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Webinar Series

Hydrogen and Hydrogen Derivates - Possibilities and Constraints

10.01.2024

The significance of hydrogen derivates

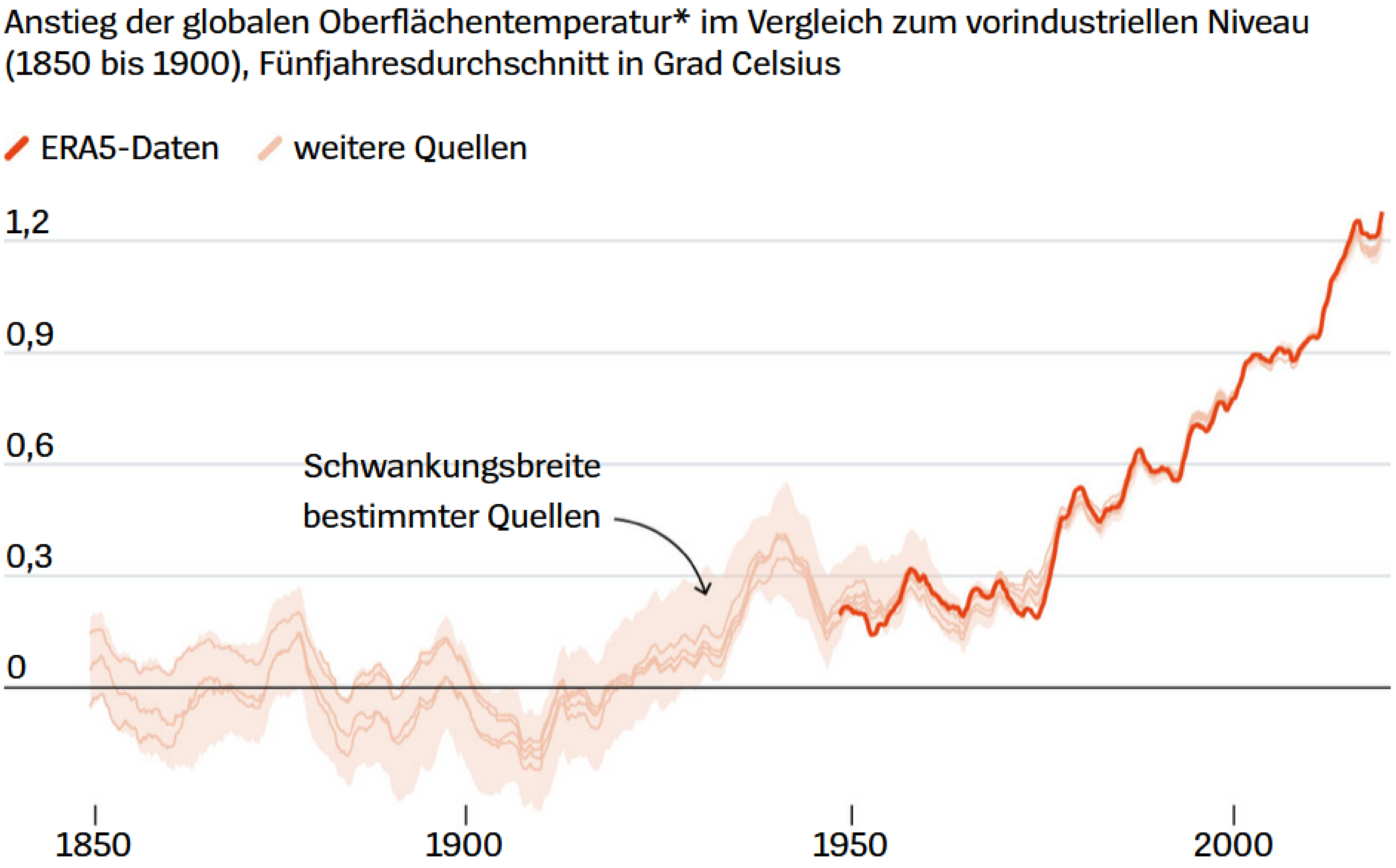
Part 1 - Background

Fabian Carels, Martin Kaltschmitt

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

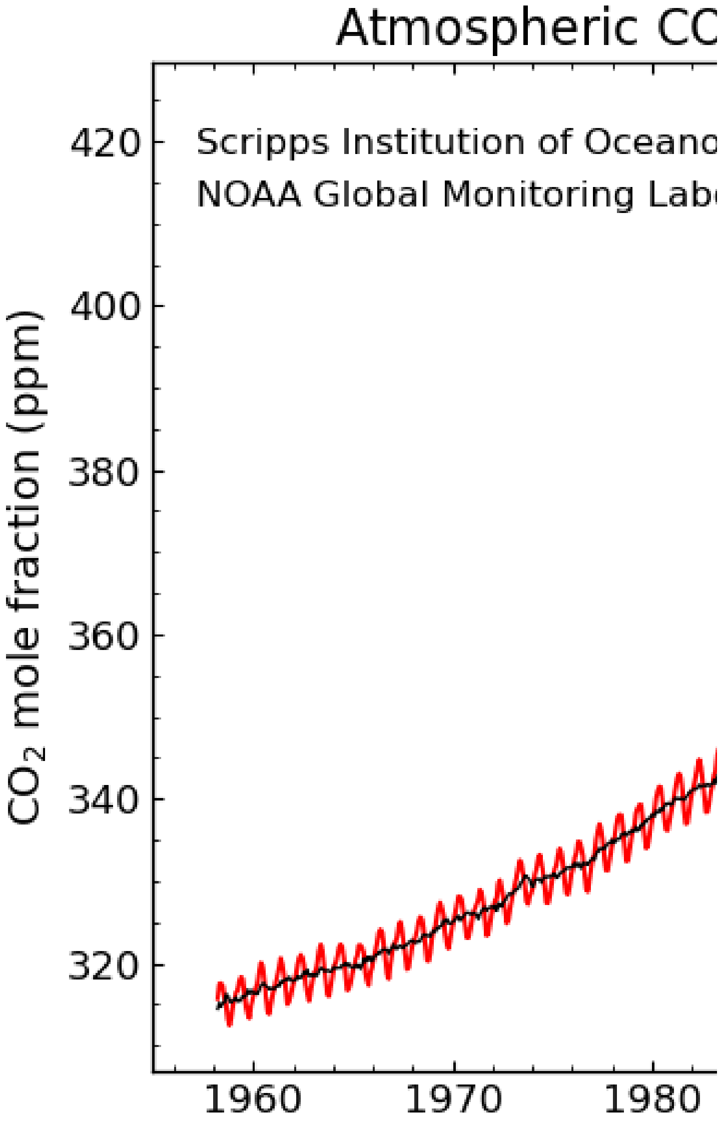
Hamburg University of Technology (TUHH), Institute of Environmental Technology and Energy Economics (IUE)

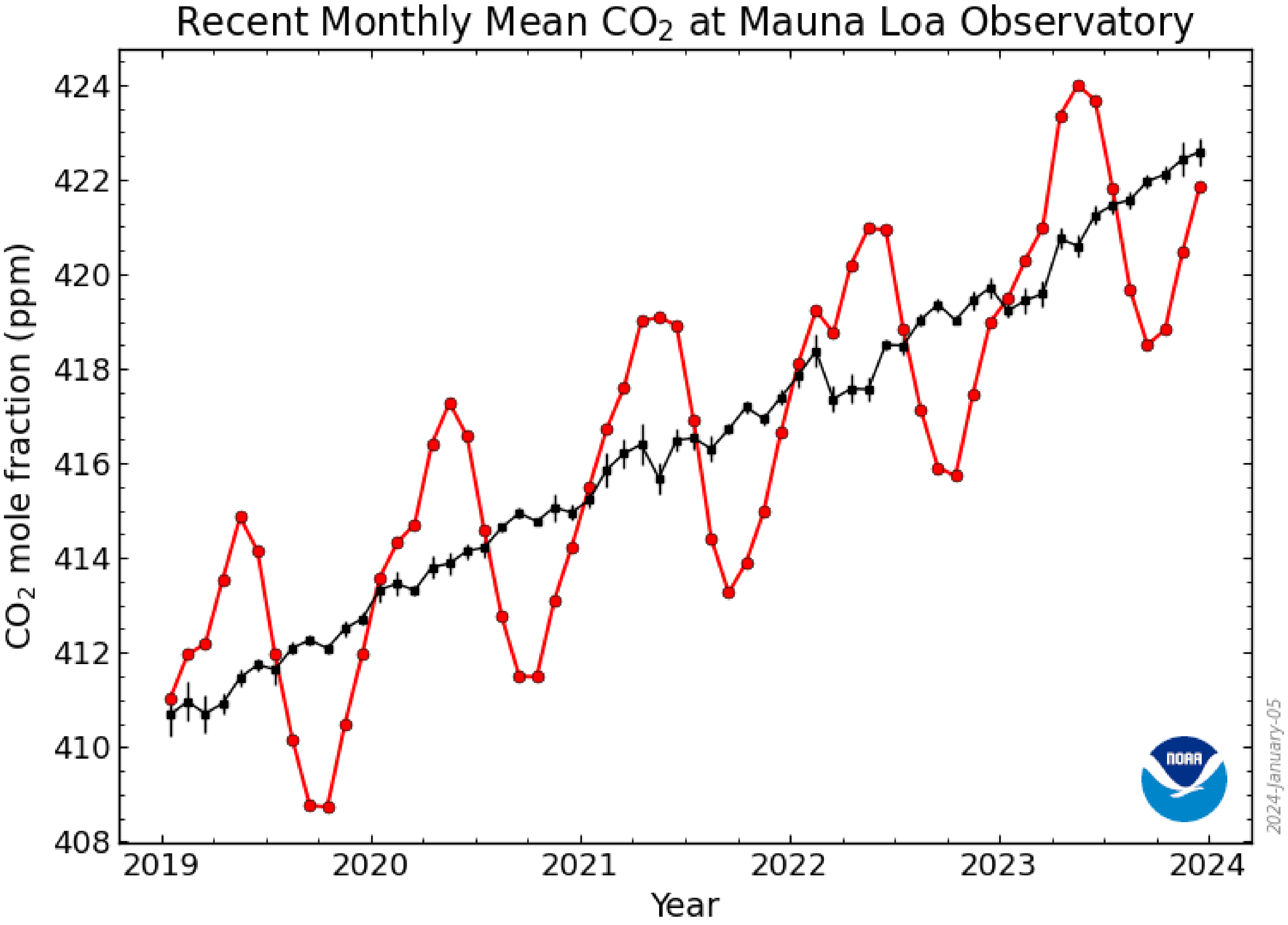
Average temperature – Example Germany



Source: Copernicus, C3S/ECMWF

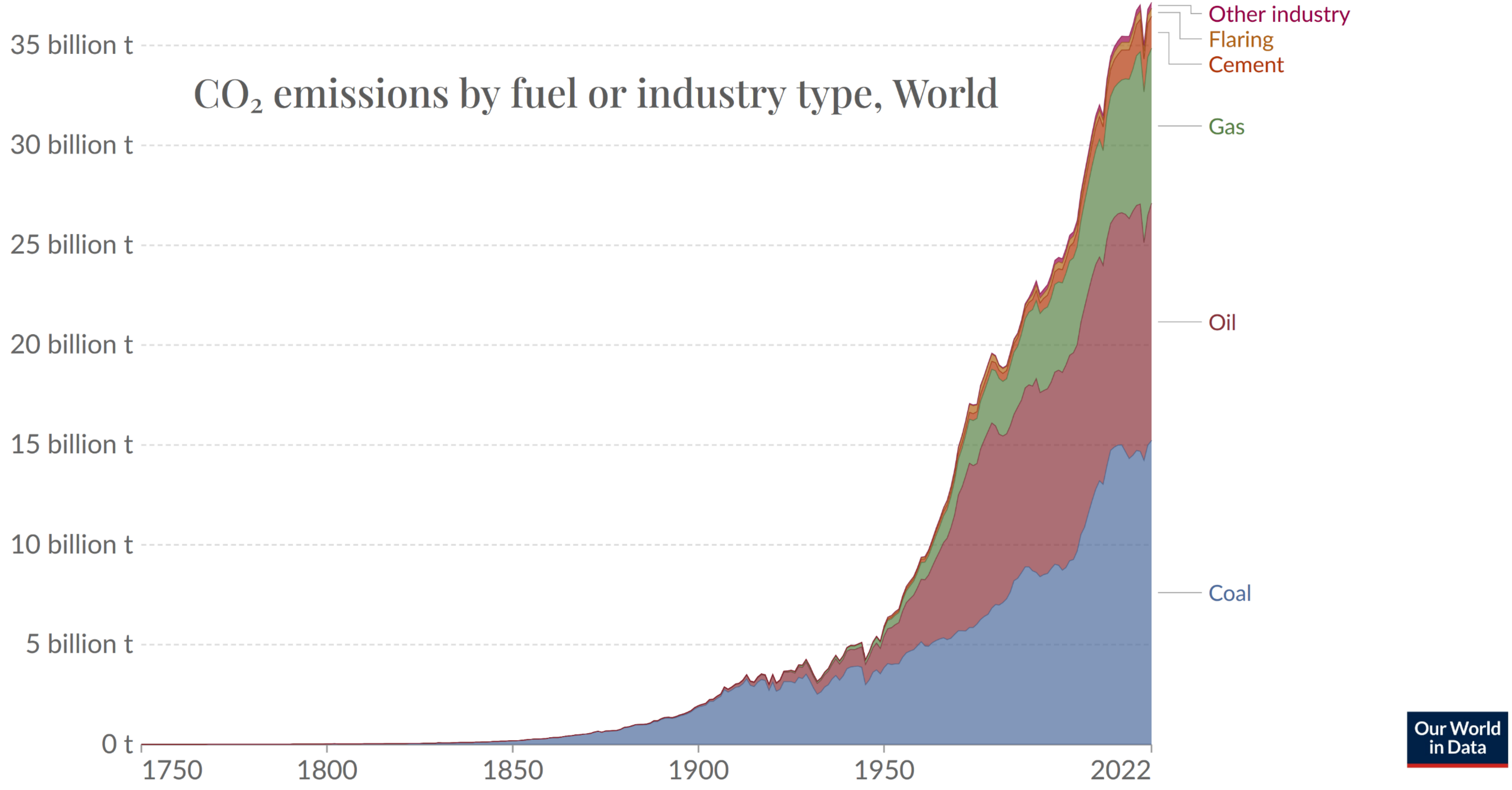
CO_2-concentration within the atmosphere





