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Green Hydrogen Supply Chains
– A Techno-economic Assessment –

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

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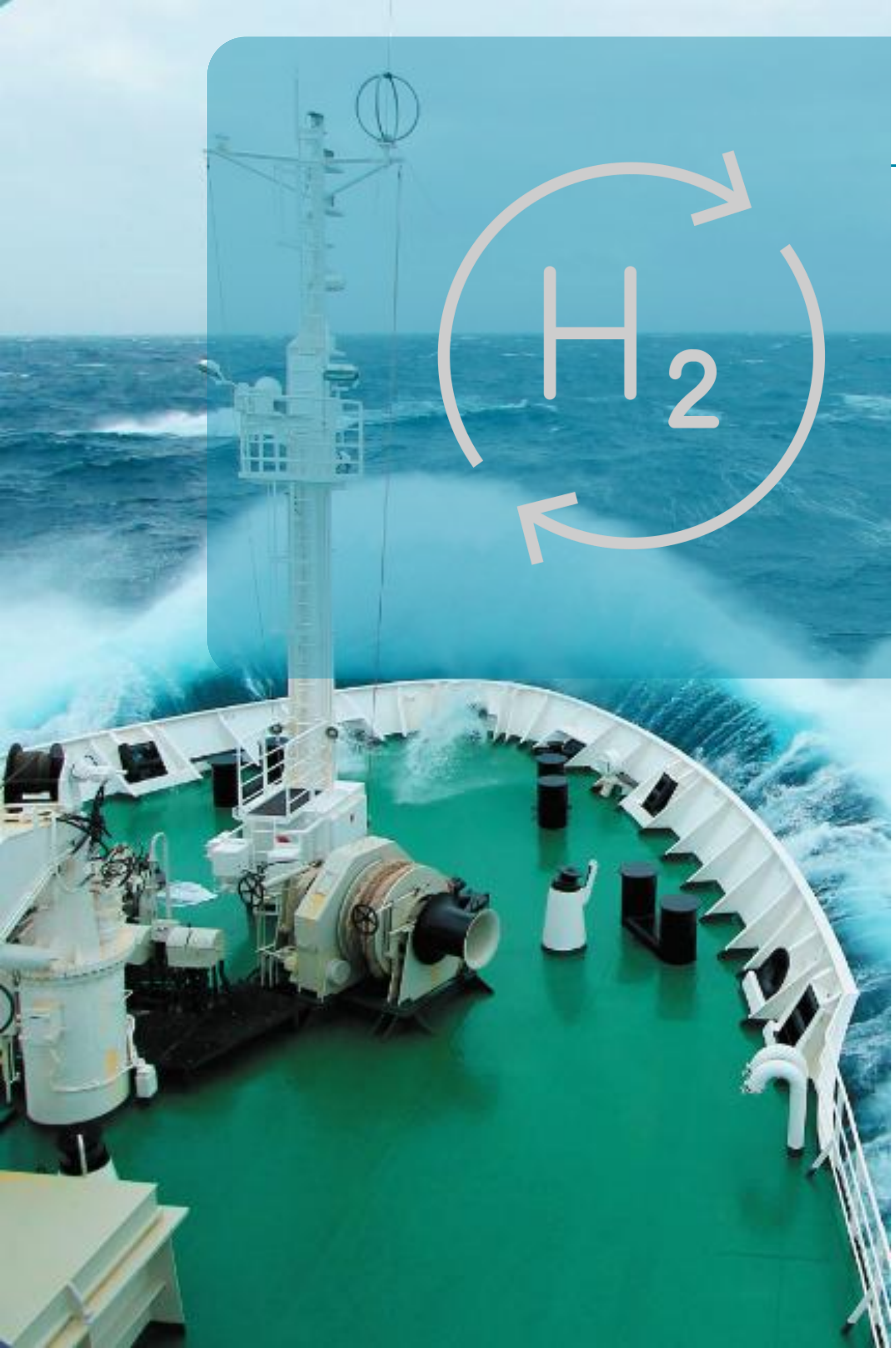
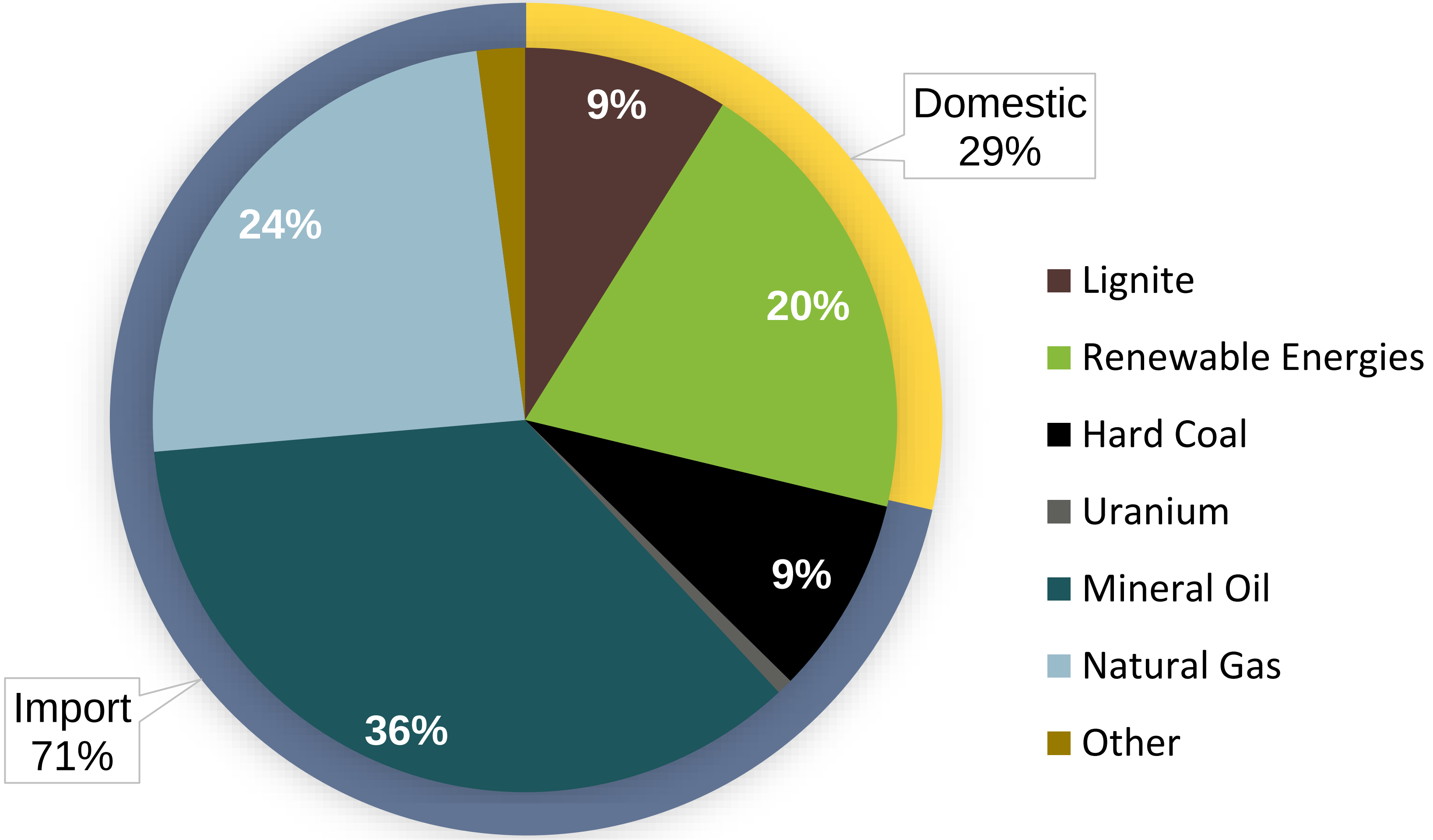


Agenda

- Green hydrogen supply in the overall context of energy transition
- Hydrogen supply chains
- Techno-economic assessment
- Conclusion

Total Primary Energy Consumption in 2023 – 2.997 TWh



Based on data from [AG Energiebilanzen e.V. 2023]

Germany’s Energy Supply – In a Climate-Neutral Future

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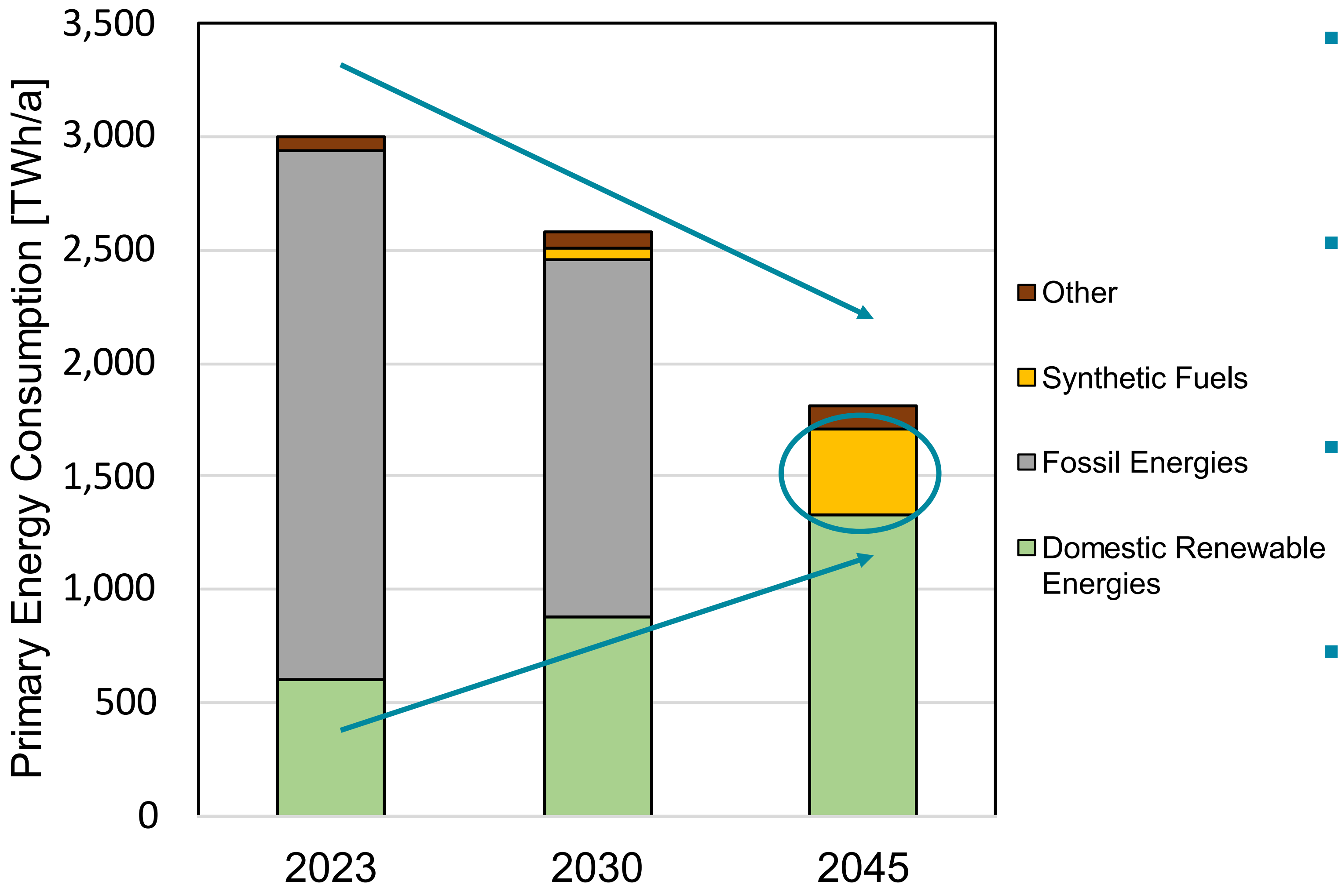
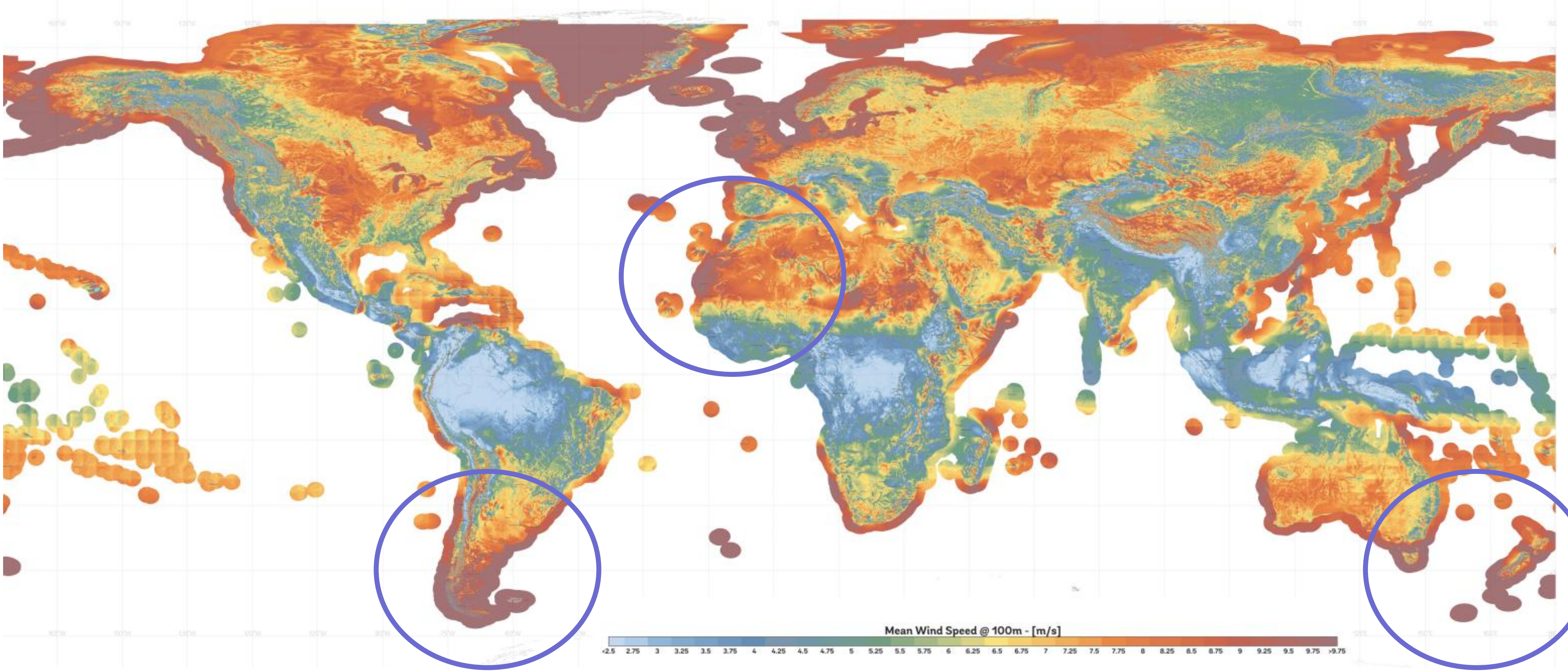


