DOI: https://doi.org/10.15480/882.4650
ORCID: https://orcid.org/0000-0001-6300-4218

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Green Hydrogen

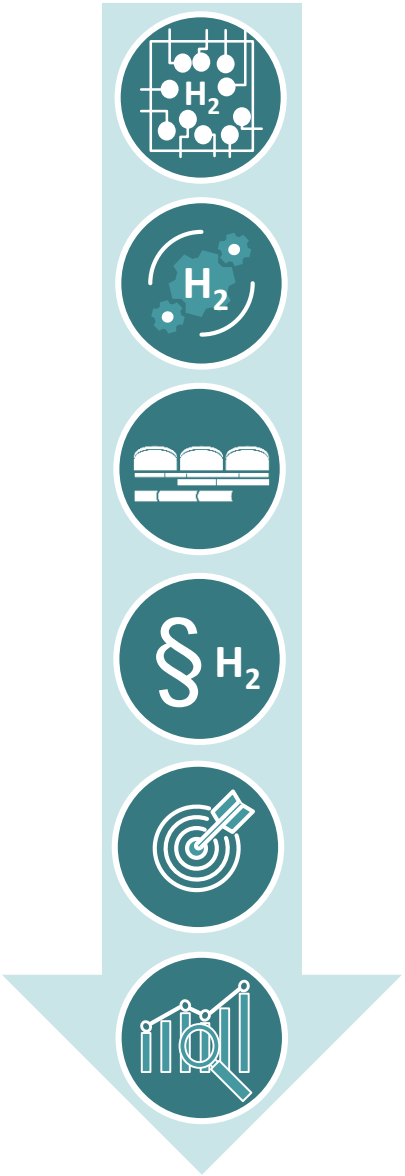
Trends and Development in Germany and the European Union

Lucas Sens, Martin Kaltschmitt

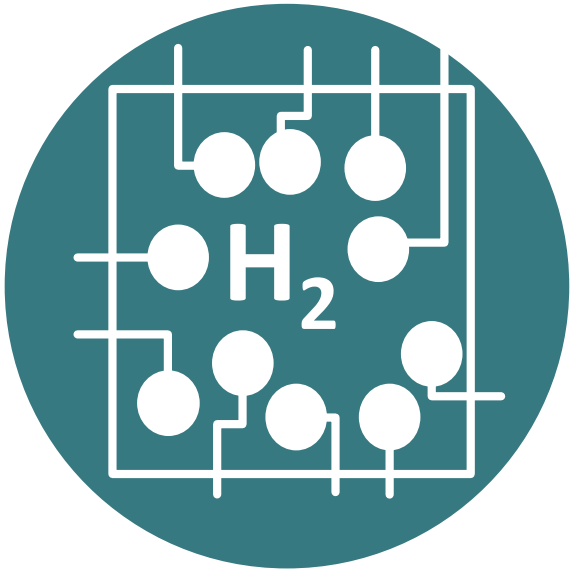
[1] [2] [3] [4] [5] [6]

Hamburg University of Technology (TUHH), Institute of Environmental Technology and Energy Economics (IUE)
www.tuhh.de/iue

Outline



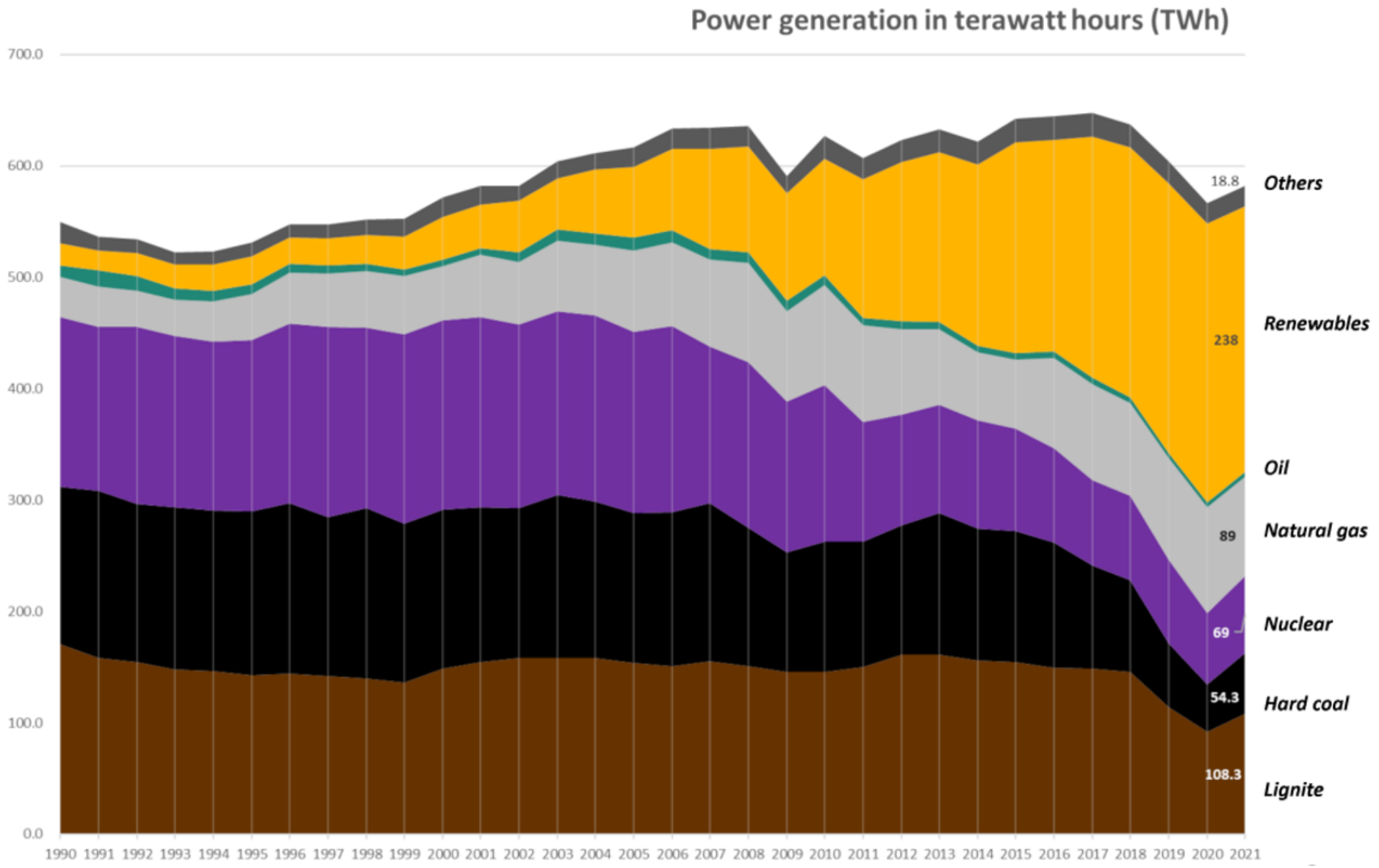
1. Hydrogen in a Green Energy System
2. Hydrogen Applications
3. Hydrogen Infrastructure
4. Regulatory Framework
5. Hydrogen Projects
6. Hydrogen Ramp Up



Why do we want green hydrogen?

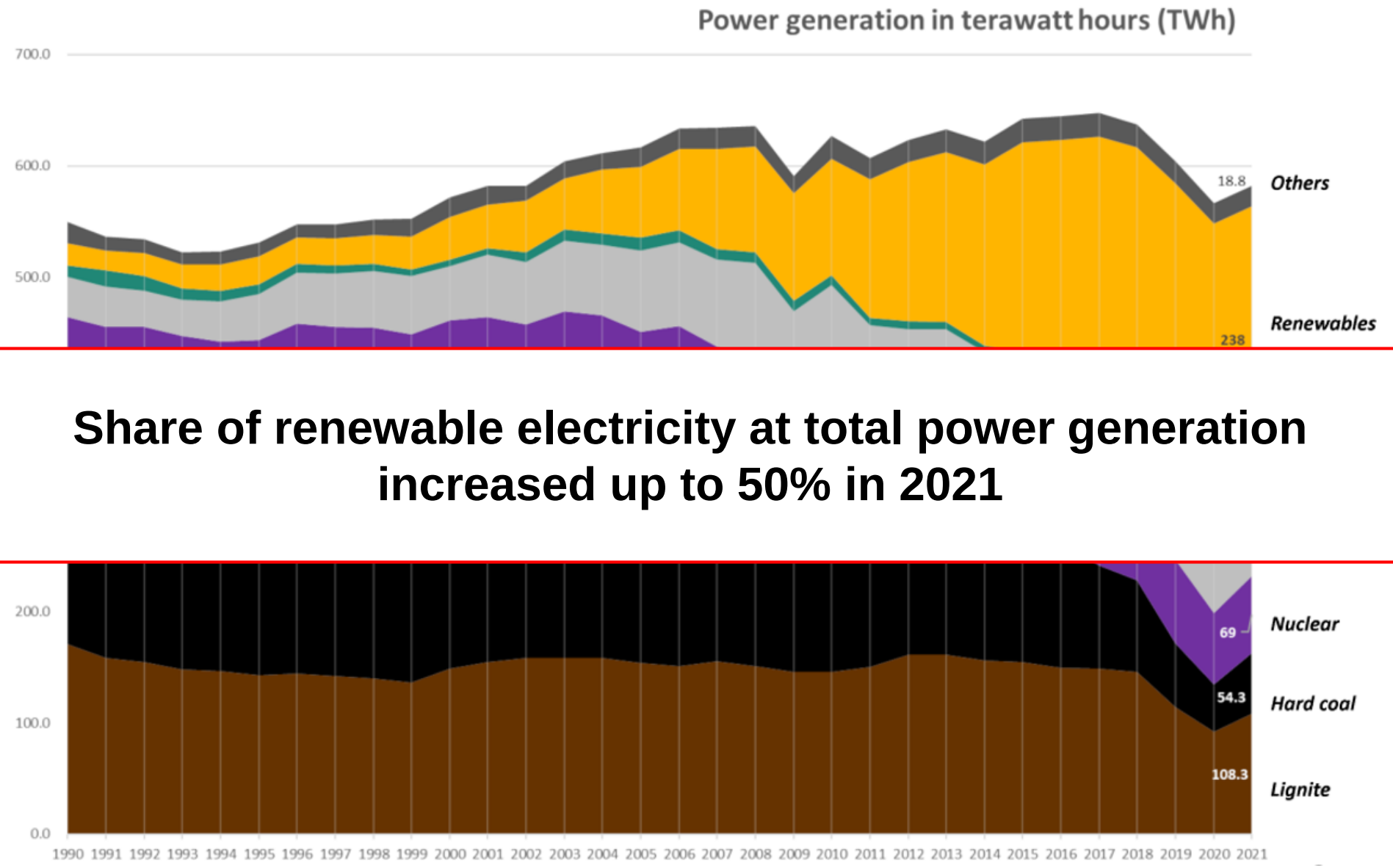
1. Hydrogen in a Green Energy System

Power Generation in Germany



Source: Clean Energy Wire

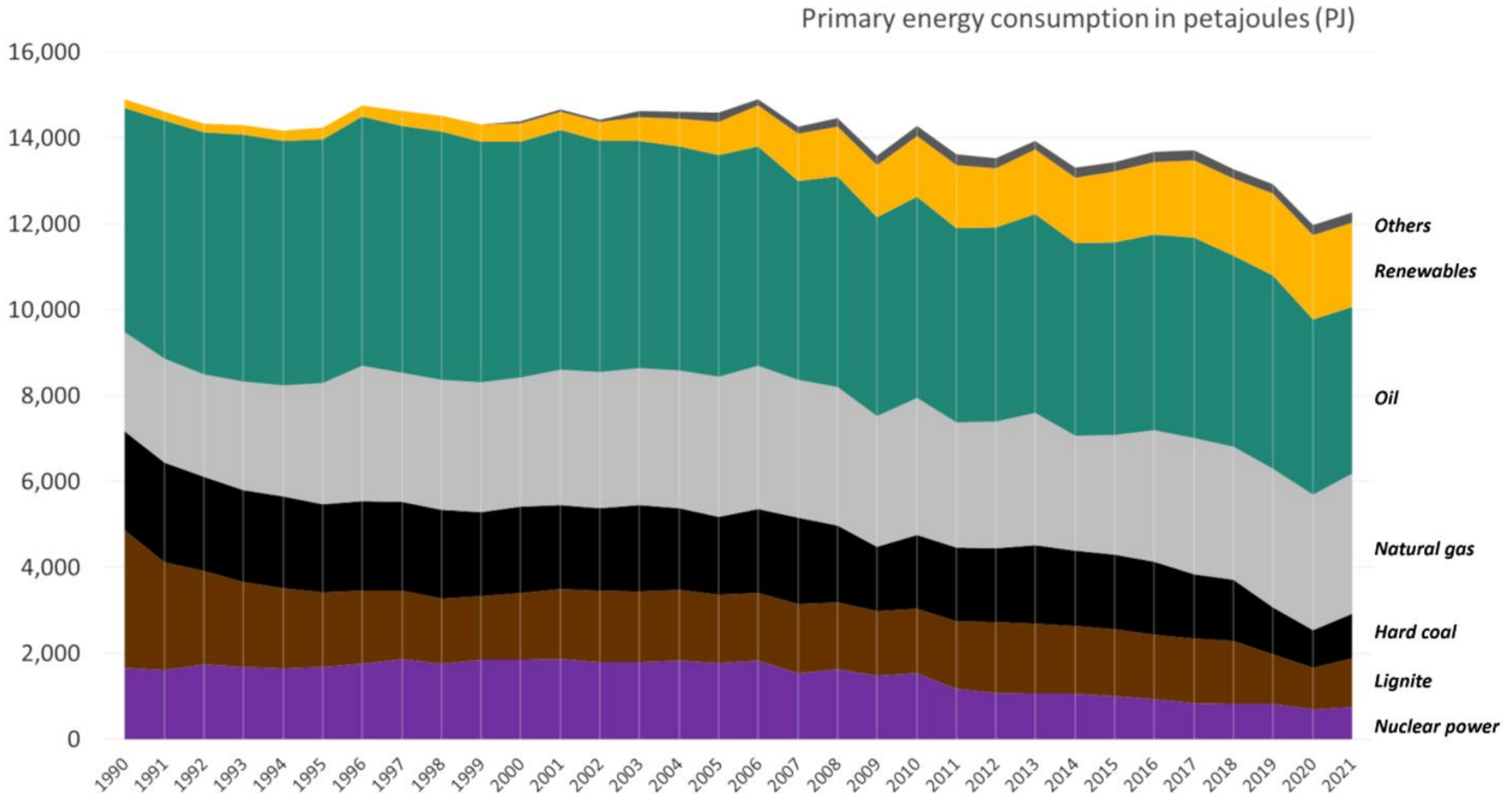
Power Generation in Germany



Share of renewable electricity at total power generation increased up to 50% in 2021