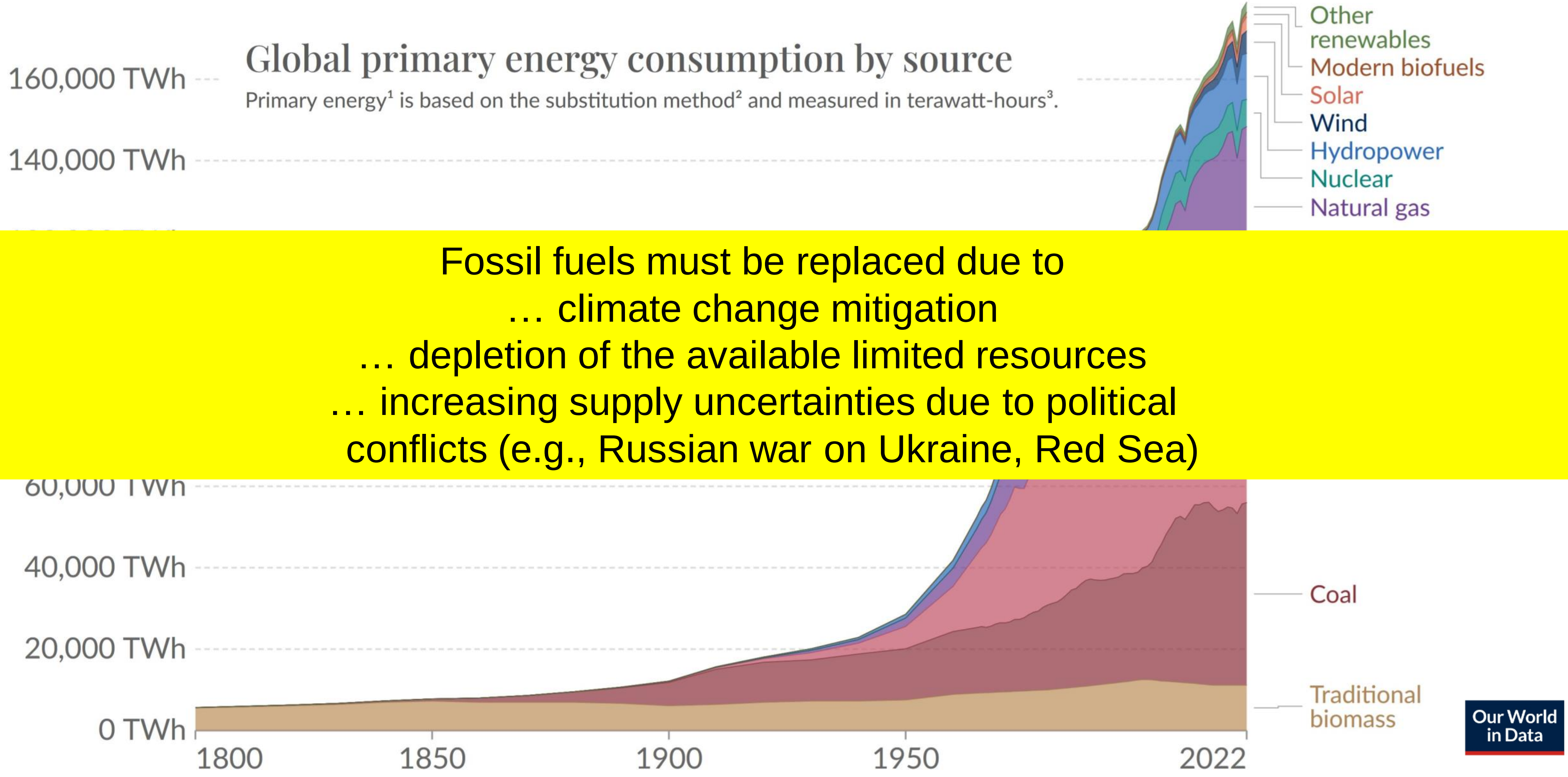
Source: https://gml.noaa.gov/ccgg/trends/

Globally emitted energy-related CO_2-emissions



Source: https://ourworldindata.org/grapher/global-energy-substitution

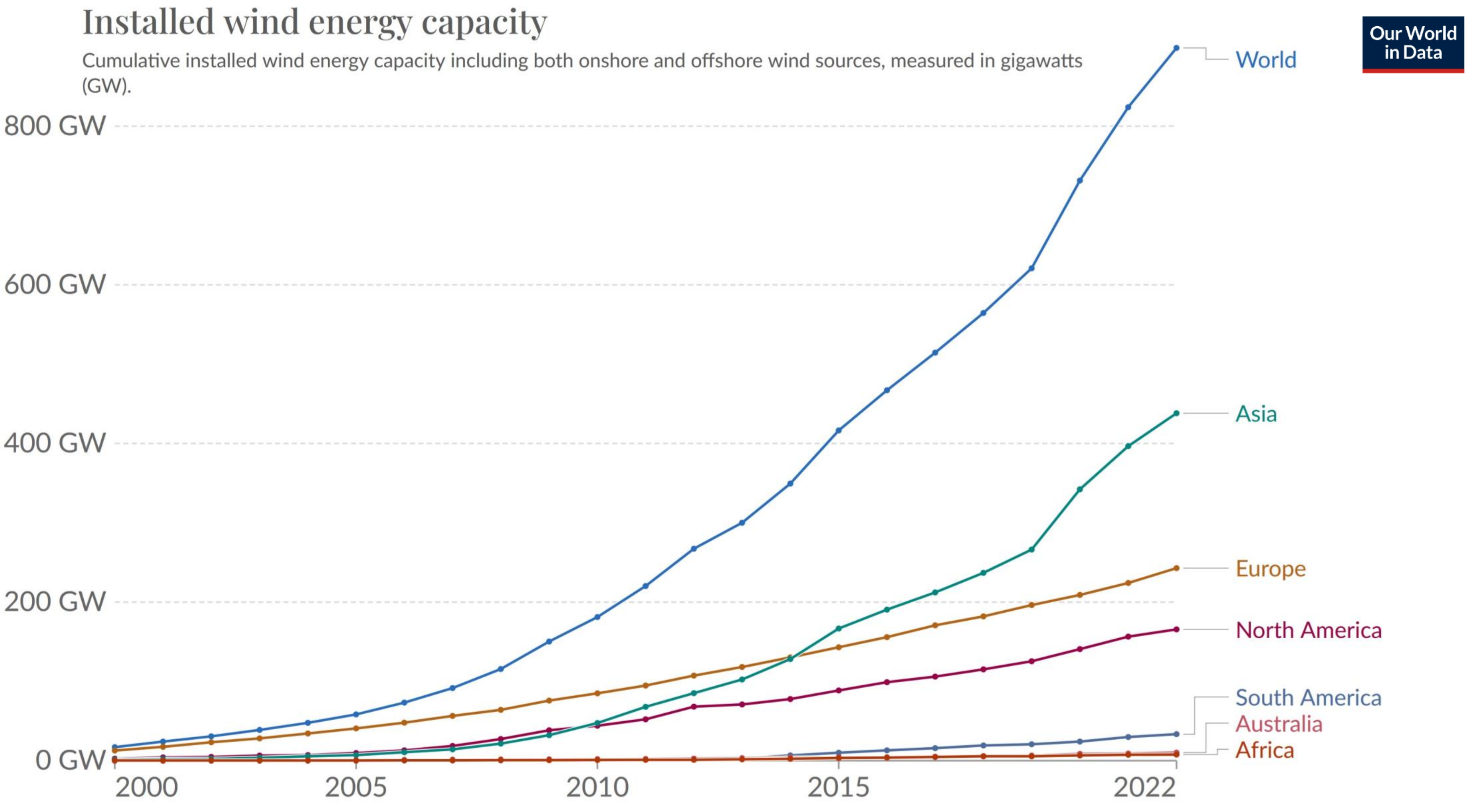
Global energy supply



Fossil fuels must be replaced due to
… climate change mitigation
… depletion of the available limited resources
… increasing supply uncertainties due to political conflicts (e.g., Russian war on Ukraine, Red Sea)

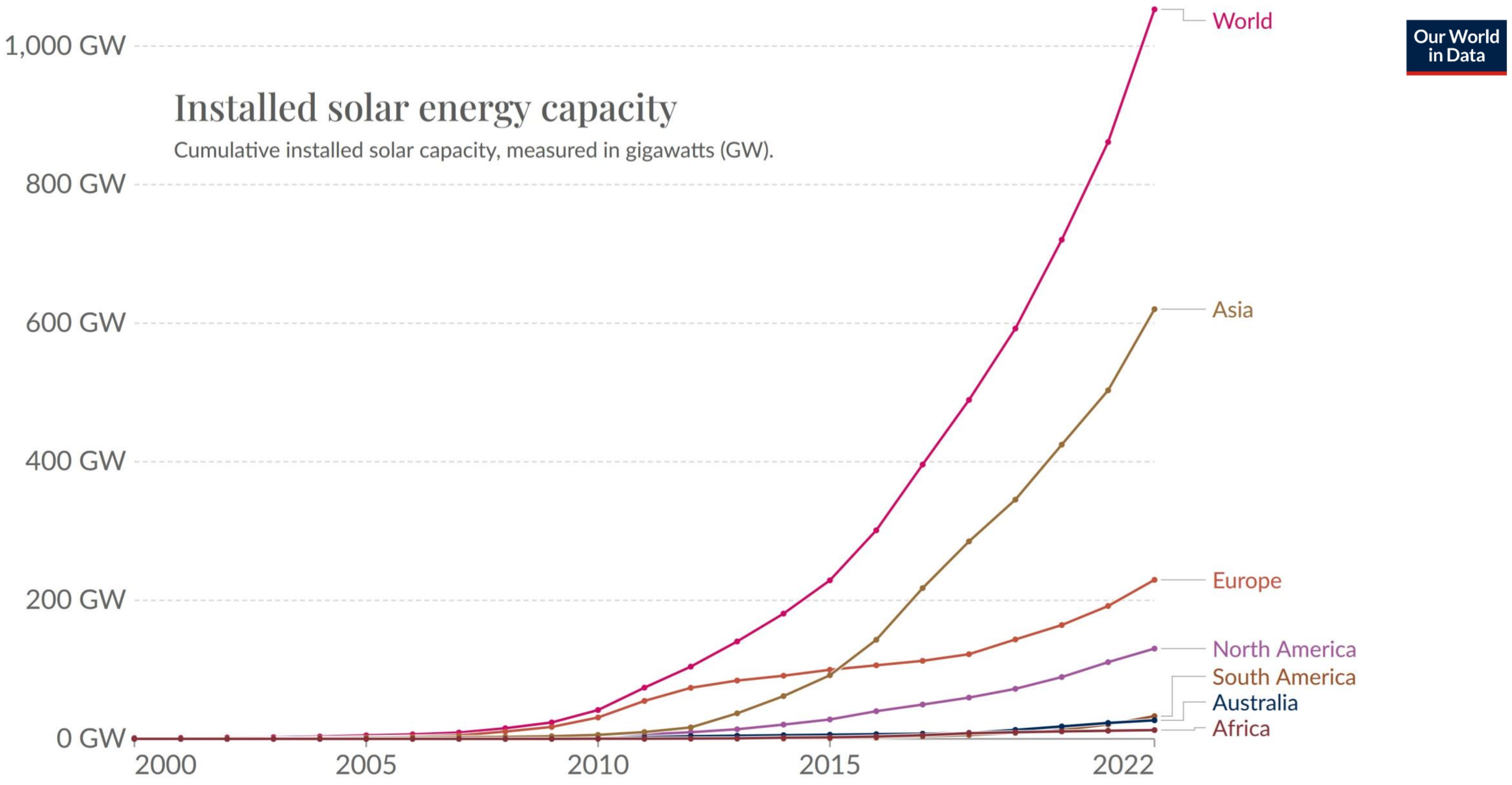
Source: https://ourworldindata.org/grapher/global-energy-substitution

Global energy supply – Low-emission energy supply options (Wind)