- Energy efficiency measures and electrification lead to a reduction in primary energy demand.
- Electricity from domestic wind and solar energy will become the central pillar of energy supply.
- PV and wind power capacities must quadruple (from 150 to ~600 GW) to supply the required renewable energy.
- An **additional** PV and wind capacity of ~300 GW would be needed to fully produce the required synthetic fuels domestically.

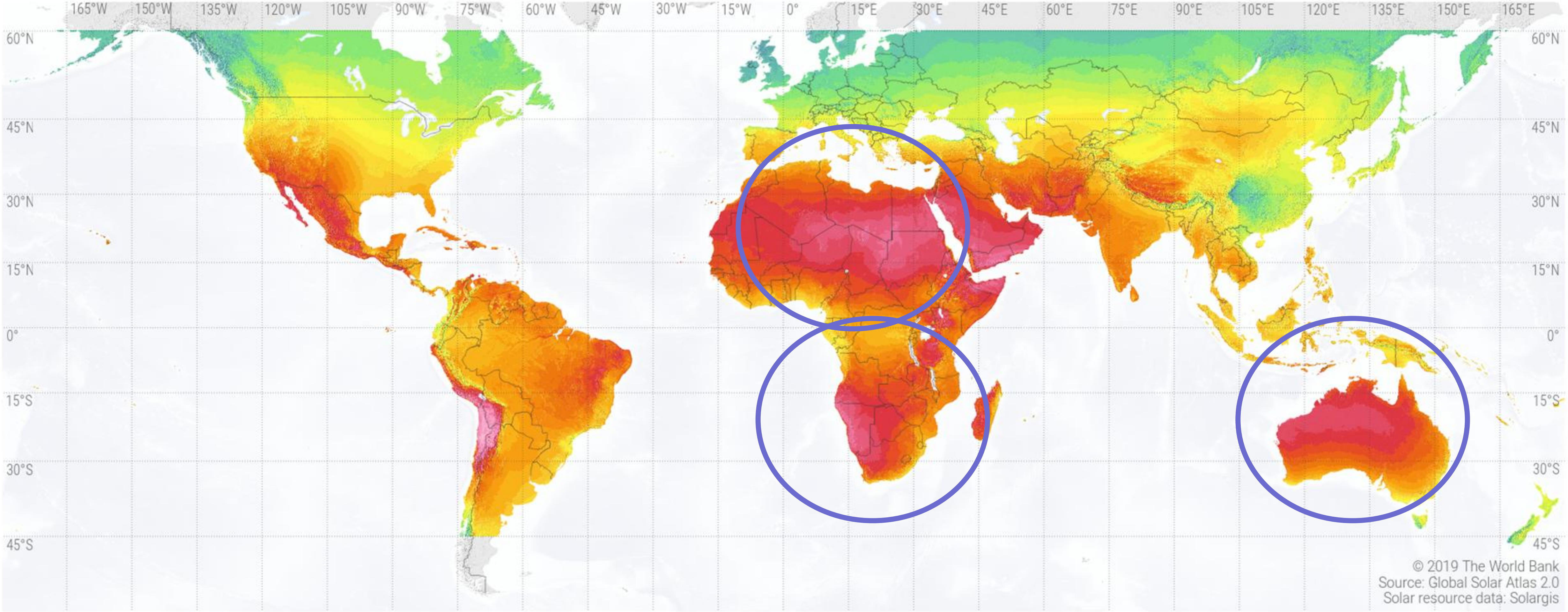
Defossilization of energy supply using only domestic renewables is theoretically possible, but hardly practicable. Importing renewable energy will likely be crucial for Germany's future energy system.

Based on Agora Energiewende 2021; dena 2021; BDI 2021; SCI4climate 2022

Global Availability of Renewable Energies – Wind



Global Availability of Renewable Energies – Solar Radiation



Long-term average of global horizontal irradiation (GHI)

Daily totals:	2.2	2.6	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.8	6.2	6.6	7.0	7.4
Yearly totals:	803	949	1095	1241	1387	1534	1680	1826	1972	2118	2264	2410	2556	2702

kWh/m^2

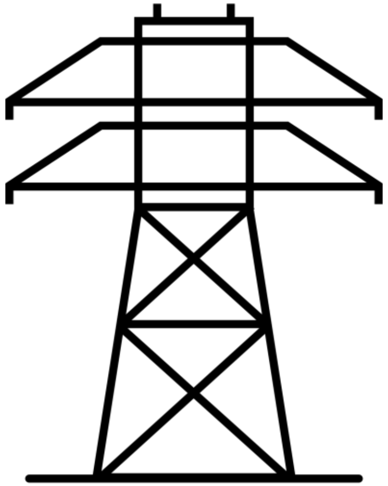
The World Bank Group (2019) / https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country

Options for (Renewable) Energy Import

„Green“ electricity

Benefits

- No / very low conversion losses
- All technology components available on a large scale



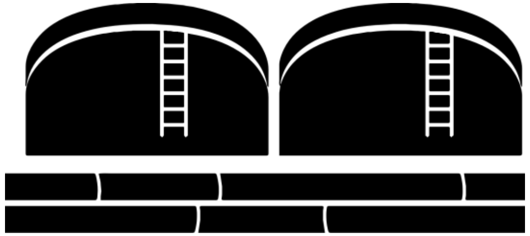
Limitations & Challenges

- Bound to inflexible infrastructure (power lines),
  → overseas transport not/barely possible
- Some sectors can’t be electrified (e.g., aviation, steel)
- Large-scale storage technology not yet available (except pumped storage power plants)

„Green“ molecules

Benefits

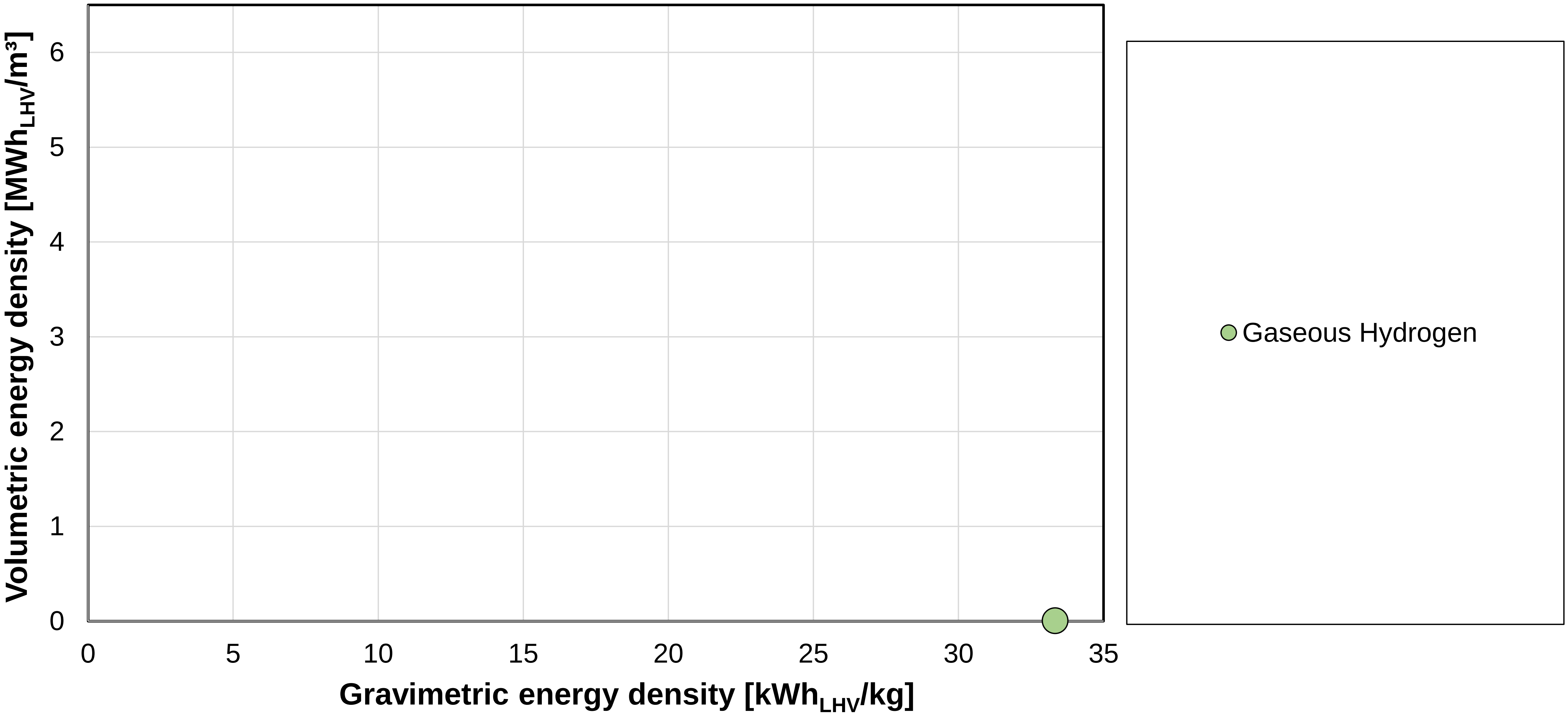
- Easy integration of large-scale energy storage
- Development of flexible, global markets possible
- Use of hydrogen and/or hydrogen derivatives is potentially in (nearly) all sectors possible



Limitations & Challenges

- Necessarily losses due to conversion from electrical energy into hydrogen and/or hydrogen derivatives
- Technological readiness and/or availability of some components currently not yet given