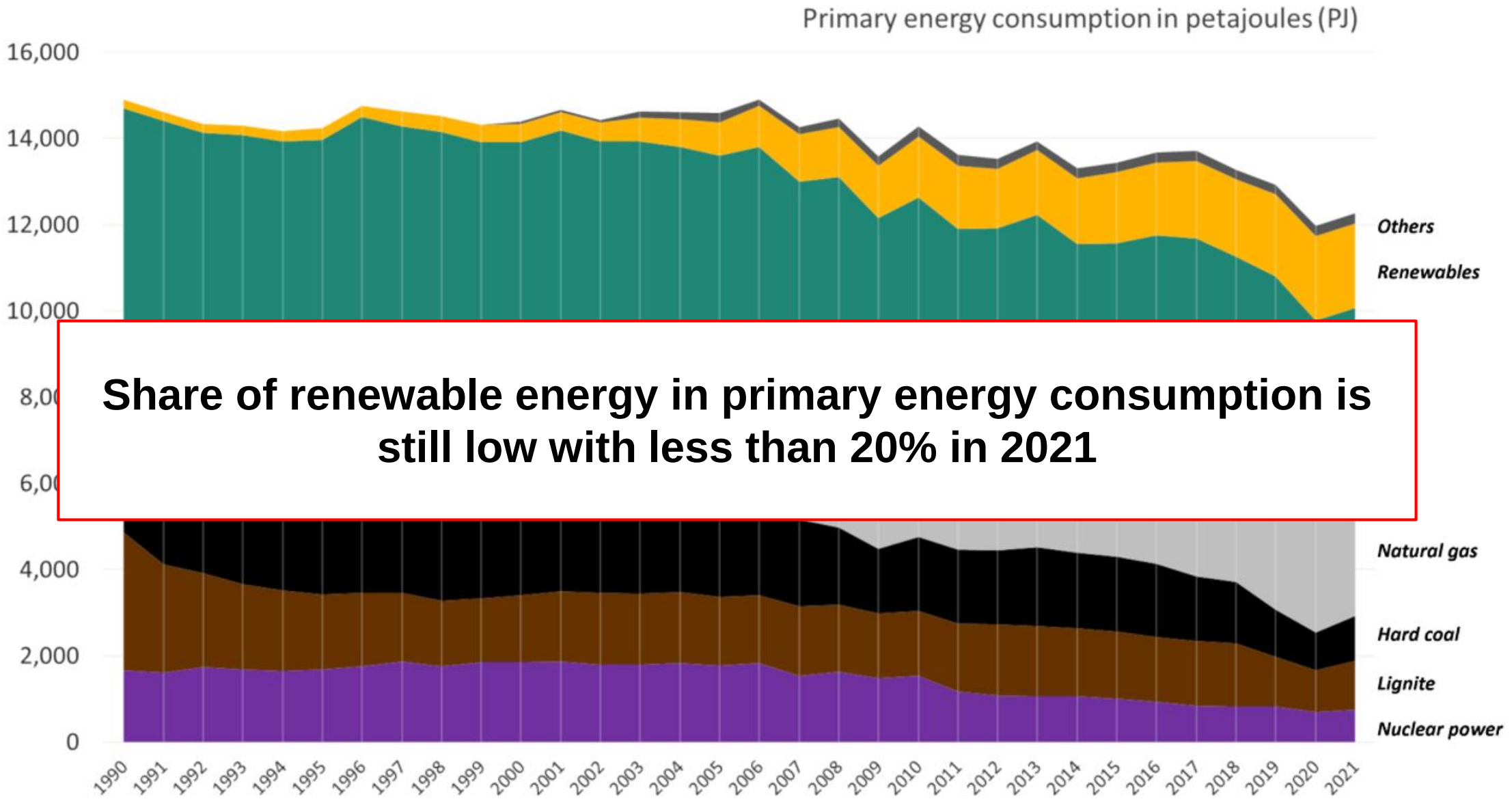
Source: Clean Energy Wire

Primary Energy Consumption in Germany



Source: Clean Energy Wire

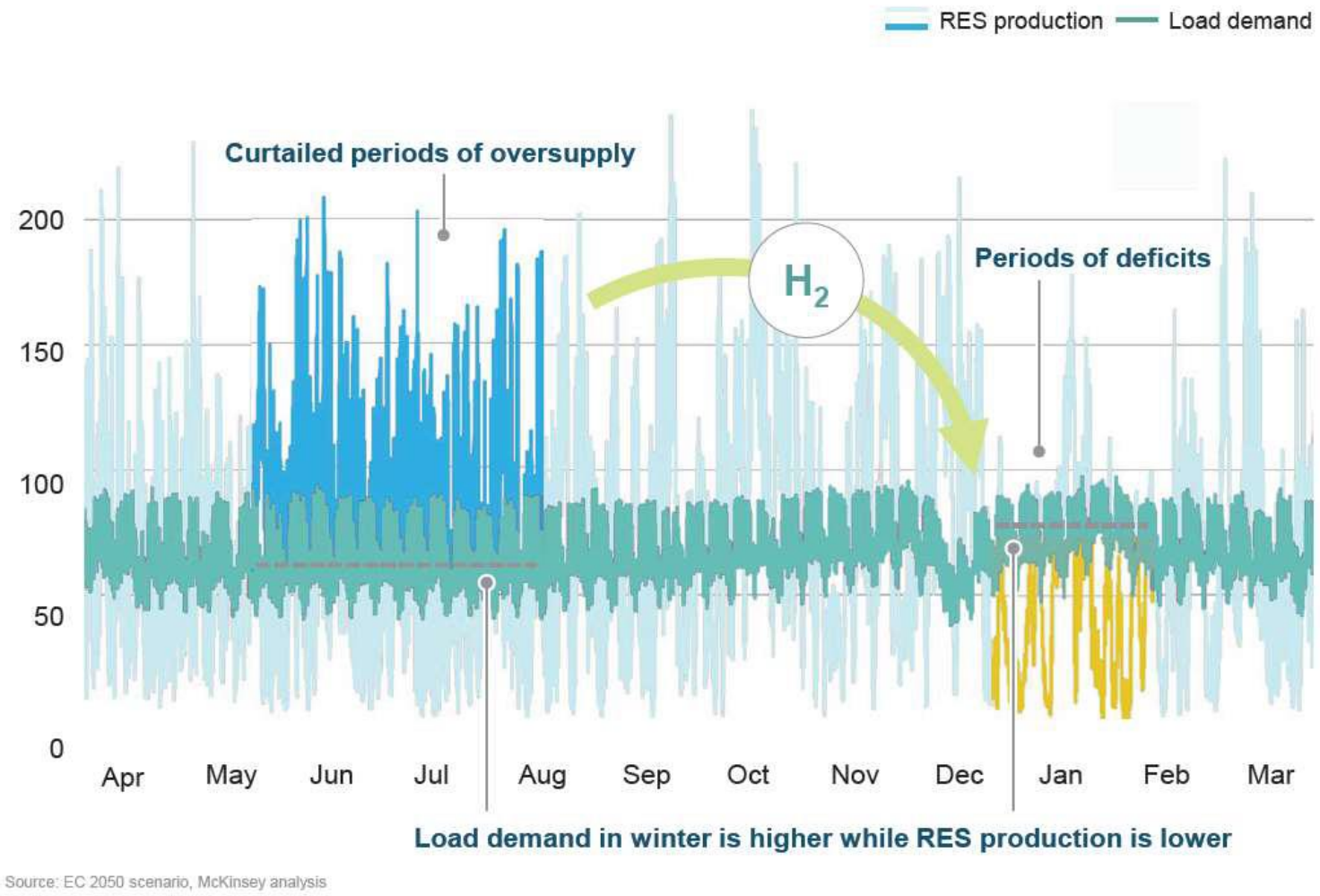
Primary Energy Consumption in Germany



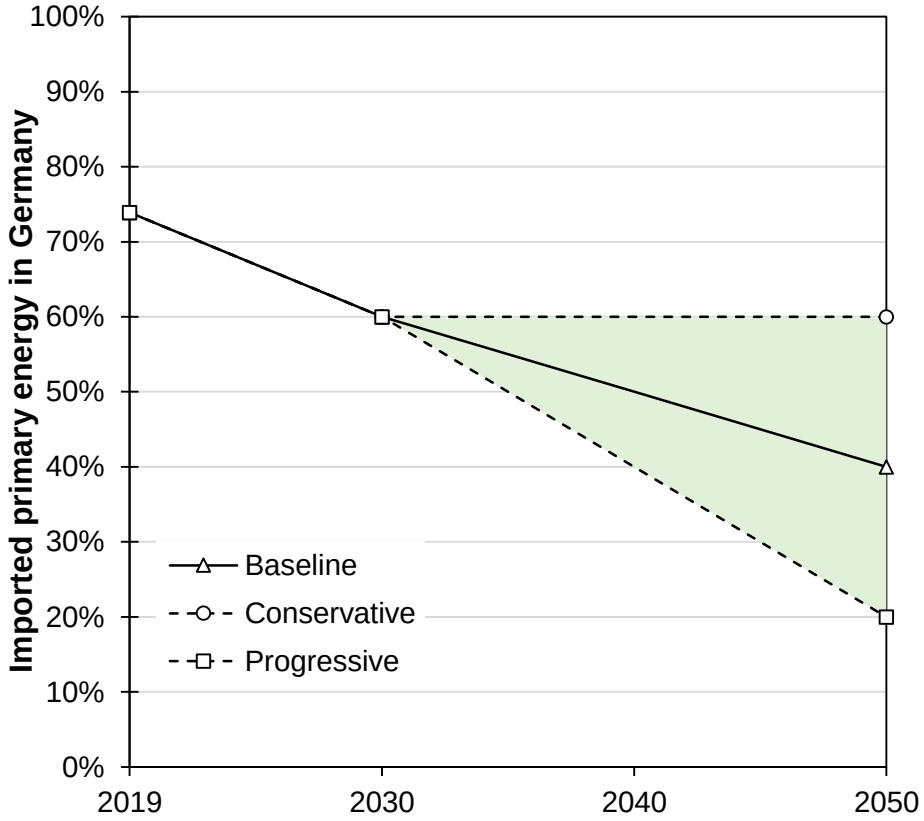
Share of renewable energy in primary energy consumption is still low with less than 20% in 2021