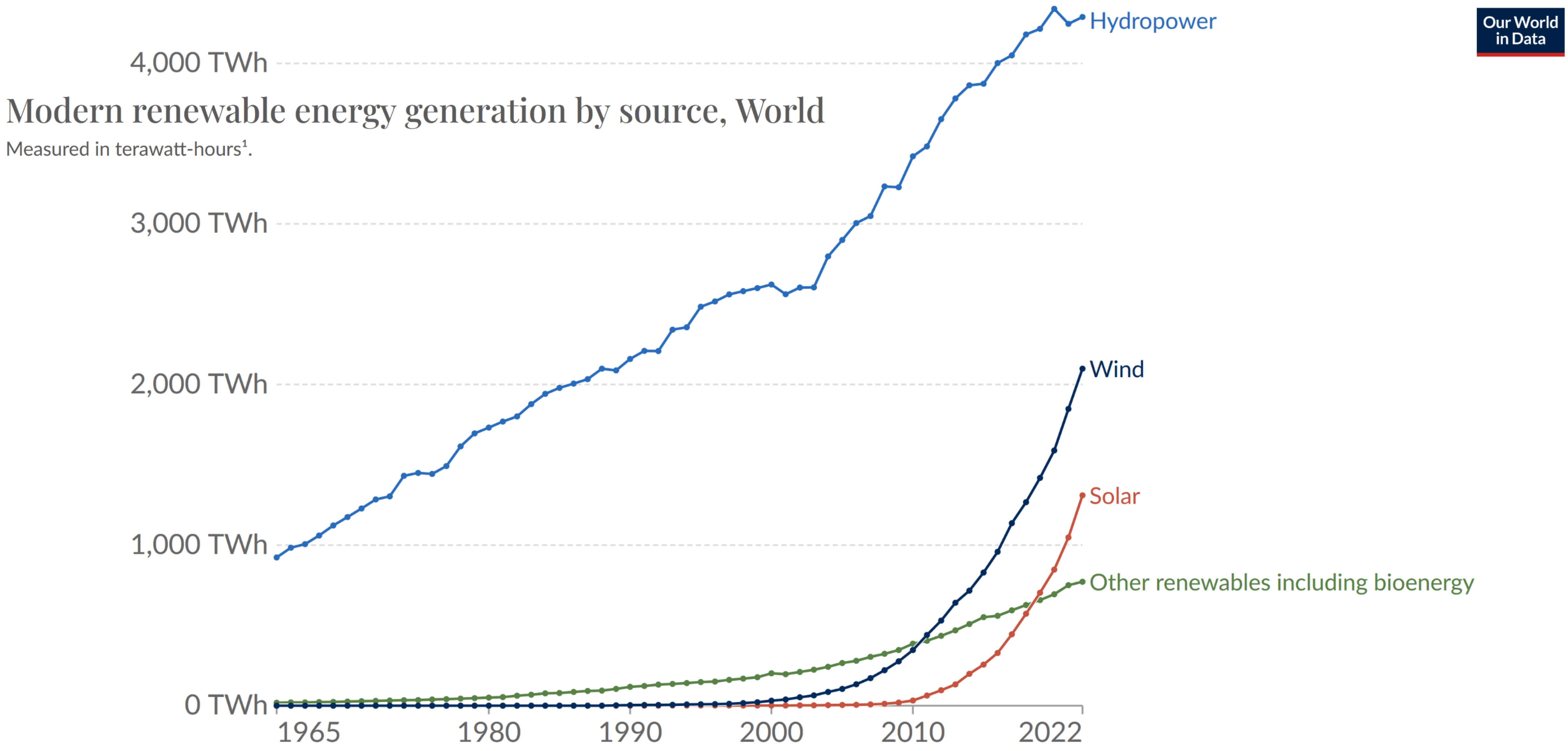
Source: https://ourworldindata.org/renewable-energy

Global energy supply – Low-emission energy supply options (PV)



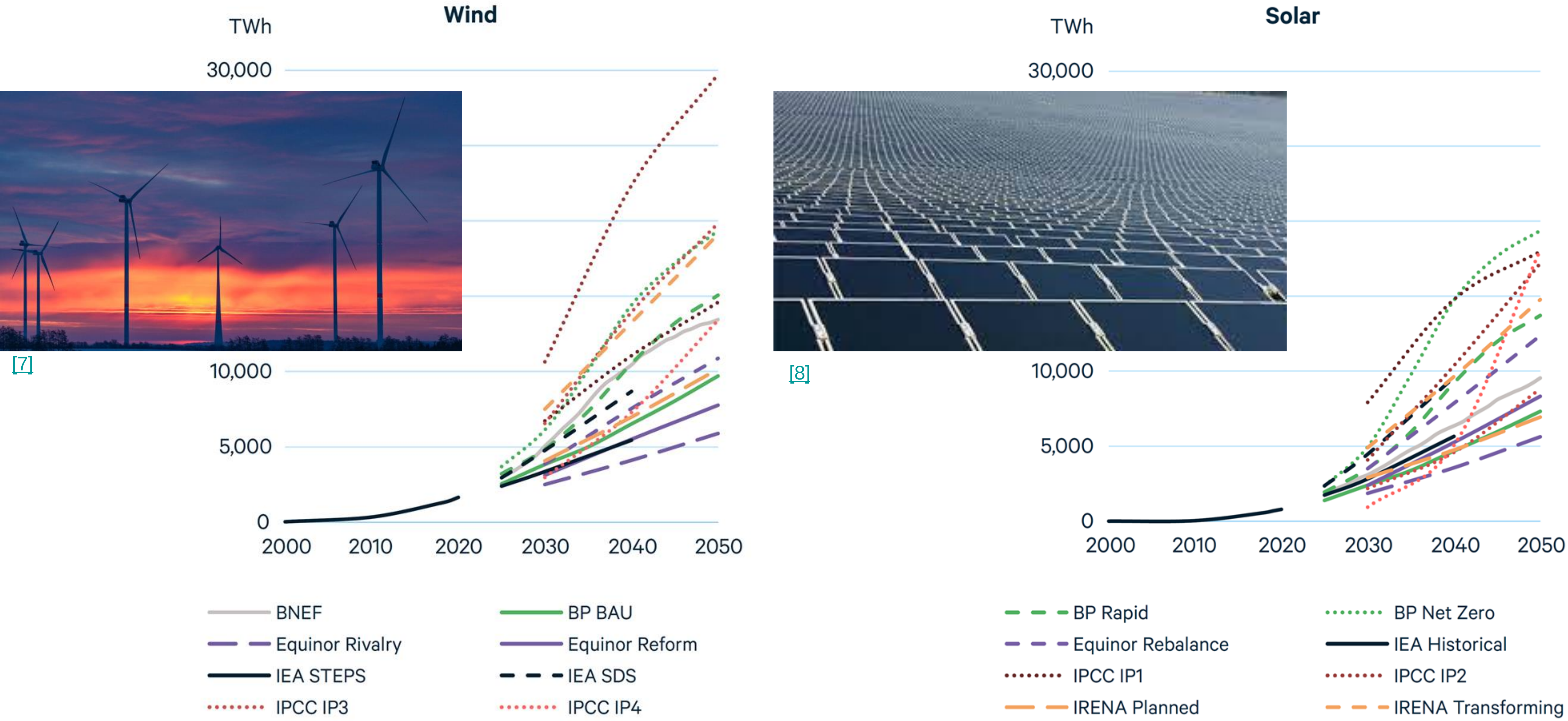
Source: https://ourworldindata.org/renewable-energy

Global energy supply – Low-emission energy supply options

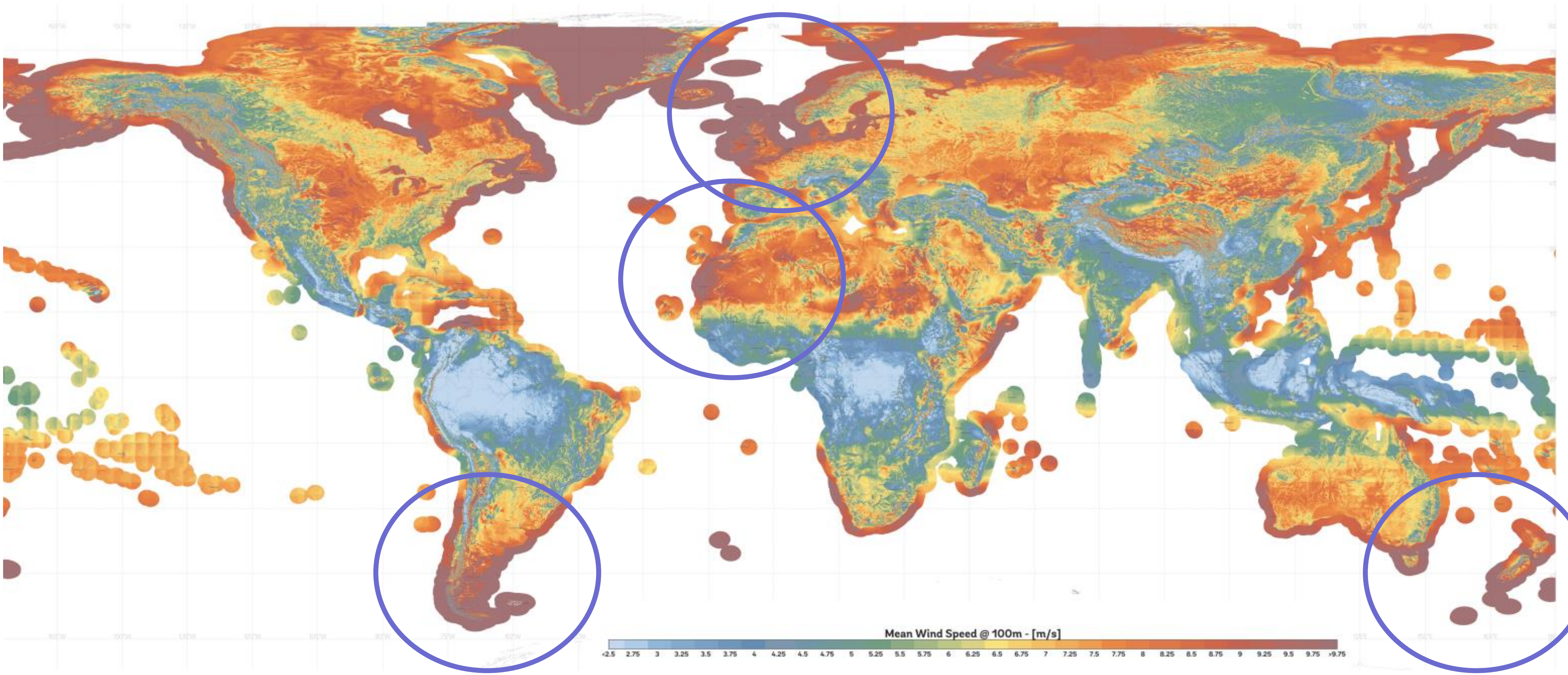


Source: https://ourworldindata.org/renewable-energy

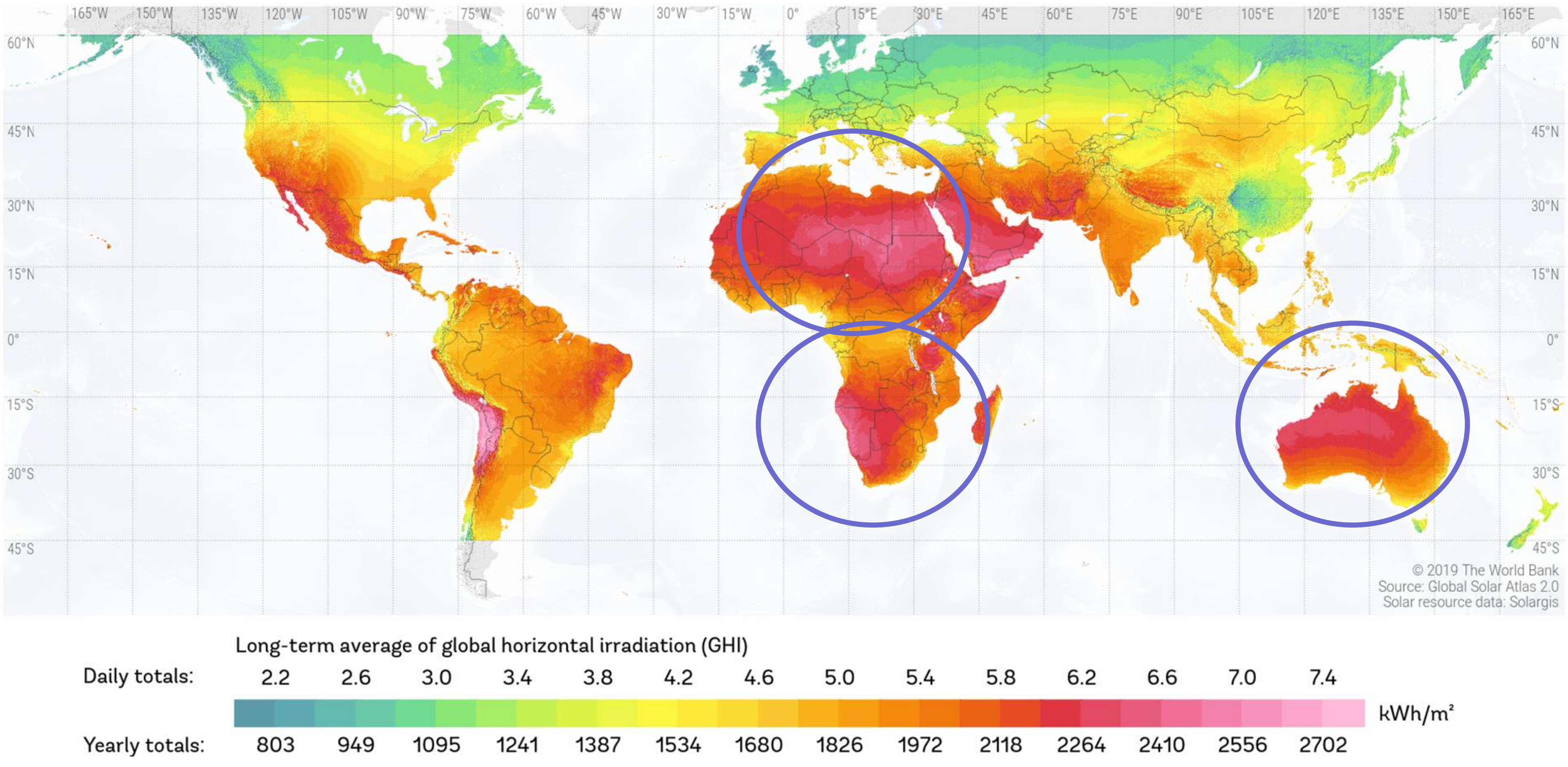
Global energy supply – Outlook low-emission supply options



