



Springschool Hydrogen Technology 2023

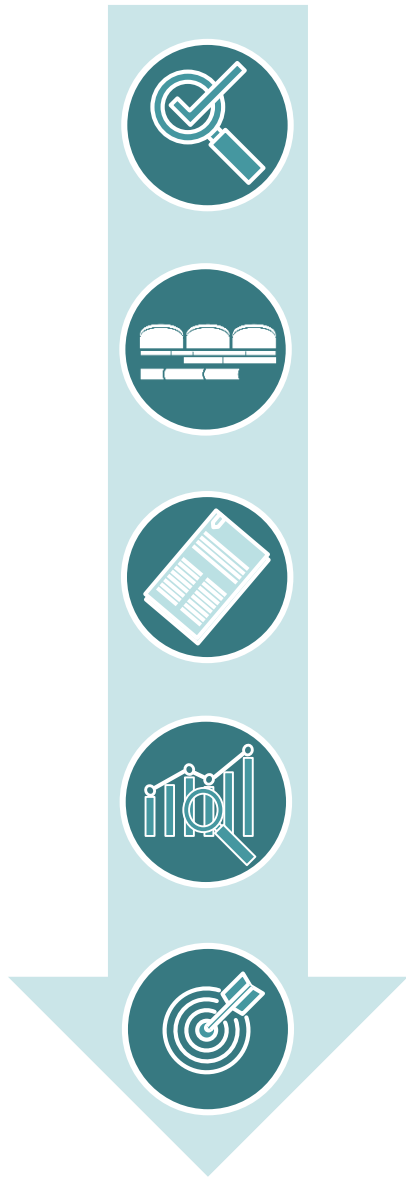
Lauenburg

29.03.2023

Green Hydrogen Seaborne Supply Chains

A Techno-Economic Assessment

Lucas Sens, Martin Kaltschmitt



1. Background

2. Hydrogen Supply Chains

3. Methodology and Data

4. Results

5. Final Assessment and Key Conclusions

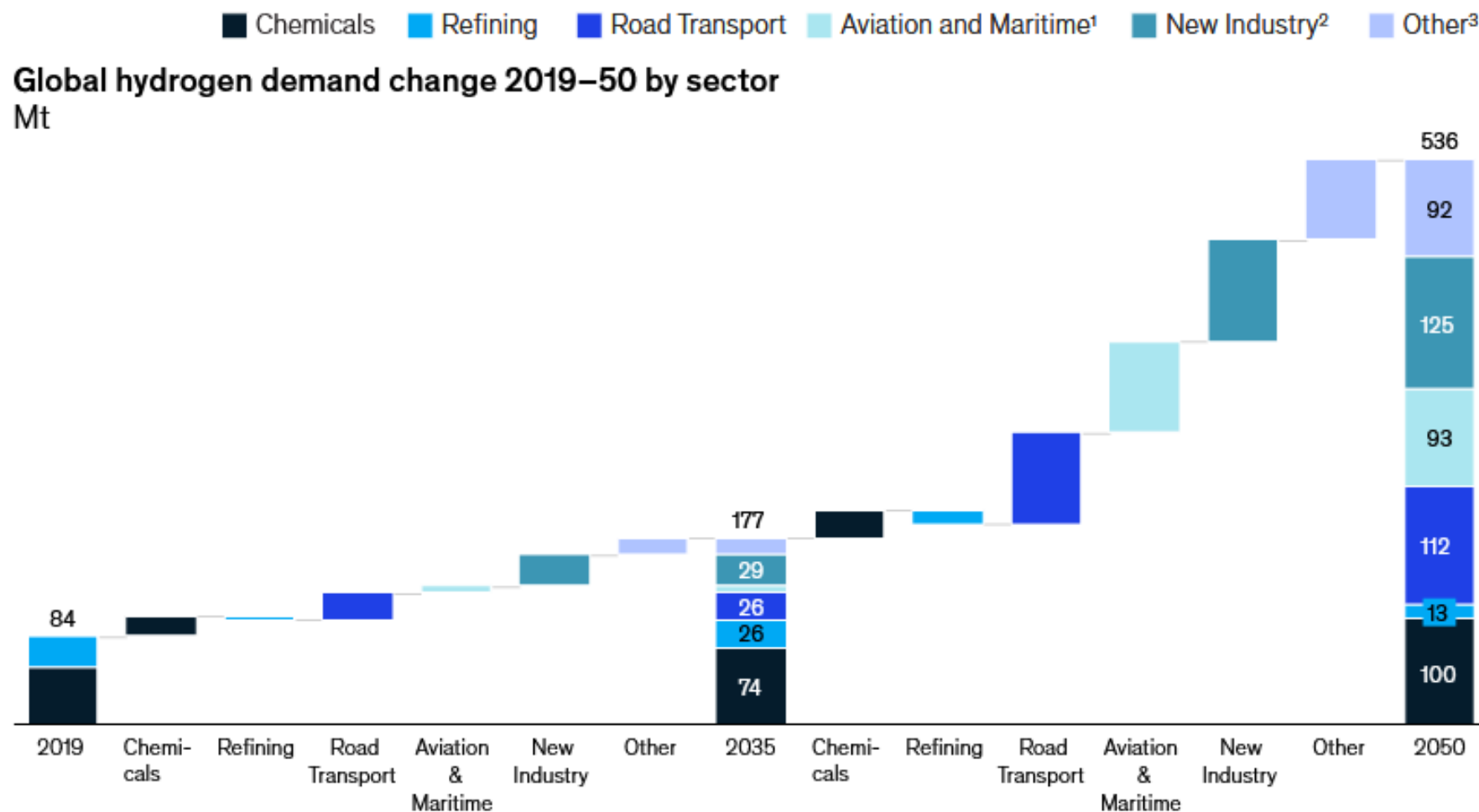


Green hydrogen in a future energy system

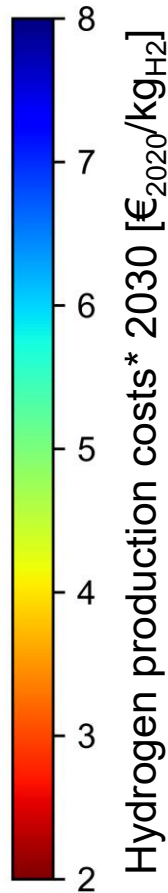
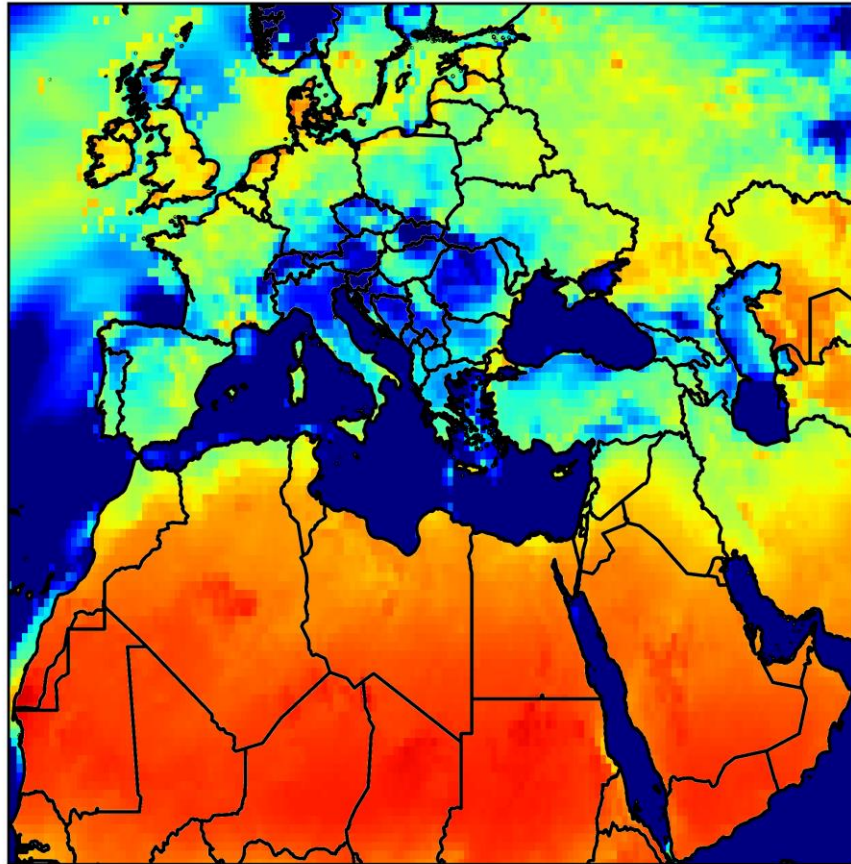
1. Background



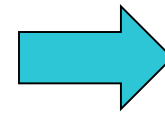
Hydrogen Demand Projections



1. Aviation and maritime include direct use of hydrogen and hydrogen-derived syngases including kerosene, diesel, methanol, gasoline, and ammonia. The category also includes some hydrogen-derived syngases 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