Source: Clean Energy Wire

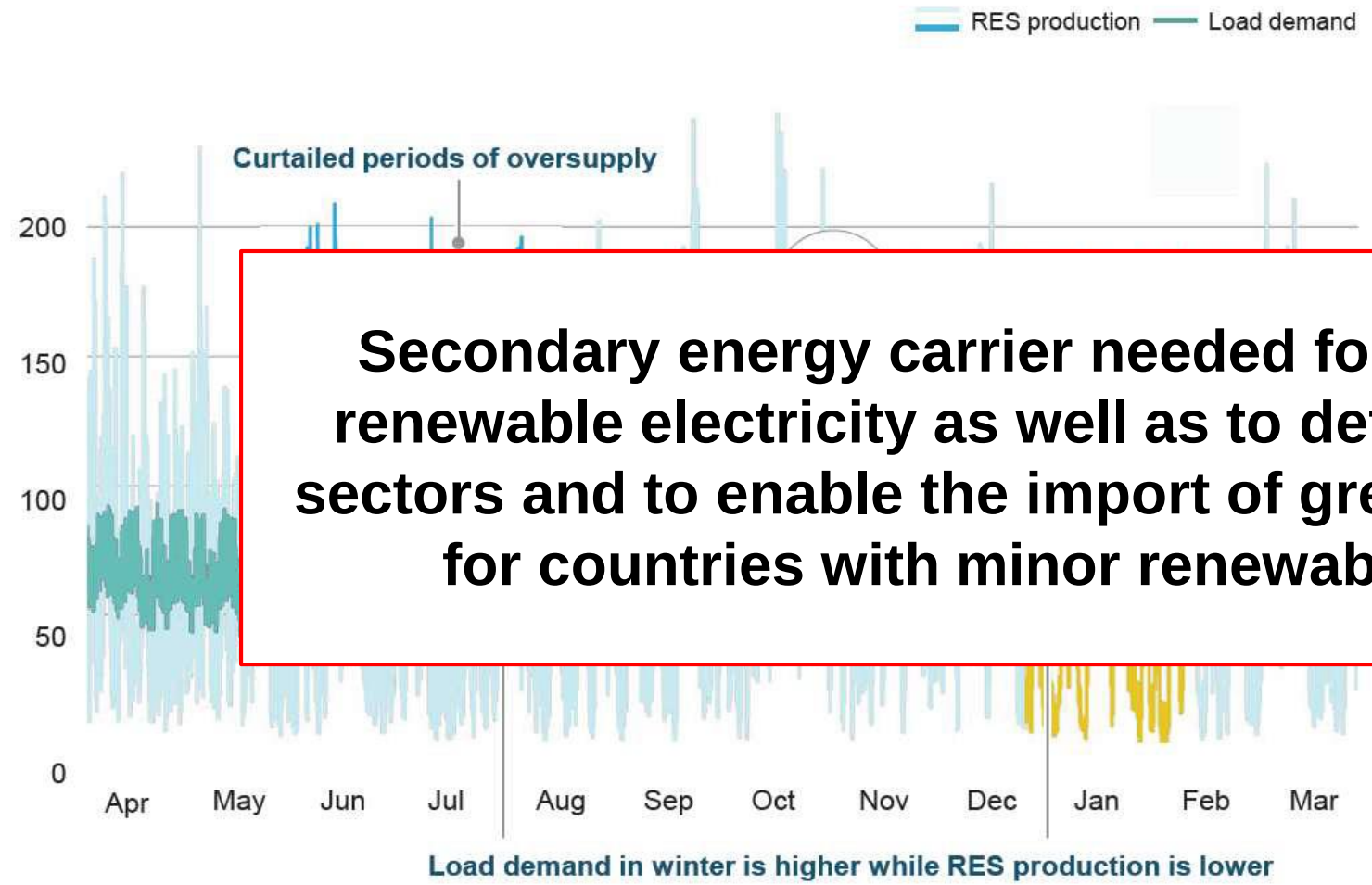
Seasonal Storage and Import Dependency



Source: EC 2050 scenario, McKinsey analysis



Seasonal Storage and Import Dependency



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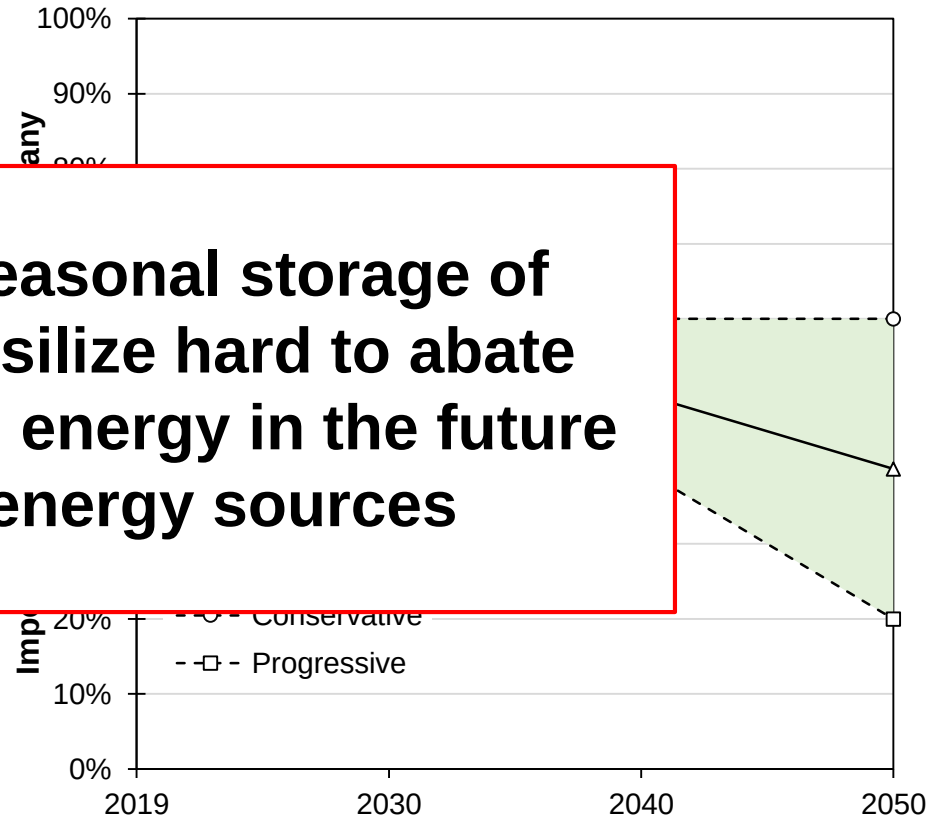
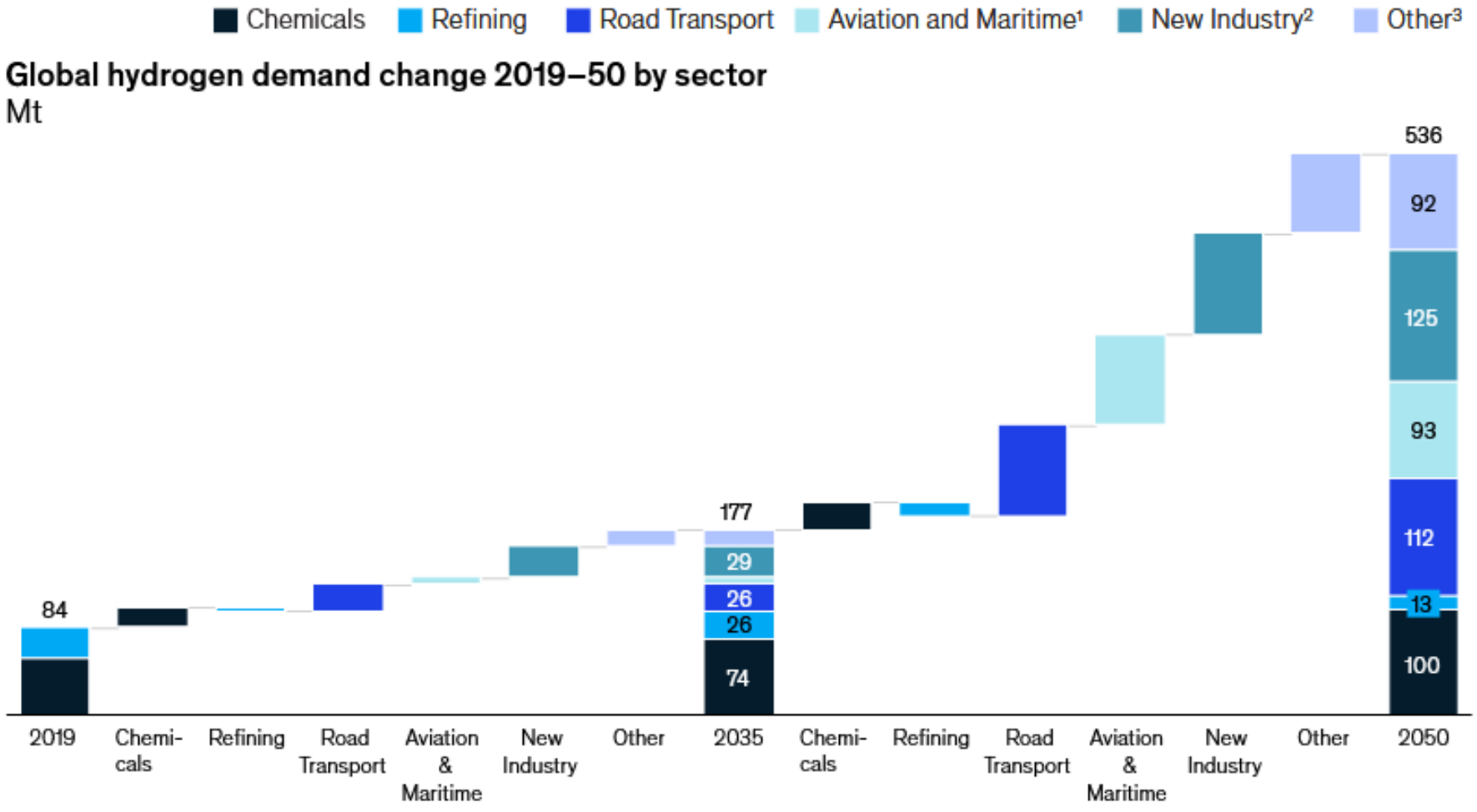


Secondary energy carrier needed for seasonal storage of renewable electricity as well as to defossilize hard to abate sectors and to enable the import of green energy in the future for countries with minor renewable energy sources

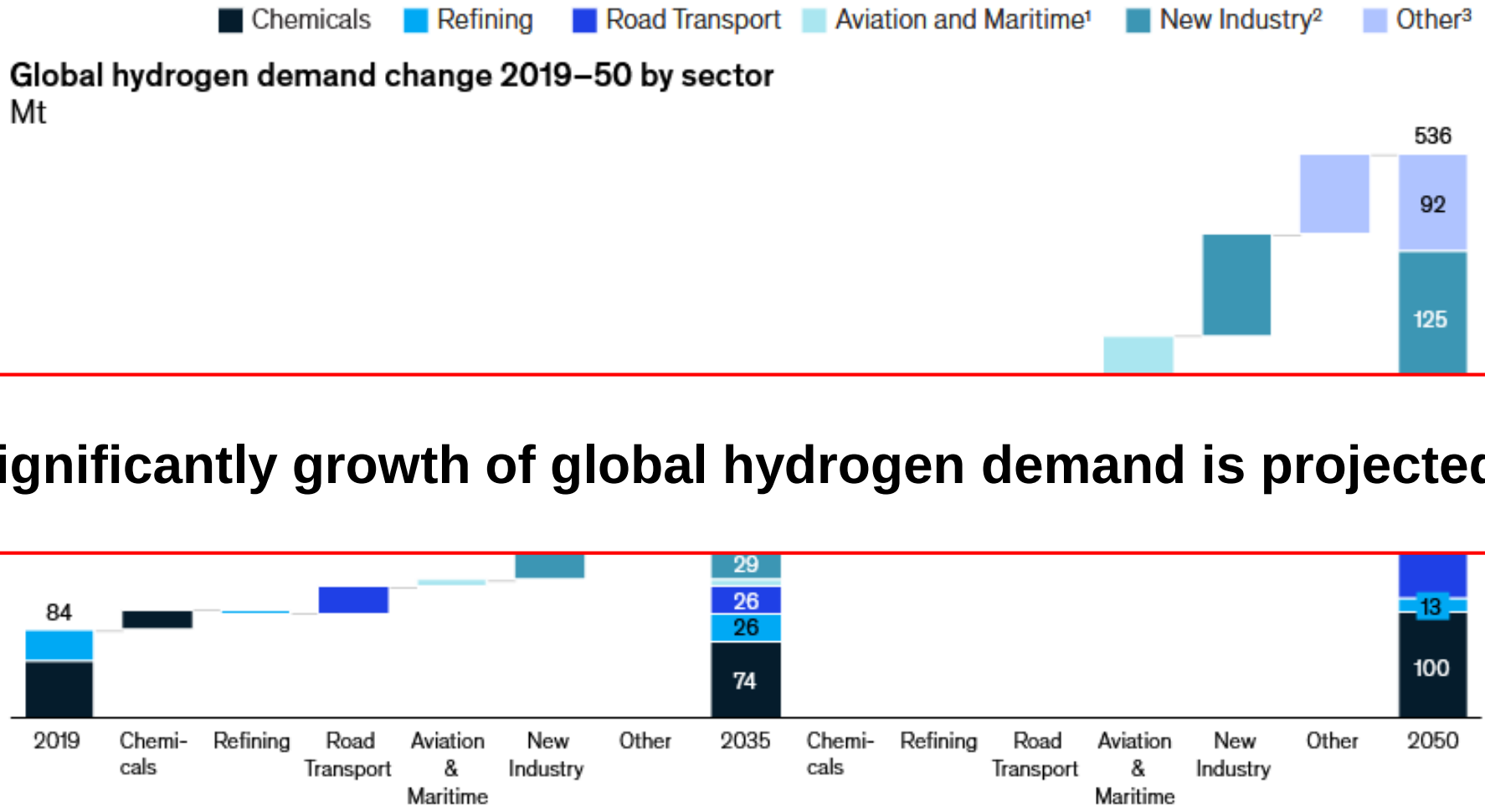
Hydrogen Demand Projections



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 Demand Projections



Significantly growth of global hydrogen demand is projected

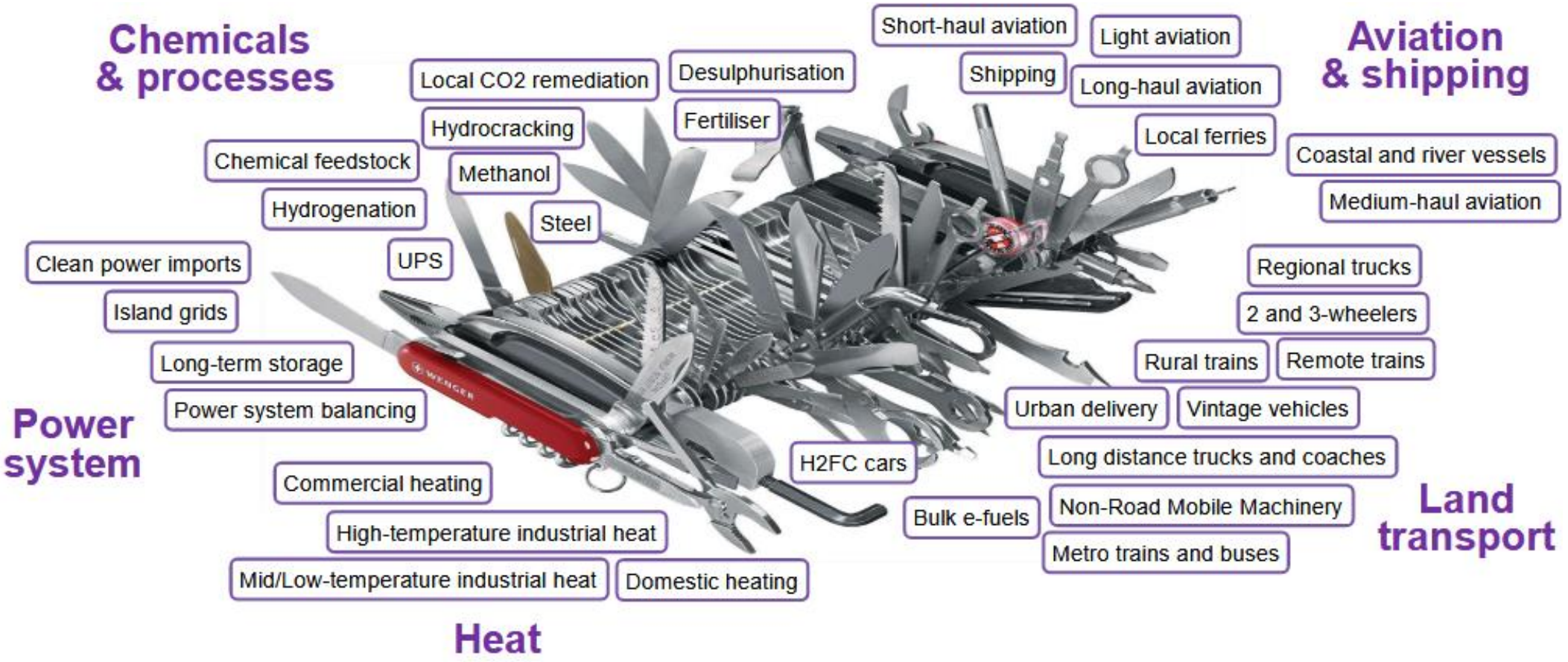
1. Aviation and maritime include direct use of hydrogen and hydrogen-derived synfuels including kerosene, diesel, methanol, gasoline, and ammonia. The category also includes some hydrogen-derived synfuels in road transport
2. New industry includes all new uses of hydrogen in Industrial processes, eg,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

Source: McKinsey 2022

Is hydrogen the Swiss-Knife for the energy transition?

2. Hydrogen Applications

Hydrogen Applications

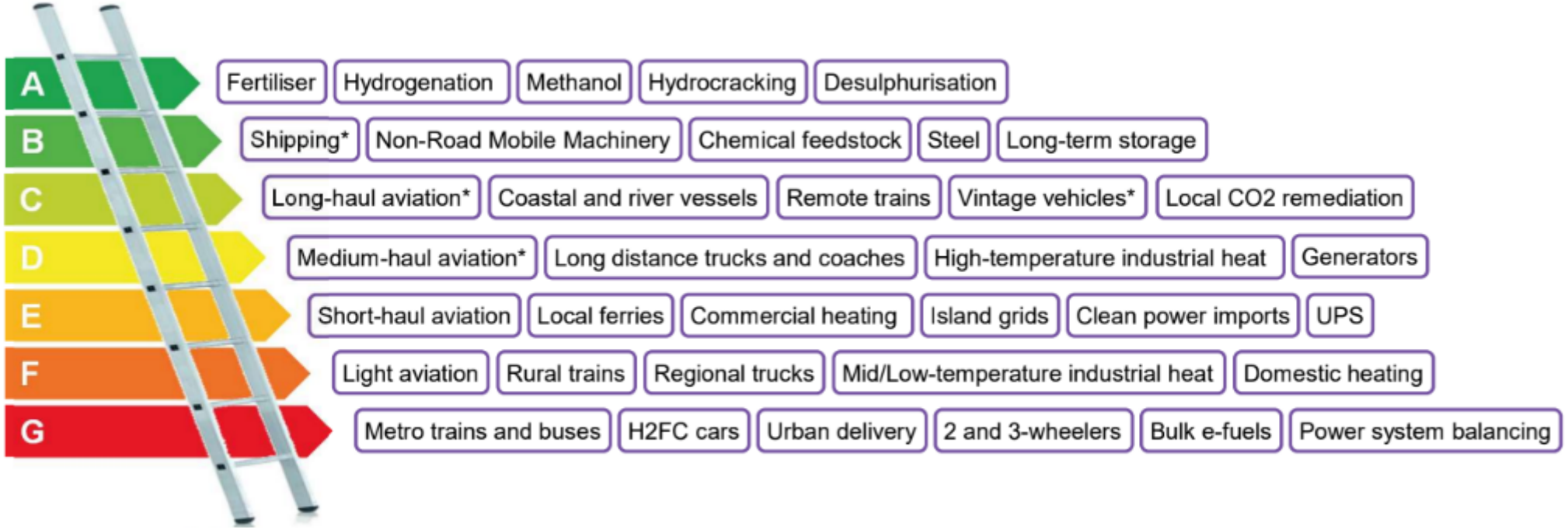


Green hydrogen has multiple cross sector application options

Source: Liebreich Associates

Green Hydrogen Ladder[1]

Unavoidable



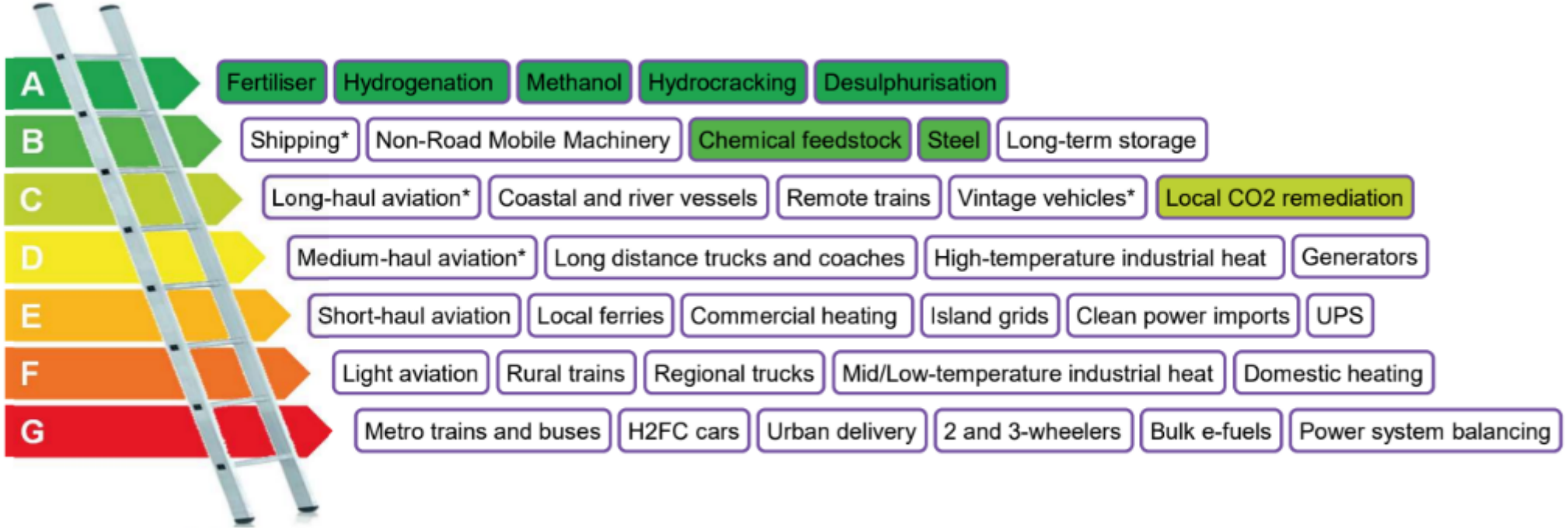
High competition

** Most likely via ammonia or e-fuel rather than H2 gas or liquid*

Source: Liebreich Associates; [1]European perspective, for other regions with different conditions (e.g. South America) some hydrogen applications can be more/less promising

