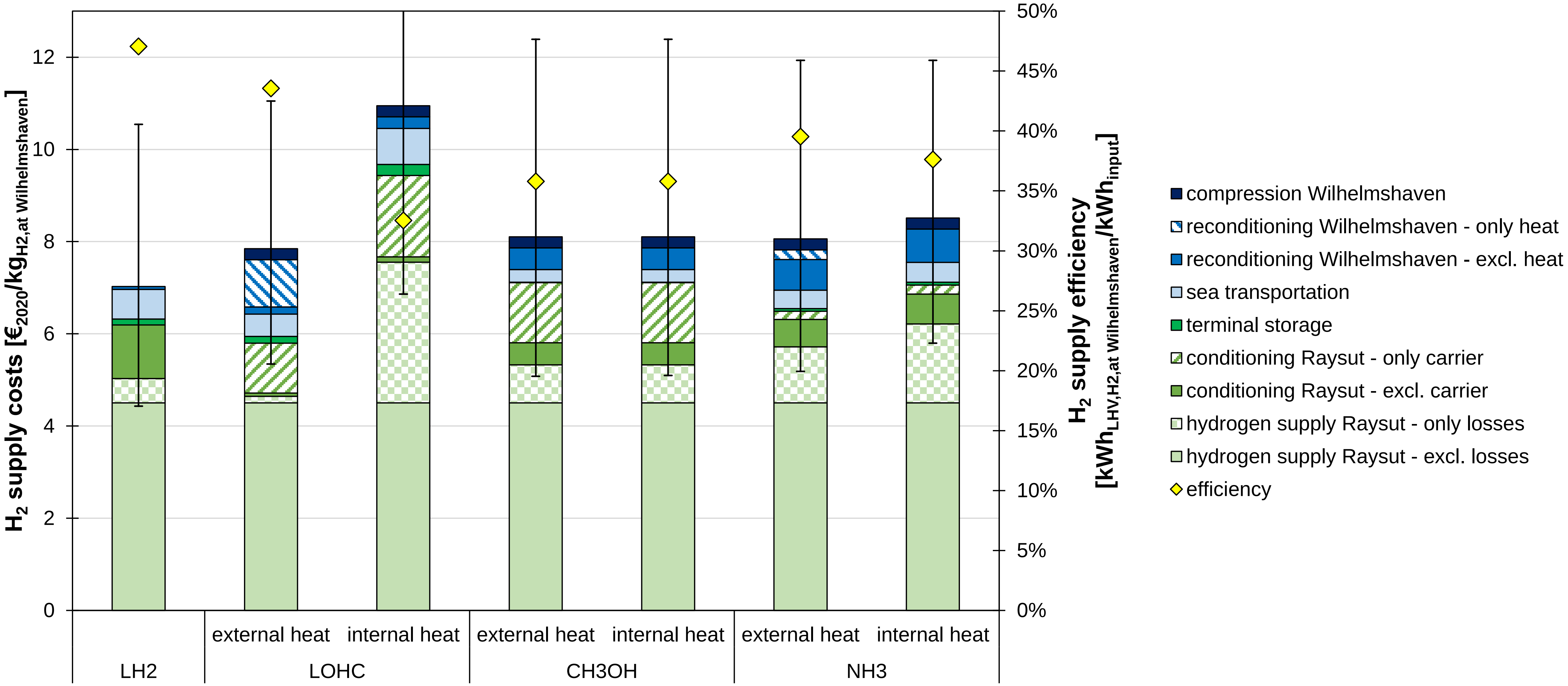

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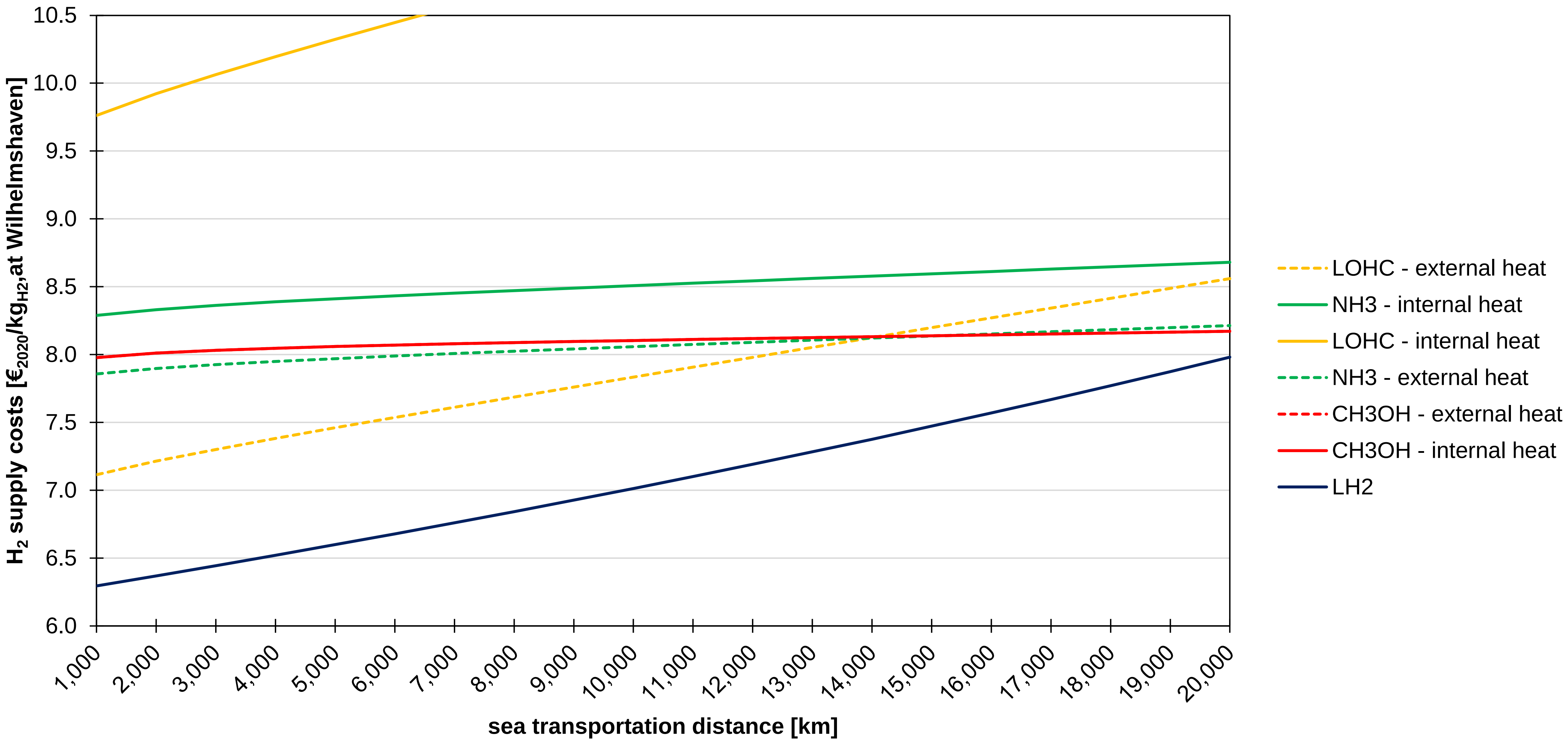
Hydrogen Supply Costs over Distance



external heat = external heat source used for reconditioning heat; internal heat = imported hydrogen used for the reconditioning heat
CH3OH = methanol; LOHC = liquid organic hydrogen carrier; LH2 = liquid hydrogen; NH3 = ammonia

Which conditioned hydrogen option is the most promising?

5. Final Assessment and Key Conclusions

Liquid Hydrogen

- Costs ≈ 7.0 $€_{2020}/kg_{H2}$ (bandwidth: 4.4 to 10.5 $€_{2020}/kg_{H2}$)
- Efficiency ≈ 47 %
- High technology uncertainties (upscaling of liquefaction, shipping)
- No international infrastructure is given so far
- Liquid hydrogen shows the **highest potential** in the future due to lowest supply cost

Liquid Organic Hydrogen Carrier (LOHC)

- Costs and Efficiency:
  - External heat supply: 7.8 $€_{2020}/kg_{H2}$ (bandwidth: 5.4 to 11.0 $€_{2020}/kg_{H2}$) & 44 %
  - Internal heat supply: 11.0 $€_{2020}/kg_{H2}$ (bandwidth: 6.9 to 17.0 $€_{2020}/kg_{H2}$) & 33 %

- Carrier costs and dehydrogenation heat demand are the most important cost drivers

- Conventional transportation and storage infrastructure can be used

- Overall, based on the actual knowledge **LOHCs do not seem to be competitive*** due to higher costs (especially compared to liquid hydrogen) and the risk of stranded assets (compared to methanol and ammonia)

*Based on a system assessment. It may differ for specific use cases e.g., with short transportation distances, a significant cost reduction for the carrier material or low cost green heat supply for the dehydrogenation