- Hydrogen production 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

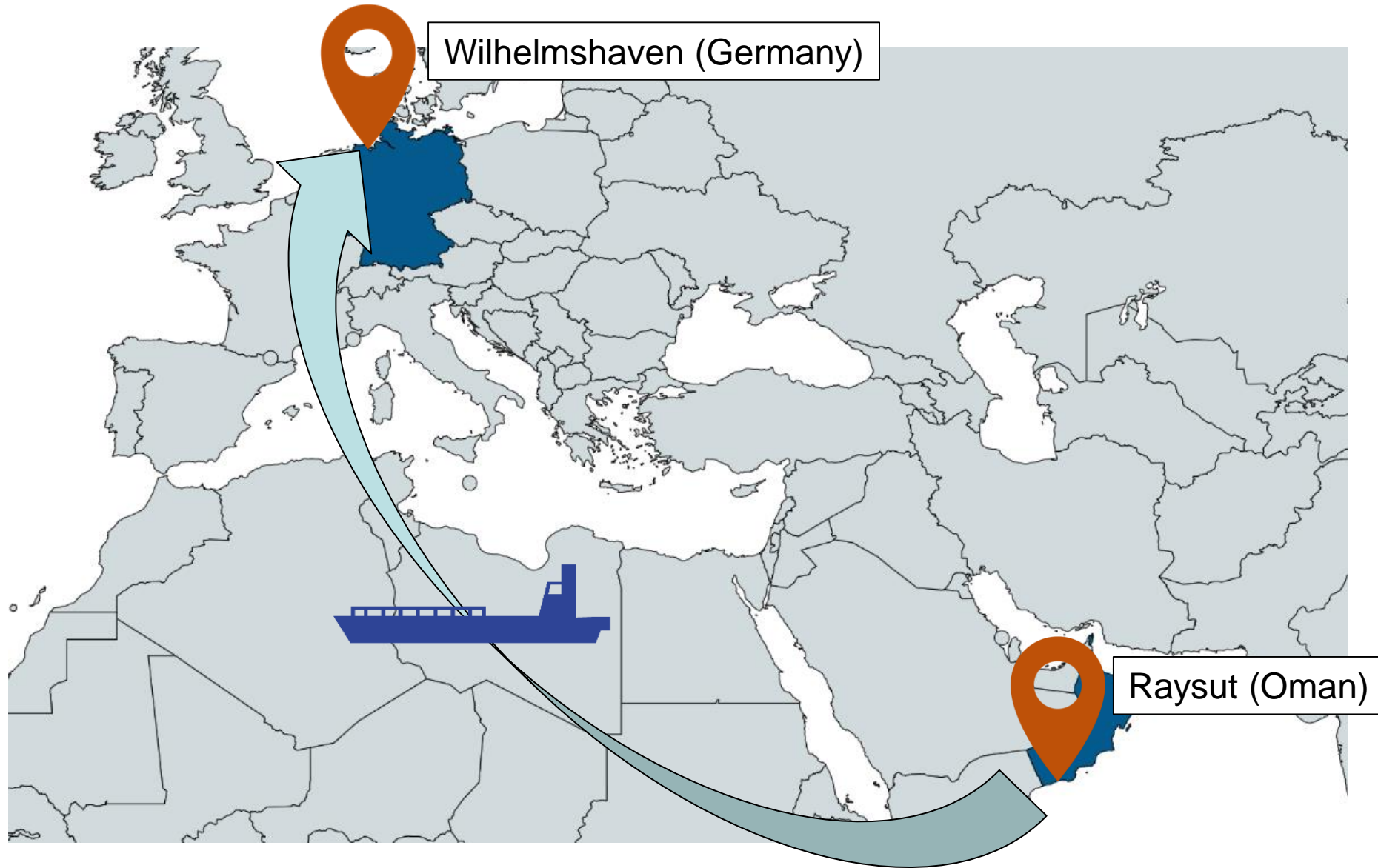


Conditioned hydrogen options and case study

2. Hydrogen Supply Chain

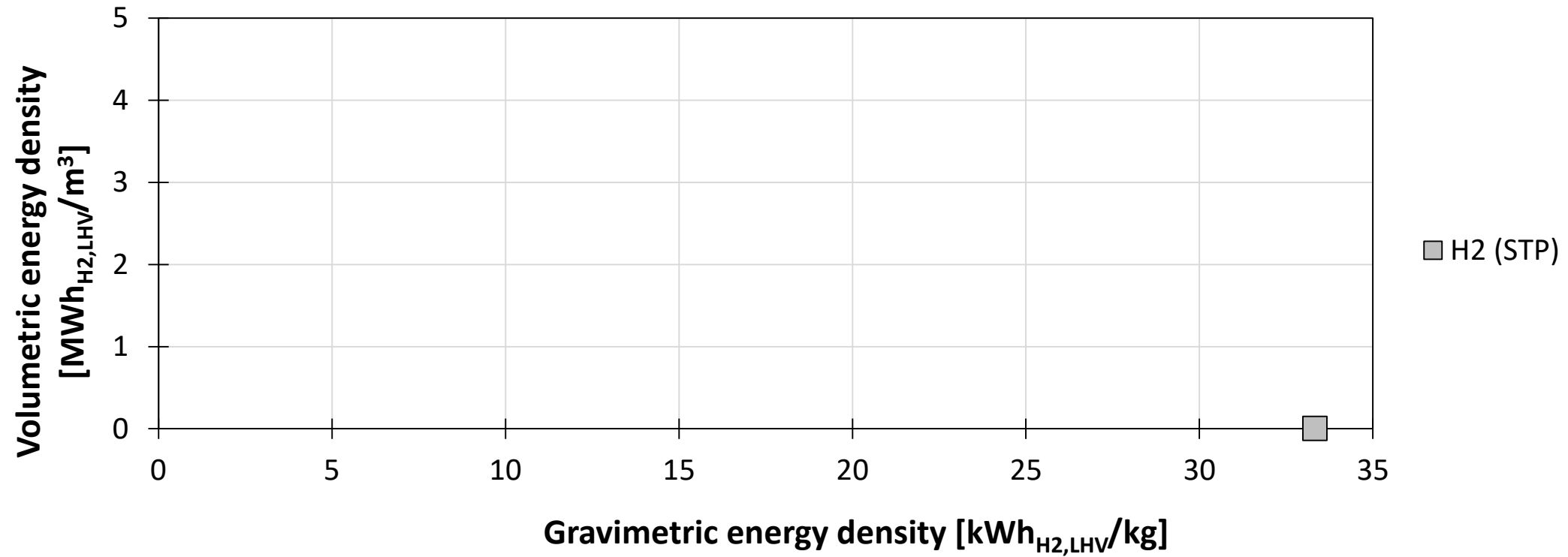


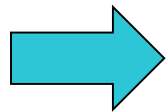
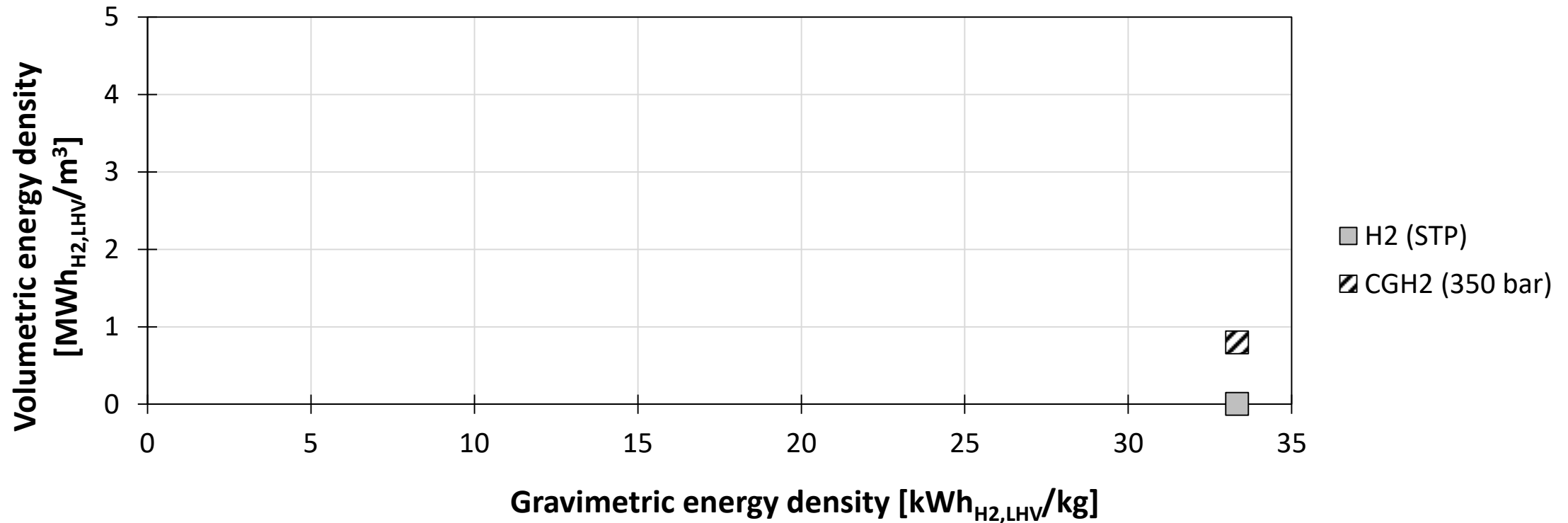
Hydrogen Delivery Route