Hydrogen Conditioning Options



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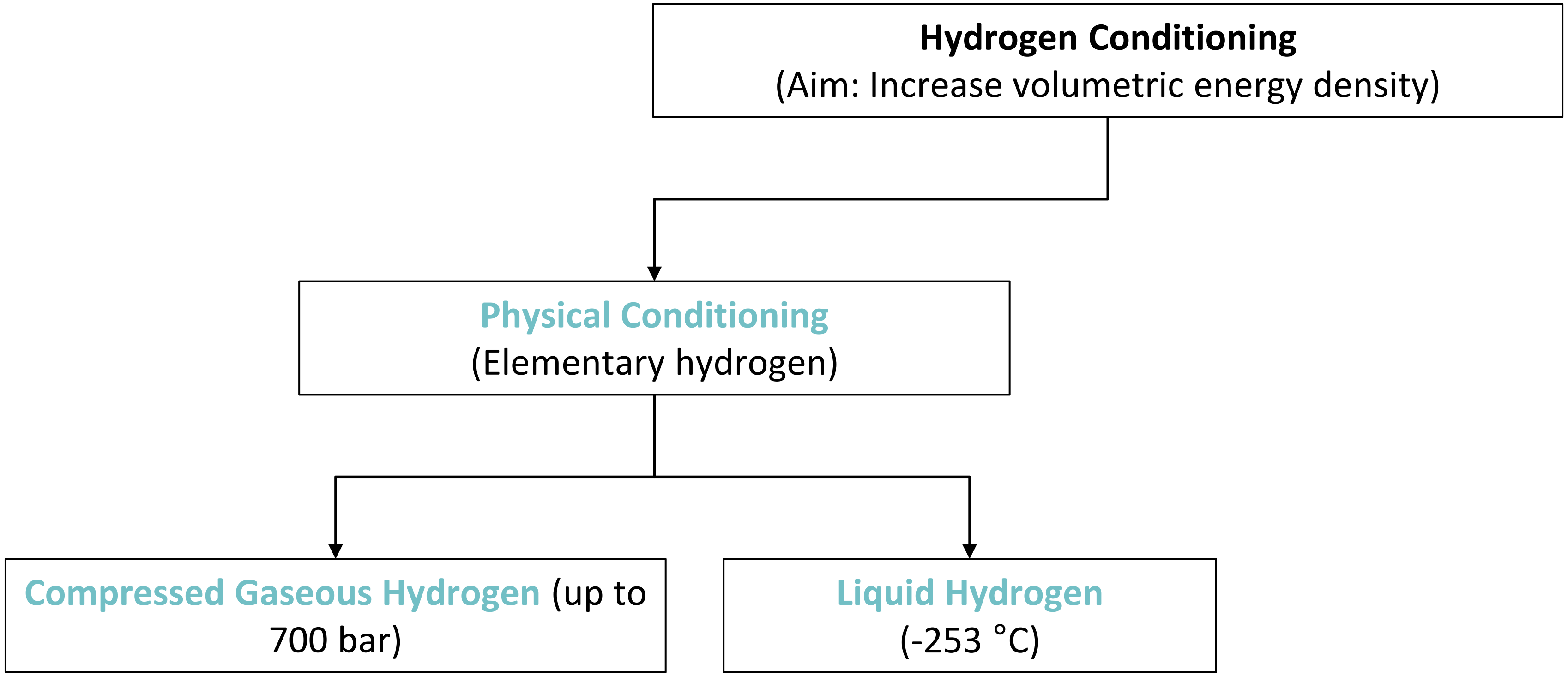

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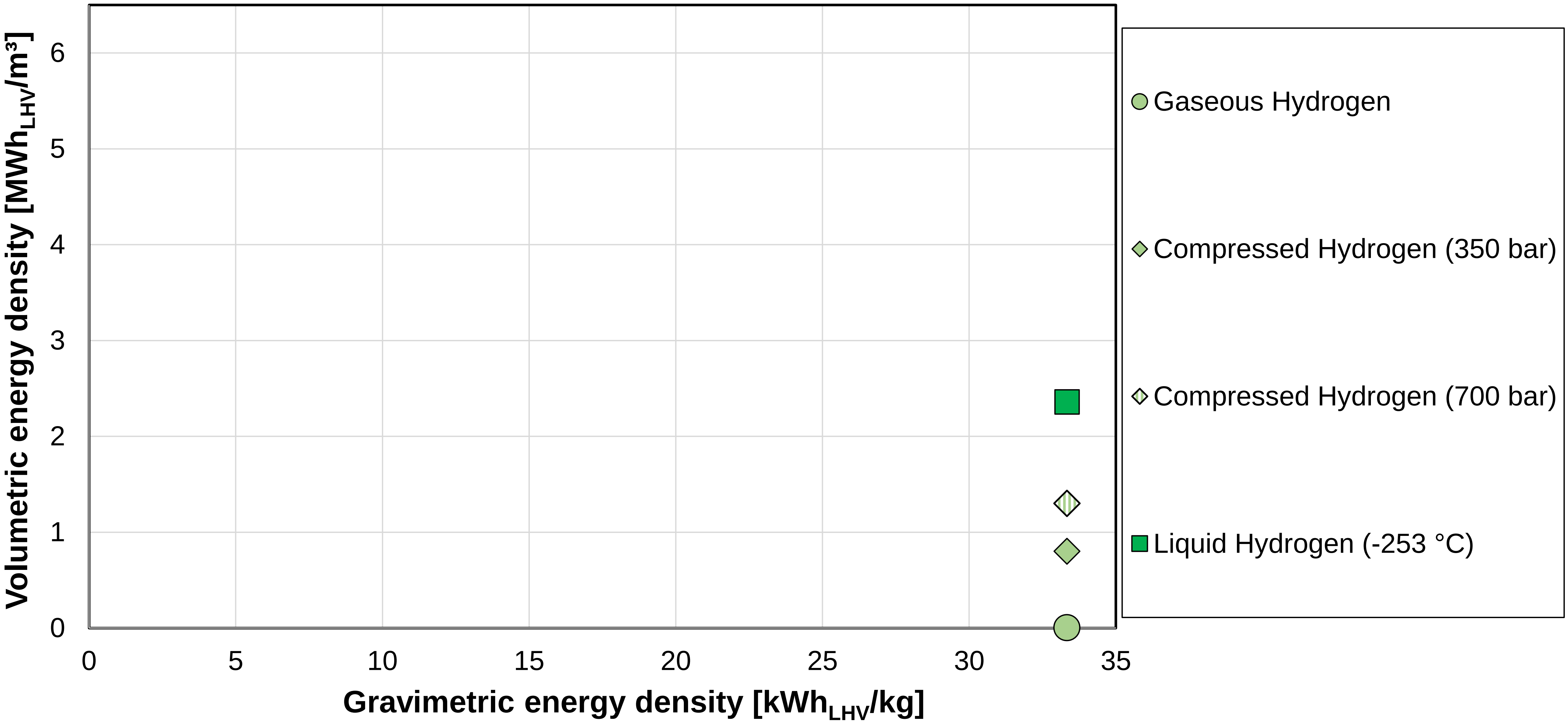

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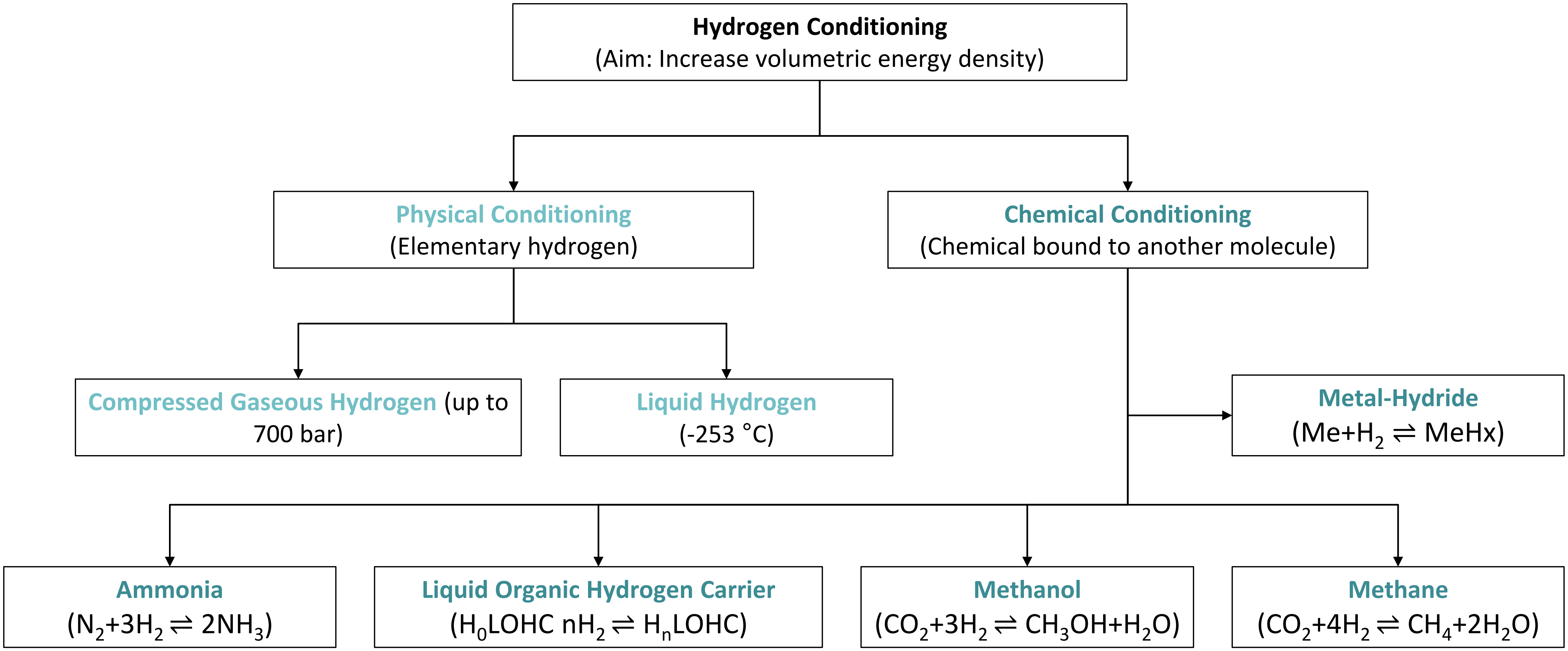