Green Hydrogen Ladder[1]: Chemicals and Processes

Unavoidable



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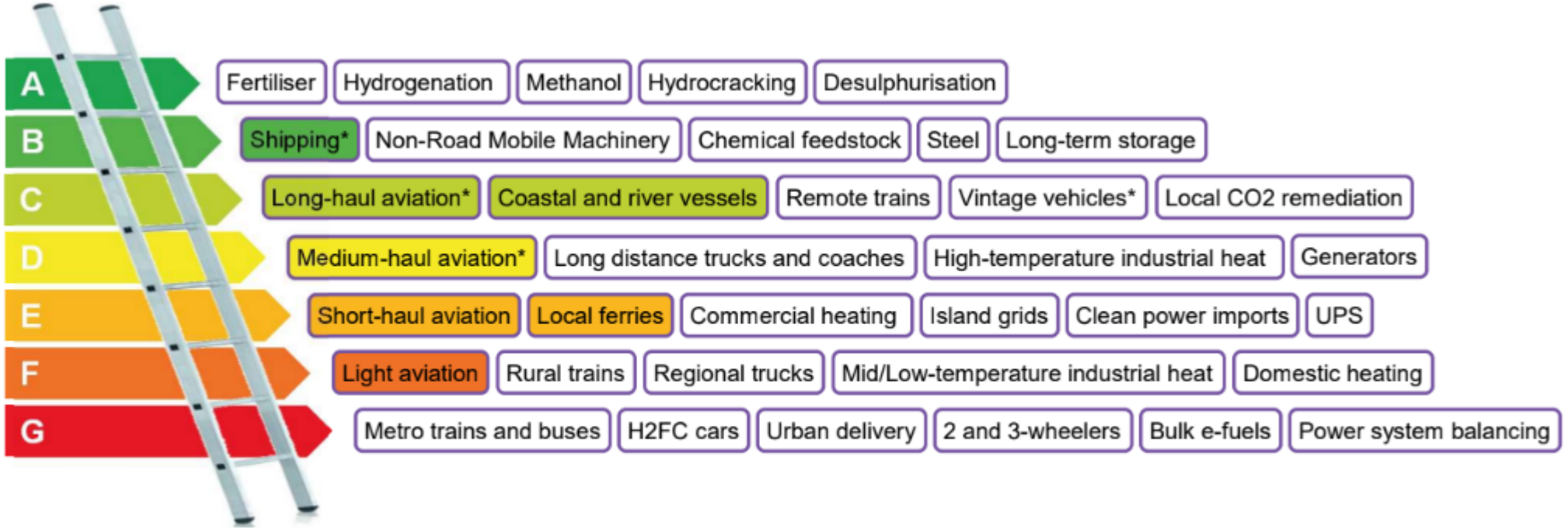
Green Hydrogen Ladder[1]: Aviation and Shipping

Unavoidable



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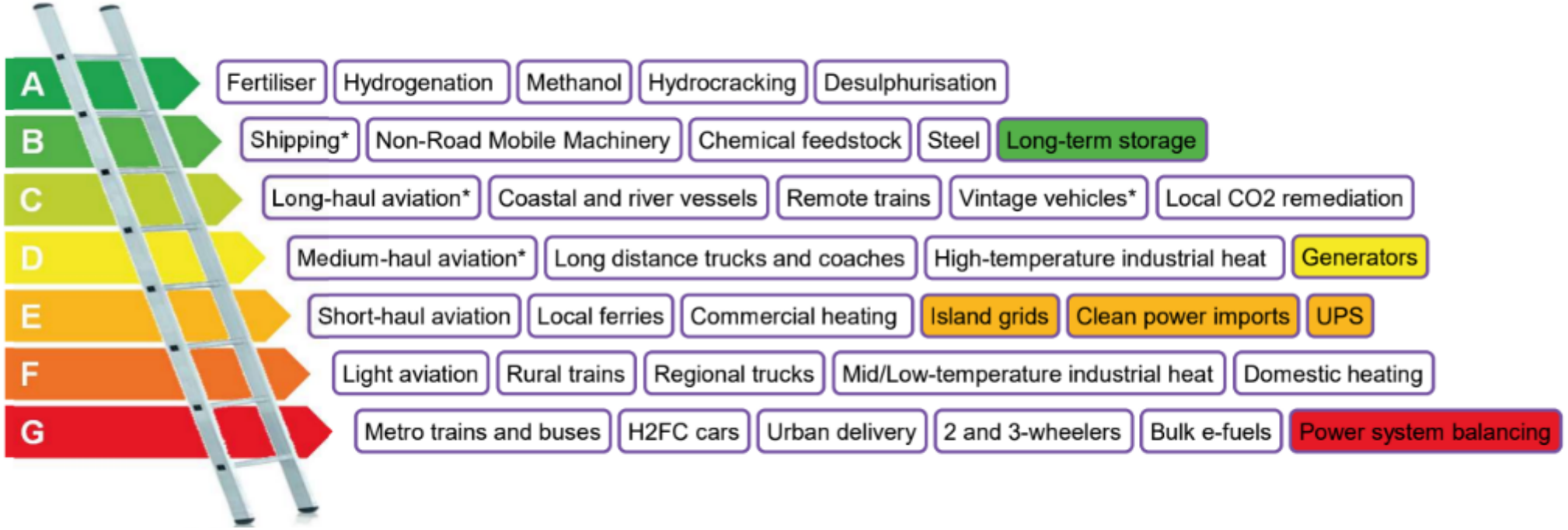
Green Hydrogen Ladder[1]: Power System

Unavoidable



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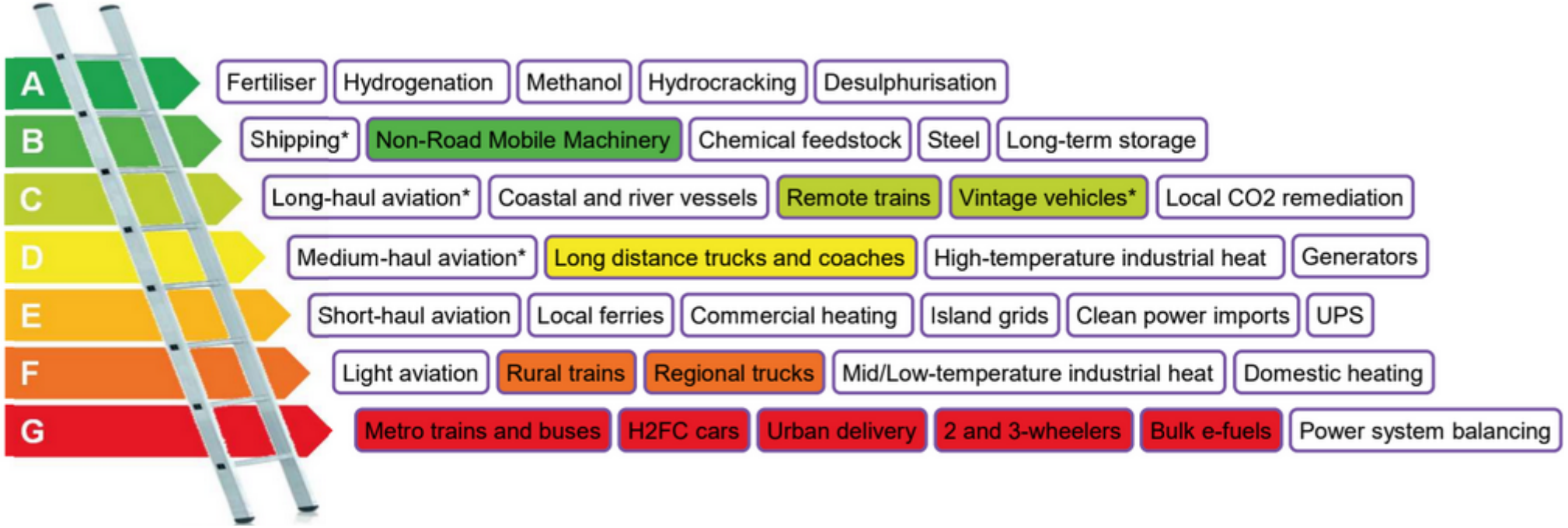
Source: Liebreich Associates; [1]European perspective, for other regions with different conditions (e.g. South America) some hydrogen applications can be more/less promising

Green Hydrogen Ladder[1]: Land Transportation

Unavoidable



High competition

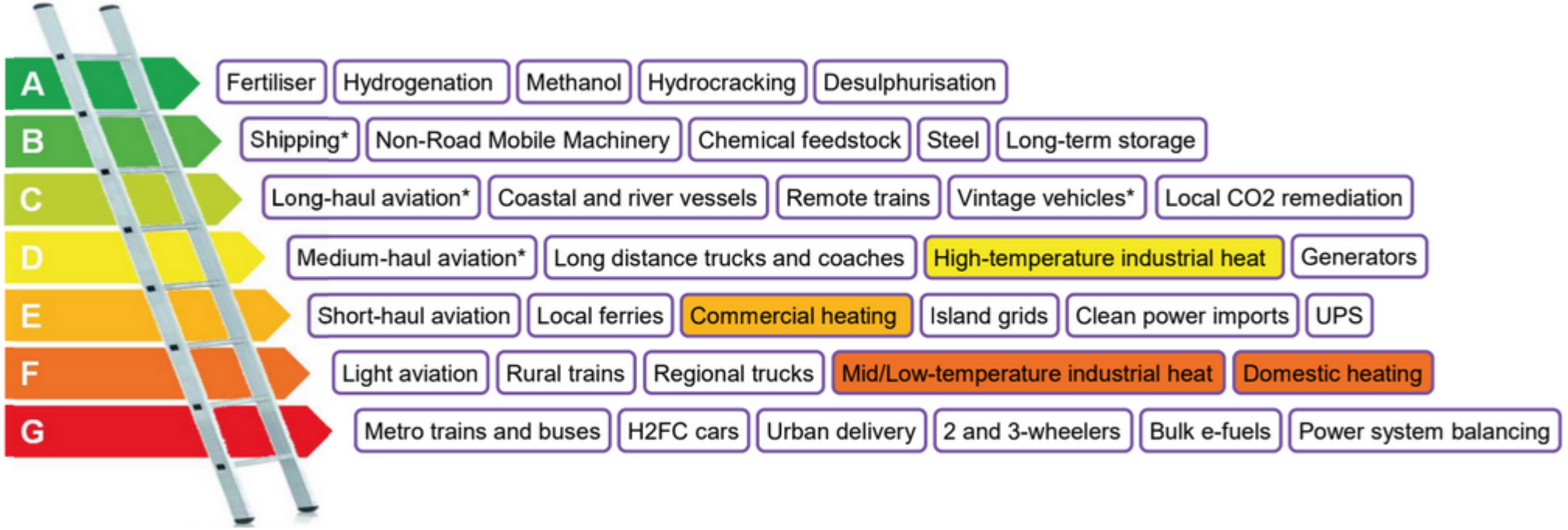
** Most likely via ammonia or e-fuel rather than H2 gas or liquid*

Due to very different conditions in Colombia than in Germany/EU (electricity grid, regulations, transport distances) the role of hydrogen in land transportation in Colombia is probably more important

Source: Liebreich Associates; [1]European perspective, for other regions with different conditions (e.g. South America) some hydrogen applications can be more/less promising

Green Hydrogen Ladder[1]: Heating

Unavoidable



High competition

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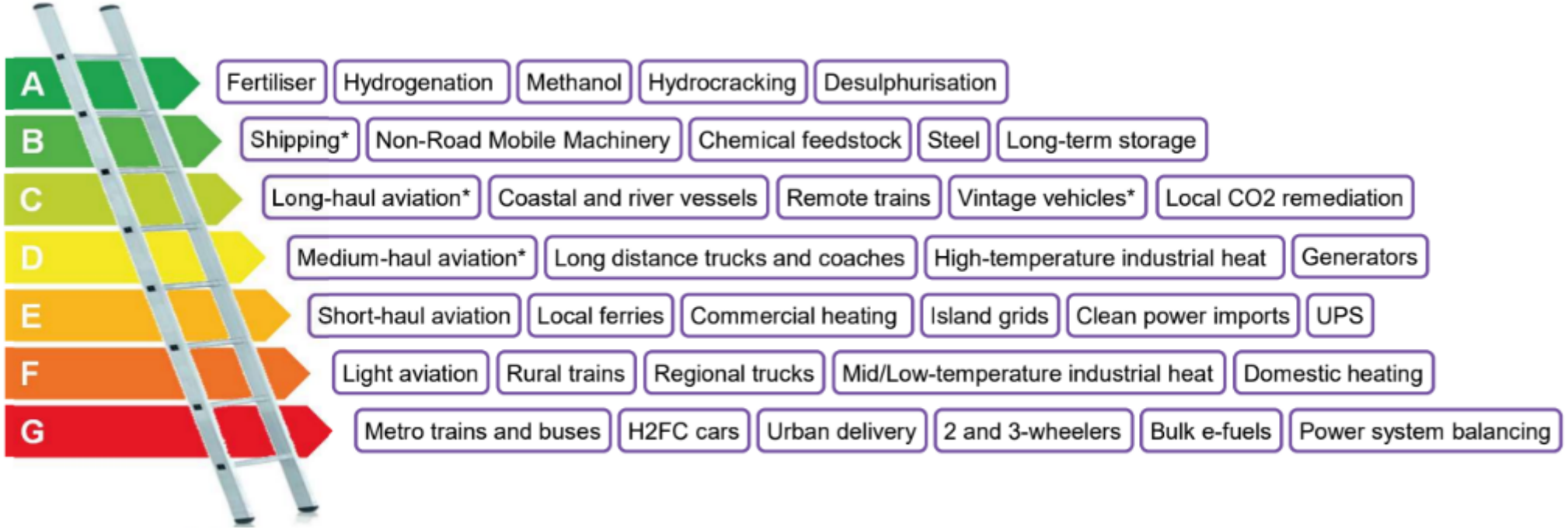
Source: Liebreich Associates; [1]European perspective, for other regions with different conditions (e.g. South America) some hydrogen applications can be more/less promising

Green Hydrogen Ladder[1]