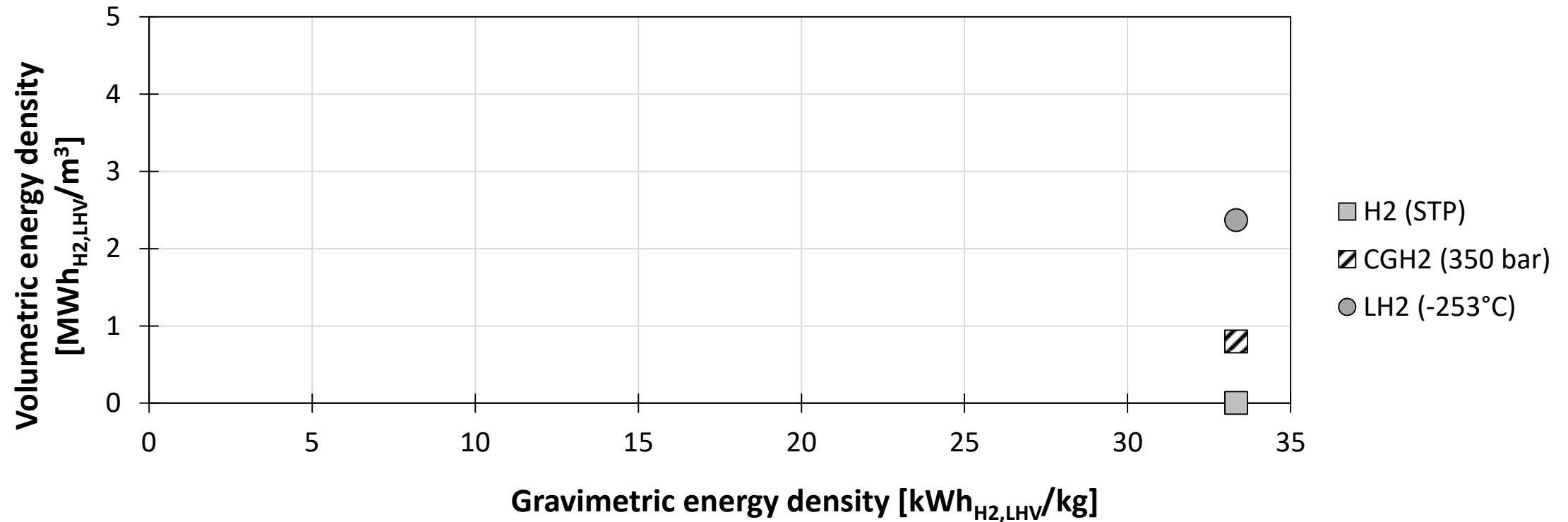


Conditioned Hydrogen – Gaseous Hydrogen



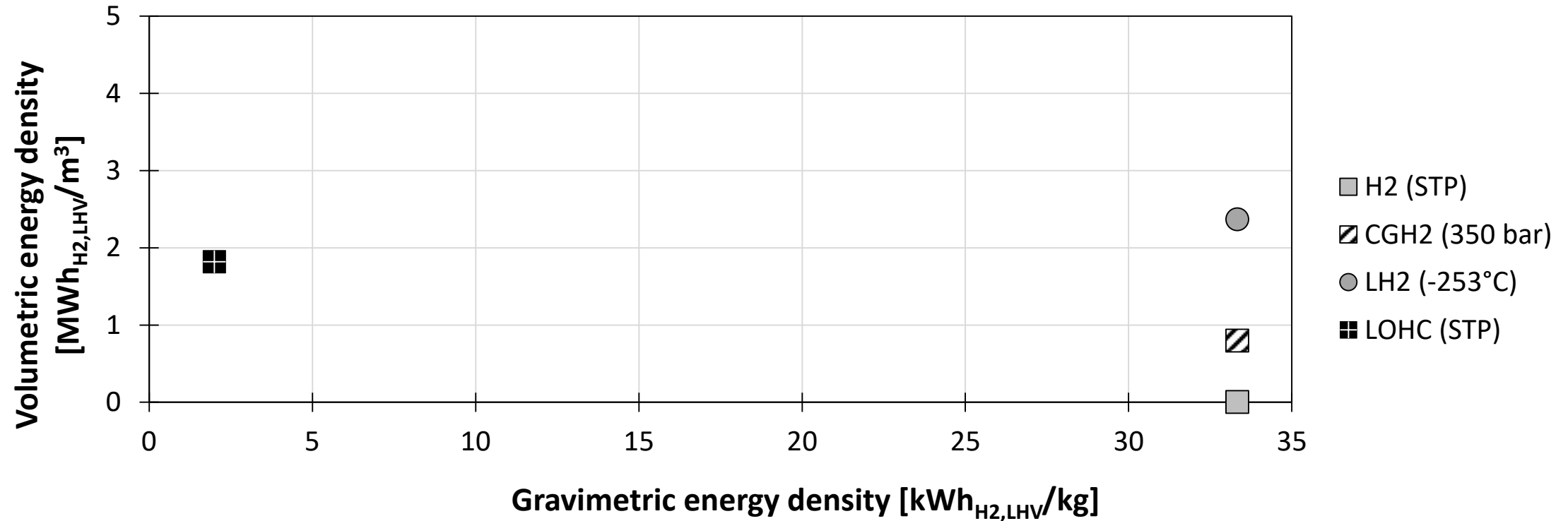


Energy density of compressed gaseous hydrogen is too low for longer distance shipping

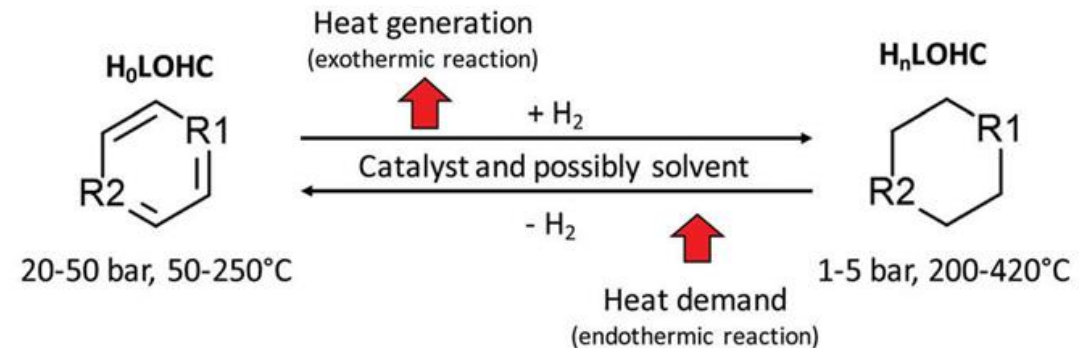


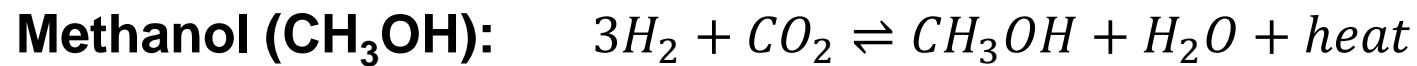
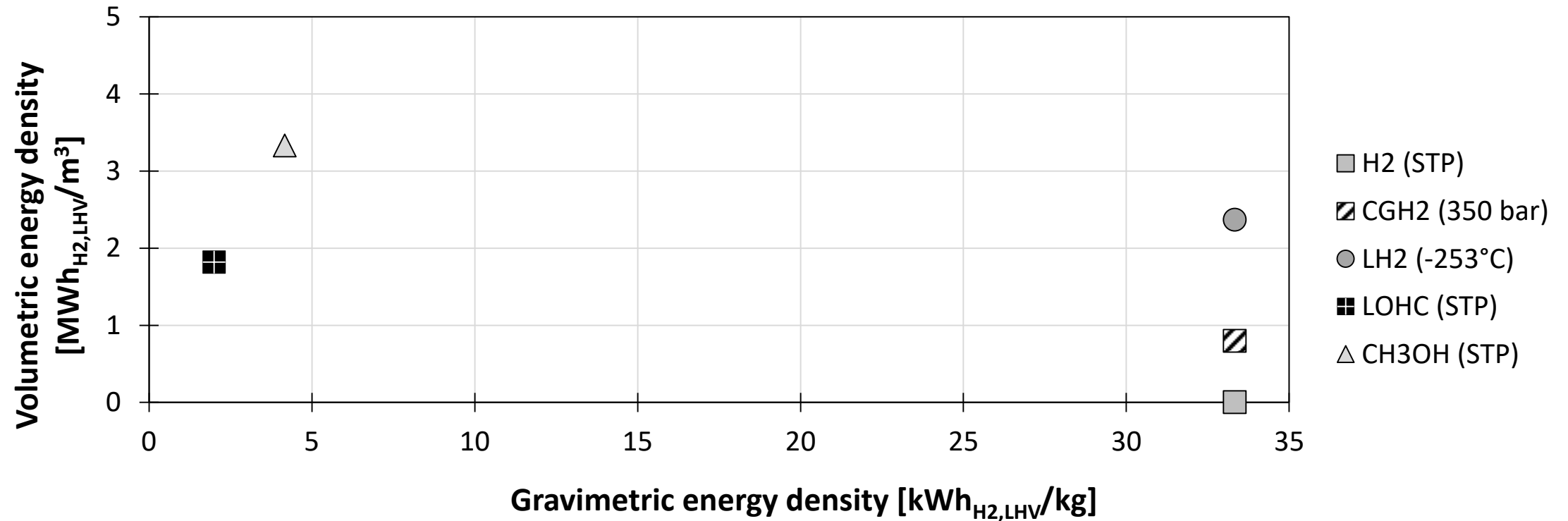
Liquid hydrogen (LH₂):





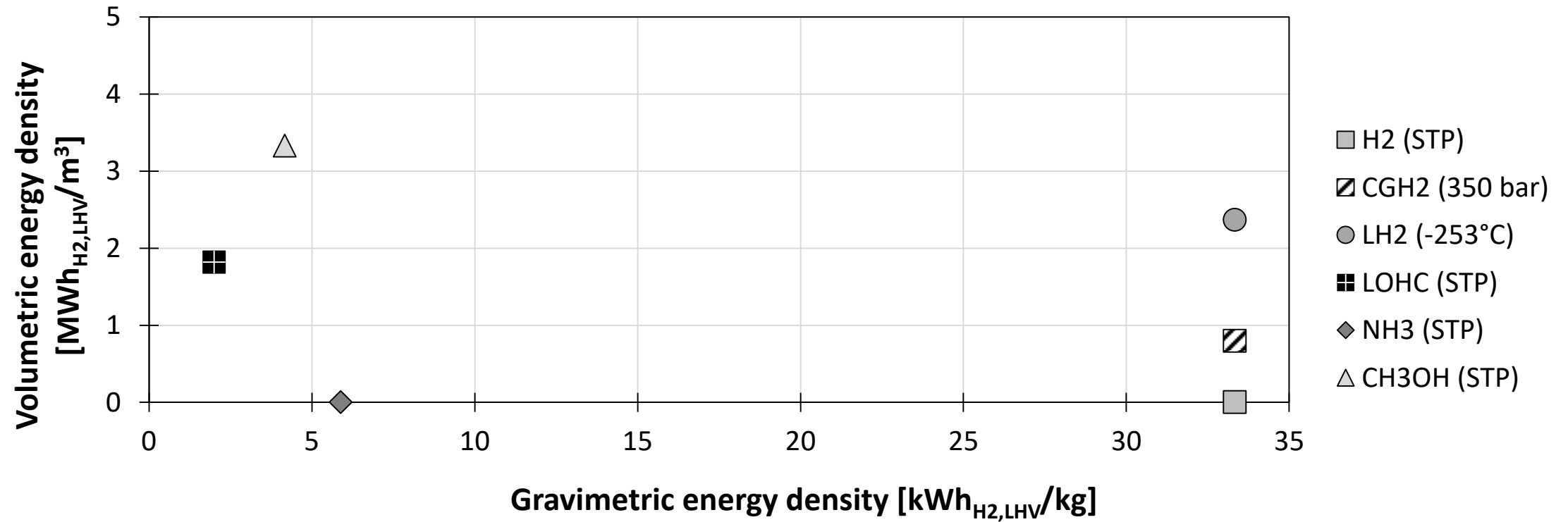
Liquid Organic Hydrogen Carriers (LOHC):