Global availability of renewable energies – Wind

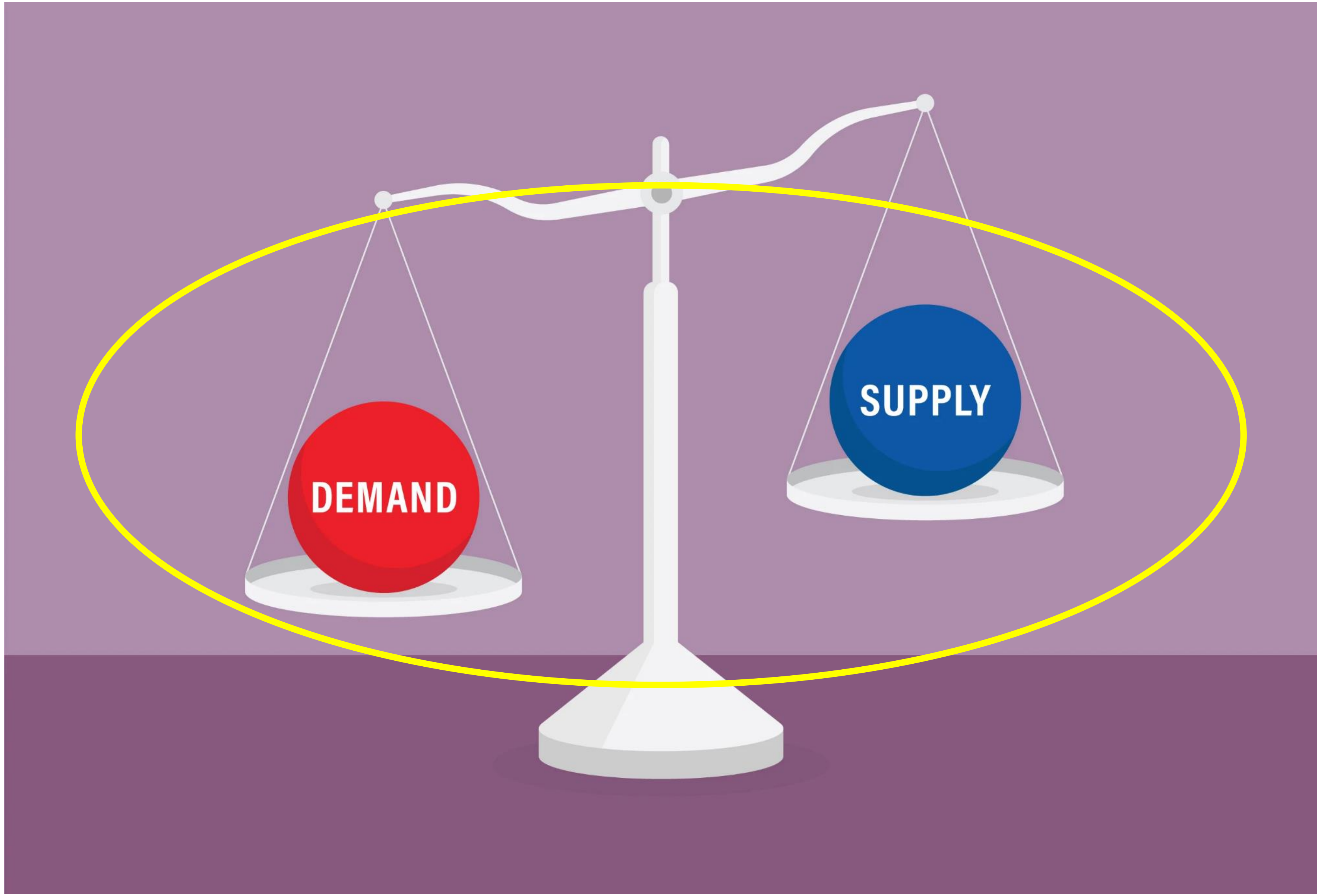


Global availability of renewable energies – Solar radiation



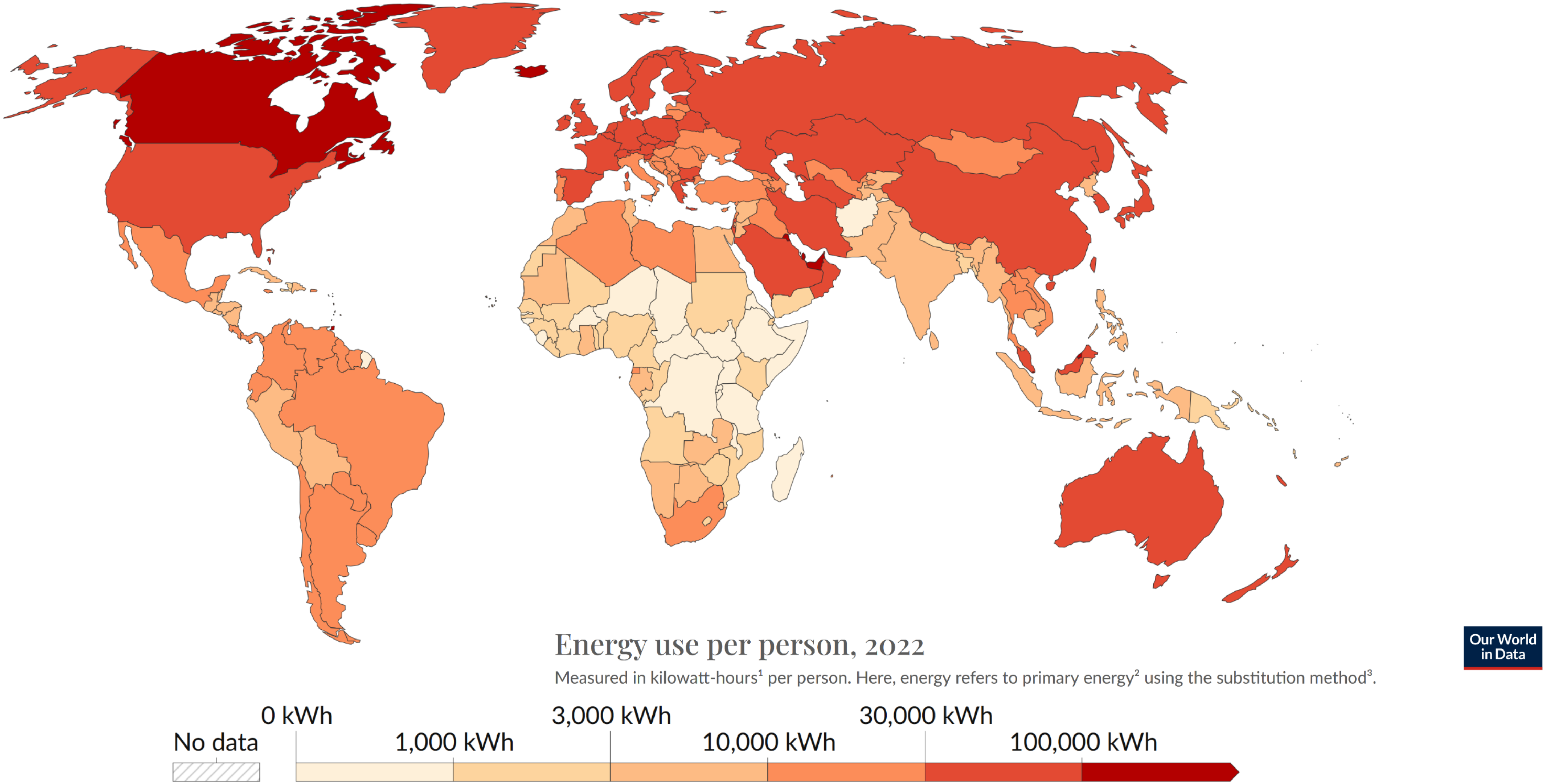
Source: The World Bank Group (2019) / https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country

Energy supply and demand



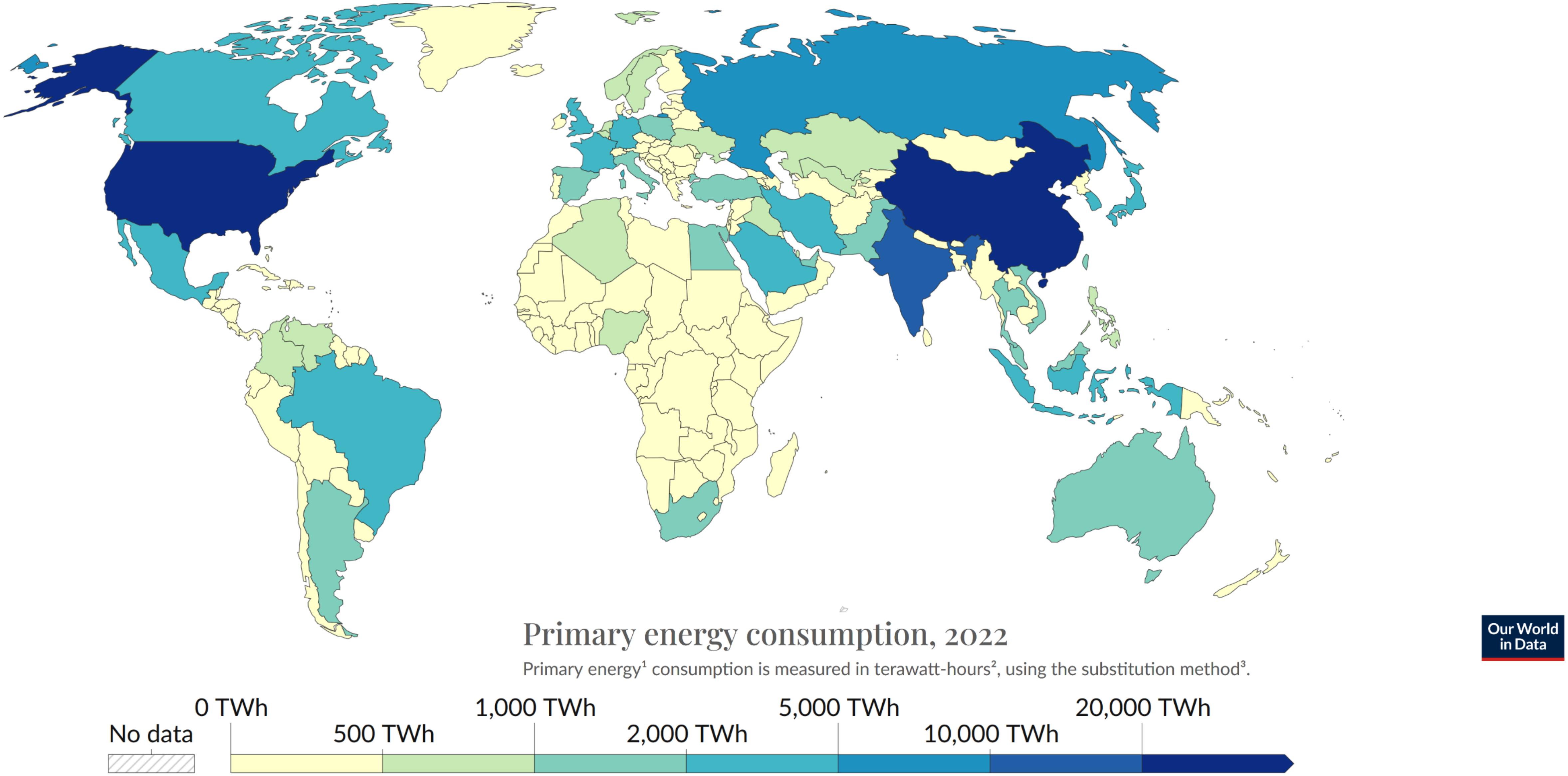
[9]

Energy demand centers – Energy use per person



Source: https://ourworldindata.org/grapher/per-capita-energy-use

Energy demand centers – Overall primary energy consumption



Source: https://ourworldindata.org/grapher/primary-energy-cons

Intermediate conclusions – Outlook

- Most likely, on a global scale the energy demand will continue to grow; if climate protection is taken serious the use of fossil fuels have to be substituted by renewable energy sources.
- The use of wind power and solar radiation contributes more and more to cover the given energy demand on a global scale – but still on a relative low level.
- From a potential point of view, technology wise and related to economics there is not “show stopper” preventing a fast expansion of an electricity provision from wind and solar. But, promising potentials are regionally not congruent with the main global energy demand centers.
- The highest energy demand correlates with the population density and the industrialization level; i.e. China, India, US and Canada as well as Europe show a high & increasing energy demand – and limited easy accessible and economically usable wind and solar resources.
- Thus, like today, also in the years to come a global energy trade will be necessary to connect areas with a promising renewable energy supply and areas with a high energy demand – but in the future “green” energy need to be traded.
- Thus, the arising key question is how this “green” energy (basically “green” electricity provided from wind turbines and from photovoltaic systems) can be transported (and stored) in a most promising way.