Methanol

- Costs and Efficiency:
  - Internal/External heat supply: 8.1 $€_{2020}/kg_{H2}$ (bandwidth: 5.1 to 12.4 $€_{2020}/kg_{H2}$) & 36 %

- Carrier costs and availability (green CO_2) as well as hydrogen losses in the cracking and purification process are the most important cost drivers

- Conventional transportation and storage infrastructure can be used

- Pure demand of methanol (bulk chemical) reduces the risk of stranded assets

- In general methanol **can be a competitive** conditioned hydrogen option compared to ammonia and especially LOHCs, if low cost green **CO_2 is available in large quantities**, which is questionable at least in a short term

- Costs and Efficiency:
  - External heat supply: 8.1 $€_{2020}/kg_{H2}$ (bandwidth: 5.2 to 11.9 $€_{2020}/kg_{H2}$) & 40 %
  - Internal heat supply: 8.5 $€_{2020}/kg_{H2}$ (bandwidth: 5.8 to 11.9 $€_{2020}/kg_{H2}$) & 38 %
- The hydrogen losses in the cracking and purification process is the most important cost driver
- Conventional transportation and storage infrastructure can be used
- Pure demand of ammonia (fertilizer) reduces the risk of stranded assets
- Ammonia **seems to be the most promising** conditioned hydrogen option realizing a hydrogen import in a **short term**, especially if the hydrogen losses in the cracking and purification process can be reduced

Thank you for your Attention!

Questions and Discussion

Technische Universität Hamburg (TUHH)
Institut für Umwelttechnik und Energiewirtschaft (IUE)
Eißendorfer Str. 40, D-21073 Hamburg
www.tuhh.de/iue

Lucas Sens | lucas.sens@tuhh.de

LinkedIn