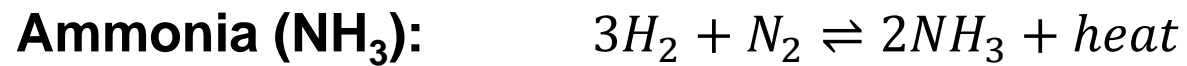
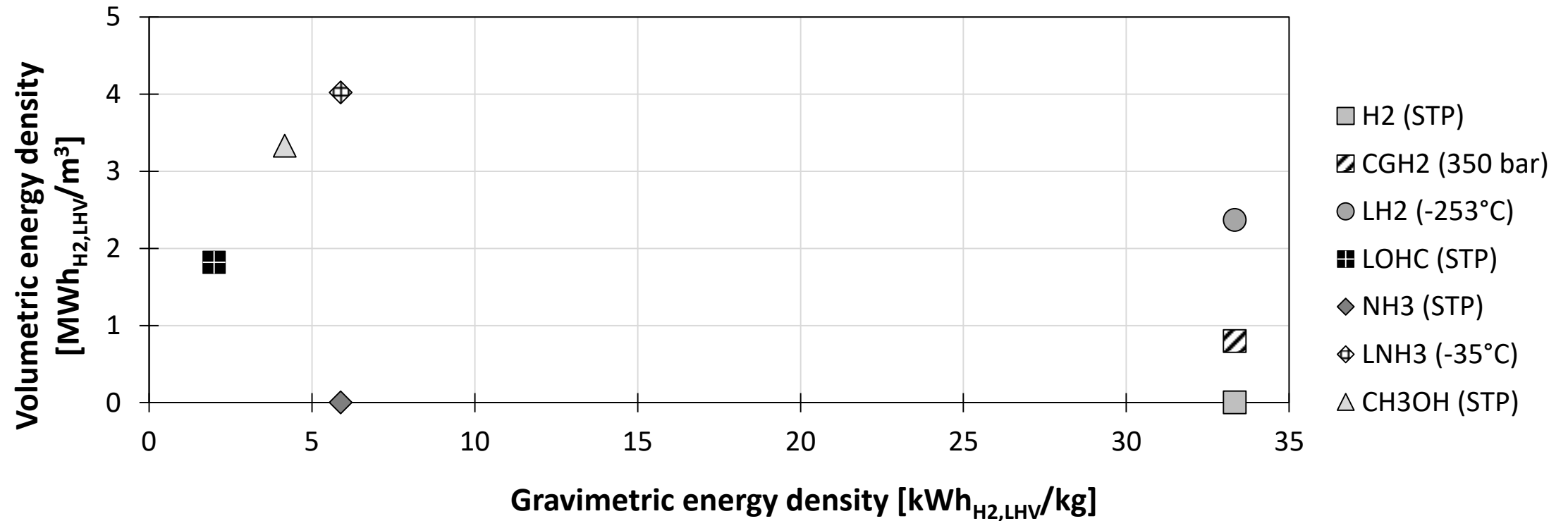


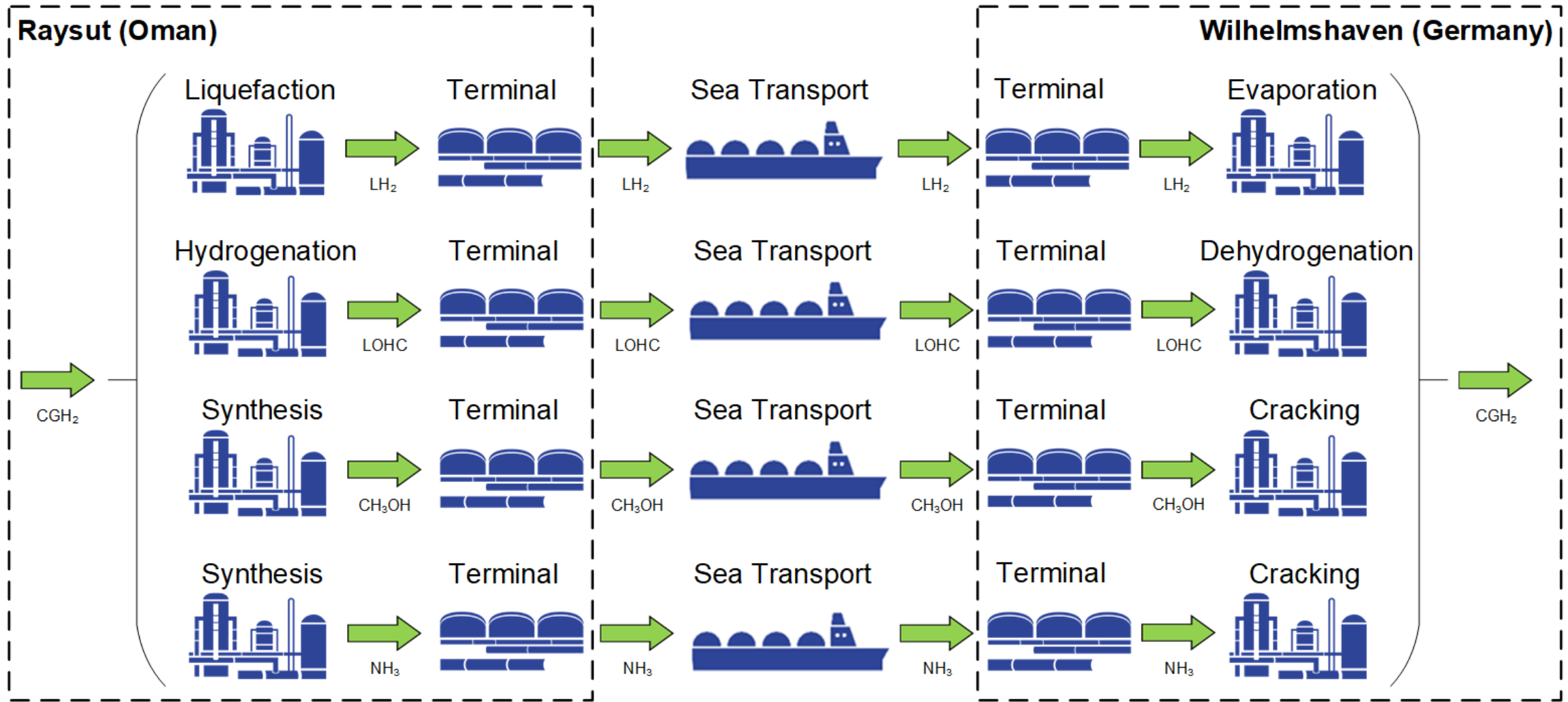




Conditioned Hydrogen – Ammonia







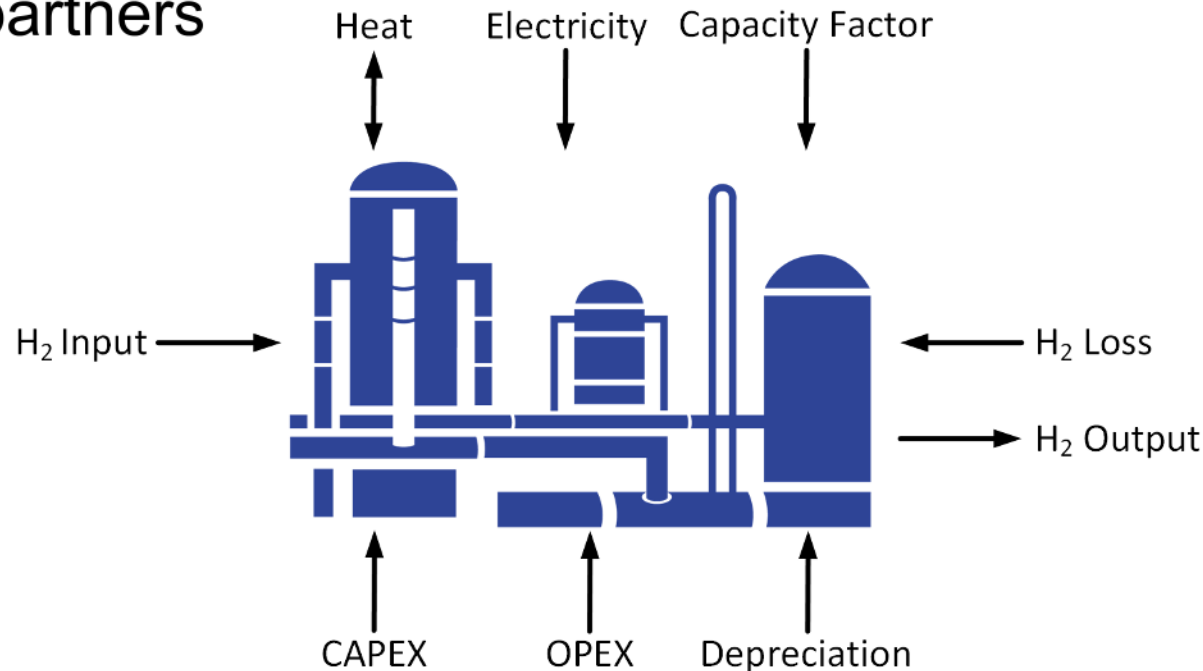


Approach and techno-economic parameters

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





	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)
H₂ 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