Webinar Series

Hydrogen and Hydrogen Derivates - Possibilities and Constraints

10.01.2024

The significance of hydrogen derivates

Part 2 - Hydrogen transport options

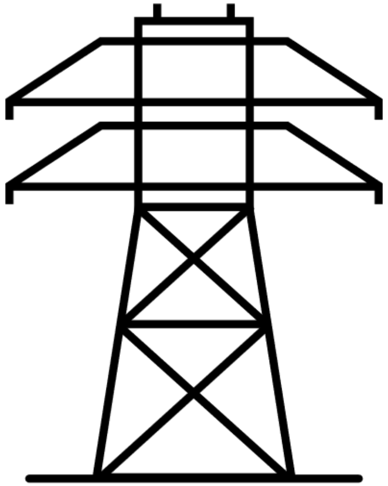
Fabian Carels, Martin Kaltschmitt

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

Hamburg University of Technology (TUHH), Institute of Environmental Technology and Energy Economics (IUE)

„Green“ electricity

Benefits



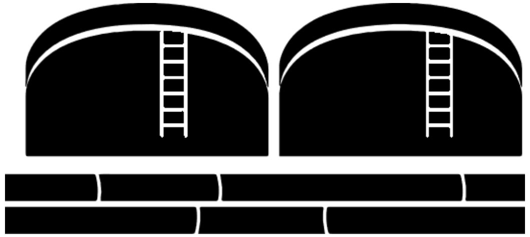
- No / very low conversion losses
- All technology components available on a large scale

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

Transport options for molecules


[10]

[12]

[11]


[13]

Ships

Benefits

- Development of flexible, global markets possible
- Minimization of dependency on single

[14]

Pipeline

Benefits

- Minimal conditioning effort
- Low energy losses for pure hydrogen supply

[15]

**Typically, both options do not compete and complement each other.
Nevertheless, the basic precondition for cost-efficient transport of “green” molecules is an adequate conditioning of these molecules.**

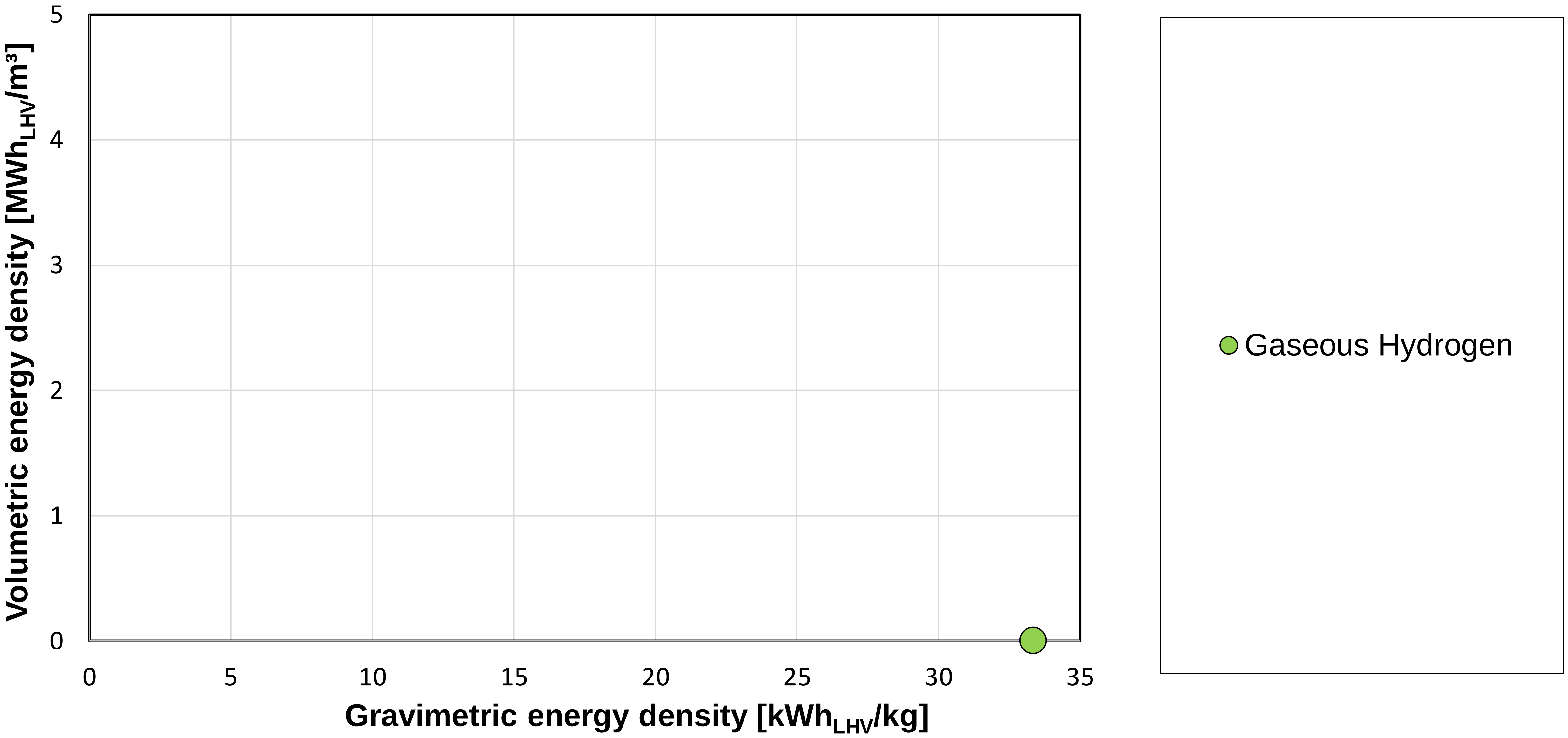
Limitations & Challenges (Ships)

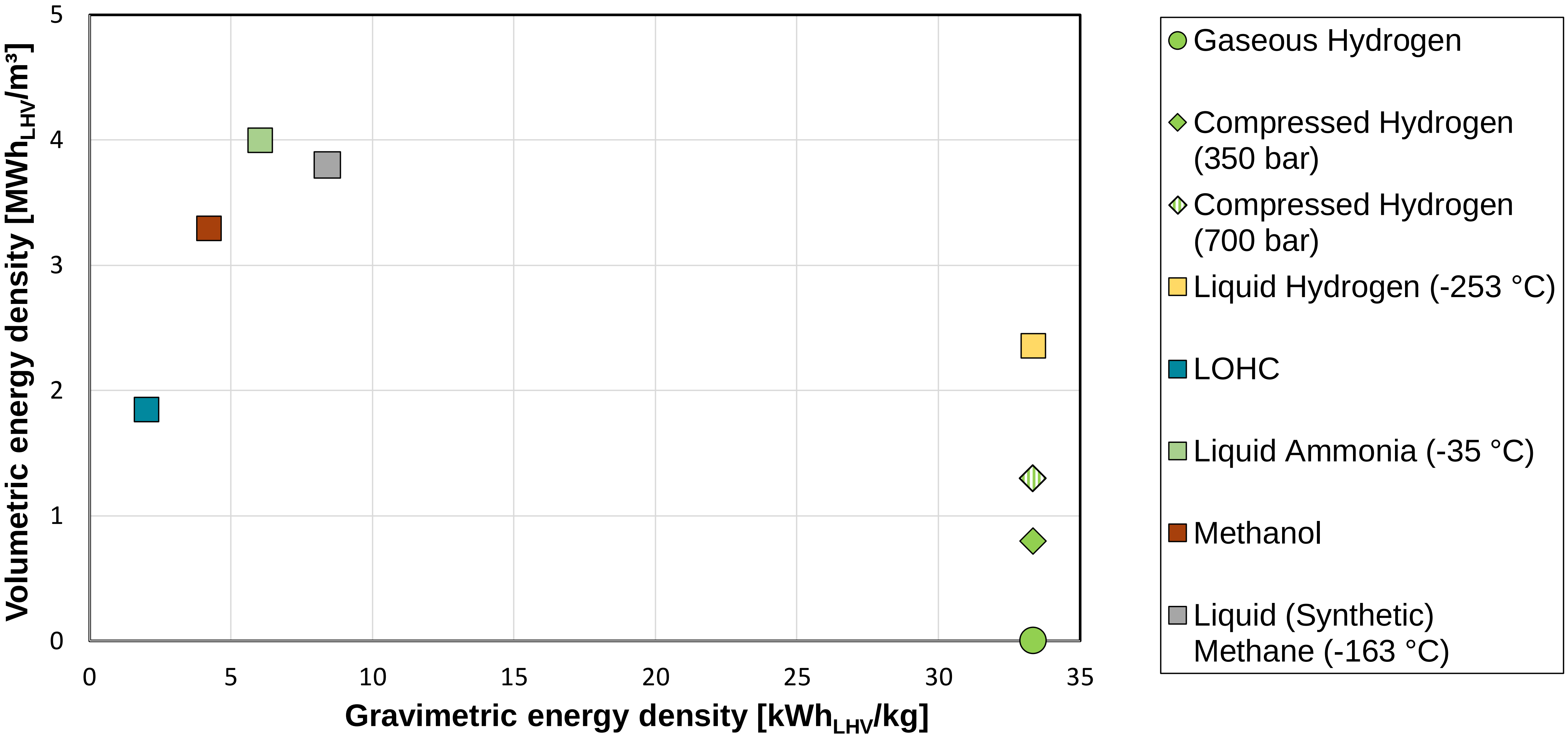
- Unavoidable losses due to conditioning
- Technological readiness and/or availability of some components currently not yet given

Limitations & Challenges (Pipeline)

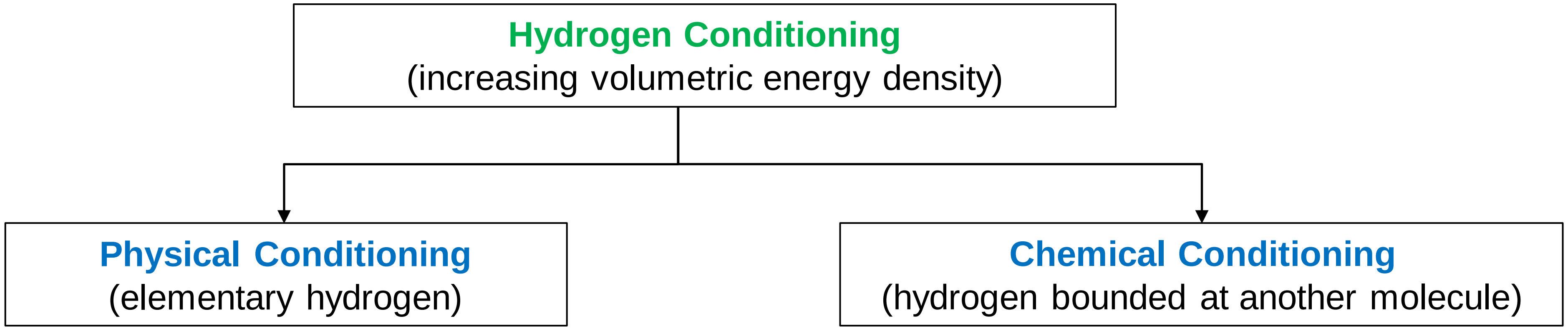
- Bound to inflexible infrastructure
  → overseas transport not/barely possible
- Potentially vulnerable to malfunctions, e.g. through sabotage

Energy supply chains based on hydrogen

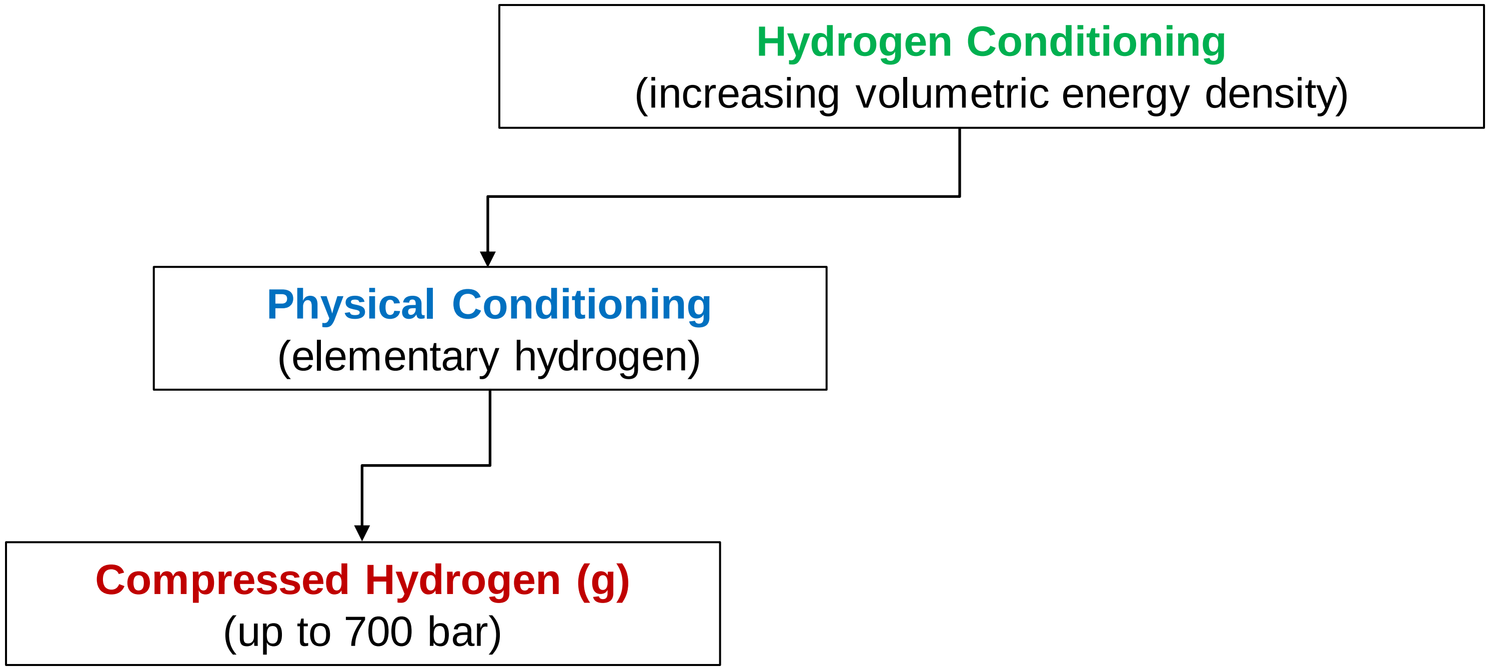



Volumetric energy density [MWh_LHV/m³]
Gravimetric energy density [kWh_LHV/kg]
0
1
2
3
4
5
0
5
10
15
20
25
30
35
Gaseous Hydrogen
Compressed Hydrogen (350 bar)
Compressed Hydrogen (700 bar)
Liquid Hydrogen (-253 °C)
LOHC
Liquid Ammonia (-35 °C)
Methanol
Liquid (Synthetic) Methane (-163 °C)

Hydrogen transportation options



Hydrogen transportation options – Compressed hydrogen



Hydrogen transportation options – Compressed hydrogen

Hydrogen Conditioning
(increasing volumetric energy density)

↓

Physical Conditioning
(elementary hydrogen)