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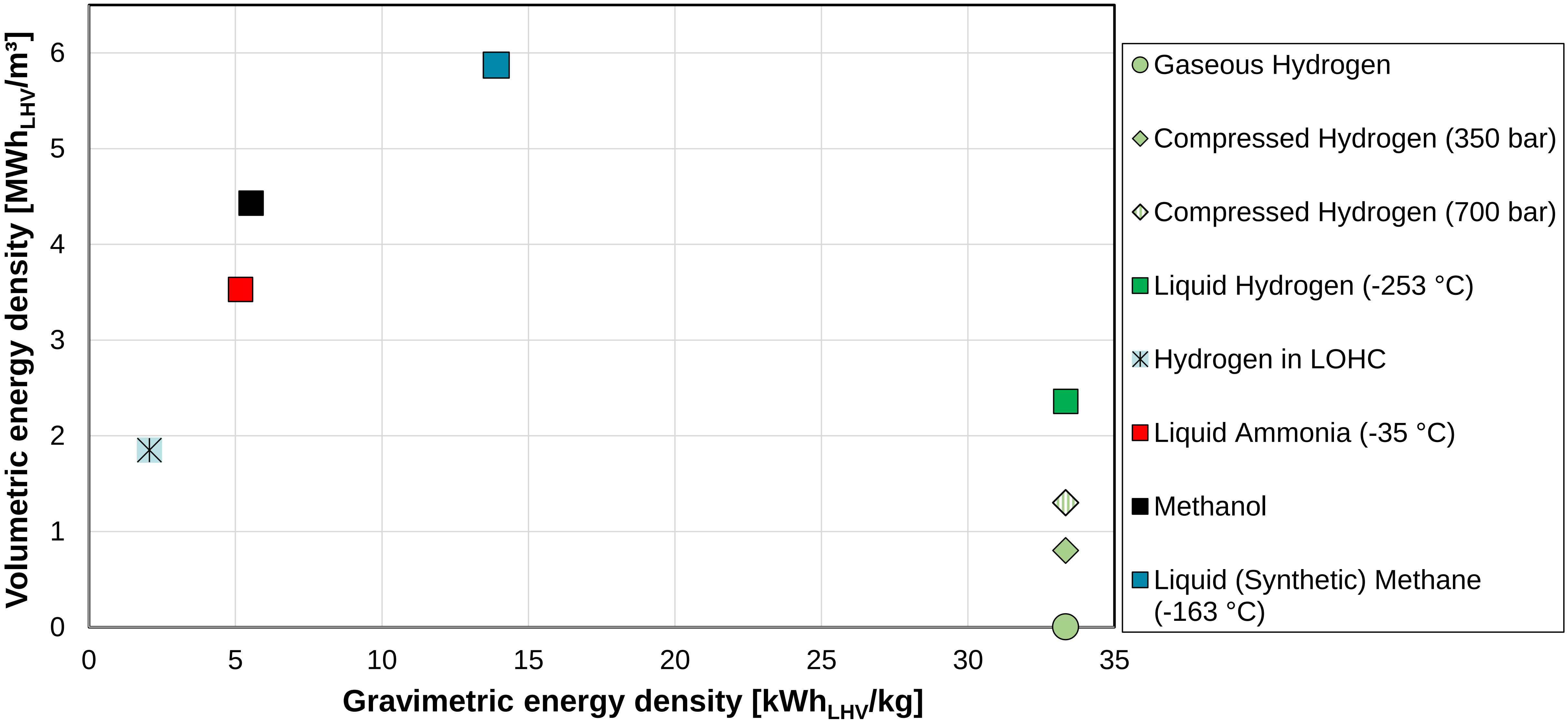
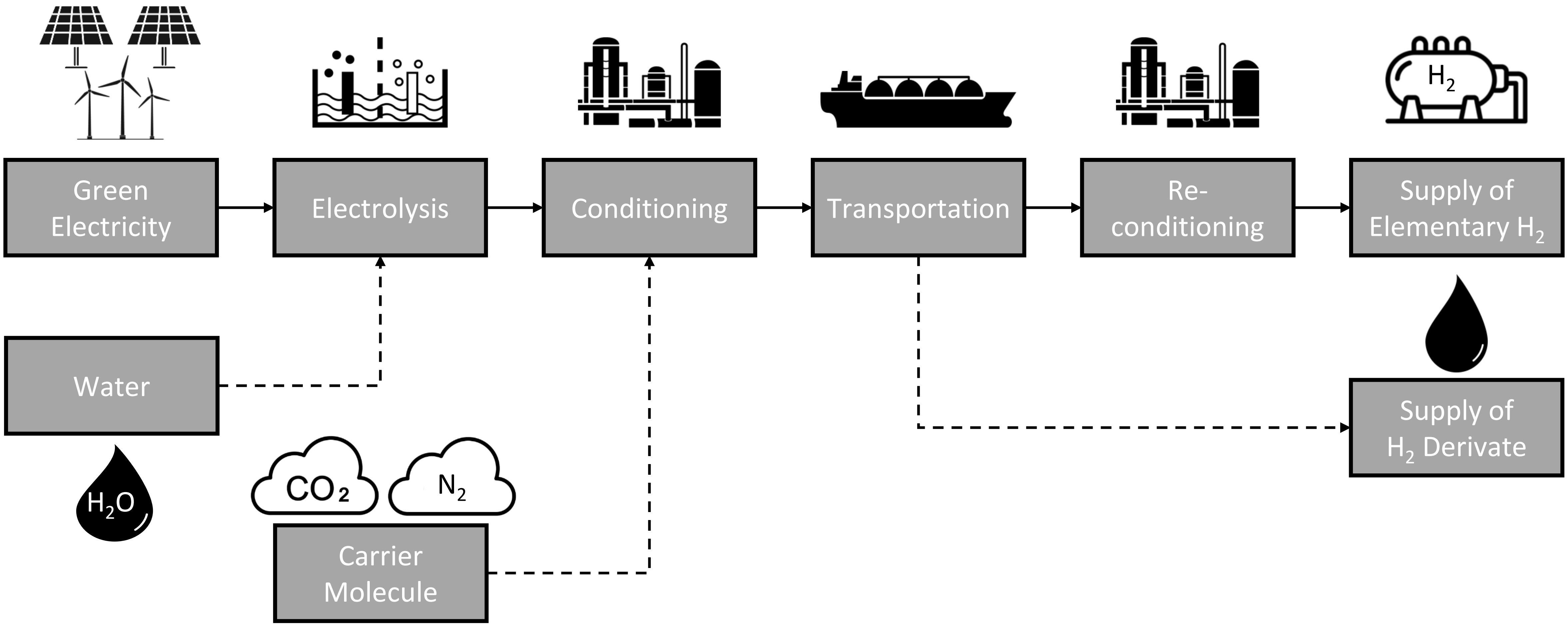
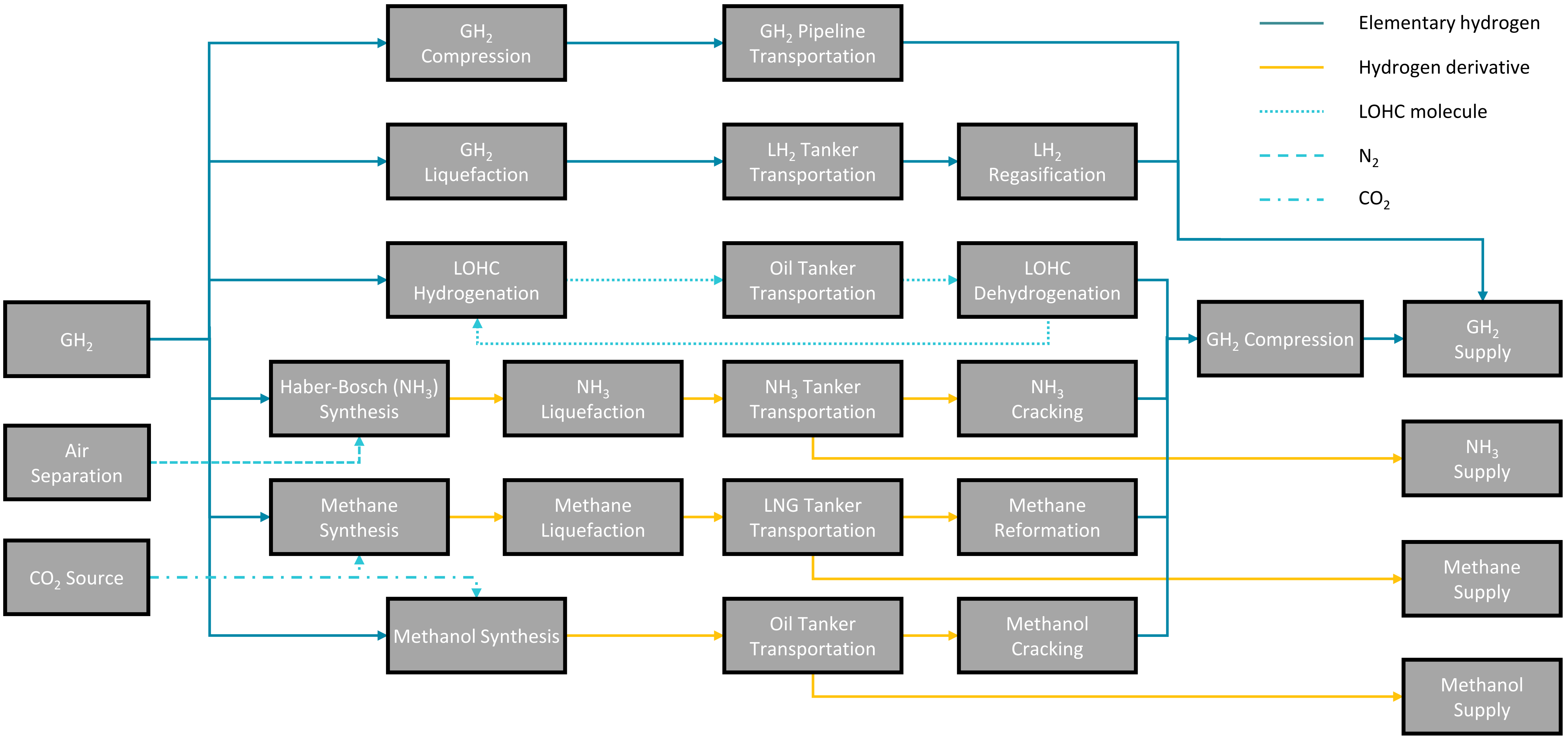


Energy Supply Chains based on Hydrogen



CO_2 : carbon dioxide | H_2 : hydrogen | H_2O : water | N_2 : nitrogen

Energy Supply Chains based on Hydrogen



CO_2 : carbon dioxide | GH_2 : gaseous hydrogen | H_2 : hydrogen | H_2O : water | LH_2 : liquid hydrogen | LNG : liquid natural gas | LOHC : liquid organic hydrogen carriers | N_2 : nitrogen | NH_3 : ammonia

Calculating Energy Supply Cost – Approach and Assumptions

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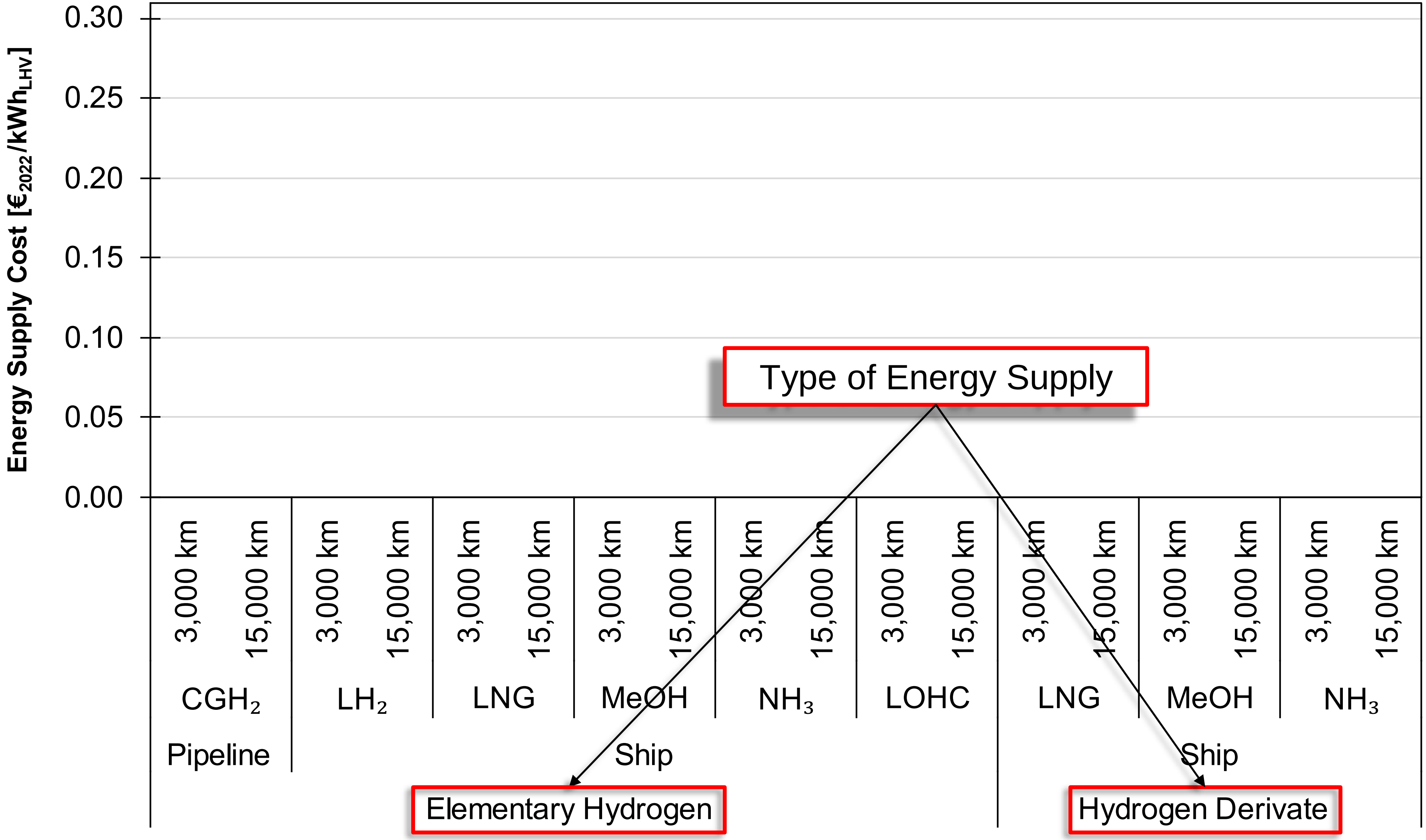
Approach