Unavoidable



High competition

** Most likely via ammonia or e-fuel rather than H2 gas or liquid*

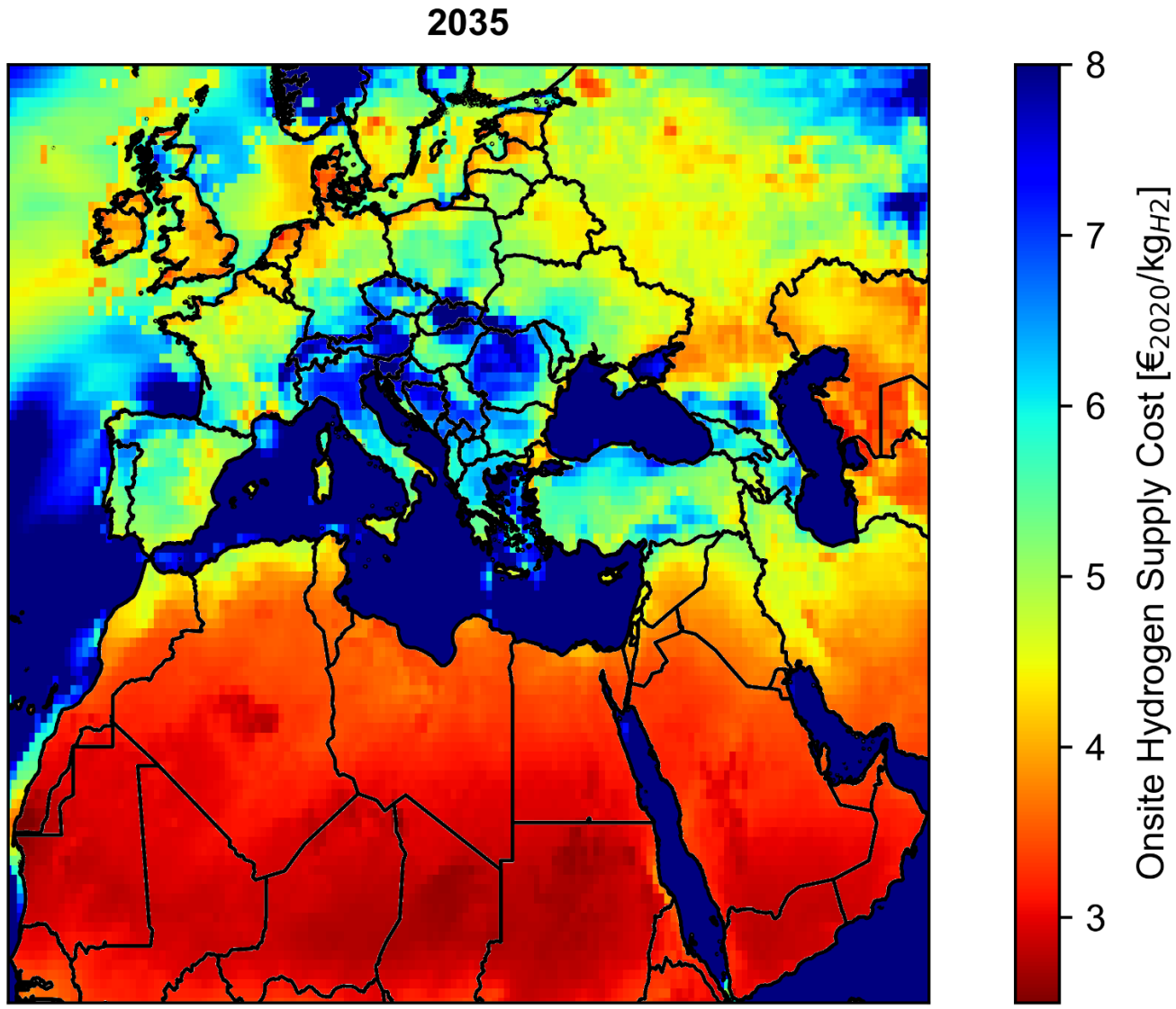
Green hydrogen is a very promising energy carrier in many sectors but should not be used dogmatically if there are more promising options

Source: Liebreich Associates; [1]European perspective, for other regions with different conditions (e.g. South America) some hydrogen applications can be more/less promising

How will we transport and distribute hydrogen?

3. Hydrogen Infrastructure

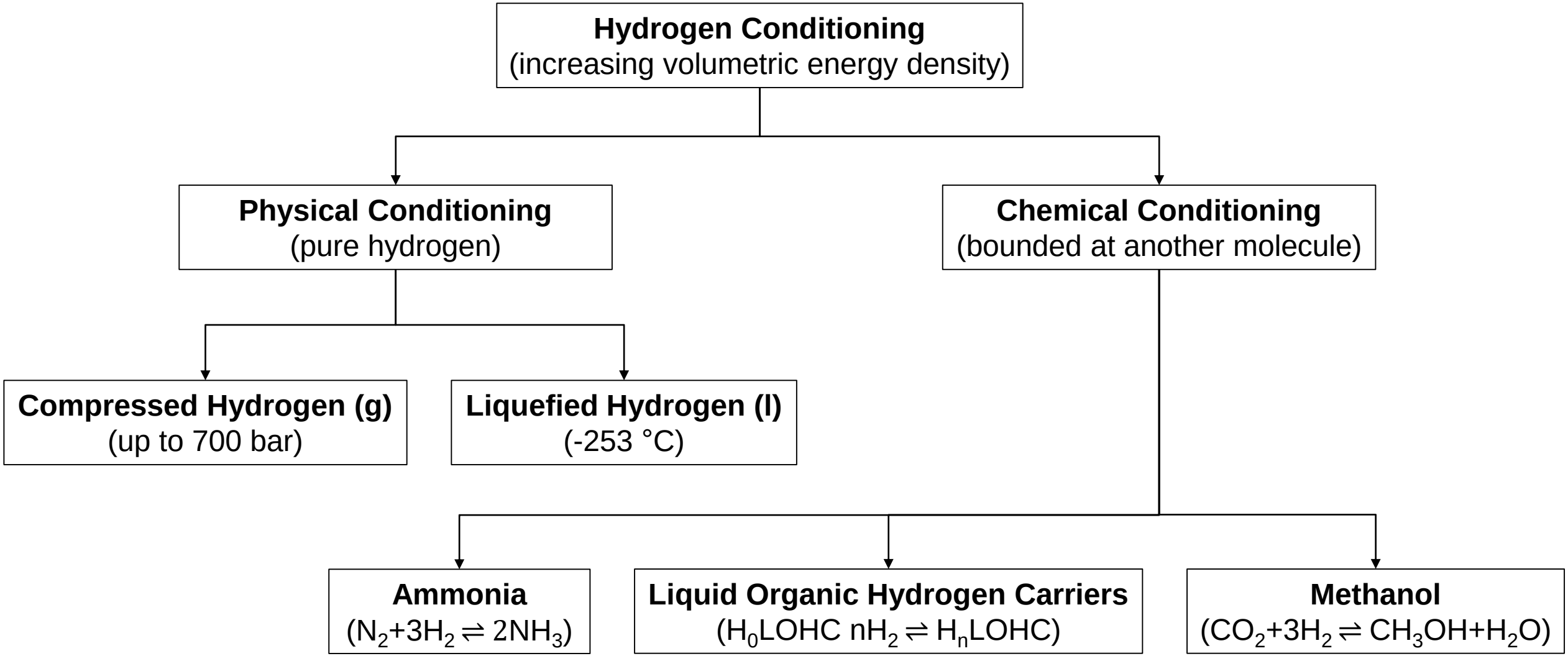
Need of Hydrogen Infrastructure



- Hydrogen production cost differ significantly between regions depending on the renewable energy resources
- Hydrogen transportation between regions is very likely
- Due to hydrogens low energy density at ambient conditions a conditioning is needed to increase the energy density

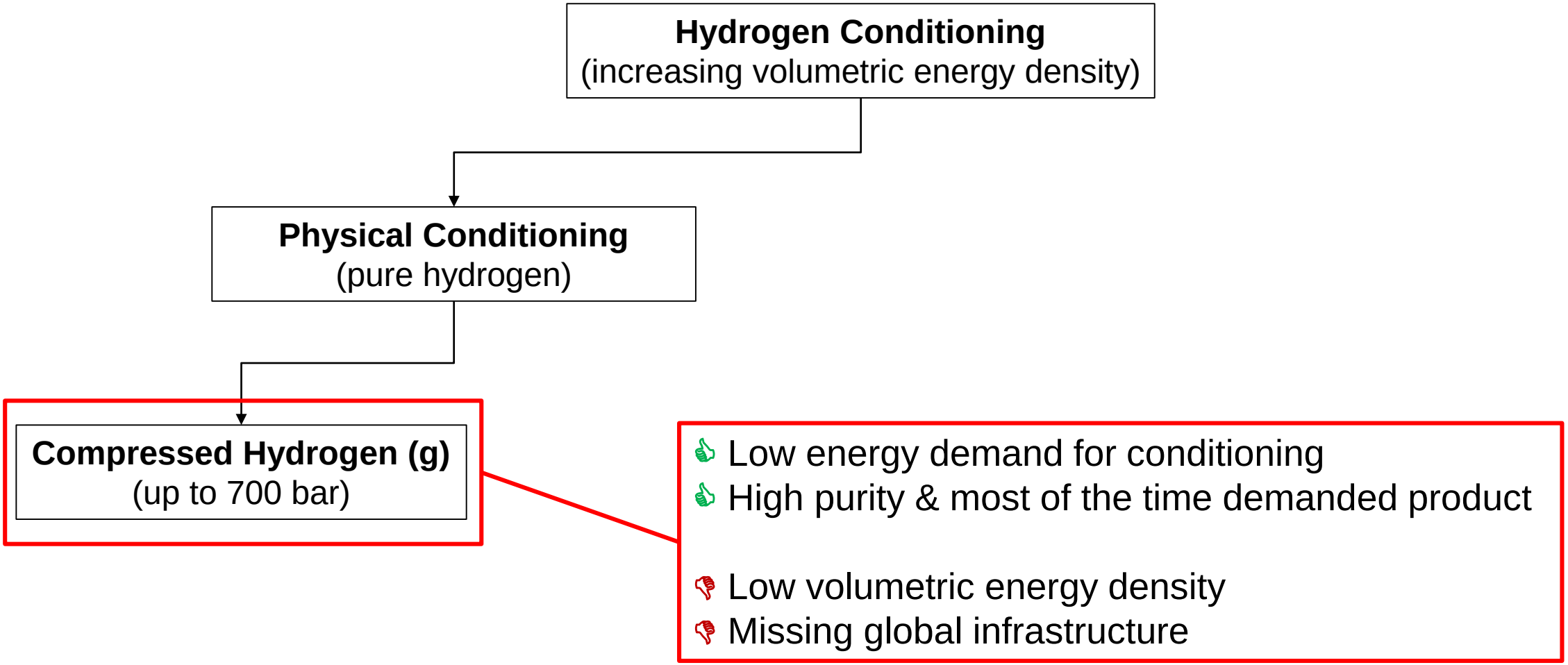
Source: Sens et al. 2022a

Hydrogen Conditioning Options



Source: Sens et al. 2022a

Hydrogen Conditioning Options



Source: Sens et al. 2022a

Hydrogen Conditioning Options

Hydrogen Conditioning
(increasing volumetric energy density)

Physical Conditioning
(pure hydrogen)

Liquefied Hydrogen (l)
(-253 °C)

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

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

Source: Sens et al. 2022a

Hydrogen Conditioning Options

Hydrogen Conditioning
(increasing volumetric energy density)

Chemical Conditioning
(bounded at another molecule)

- 👍 Handling in given infrastructure
- 👍 Demand for pure ammonia

- 👎 High energy demand for dehydrogenation
- 👎 Purity of dehydrogenated hydrogen

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

Source: Sens et al. 2022a

Hydrogen Conditioning Options

Hydrogen Conditioning
(increasing volumetric energy density)

Chemical Conditioning
(bounded at another molecule)

- 👍 Easy handling in given infrastructure
- 👍 Demand for pure methanol

- 👎 High energy demand for dehydrogenation
- 👎 Availability and high cost for green carbon dioxide

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

Source: Sens et al. 2022a

Hydrogen Conditioning Options

Hydrogen Conditioning
(increasing volumetric energy density)

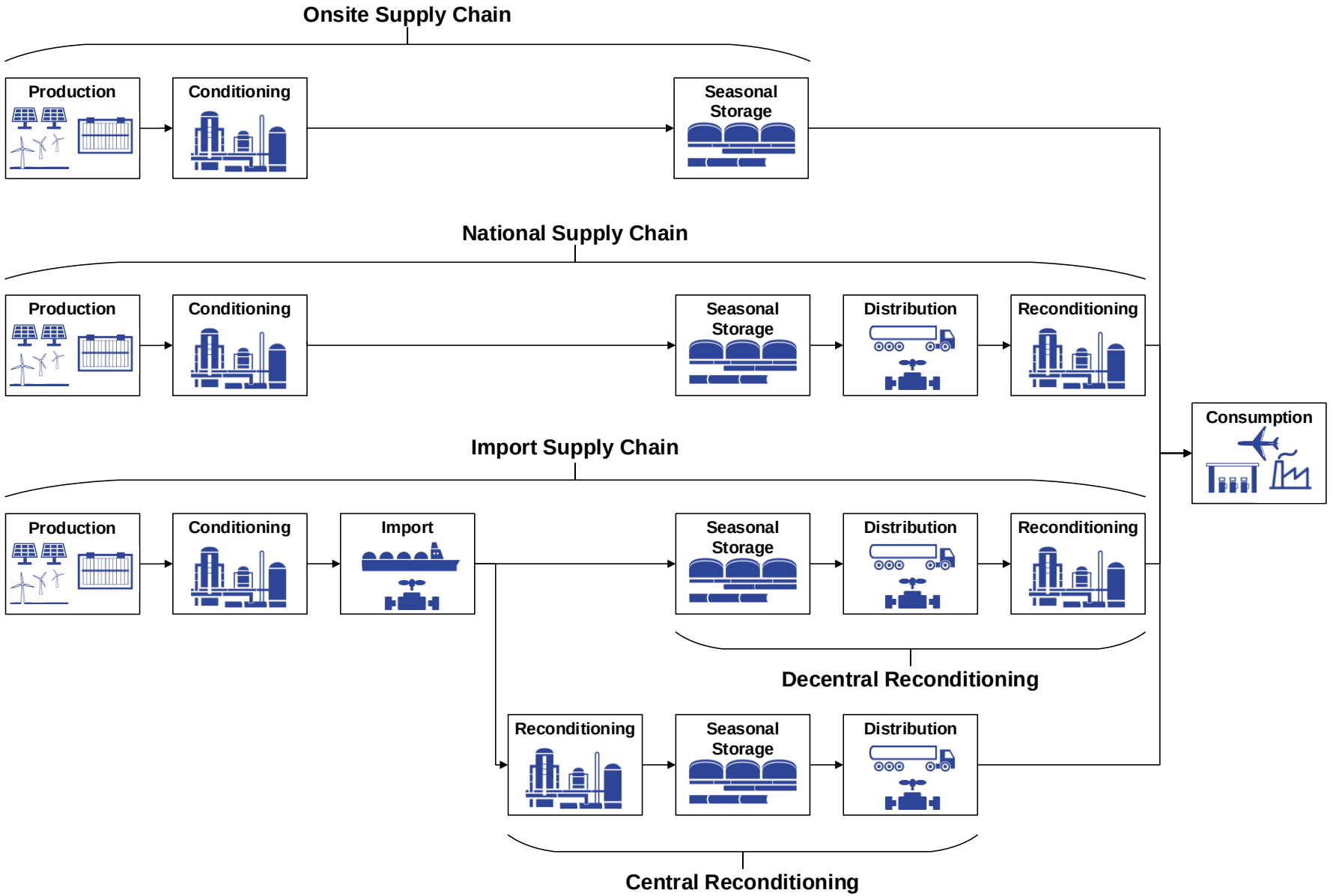
- 👍 Easy handling in given infrastructure
- 👍 Not flammable / explosive
- 👎 Very high energy demand for dehydrogenation
- 👎 High cost for carrier material

Chemical Conditioning
(bounded at another molecule)