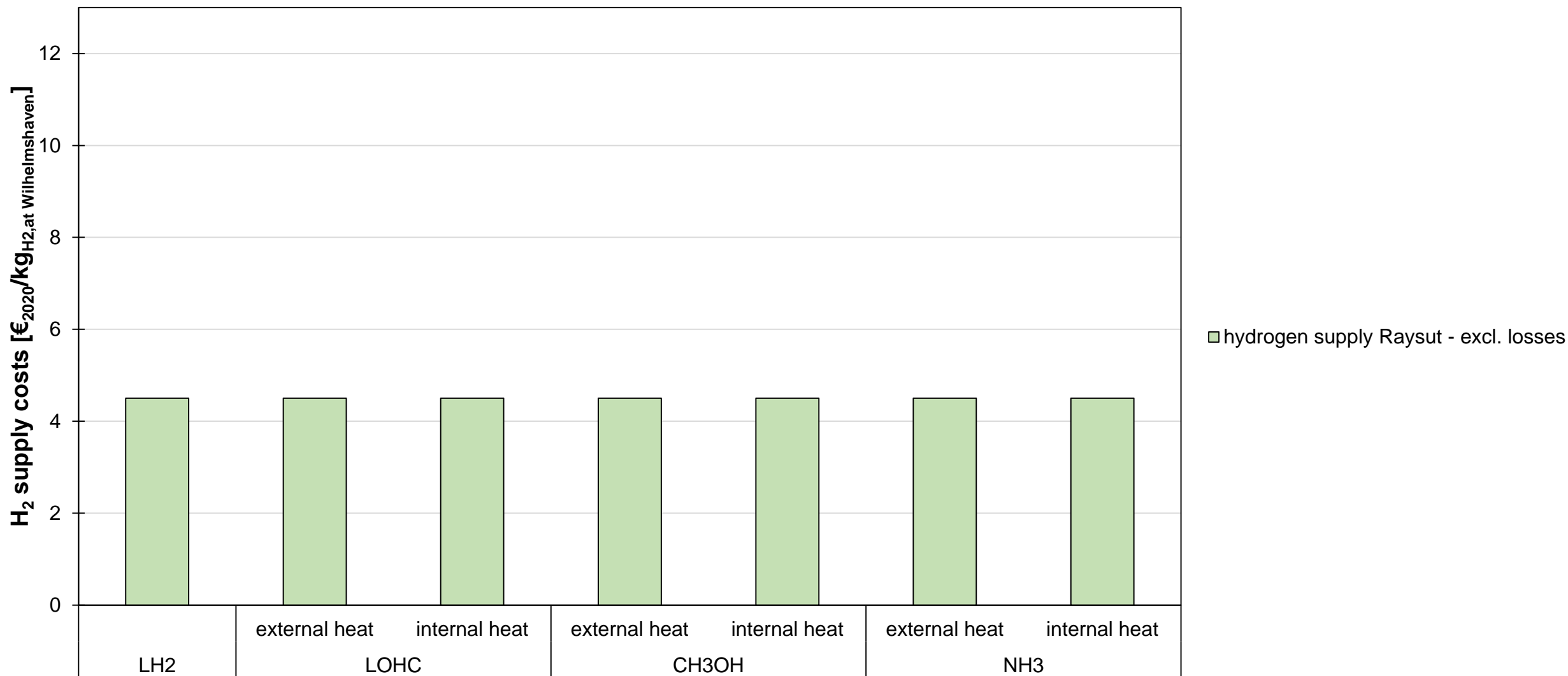


Hydrogen supply costs and efficiencies

4. Results



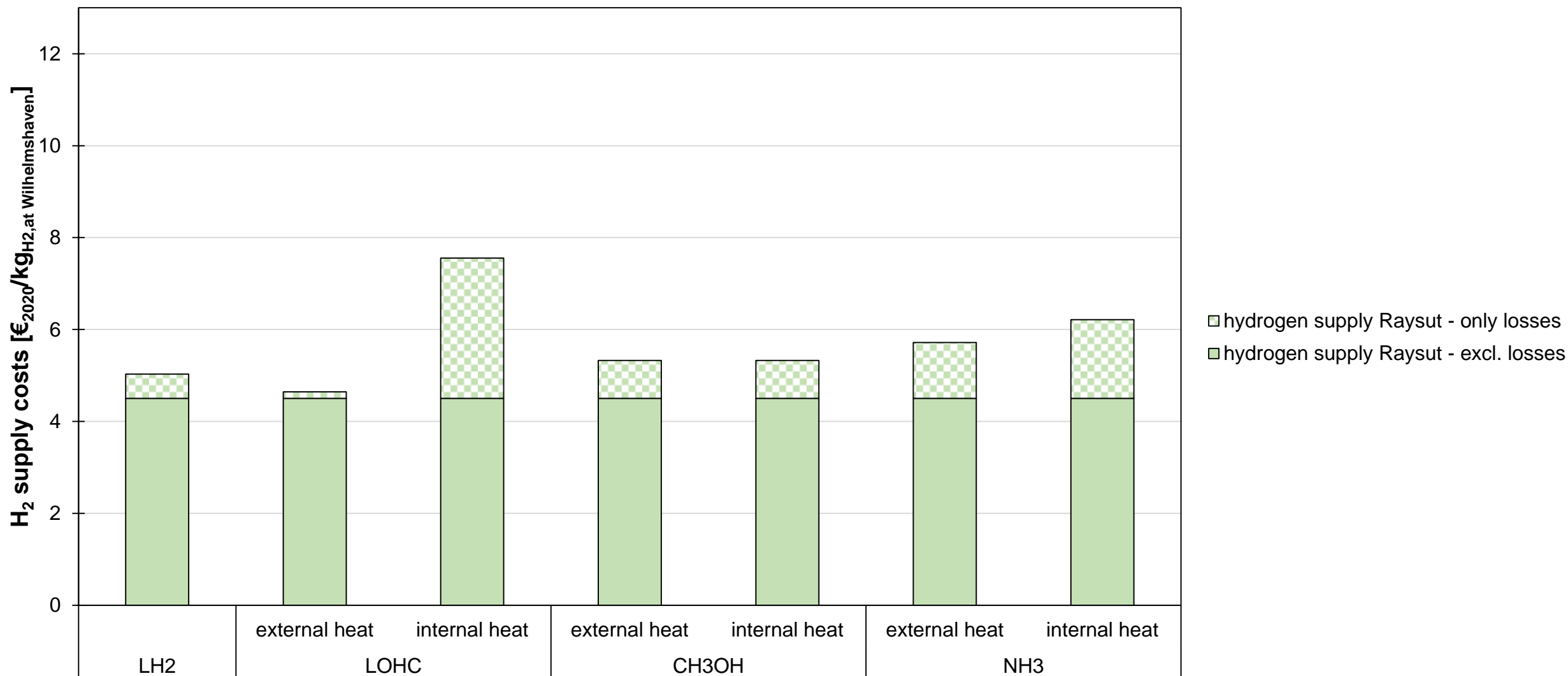
Hydrogen Supply Costs



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



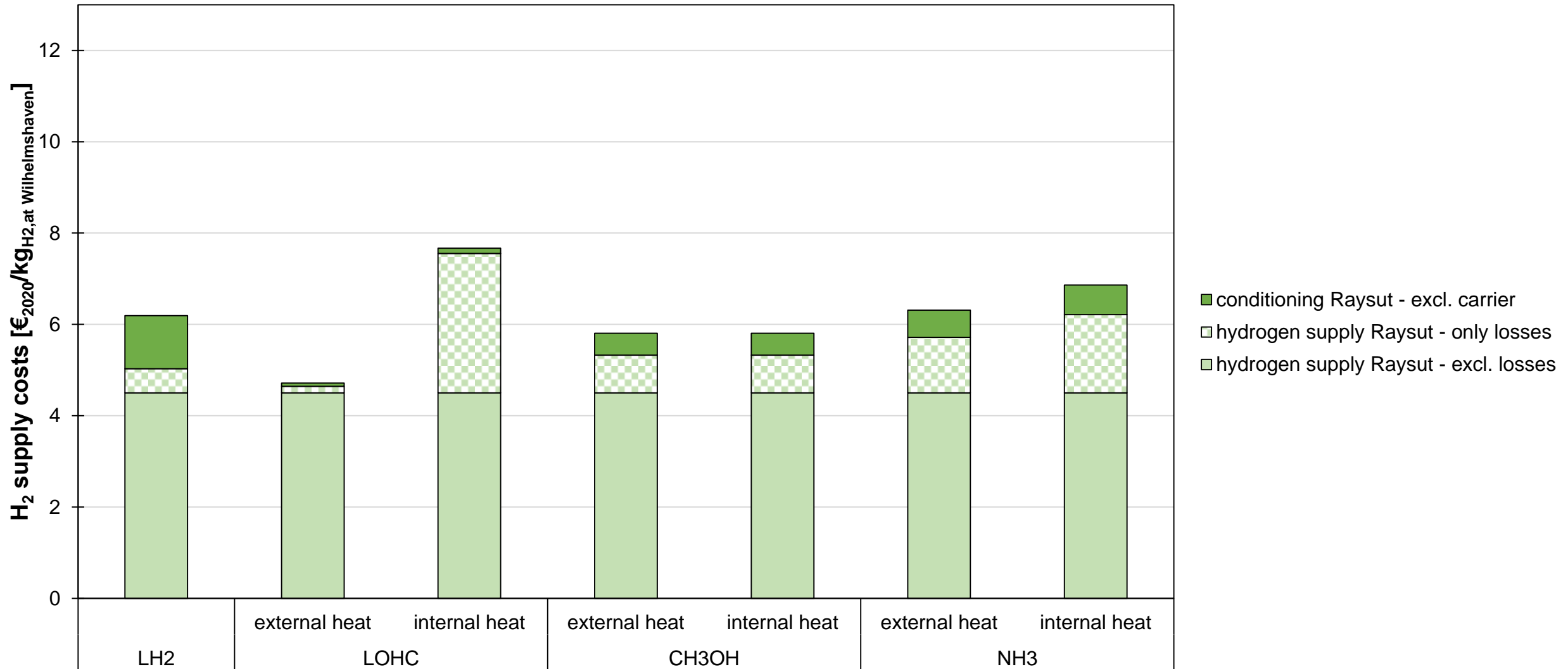
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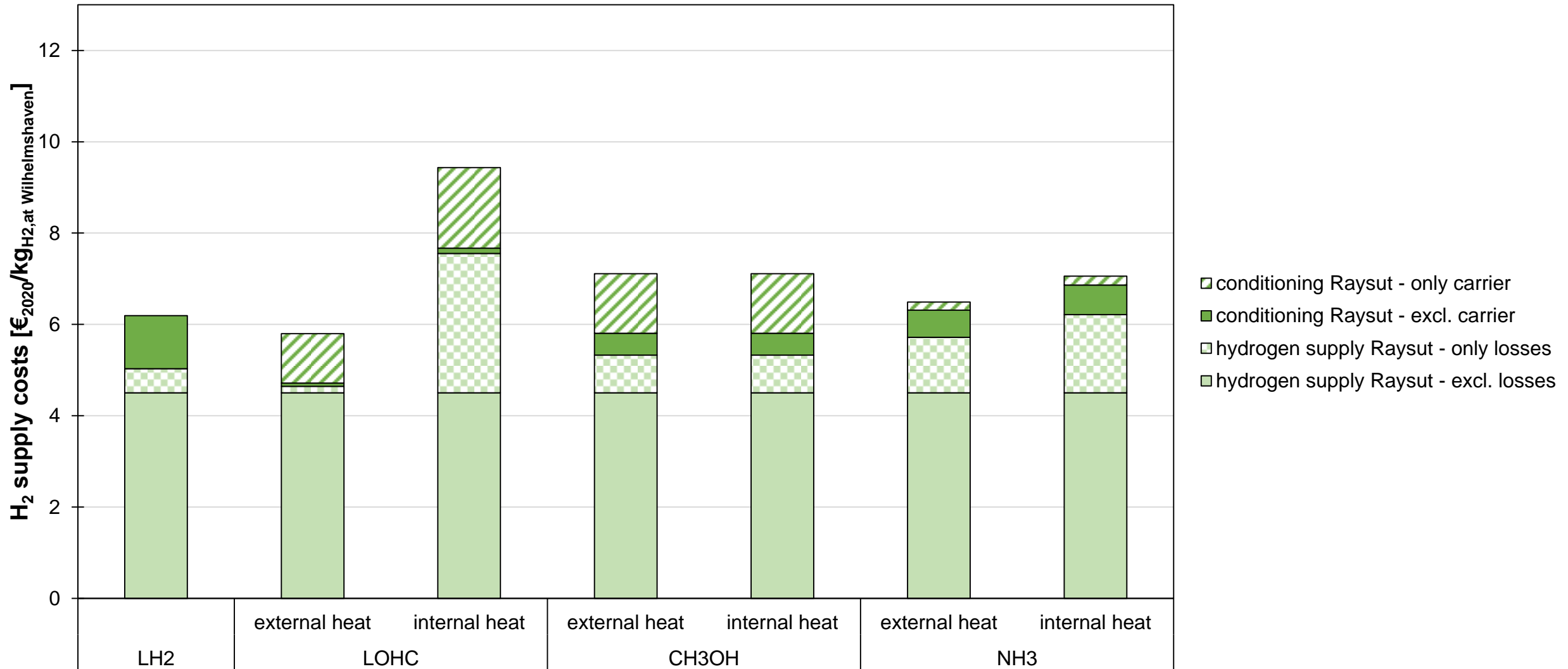
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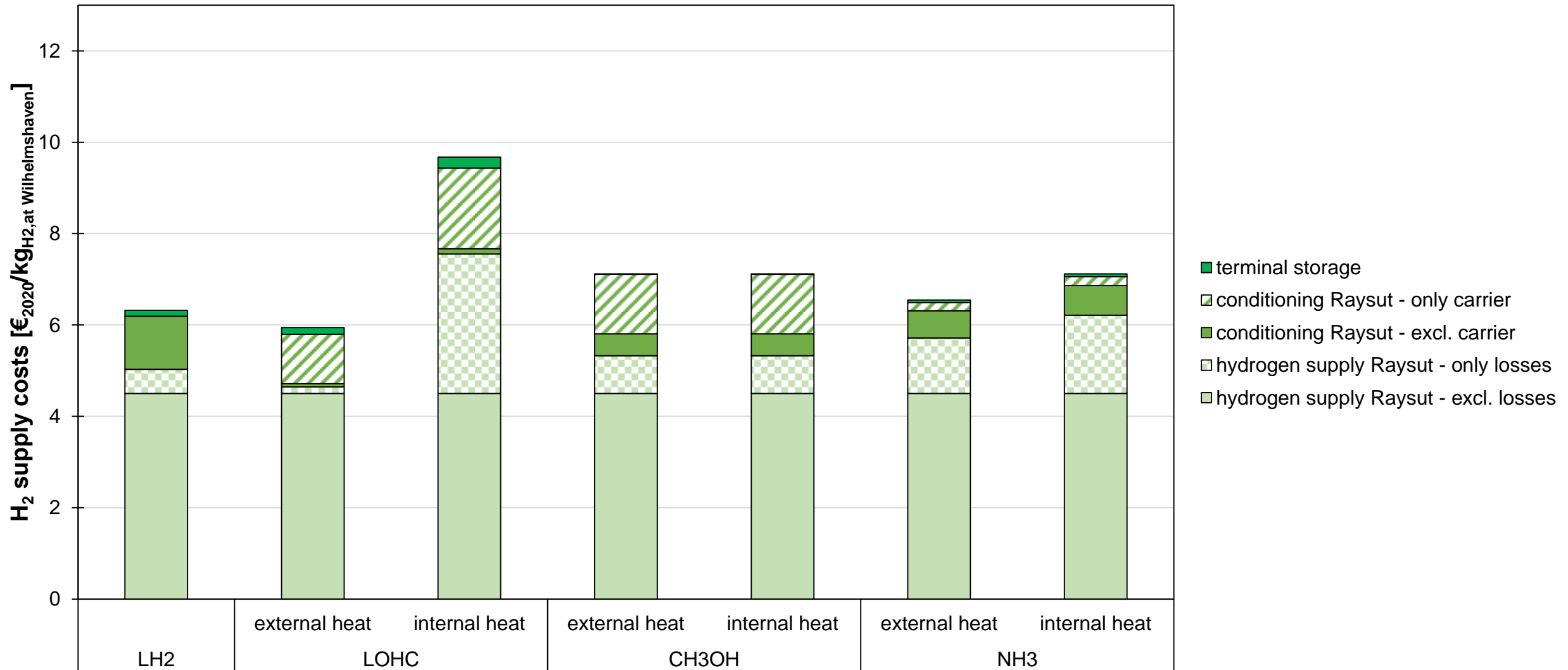