- Annuity method
- Depreciation time = technology lifetime
- Real weighted average cost of capital (WACC) = 6%
- Time horizon: Year 2035 (large scale technology roll out assumed)

Assumptions

- Techno-economic parameters based on literature
- Cost of gaseous hydrogen at the point-of-export: 3.35 $€_{2022}/kg_{H2}$
- CO_2 supply via DAC considering the integration of synthesis waste heat leading to cost between 130 $€_{2022}$ and 150 $€_{2022}$ $/t_{CO2}$
- Internal heat supply for reconversion to hydrogen

Energy Supply Cost



CGH_2: compressed gaseous hydrogen | LH_2: liquid hydrogen | LOHC: liquid organic hydrogen carrier (benzyl-toluene) | MeOH: Methanol | NH_3: ammonia | SNG : synthetic natural gas
Results based on work from: Carels et al. 2023; Sens et al. 2022a; Sens et al. 2022b

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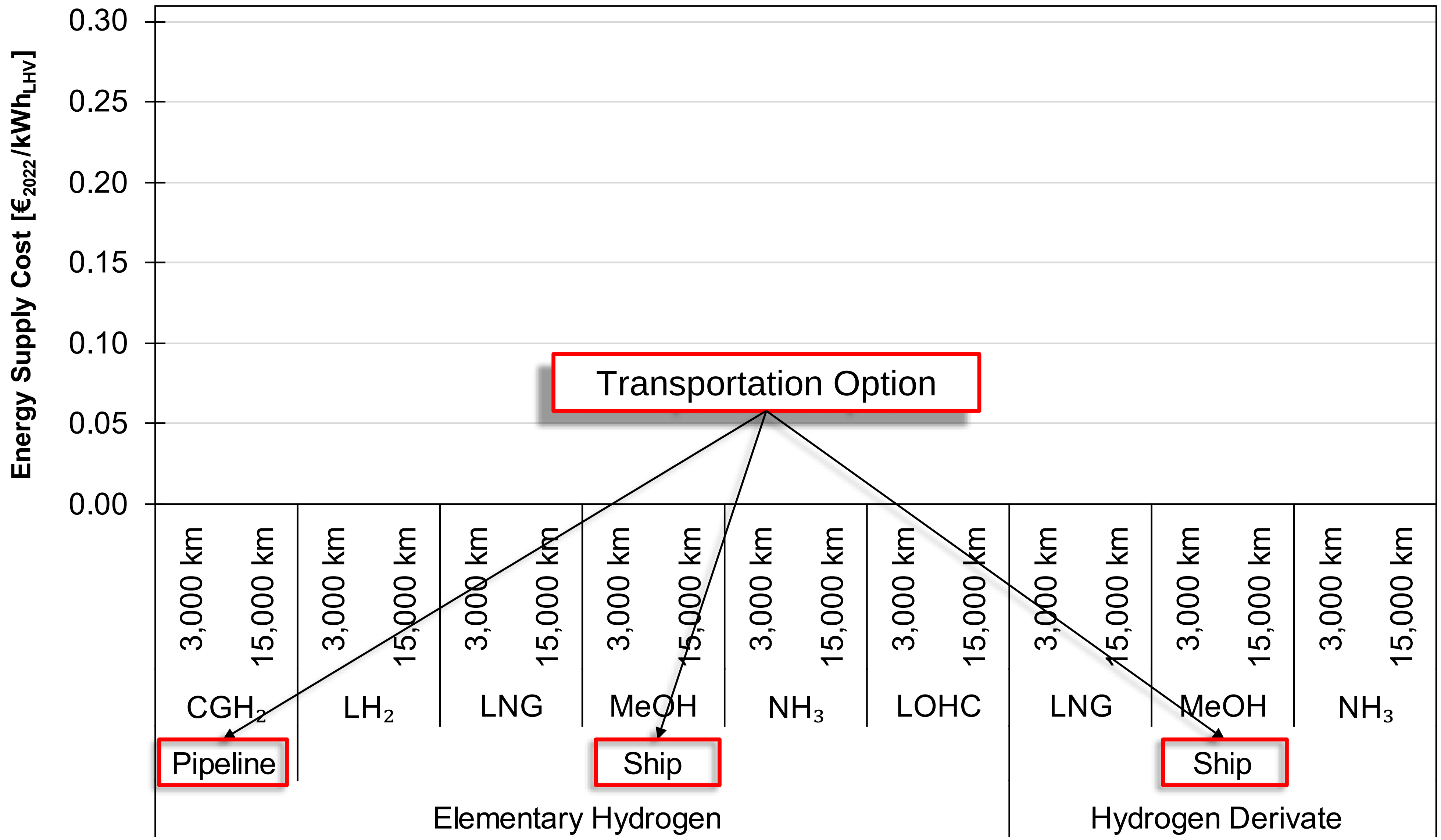

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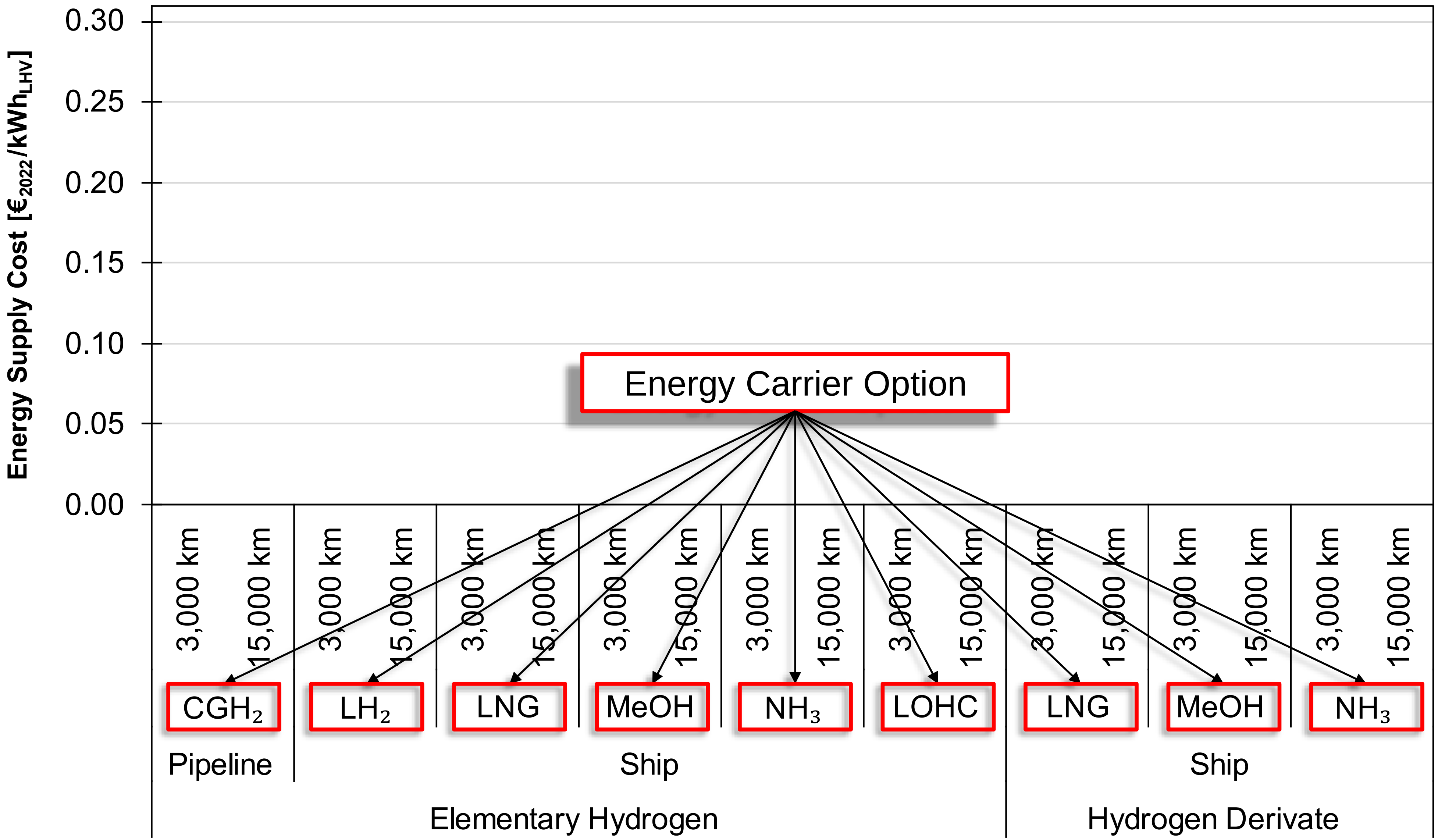

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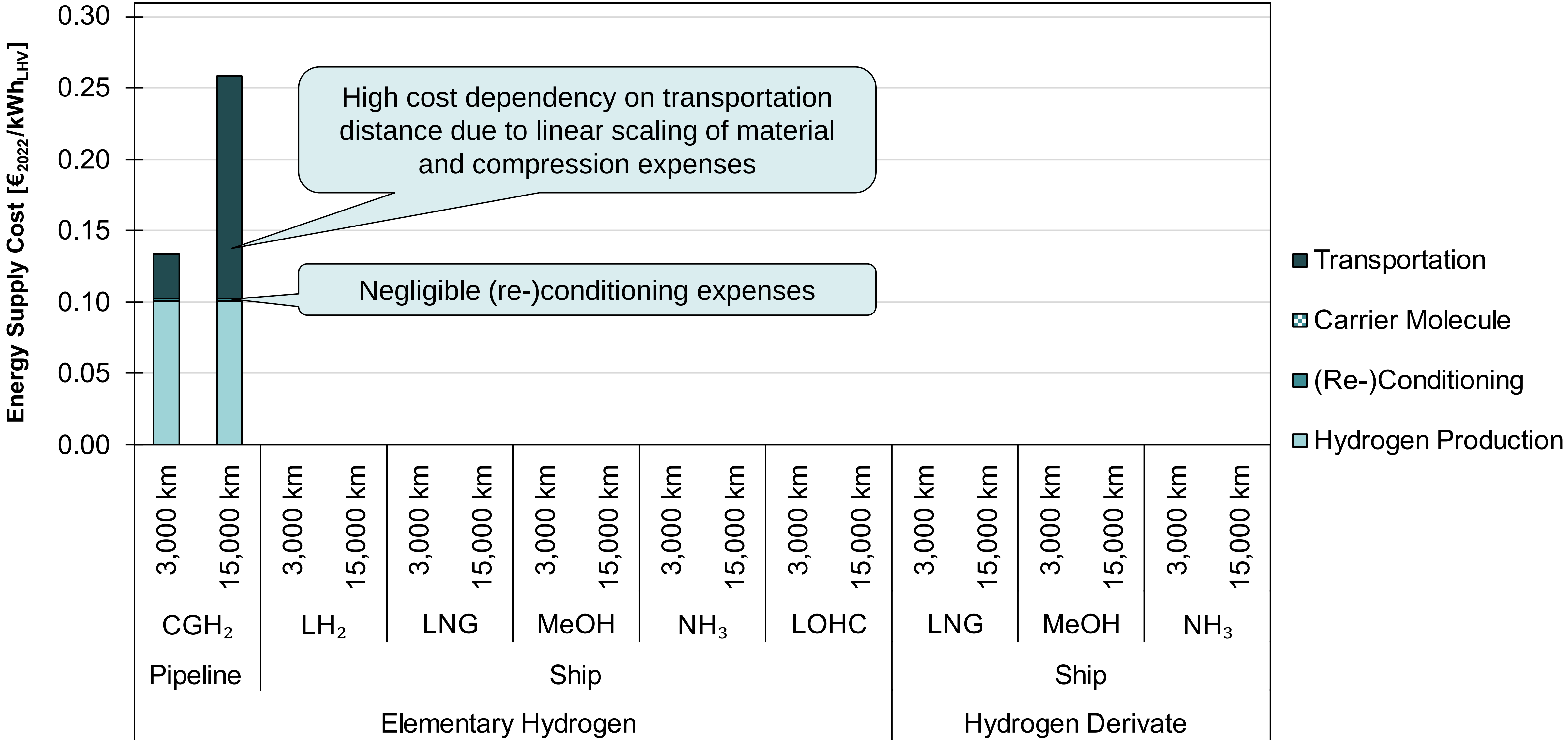