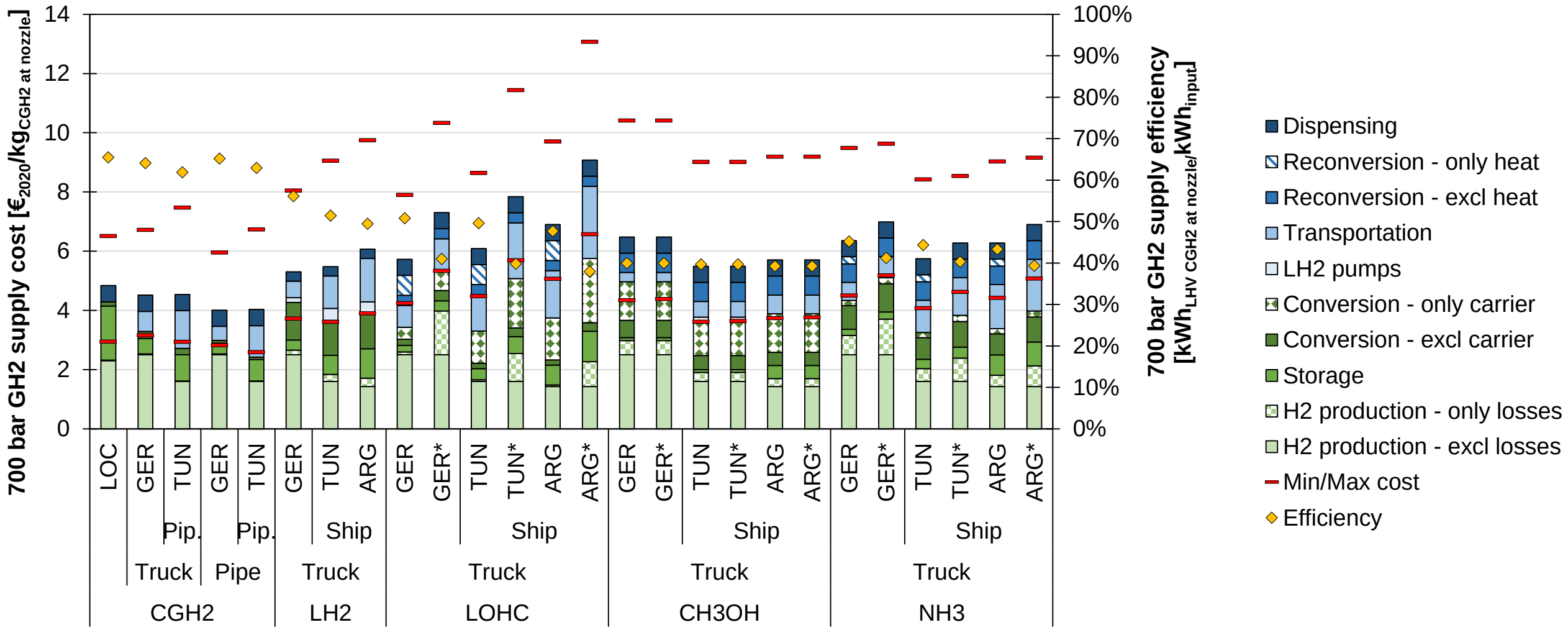
Liquid Organic Hydrogen Carriers
($H_0LOHC\ nH_2 \rightleftharpoons H_nLOHC$)

Source: Sens et al. 2022a

Hydrogen Supply Chains



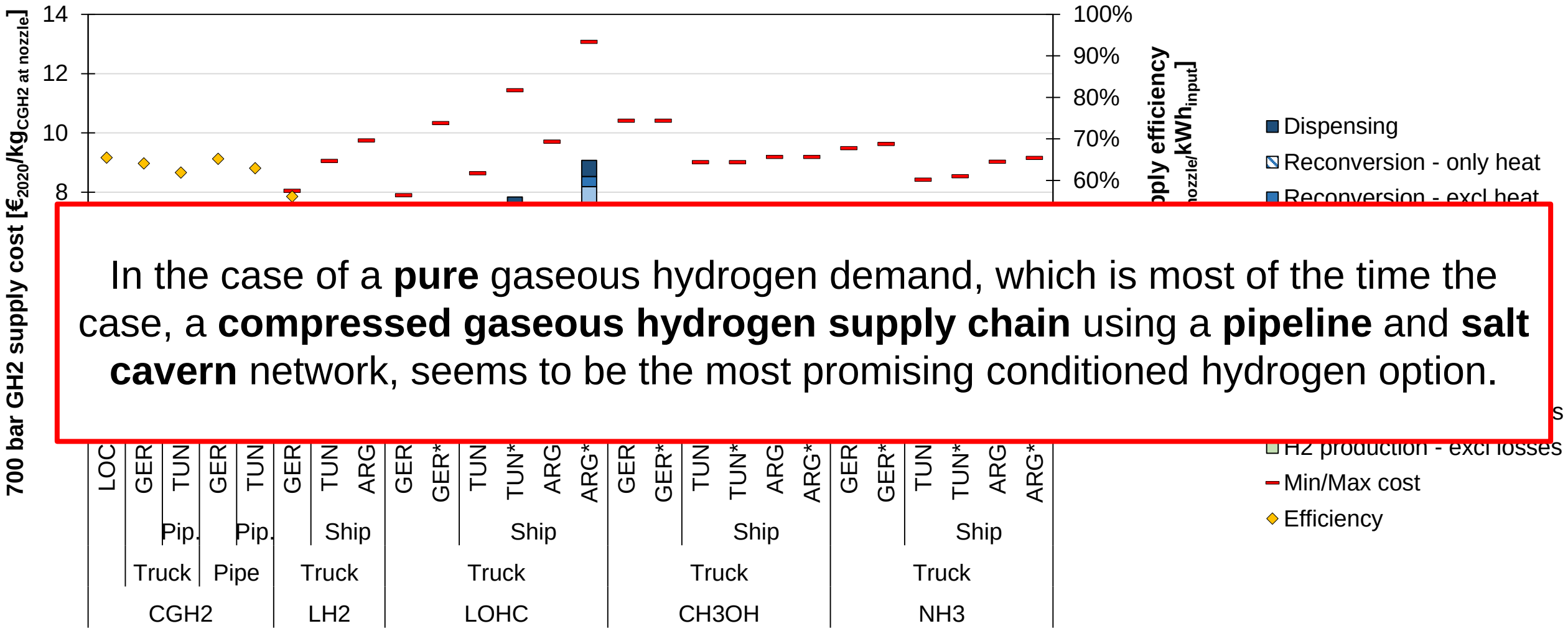
Hydrogen Supply Cost in 2050



(* = 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

Source: Sens et al. 2022b

Hydrogen Supply Cost in 2050



In the case of a **pure** gaseous hydrogen demand, which is most of the time the case, a **compressed gaseous hydrogen supply chain** using a **pipeline** and **salt cavern** network, seems to be the most promising conditioned hydrogen option.

(* = 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

Source: Sens et al. 2022b

What will be the gold standard?

4. Regulatory Framework

The Colors of Hydrogen

- **Most important:**
  - **Green H_2**: Electrolysis powered by renewable energy
  - **Turquoise H_2**: Methane pyrolysis producing elementary carbon
  - **Blue H_2**: Steam methane reformation with CCS
  - **Grey H_2**: Steam methane reformation without CCS
- **Further:**
  - **Brown H_2**: Coal gasification without CCS
  - **Red H_2**: Electrolysis powered by nuclear energy
  - **White H_2**: Naturally occurring geological hydrogen
  - **Orange H_2**: Biomass or waste based production

Type of hydrogen which is probably promoted by the upcoming legal EU framework

TBD

Regulatory Framework – Revised RED 2

- **Additionality:**
  - New renewable power generation is needed for new hydrogen projects
  - Installation of electrolyzer and renewable power within 36 months
  - Phase-in period until 2026

- **Temporal correlation:**
  - Hydrogen production occurring in the same hour than electricity generation from 2027 on
  - Until 2026 a monthly correspondence is sufficient

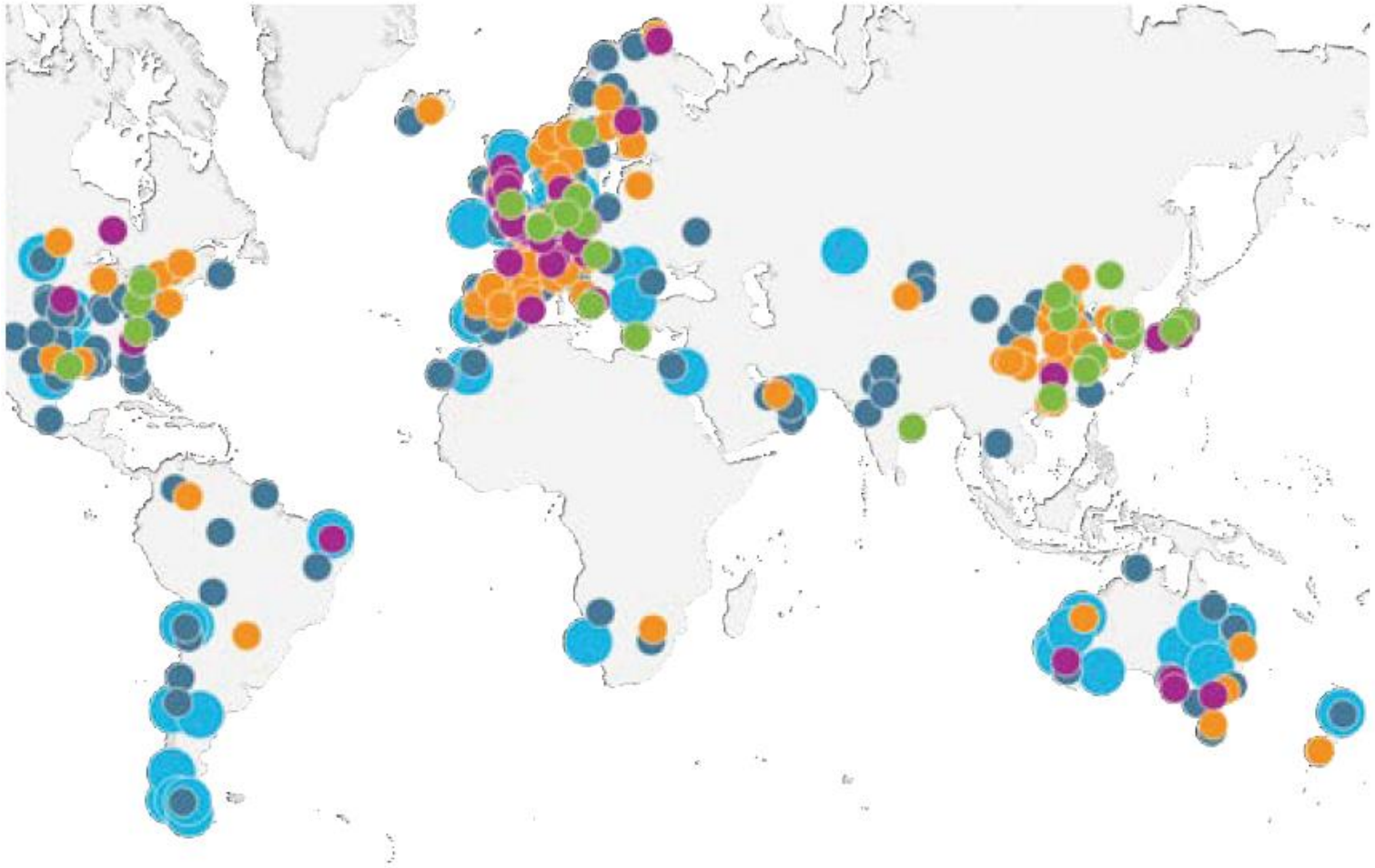
- **Exceptions:**
  - Electrolyzers supporting the integration of renewable power into the electricity system
  - Bidding zones where renewable power generation represents the dominant share of the power mix in the electricity system*

RED = Renewable Energy Directive ;* and additional renewable power generation capacity would not be necessary or possible

Only announcements or also final investment decisions?

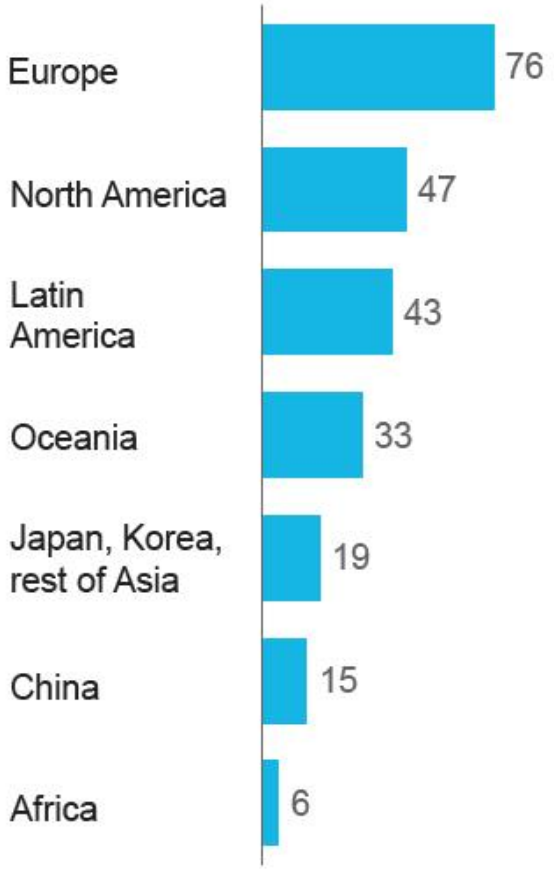
5. Hydrogen Projects

Announced Hydrogen Projects



USD 240bn

investments required for announced projects until 2030



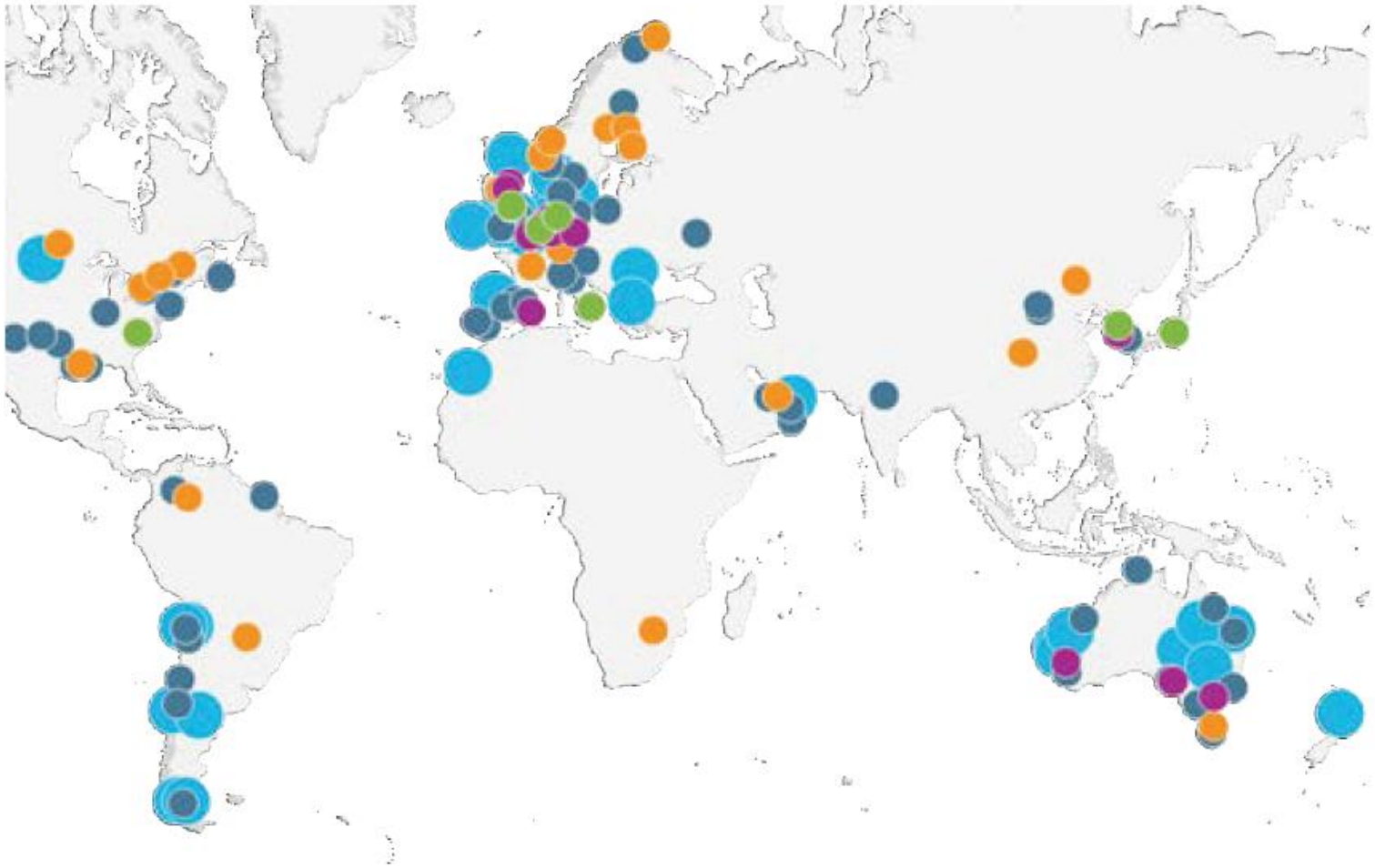
# of projects

- **51** Giga-scale production
- **262** Large-scale industrial use
- **128** Transport
- **53** Integrated H_2 economy
- **40** Infrastructure projects