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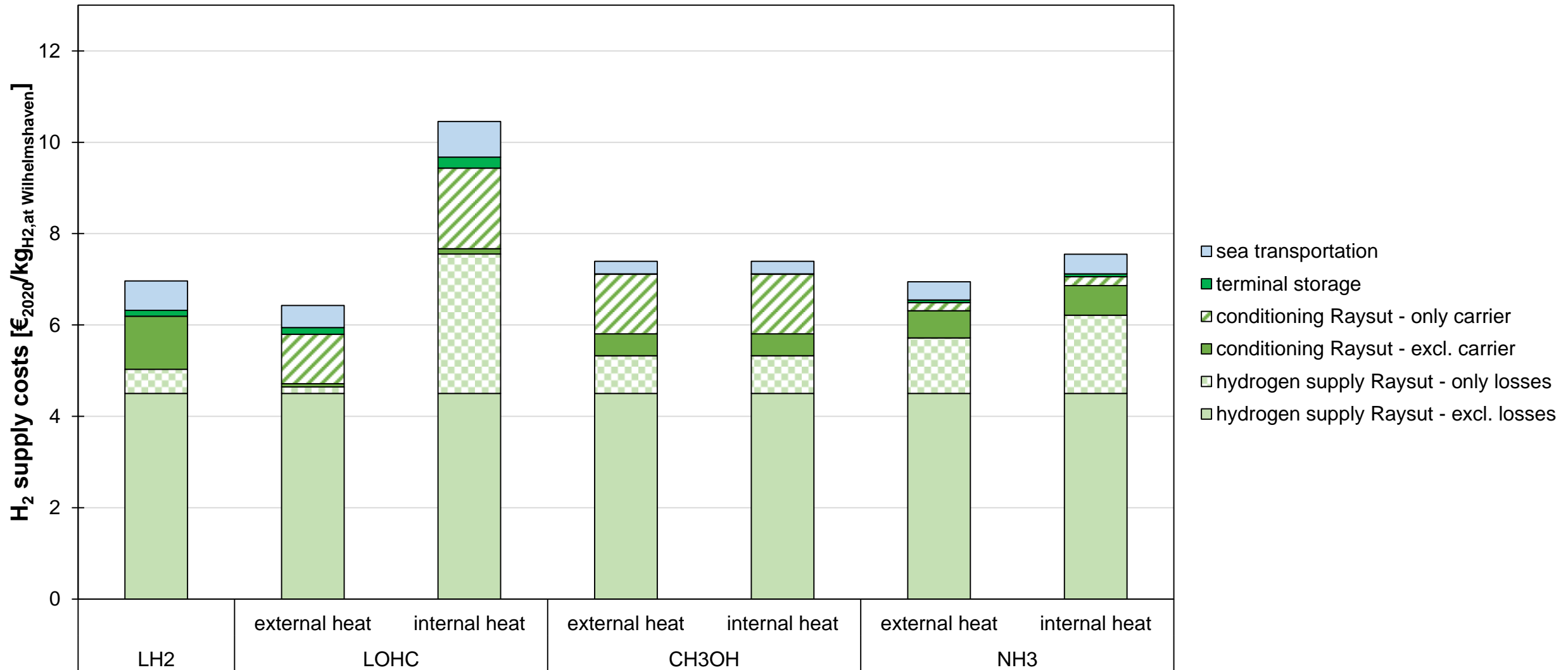
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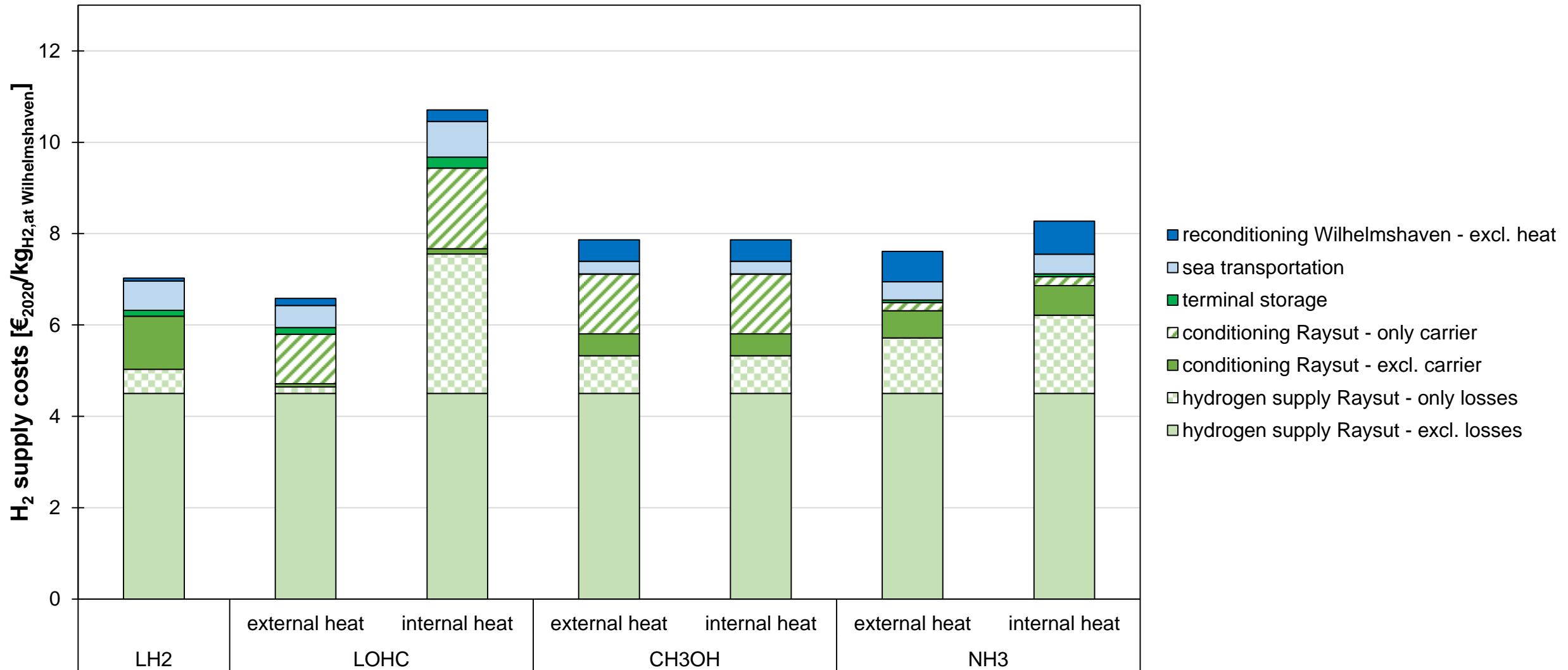
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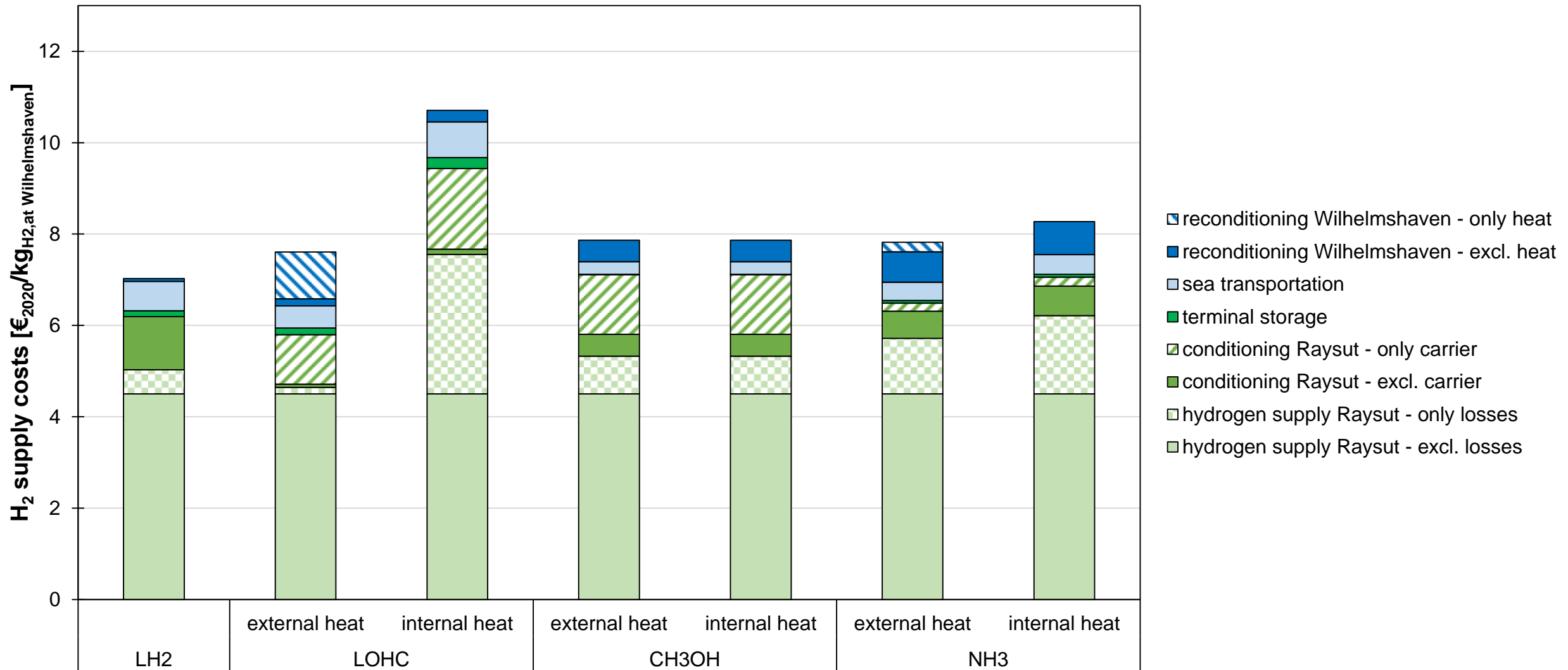
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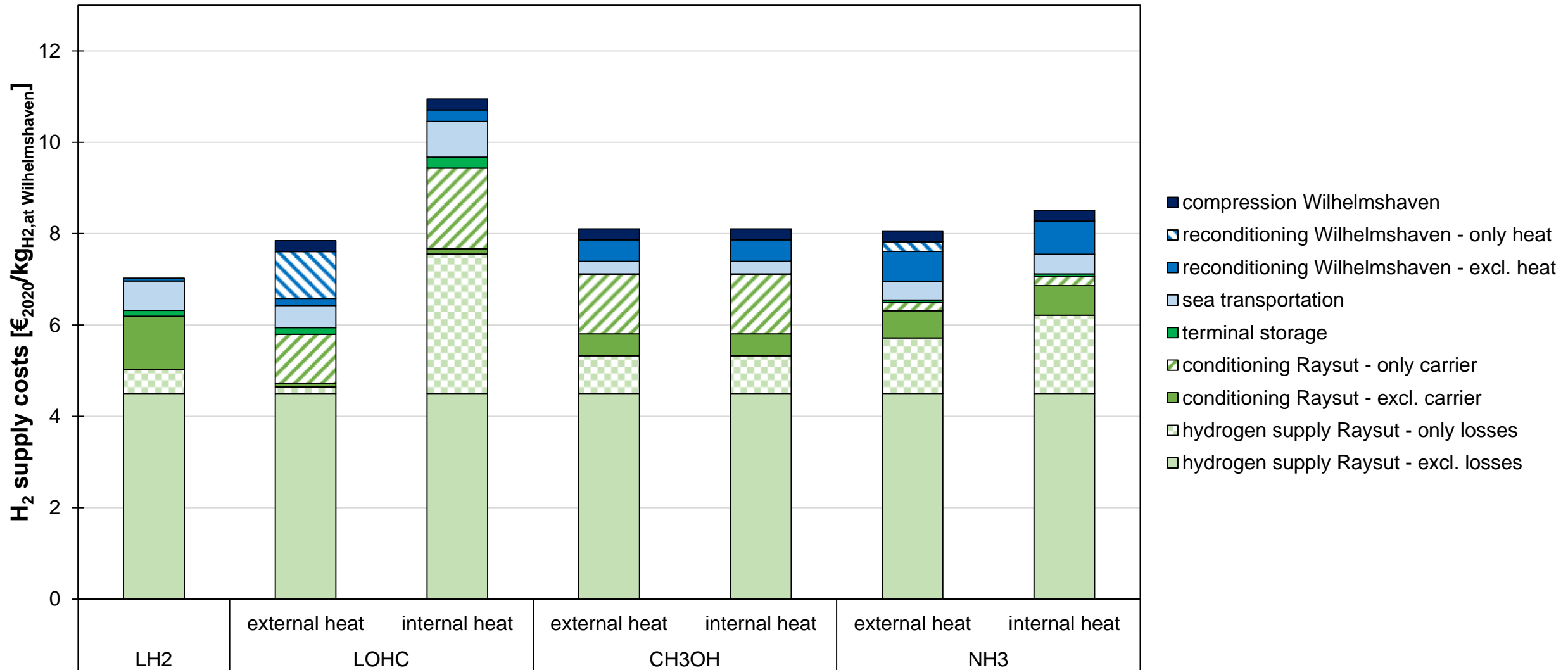
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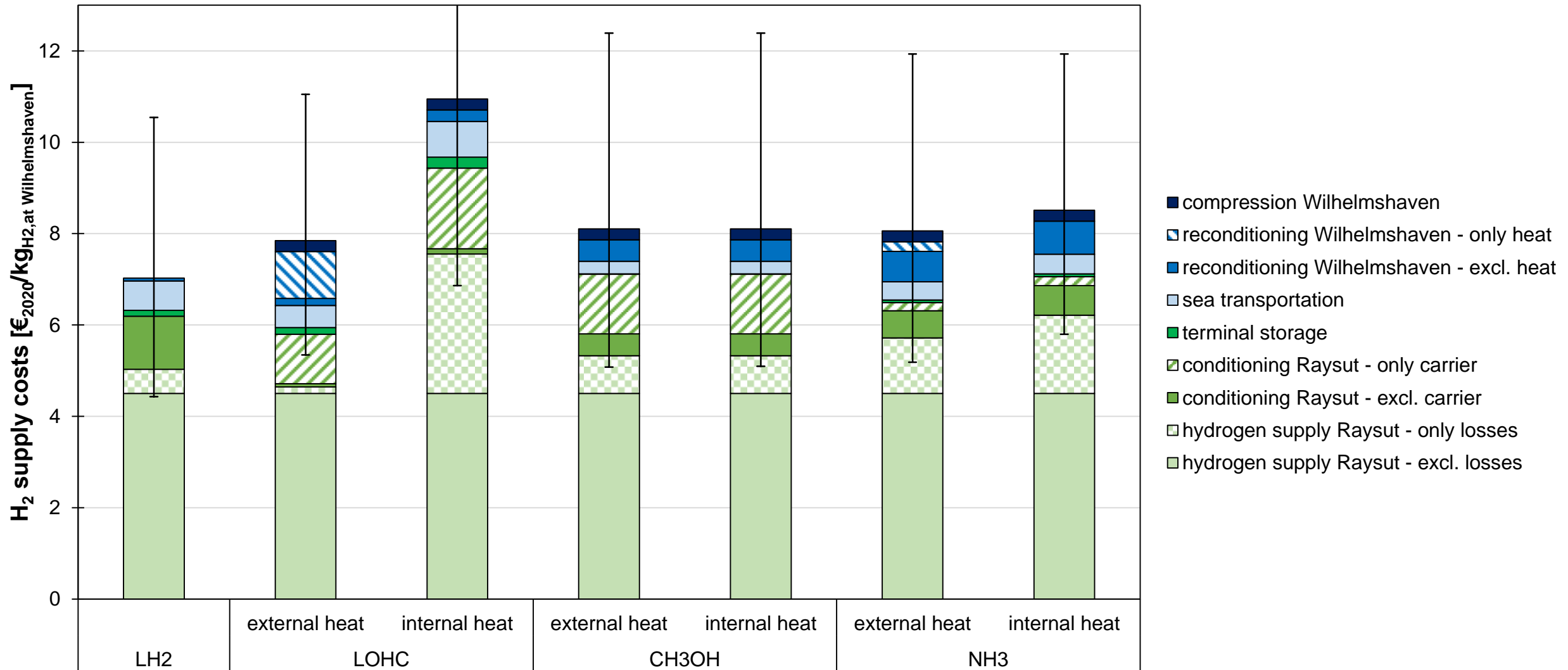