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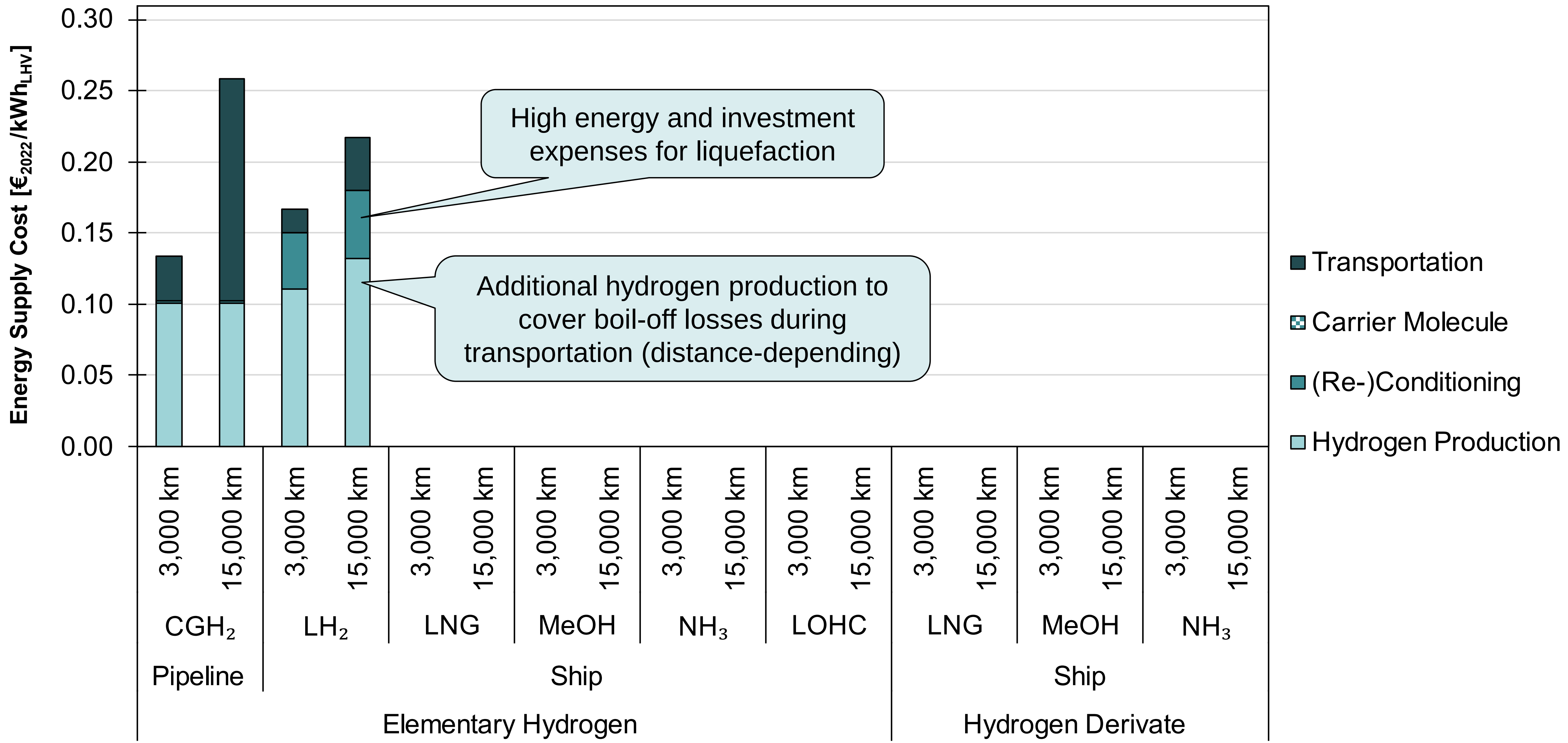

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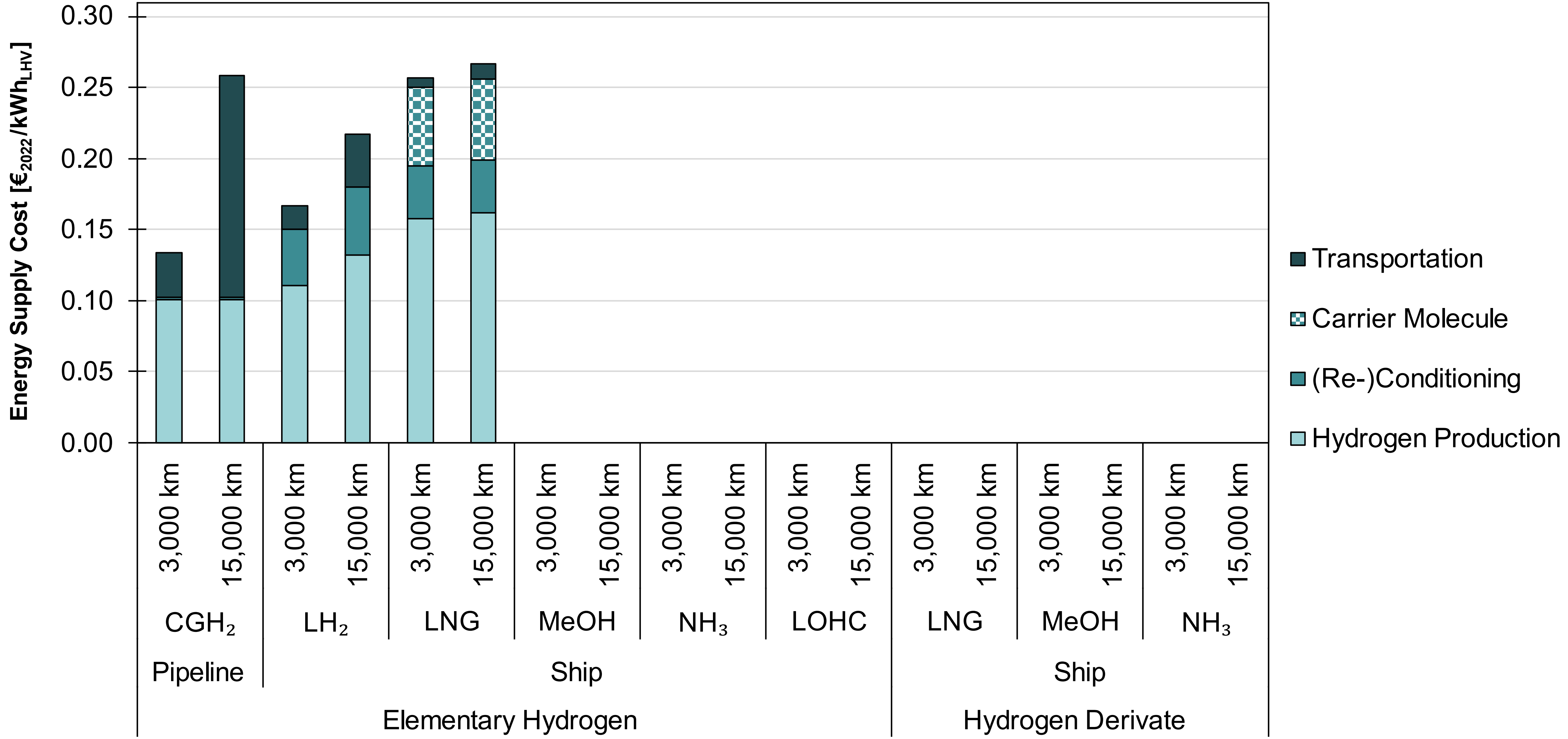

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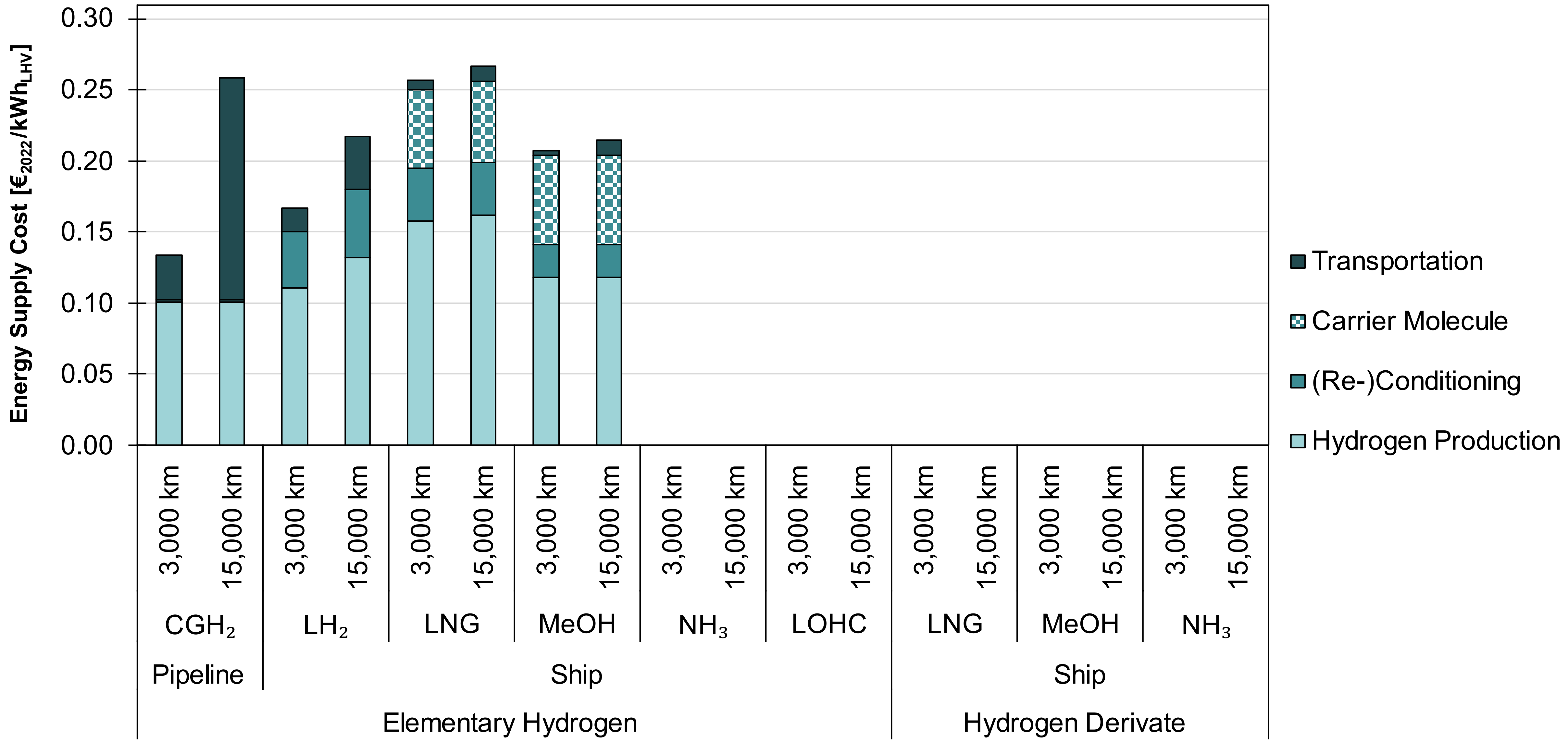