In 2022 around $ 2,400bn have been invested in the global energy sector

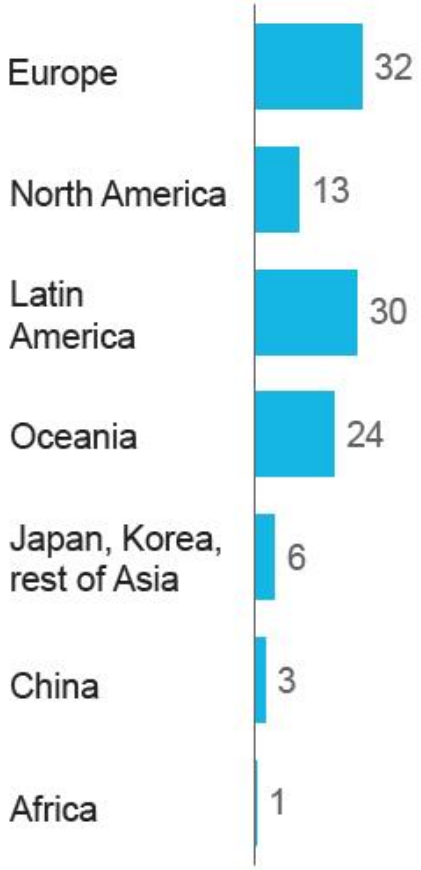
Source: Hydrogen Council 2022

Hydrogen Projects Undergoing Feasibility Studies



USD 109bn

investments until 2030, related to projects in planning



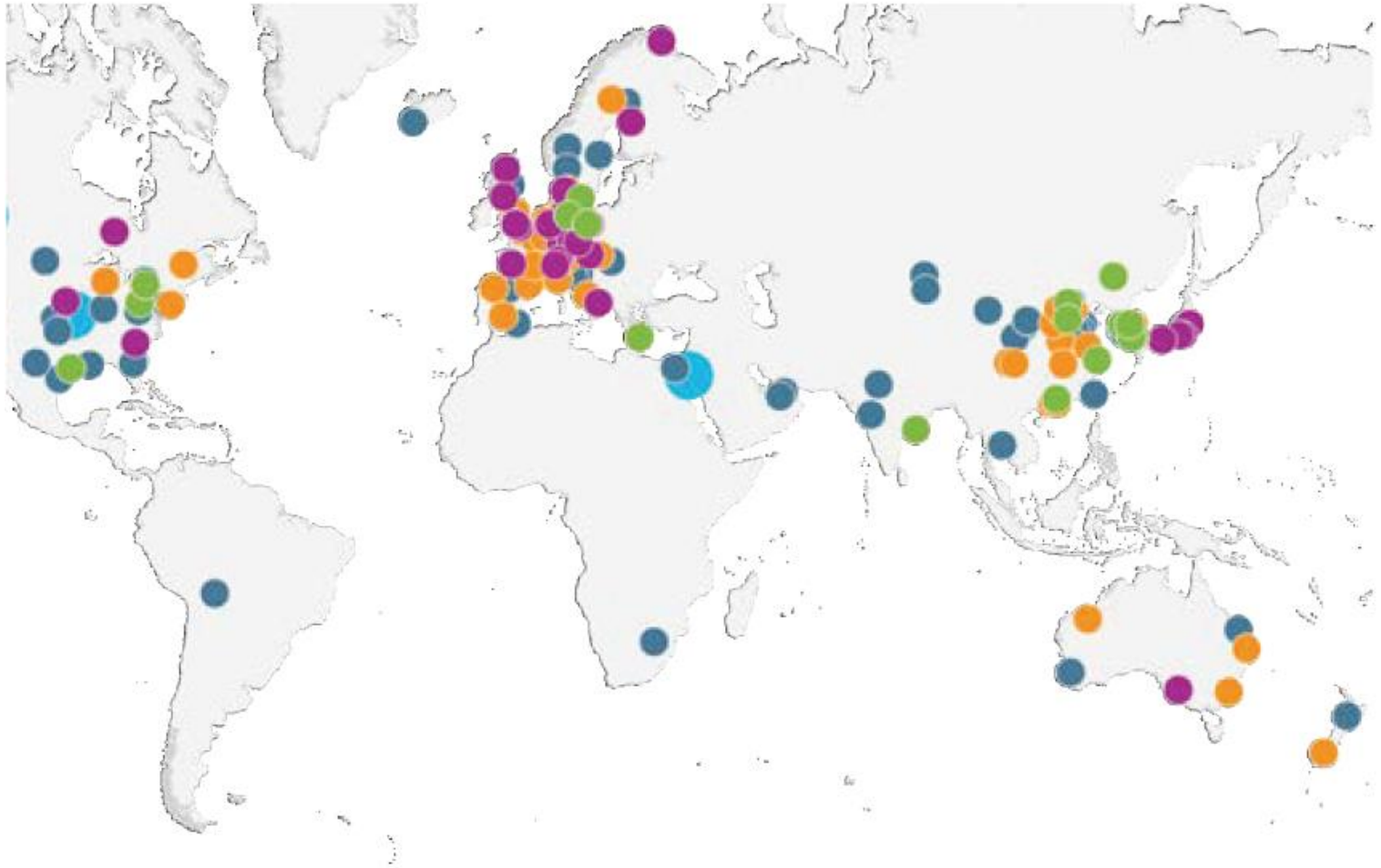
# of projects

- **33** Giga-scale production
- **86** Large-scale industrial use
- **26** Transport
- **13** Integrated H_2 economy
- **7** Infrastructure projects

Around 45% is undergoing feasibility studies

Source: Hydrogen Council 2022

Hydrogen Projects Achieved Final Investment Decisions



USD 22bn

investments until 2030, related to committed projects

Europe	6
North America	8
Latin America	<1
Oceania	<1
Japan, Korea, rest of Asia	6
China	2
Africa	<1

# of projects

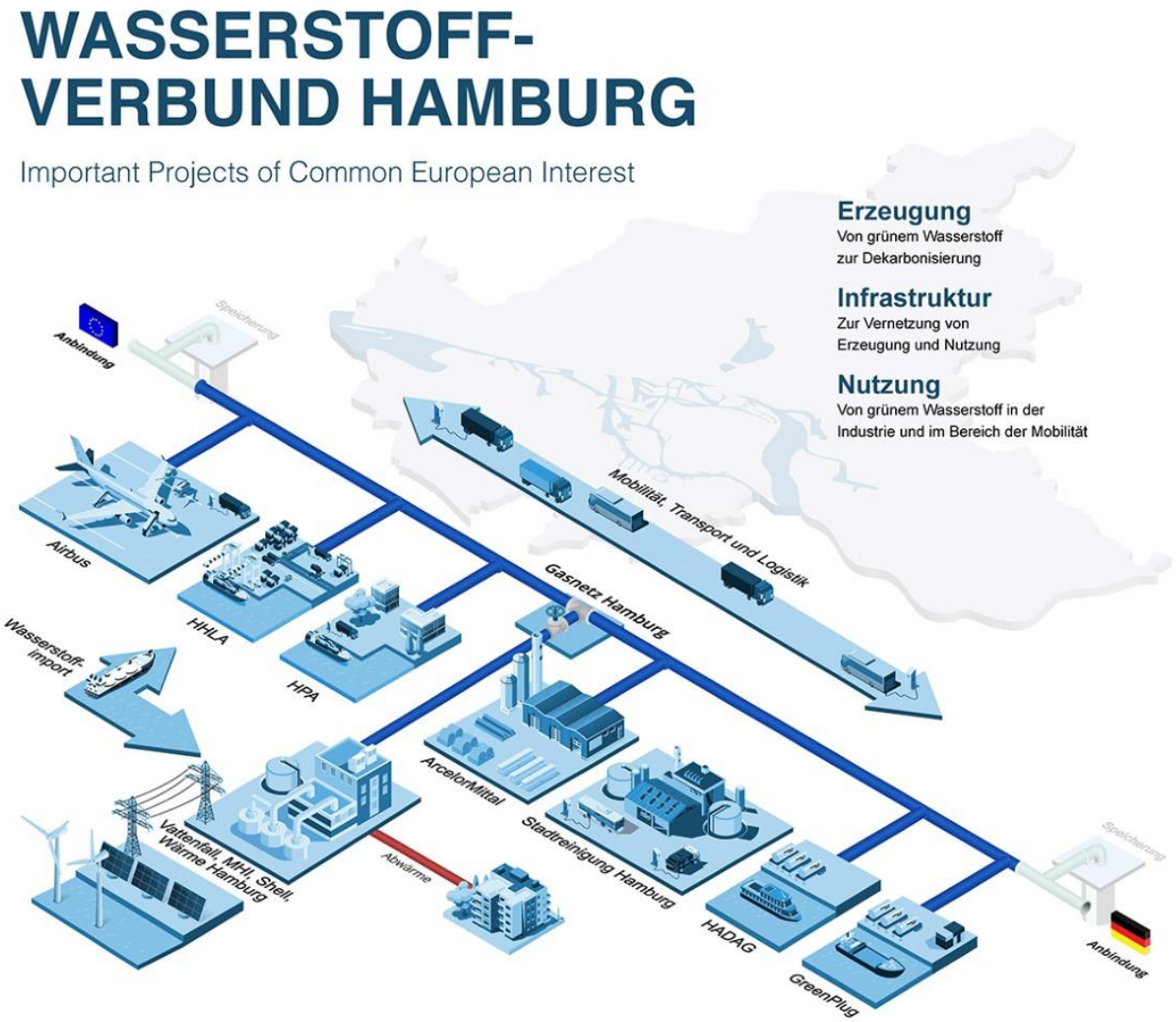
- **3** Giga-scale production
- **77** Large-scale industrial use
- **61** Transport
- **29** Integrated H_2 economy
- **19** Infrastructure projects

But less than 10% as achieved a final investment decision

Source: Hydrogen Council 2022

Hamburg Green Hydrogen Hub (Germany)

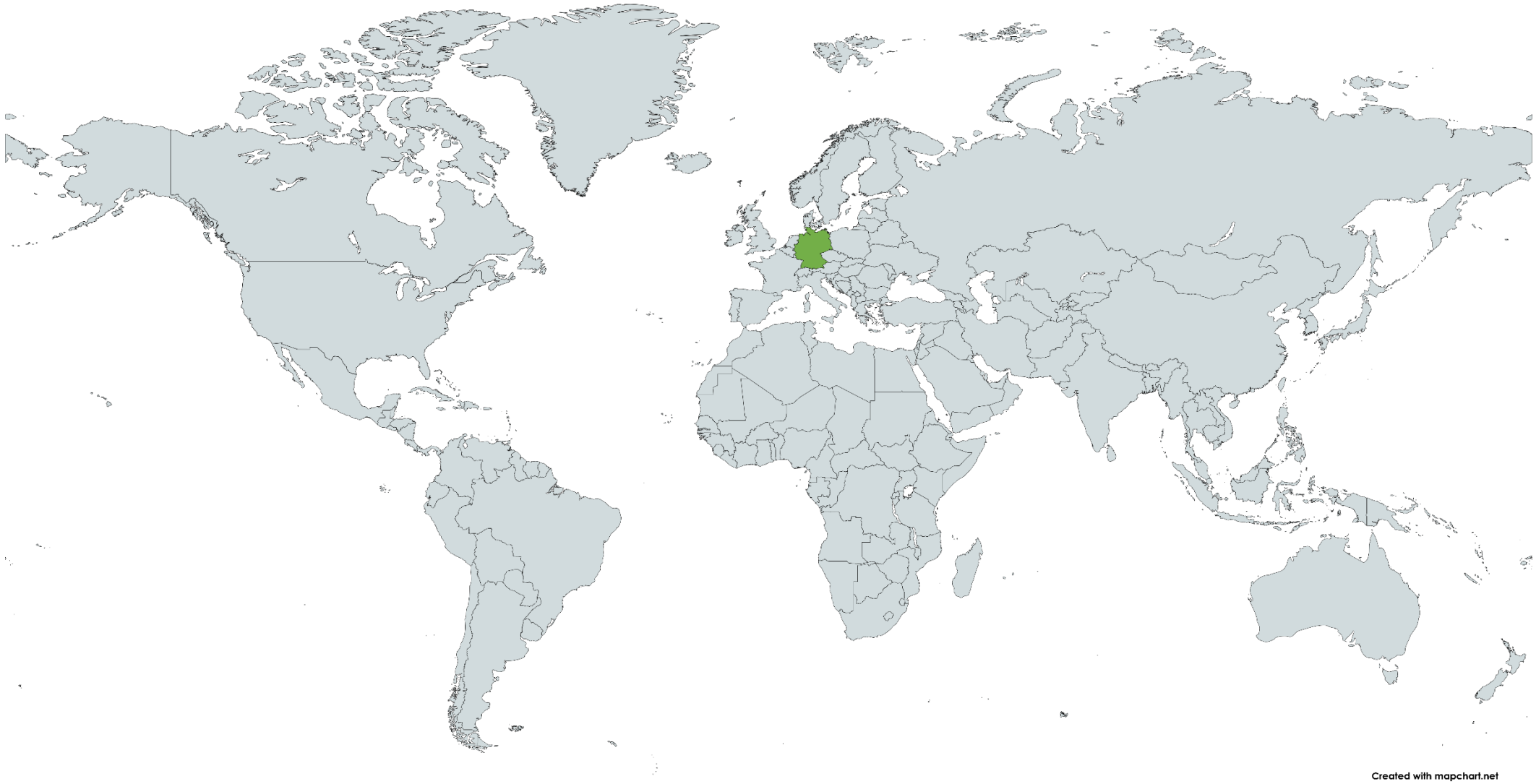
Hamburg Green Hydrogen Hub (Germany)



- Aiming for a local **hydrogen hub** covering production, infrastructure & consumption
- Construction of a local **hydrogen pipeline network of 40 km** starting in 2023, connecting industrial costumers with a 100 MW electrolysis
- Hydrogen **import terminal** planned
- **End use of hydrogen** in industry, logistics, trucks, ships & aviation aimed