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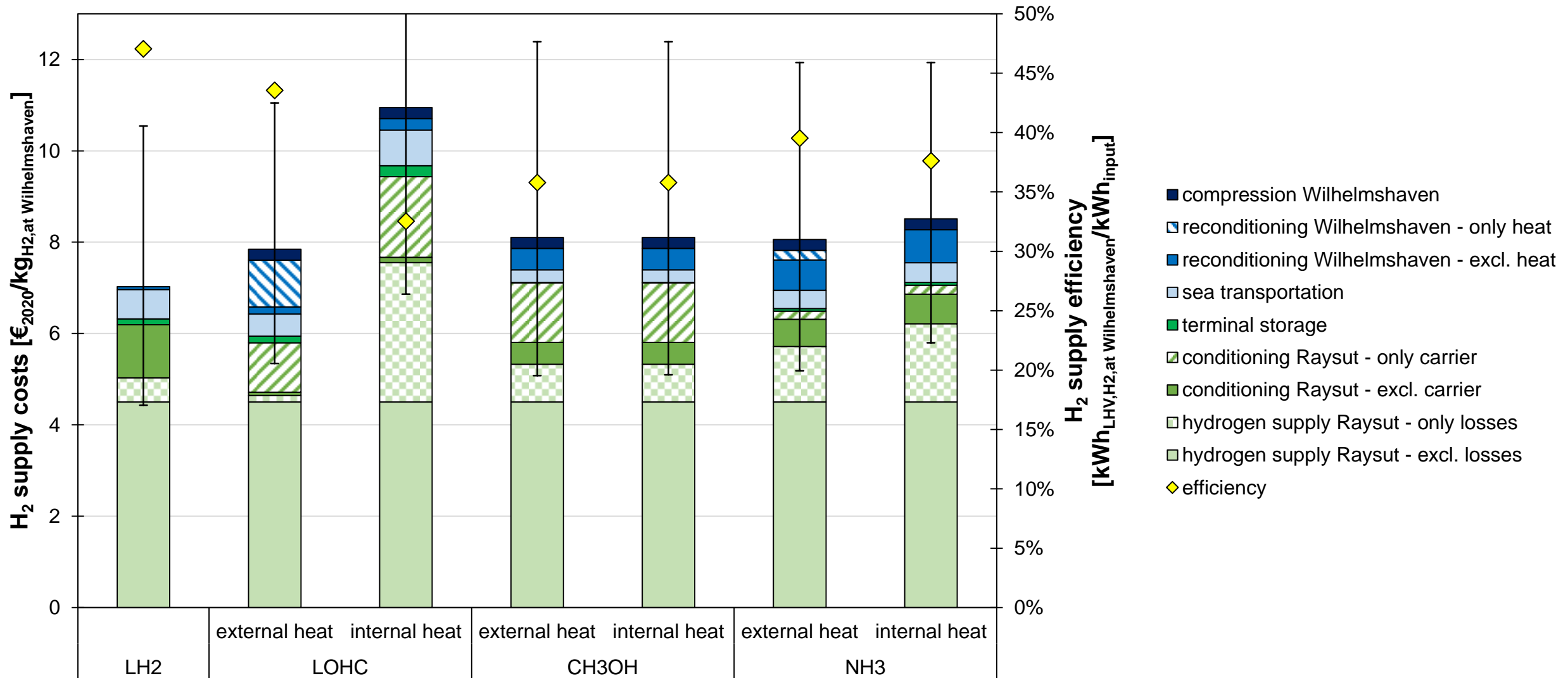
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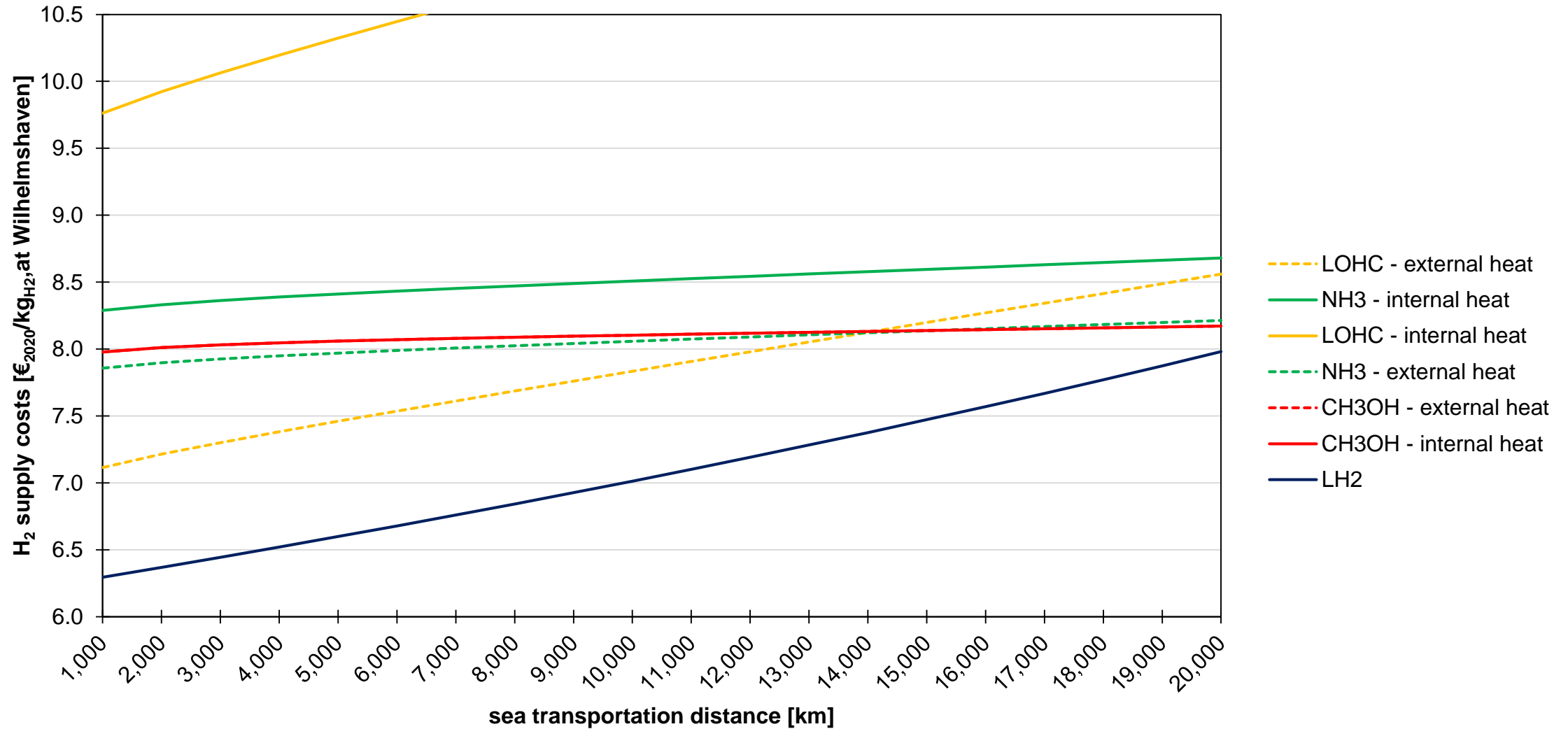
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Hydrogen Supply Costs over Distance





Which conditioned hydrogen option is the most promising?

5. Final Assessment and Key Conclusions



- Costs $\approx 7.0 \text{ €}_{2020}/\text{kg}_{\text{H}_2}$ (bandwidth: 4.4 to 10.5 $\text{€}_{2020}/\text{kg}_{\text{H}_2}$)
- Efficiency $\approx 47 \%$
- 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



- 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)



- 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 CO₂) 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 **CO₂ 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

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