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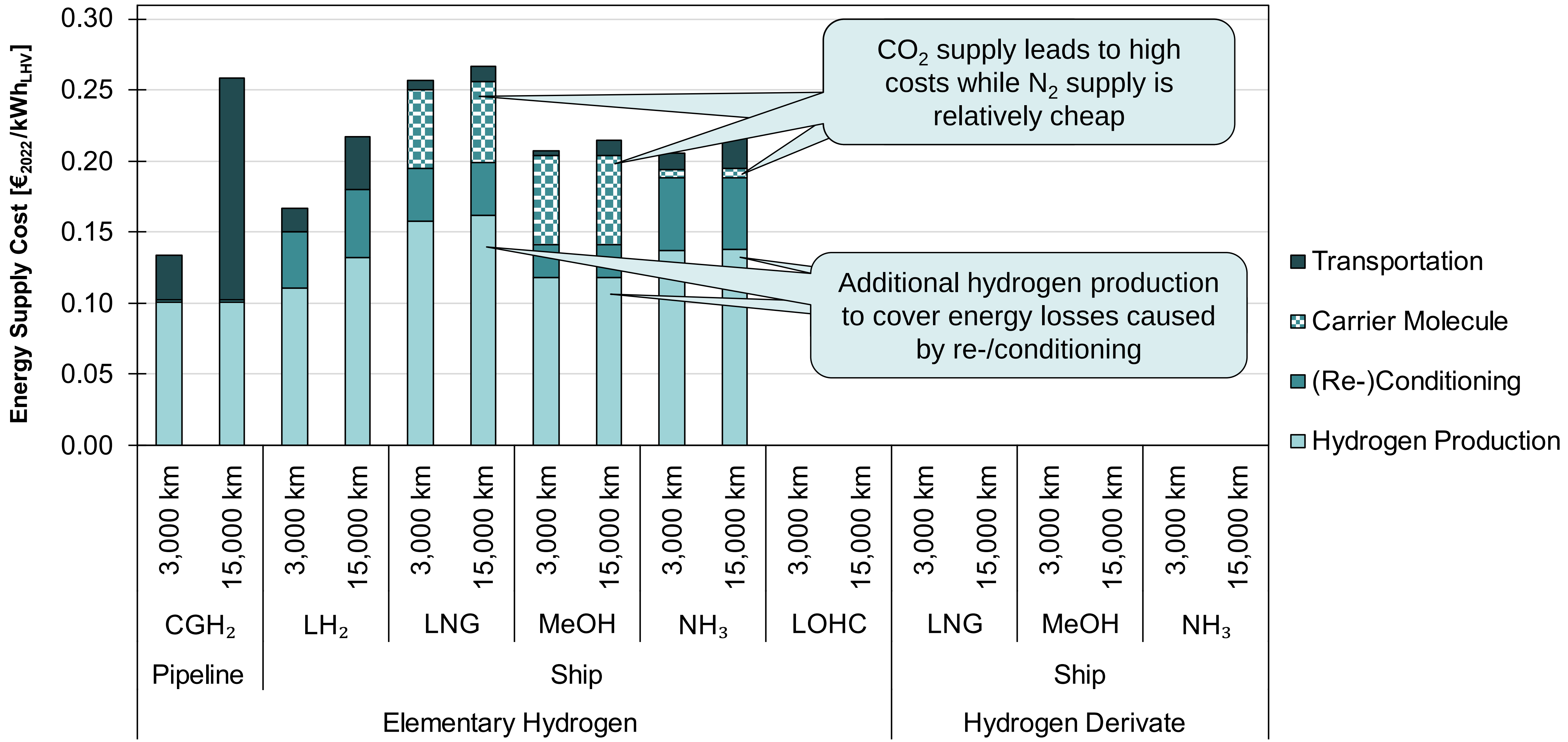

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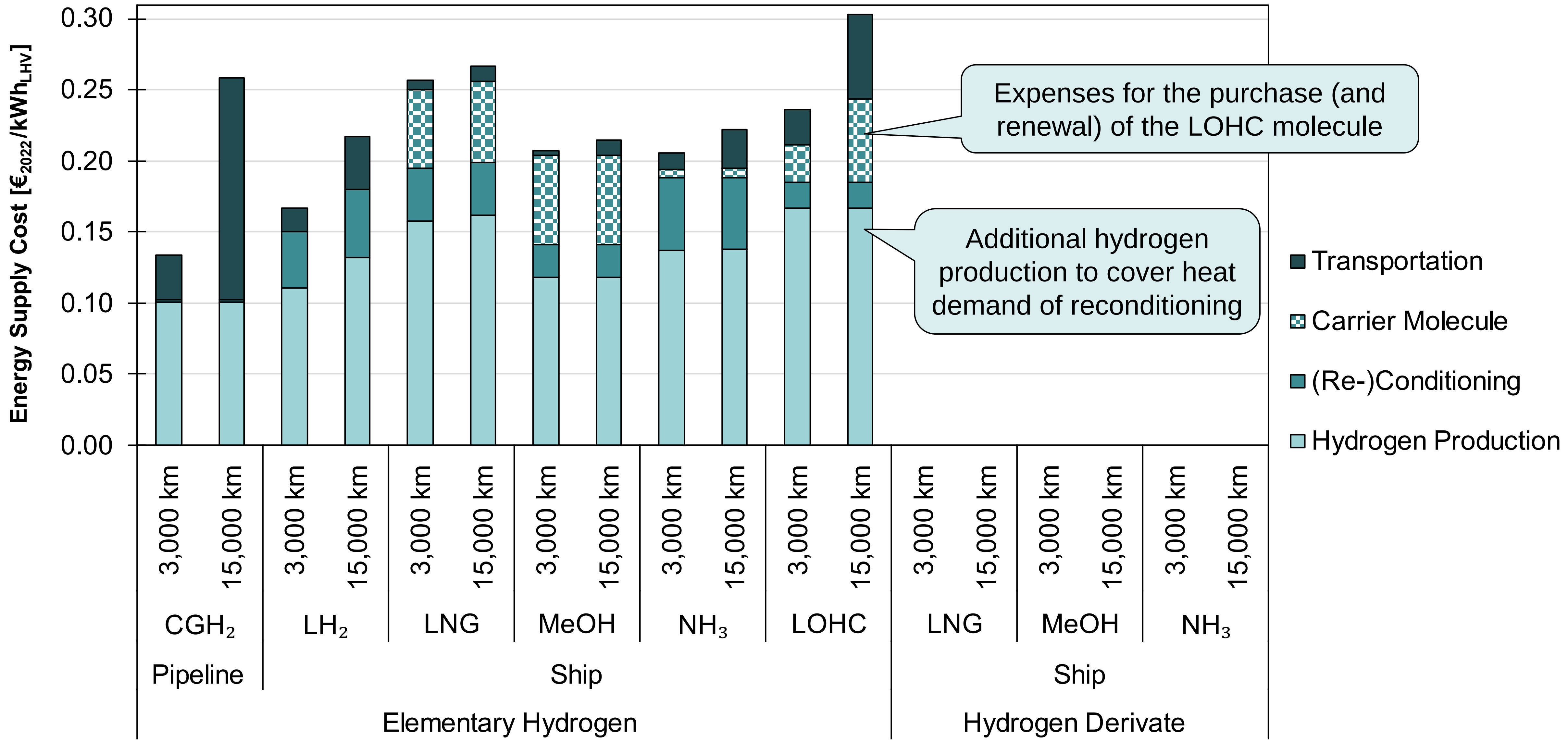

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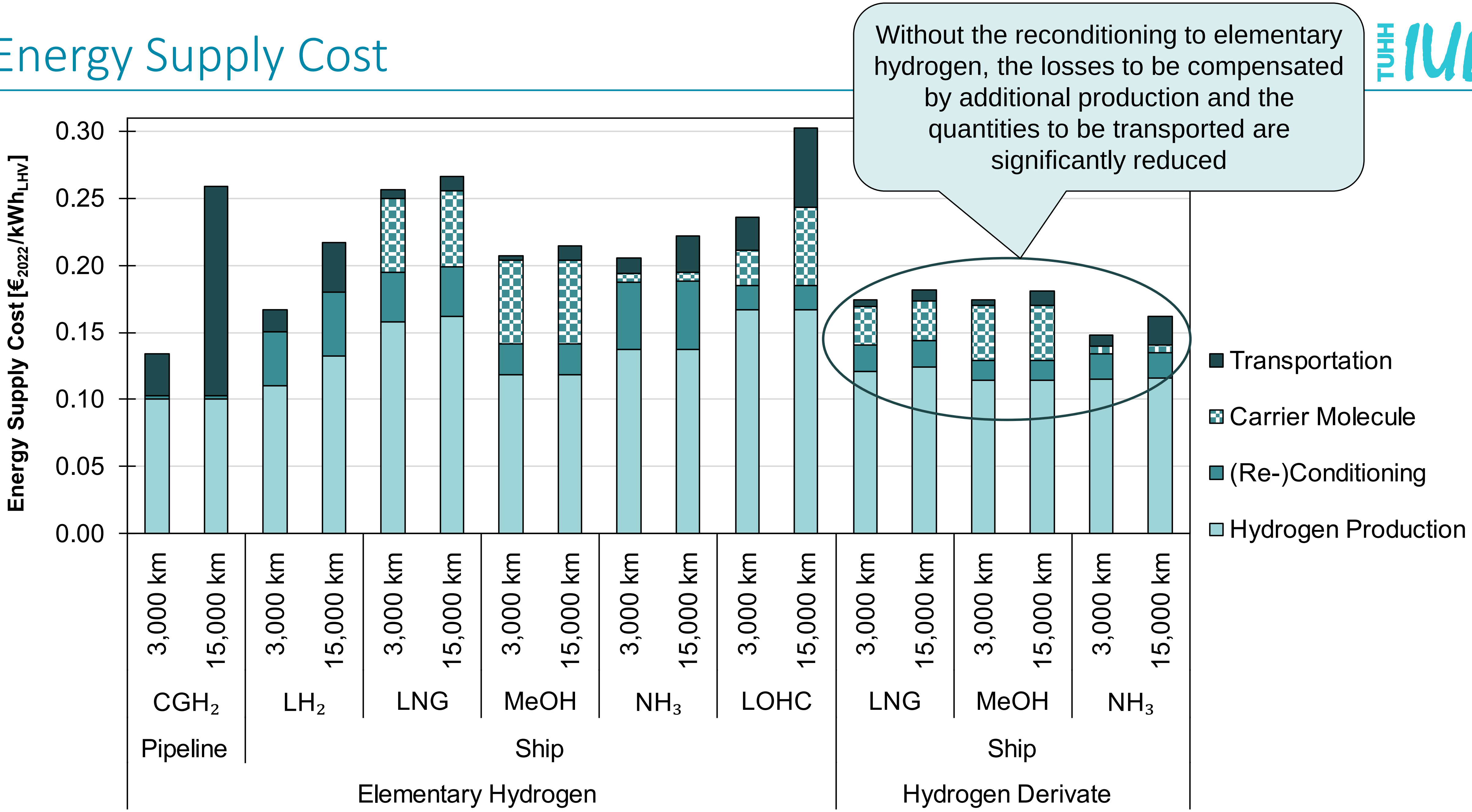