Source: Vattenfall

Hydrogen in Germany

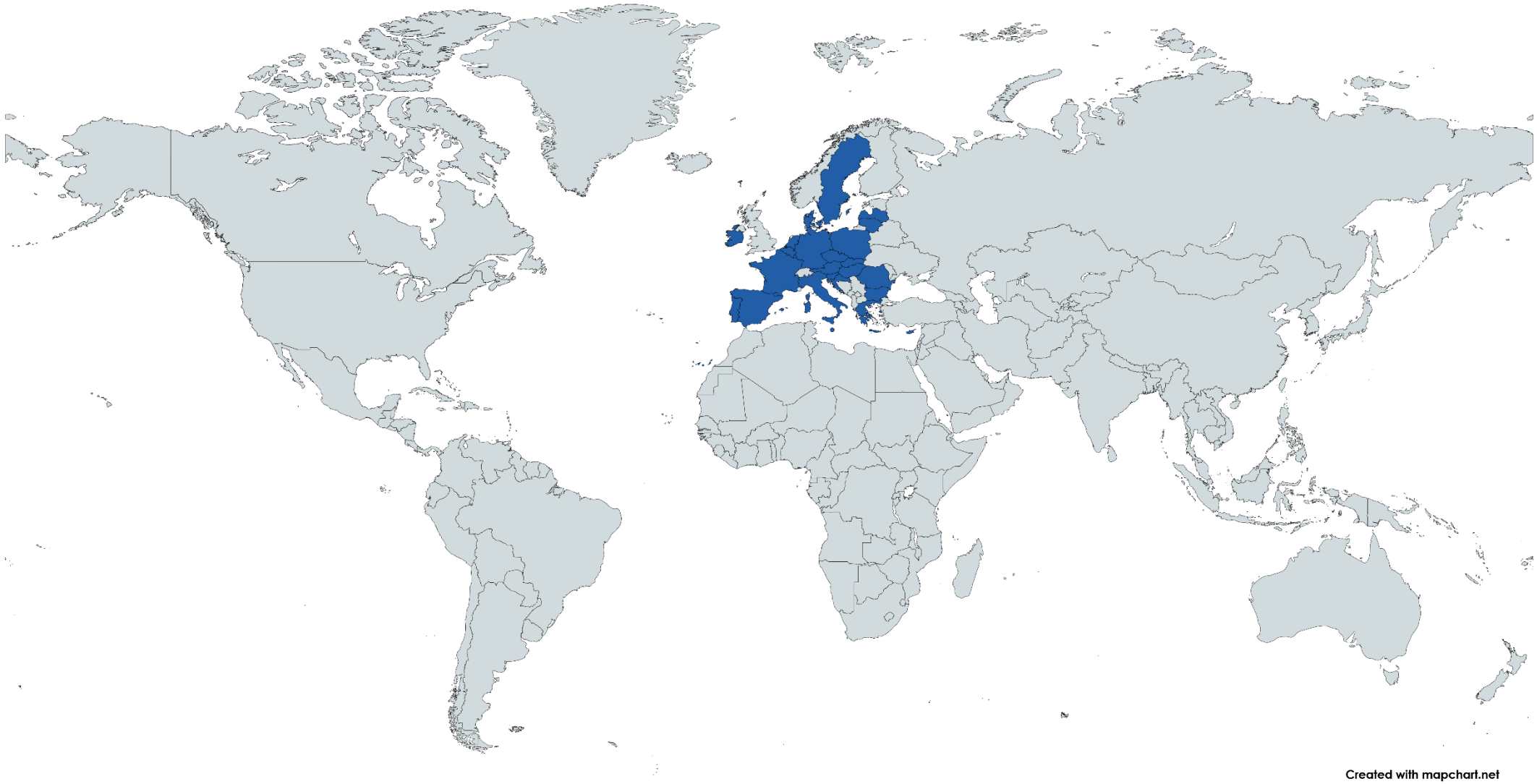


Hydrogen in Germany

- National Hydrogen Strategy set **10 GW electrolzyer** capacity installed in Germany as a target for 2030
- Germany is looking for international (import) **hydrogen partnerships**
- € 700m for **lighthouse hydrogen projects**:
  - Upscaling and mass production of electrolysers (H2Giga)
  - Offshore hydrogen generation without grid connection (H2Mare)
  - Technologies for the transport of hydrogen (TransHyDE)
- **€ 8bn state aid** to trigger € 33bn investment for 50 projects including 2 GW electrolyzer capacity and 1,700 km hydrogen pipelines

Source: Daimler, Airbus, FAZ

Hydrogen in the European Union

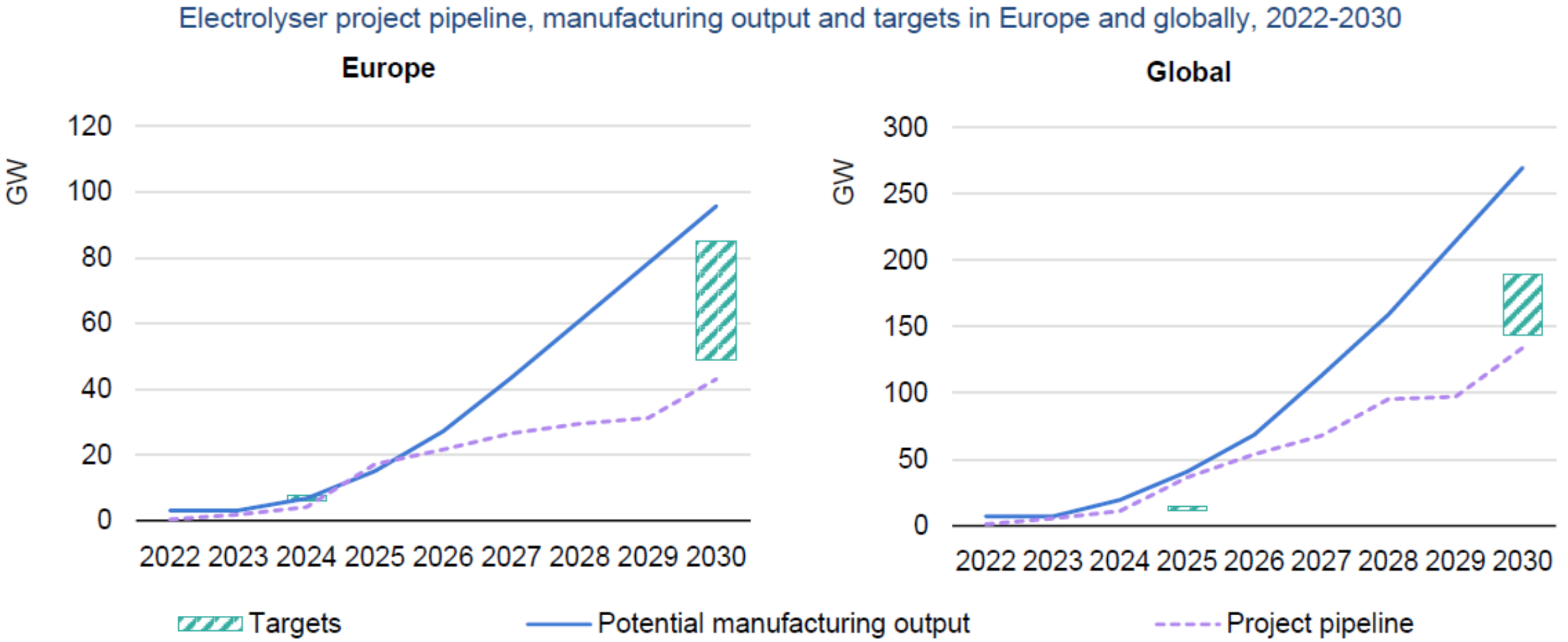


Hydrogen in the European Union

- The „REPowerEU“ program sets a target of **10m tons** of green hydrogen **domestically** by 2030 and **importing** additional **10m tons**
- **€ 225bn*** is already available in loans for the REPower EU programm
- € 20bn* are proposed to make available as funds
- Further up to € 40bn* are planned to provide in addition
- First round of hydrogen **IPCEI unlocks € 5.4bn state aid** for 35 companies unlocking an additional € 8.8bn in private investments

* Money for the green energy transition including hydrogen

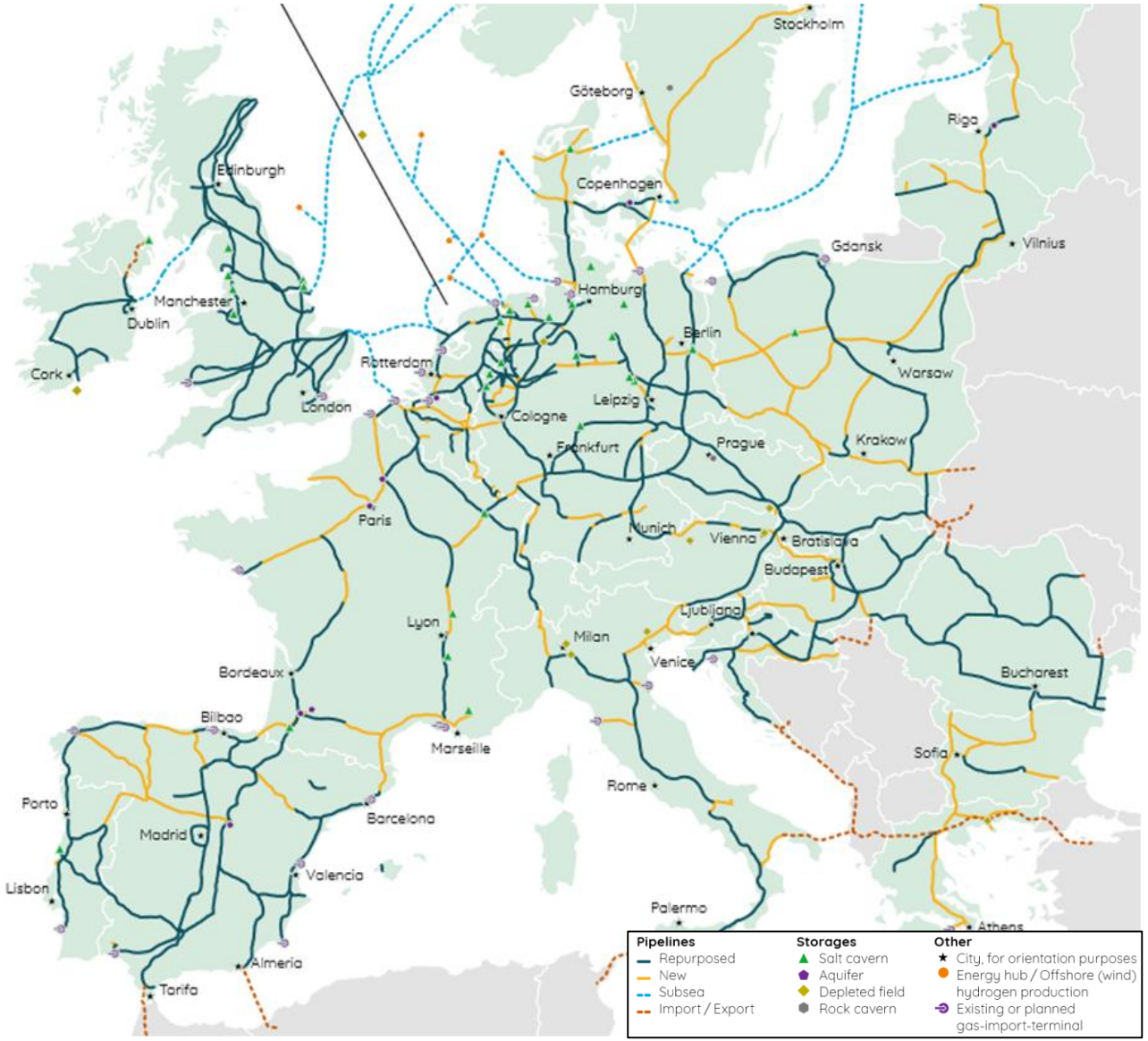
Eletrolyzer Production Capacities



Around one third of the global electrolyzer production capacity is expected in Europe

Source: IEA 2022

European Hydrogen Backbone



- **53,000 km** of hydrogen backbone pipelines
- **€ 80 to 143bn** investment needed
- **60% repurposed** natural gas pipelines and **40% new** hydrogen pipelines
- **€ 0.1 to 0.2** per kg of hydrogen when transporting over 1,000 km

Source: European Hydrogen Backbone

Which challenges are we facing and how can we solve them?

6. Hydrogen Ramp Up

Challenges

- Enable **demand visibility** and **regulatory certainty** by adopting legally binding measures
- **Fast-track access** to public funding for hydrogen projects
- Ensure **international coordination** and support credible **common standards** and robust tradable certification systems
- Build up the needed **renewable power** and electrolyzer capacities

H2Global Mechanism

- Double auction model enables **price security** for supply an demand side and therefore investment security
- Based on a mechanism in analogy to the Contracts for Difference approach, the **difference between supply prices** (production and transport) and **demand prices** will be **compensated** by using grant funding from the German government
- Long-term purchase contracts (10 a) on the supply side and short-term sales contracts on the demand side (both **competition-based bidding**)
- Initially granted with € 900m funding but is expected to reach **at least € 5bn** to provide sufficient security in Germany

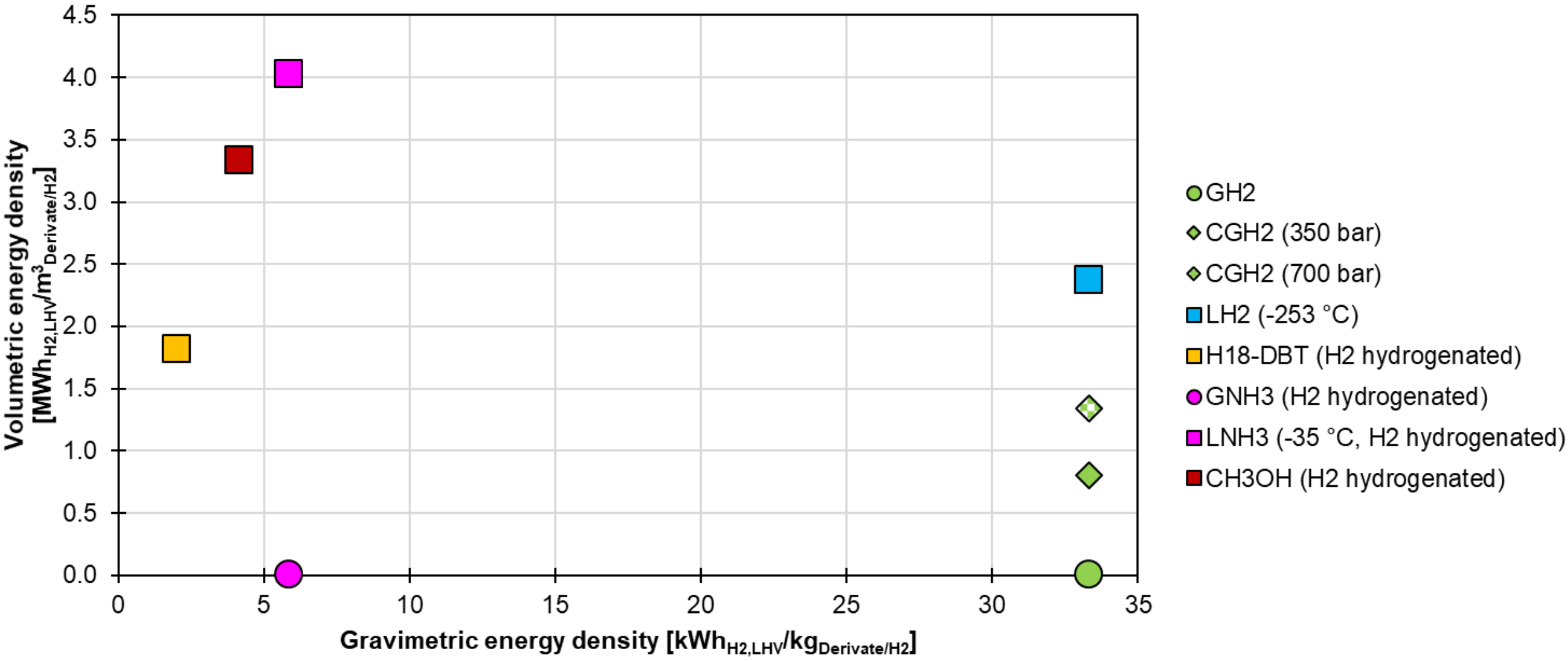
Thank you for your Attention!

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

Conditioned Hydrogen Options



Source: Sens et al. 2022c

Onsite Hydrogen Supply Cost in Colombia