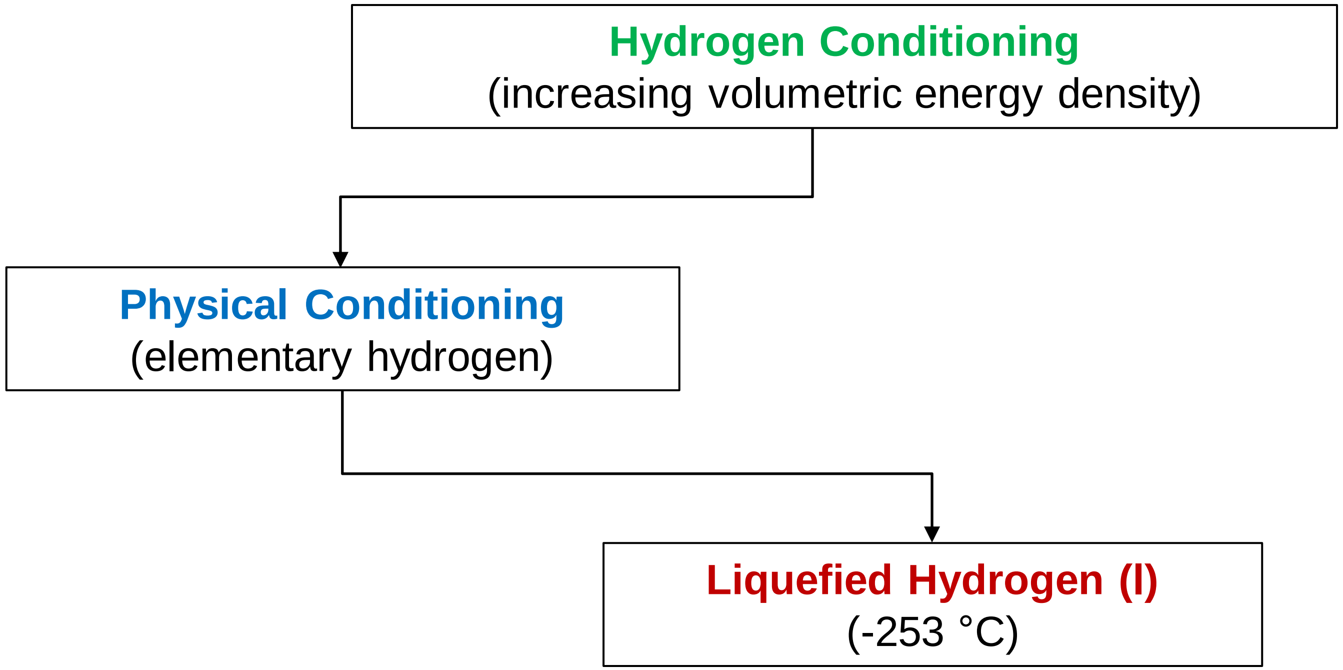
↓

Compressed Hydrogen (g)
(up to 700 bar)

- 👍 Low energy demand for conditioning
- 👍 No expense for reconditioning
- 👍 High purity

- 👎 Low volumetric energy density
- 👎 High material requirements due to the high pressure
- 👎 Missing global infrastructure

Hydrogen transportation options – Liquefied Hydrogen



Hydrogen transportation options – Liquefied Hydrogen

Hydrogen needs to be cooled to 20 K (-253.15 °C) to become liquid.

Energy demand

- Theoretical minimum: 3.92 kWh/kg_{H2}
- State of the art: 10-13 kWh/kg_{H2}
- ➢ Long-term goal: 6.5 kWh/kg_{H2}

[17]

COMPRESSION

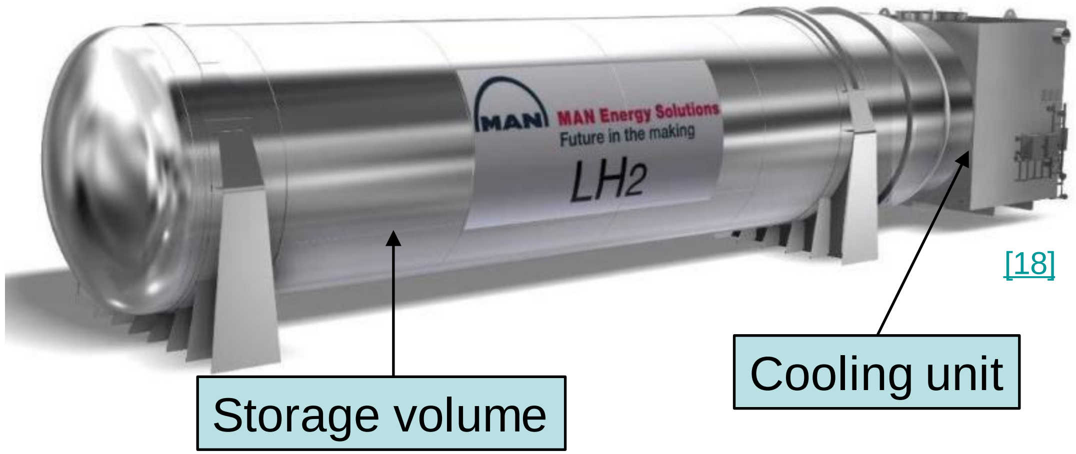
↓ *ca. 300 K*

COOLING

↓ *ca. 22-45 K*

EXPANSION

ca. 20 K



[18]

Hydrogen transportation options – Liquefied Hydrogen

Hydrogen Conditioning
(increasing volumetric energy density)

↓

Physical Conditioning
(elementary hydrogen)

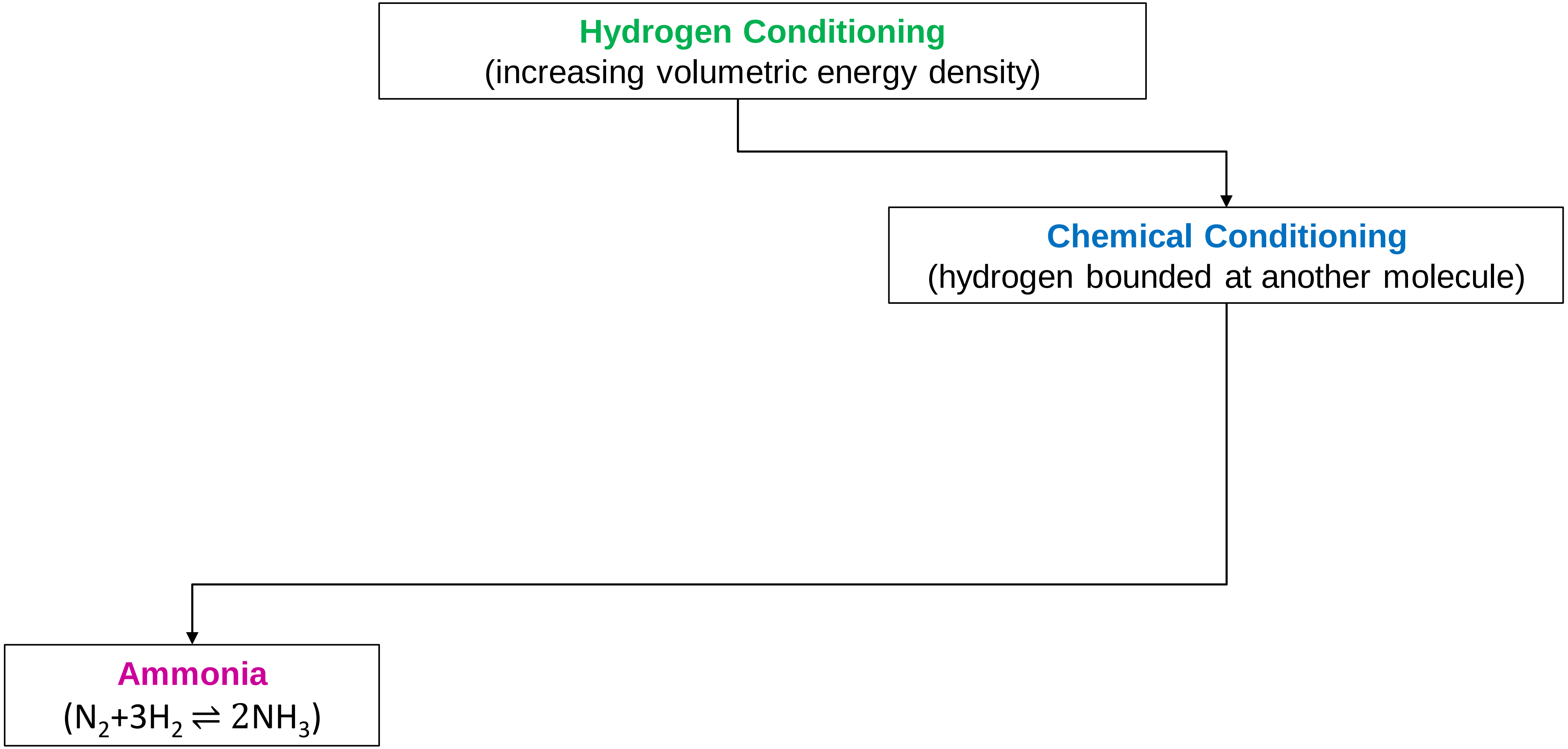
↓

Liquefied Hydrogen (l)
(-253 °C)

- 👍 High volumetric energy density
- 👍 Low reconditioning effort
- 👍 High purity

- 👎 High conditioning energy demand (liquefaction)
- 👎 Unavoidable boil-off losses during storage & transport
- 👎 Missing global infrastructure

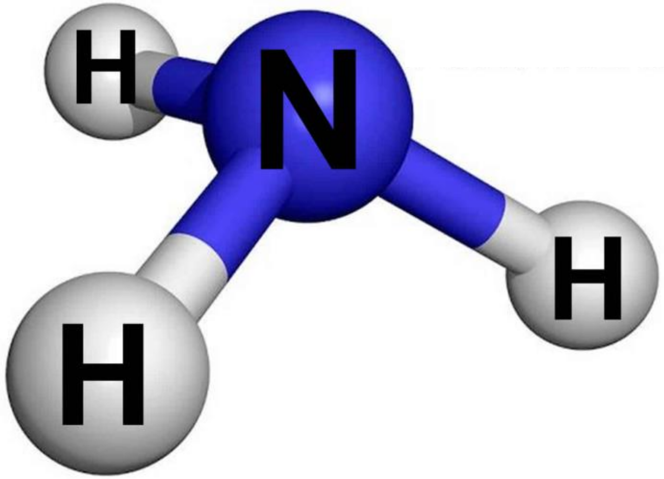
Hydrogen transportation options – Ammonia



Haber-Bosch Synthesis

$0{,}5\ N_2 + 1{,}5\ H_2$ — Exotherm 46 kJ/mol$_{NH3}$, 300 – 500 °C, 150 – 350 bar → NH_3

[19]



[20]

Ammoniak Cracking

NH_3 — Endotherm 46 kJ/mol$_{NH3}$, 500 °C, < 2 bar → $0{,}5\ N_2 + 1{,}5\ H_2$

Hydrogen transportation options – Ammonia

Hydrogen Conditioning
(increasing volumetric energy density)

Chemical Conditioning
(hydrogen bounded at another molecule)

- 👍 Handling in given infrastructure
- 👍 Easy supply of carrier material (N_2)
- 👍 Demand for pure ammonia

- 👎 High energy demand for dehydrogenation
- 👎 Low purity of dehydrogenated hydrogen
- 👎 Hazardous to water and health

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

Hydrogen transportation options – Liquid Organic Hydrogen Carrier

Hydrogen Conditioning
(increasing volumetric energy density)

↓

Chemical Conditioning
(hydrogen bounded at another molecule)

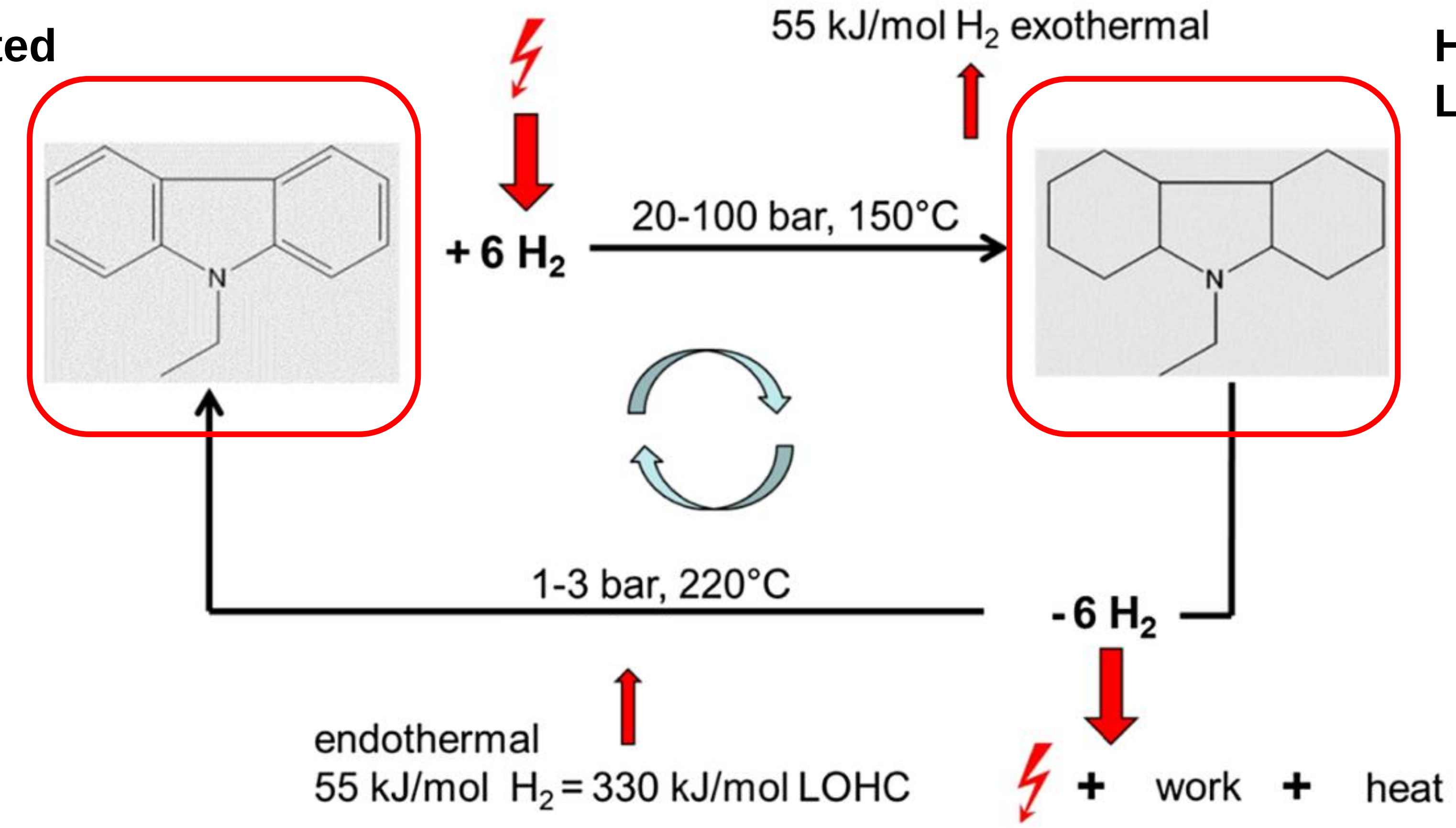
↓

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

Hydrogen transportation options – Liquid Organic Hydrogen Carrier

Dehydrogenated LOHC

[21]