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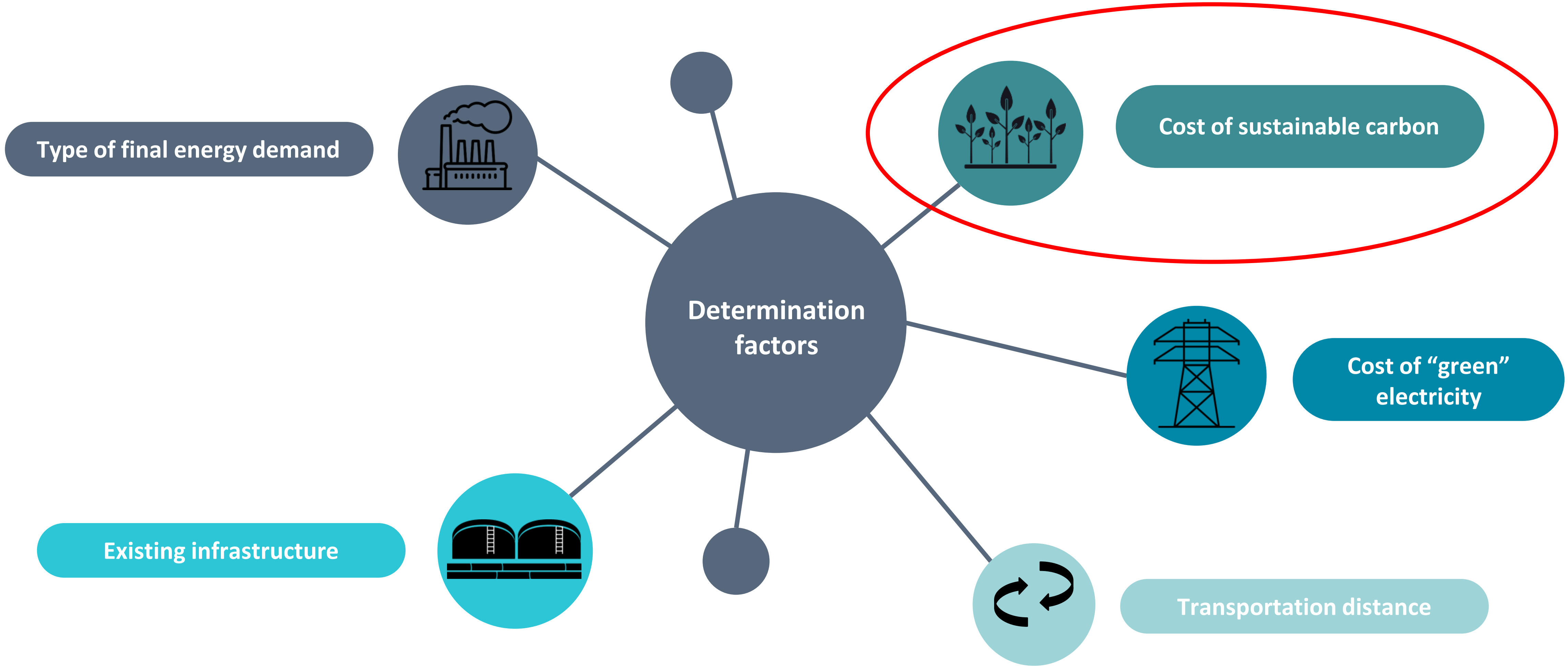
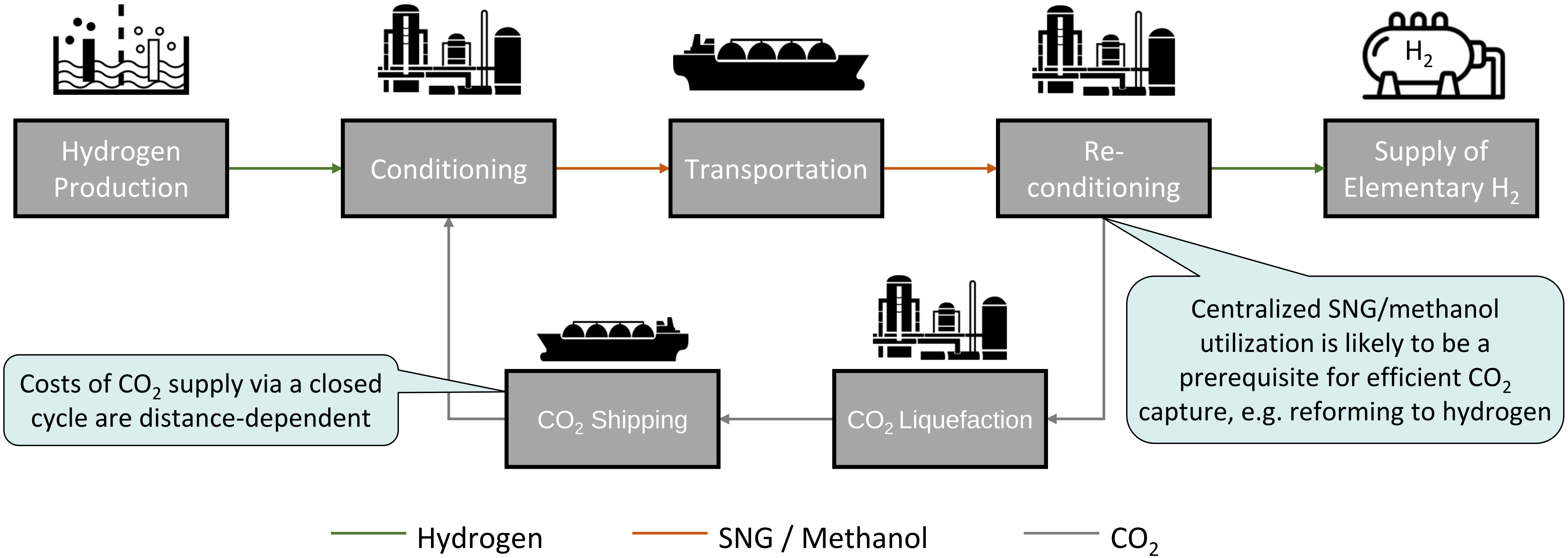
Energy Supply Cost – Determination Factors



Energy Supply Cost – Implementing Closed CO_2 Cycles

Closed CO_2 cycles can be a way to reduce the cost of CO_2 provision and thereby the cost of energy supply based on green carbon-based carriers.



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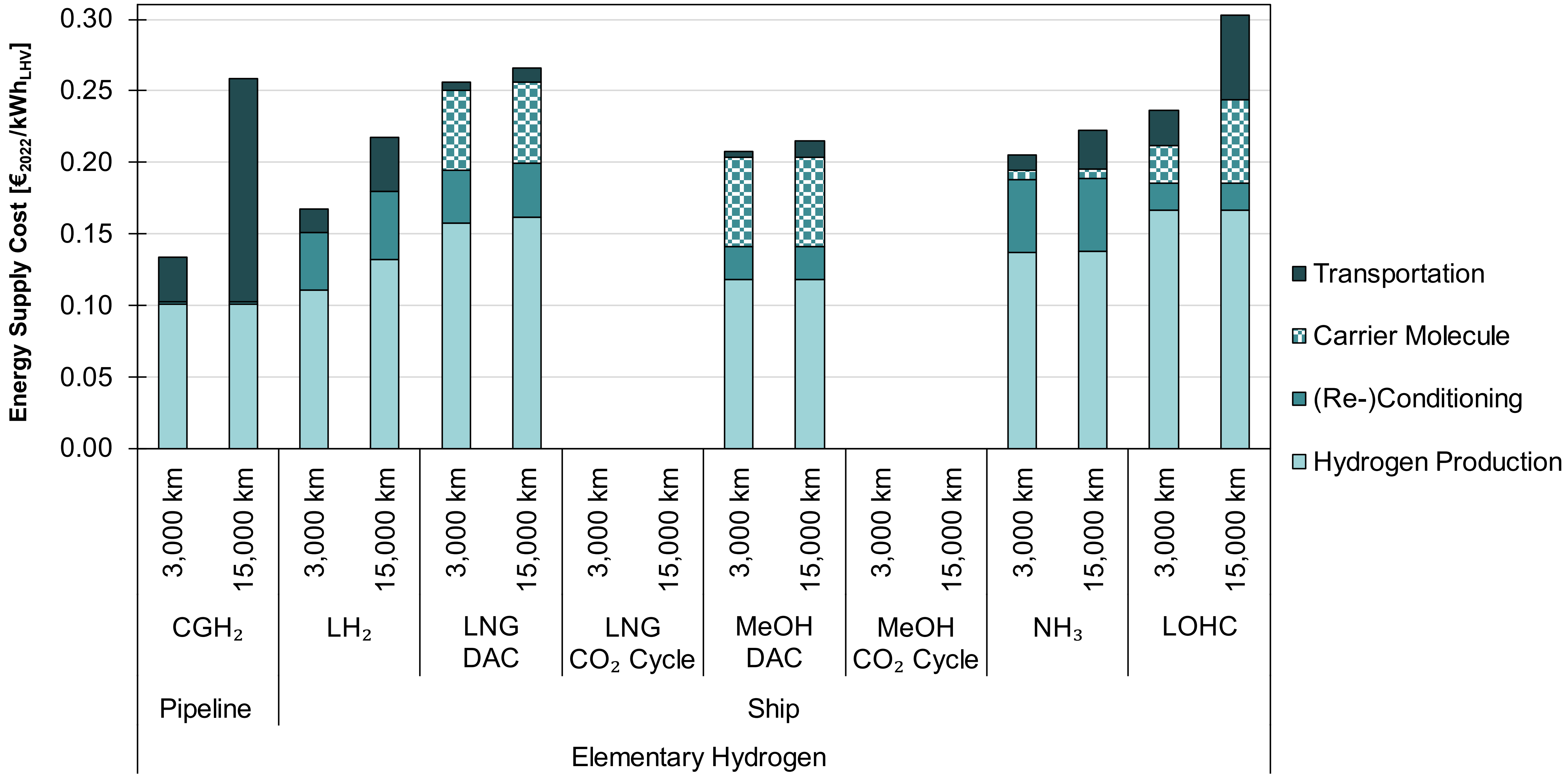

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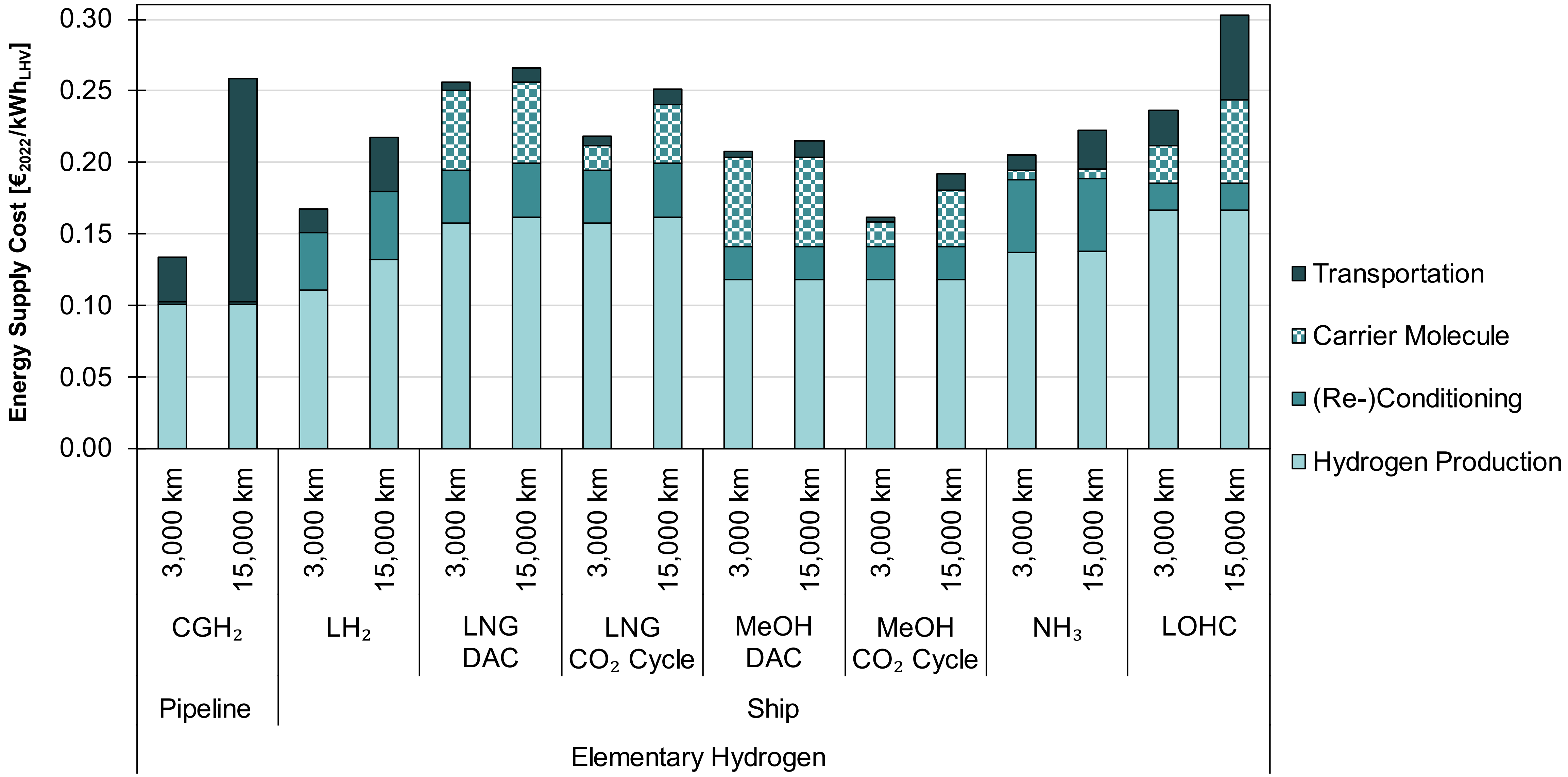

Conclusion

- The import of hydrogen and/or hydrogen-based energy carriers will an all likelihood play a crucial role in a defossilized energy supply.
- For shorter distances, the import of gaseous hydrogen via pipelines (< 0.14 $€_{2022}/kWh_{LHV}$) and of liquid hydrogen via ship (≈ 0.16 $€_{2022}/kWh_{LHV}$) obtain the lowest energy supply cost.
- Supply of elementary hydrogen based on hydrogen carrier molecules imported via ships generally shows higher costs. Hence, supply costs are less dependent on transportation distance.
- If hydrogen derivates are supplied, the energy supply cost can be decrease significantly (≈ 0.15 $€_{2022}/kWh_{LHV}$), since the energy and cost intensive recondition process is not needed.
- Energy supply based on green hydrocarbons is significantly influenced by the cost of CO_2 provision. The implementation of a closed CO_2 cycle might reduce the overall energy supply cost.

Questions and Discussion

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