Hydrogenated LOHC

[21]

Hydrogen transportation options – Liquid Organic Hydrogen Carrier

Hydrogen Conditioning
(increasing volumetric energy density)

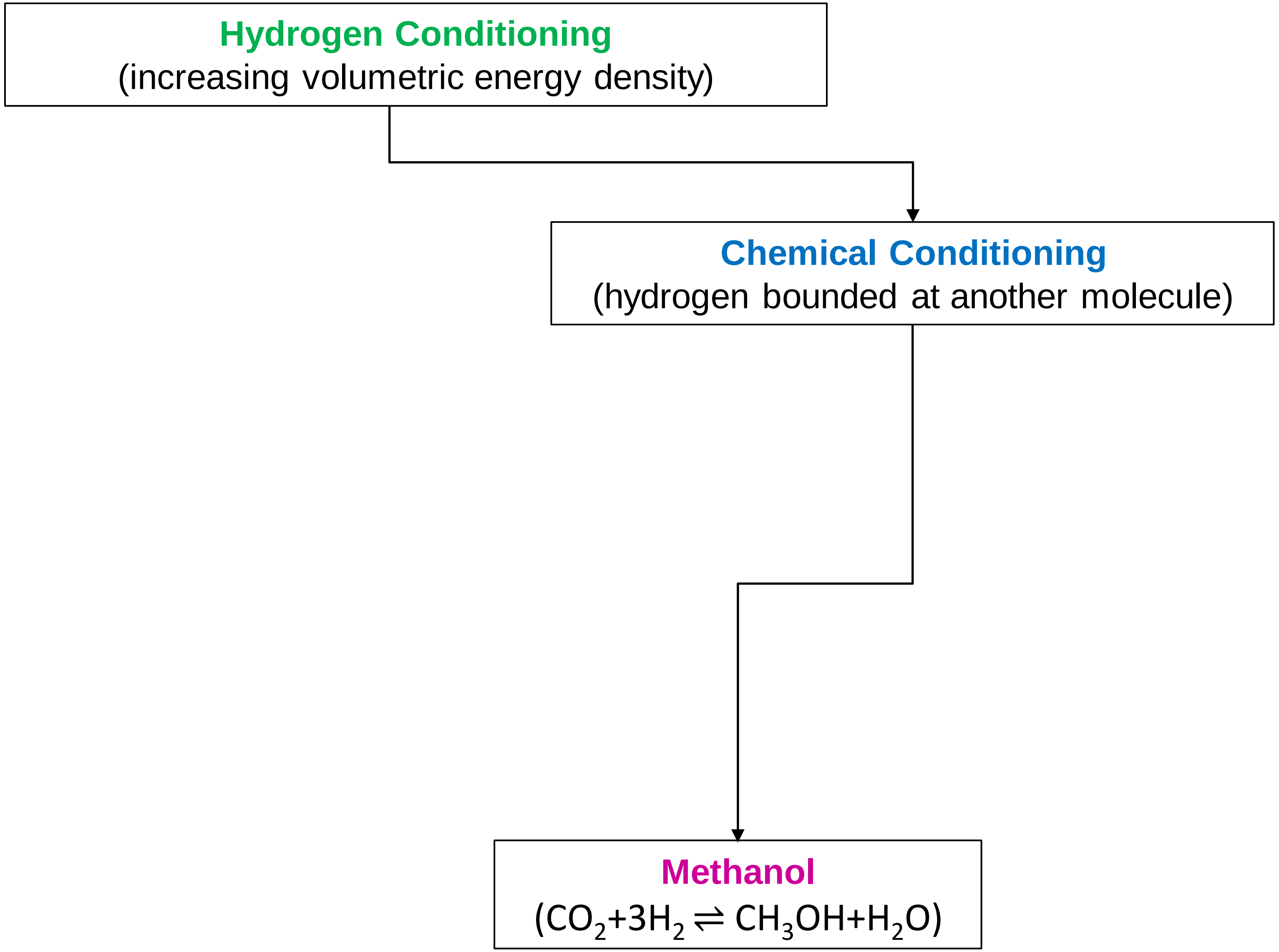
Chemical Conditioning
(hydrogen bounded at another molecule)

- 👍 Easy handling in given infrastructure
- 👍 Transport & storage at ambient conditions
- 👍 Not flammable / explosive

- 👎 Very high energy demand for dehydrogenation
- 👎 High cost for carrier material
- 👎 Large-scale hydrogenation & dehydr. plants unproven

Liquid Organic Hydrogen Carrier
($H_0LOHC \; nH_2 \rightleftharpoons H_nLOHC$)

Hydrogen transportation options – Methanol



Hydrogen transportation options – Methanol

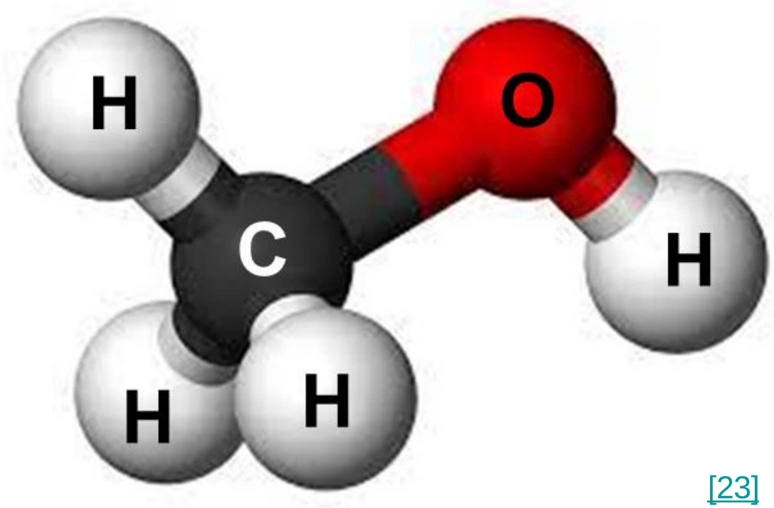
Methanol Synthesis

Exothermal

200 – 300 °C, 30 – 120 bar

$$CO_2 + 3\,H_2 \rightarrow CH_4O + H_2O$$

[22]



[23]

[24]

Methanol Reforming (e.g. Steam Reforming)

Endothermal

250 – 300 °C, < 20 bar

$$CH_4O + H_2O \rightarrow CO_2 + 3\,H_2$$

Hydrogen transportation options – Methanol

Hydrogen Conditioning
(increasing volumetric energy density)

Chemical Conditioning
(hydrogen bounded at another molecule)

- Easy handling in given infrastructure
- Transport & storage at ambient conditions
- Demand for pure methanol

- High energy demand for dehydrogenation
- Uncertain availability and high cost for green CO_2

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

Hydrogen transportation options – Synthetic Methane

Hydrogen Conditioning
(increasing volumetric energy density)

Chemical Conditioning
(hydrogen bounded at another molecule)

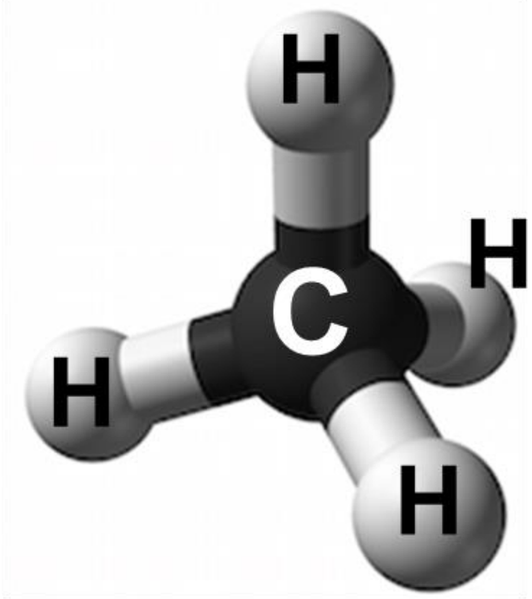
Methane
($CO_2+4H_2 \rightleftharpoons CH_4+2H_2O$)

Hydrogen transportation options – Synthetic Methane

Methanation

Exothermal
250 – 550 °C, > 10 bar

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$



Methan Reforming (e.g., Steam Methane Reforming)

Endothermal
650 – 1000 °C, 5 – 40 bar

$$CH_4 + 2\ H_2O \rightarrow CO_2 + 4\ H_2$$

Hydrogen transportation options – Synthetic Methane

Hydrogen Conditioning
(increasing volumetric energy density)

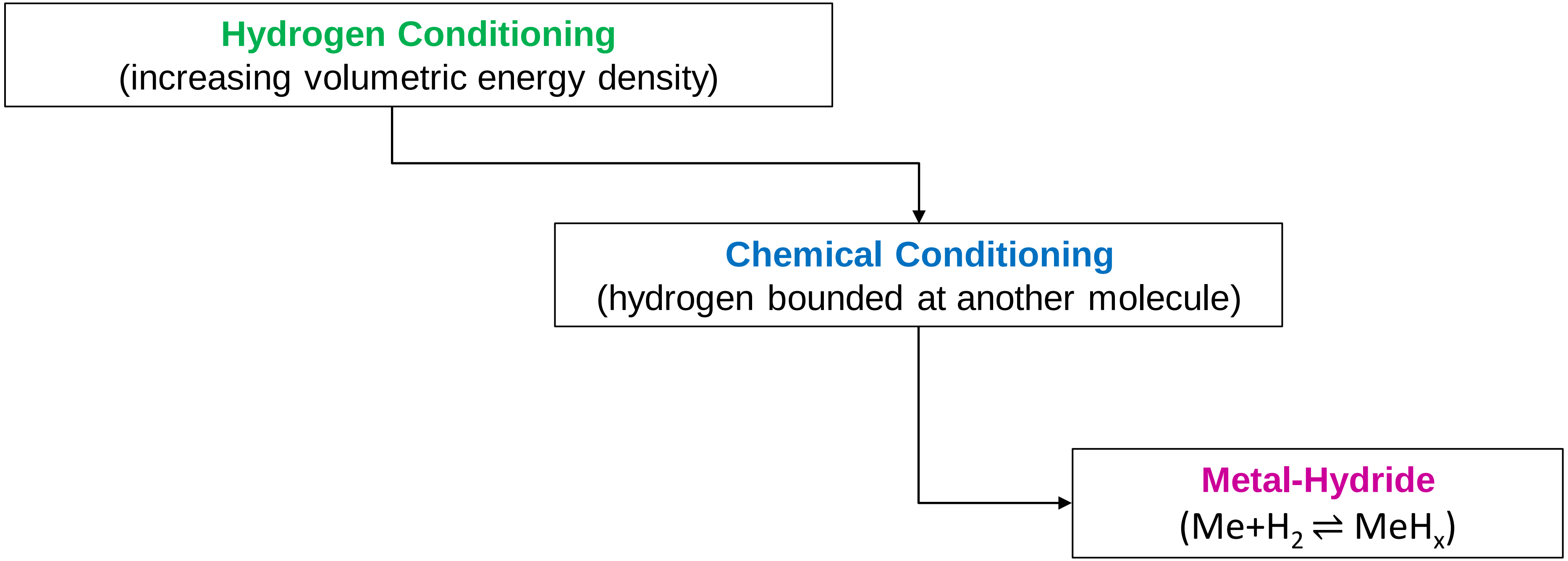
Chemical Conditioning
(hydrogen bounded at another molecule)

- 👍 Easy handling in given infrastructure
- 👍 Very high demand for pure methane
- 👍 Flexible use of methane in various applications

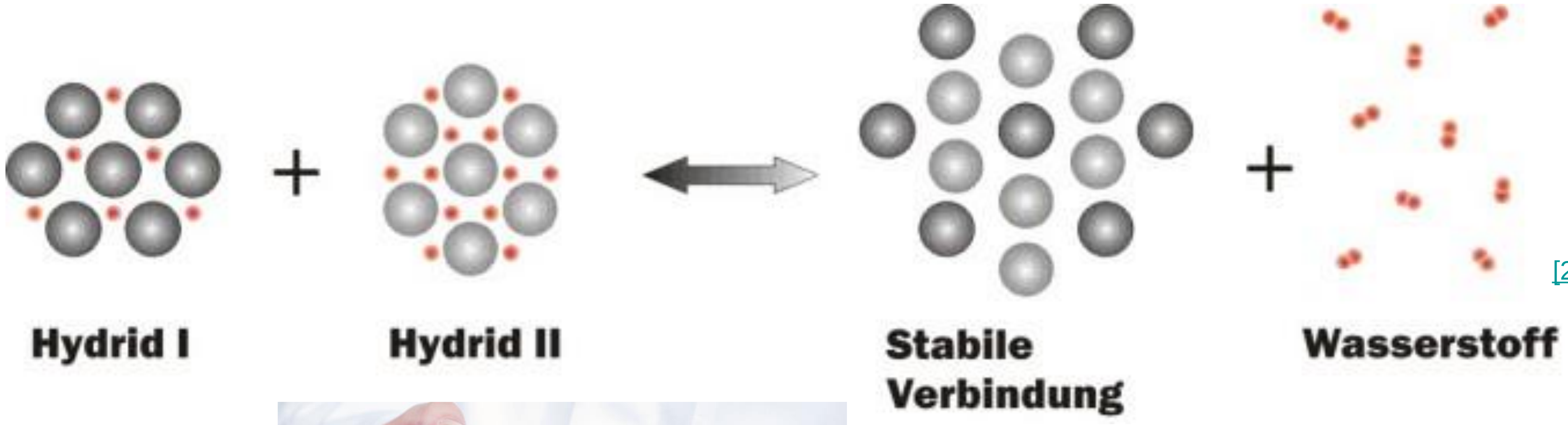
- 👎 High energy demand for dehydrogenation
- 👎 Uncertain availability and high cost for green CO_2
- 👎 Climate impact due to methane leakage

Methane
($CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$)

Hydrogen transportation options – Metal-Hydride



Metal hydride loaded with hydrogen | **Hydrogen release from metal-hydride**



[25]

[25]

Hydrogen transportation options – Metal-Hydride

Hydrogen Conditioning
(increasing volumetric energy density)

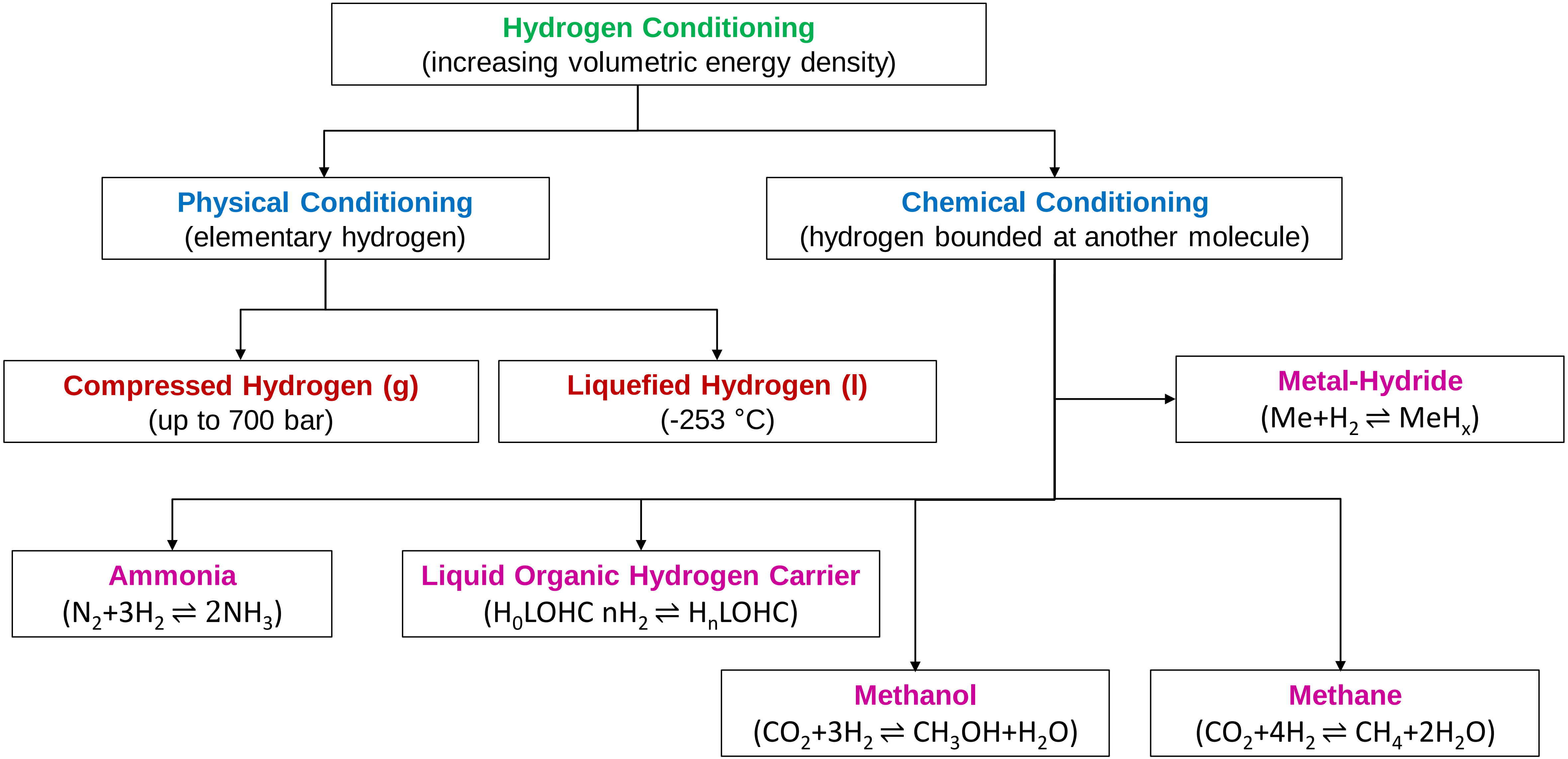
Chemical Conditioning
(hydrogen bounded at another molecule)

Metal-Hydride
$(Me+H_2 \rightleftharpoons MeH_x)$

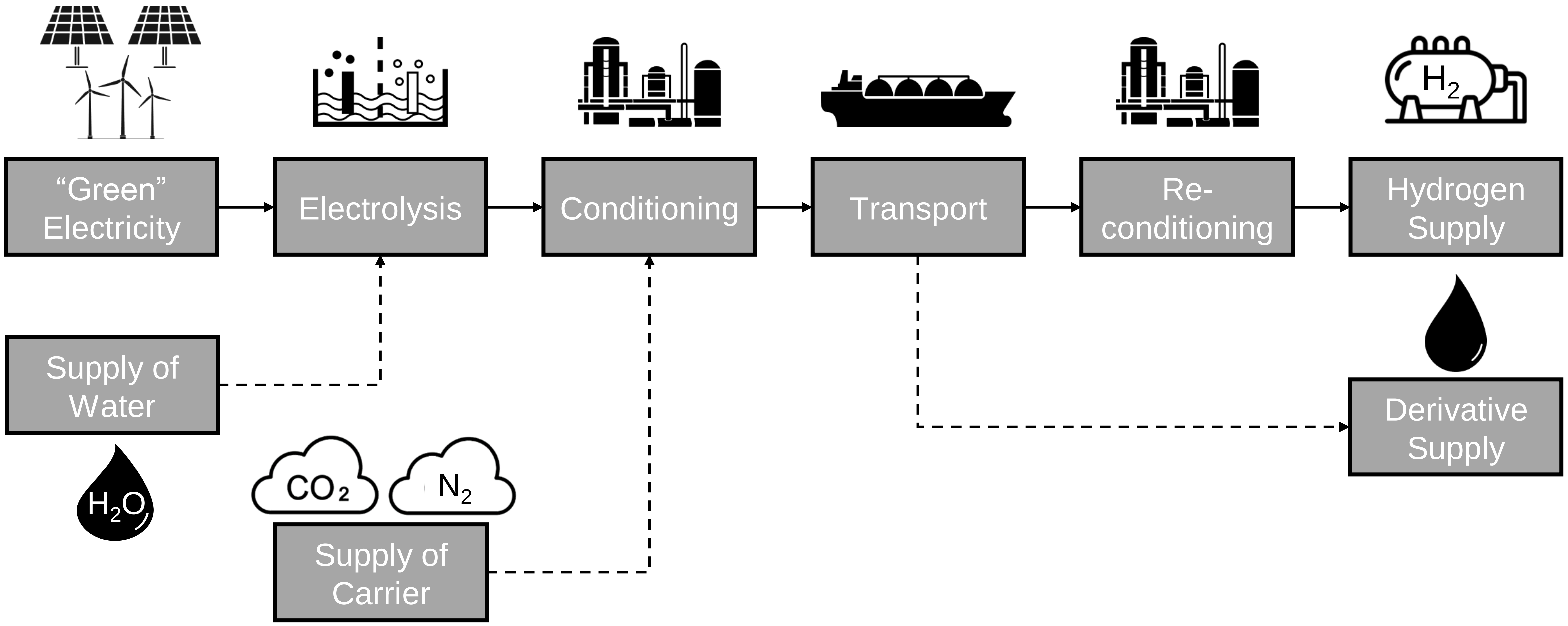
- 👍 No hazardous or flamable substances
- 👍 Very high volumetric energy density
- 👍 Long-term safe hydrogen storage at ambient conditions

- 👎 High weight and material requirement
- 👎 High technical effort for loading & unloading
- 👎 High energy demand for hydrogen recovery

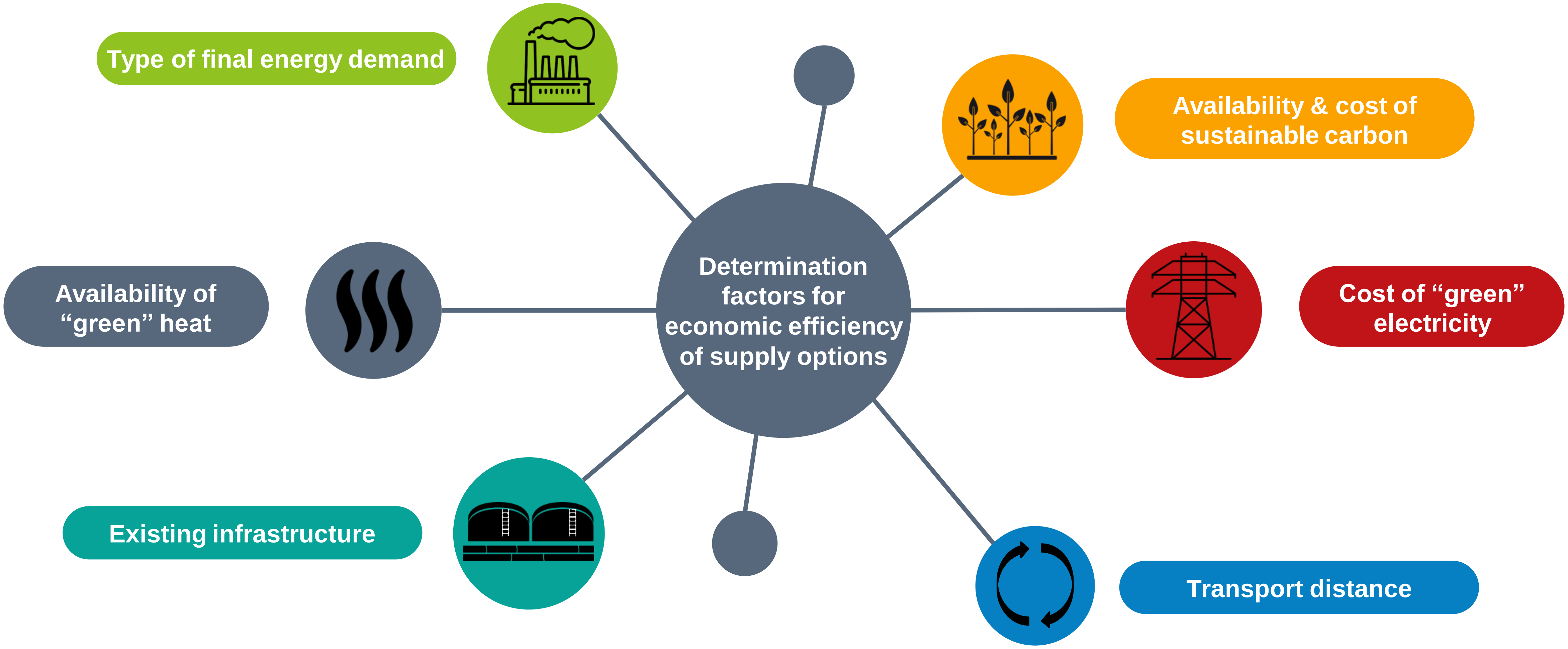
Hydrogen transportation options



Energy supply chains based on hydrogen



Energy supply chains based on hydrogen



Conclusion

- Due to the limitations in electricity transportation (inflexible infrastructure, large-scale storage), most likely the international transport of “green” molecules will, like the trade of fossil fuel energy today, play an important role within a defossilized energy system.
- “Green” molecules can be transported via ships and pipelines; both options characterized by supplementing pros and cons are needed. Besides the typically “cheap” transport of “green” molecules by pipeline, ship-based transport of these molecules is likely to gain relevance due to its high flexibility and the longer distances to overcome under commercial conditions.
- Hydrogen as a “green” gas is characterized by a low gravimetric and a low volumetric density making a ship transport economically challenging. Thus, options to transform hydrogen into a another gas or into a liquid produced allow for more promising material characteristics related to a cost-efficient ship transport.
- All forms of such a hydrogen transformation into derivates are associated with specific advantages and disadvantages. So far, especially the hydrogen derivatives ammonia, methanol and synthetic natural gas (SNG) are particularly promising for the transportation of “green” molecules due to existing technological solutions.
- But the economic advantage of a specific derivate is additionally determined by the requirements of the final customer.

Webinar Series

Hydrogen and Hydrogen Derivates - Possibilities and Constraints

10.01.2024

The significance of hydrogen derivates

Part 3 - Market demands

Fabian Carels, Martin Kaltschmitt

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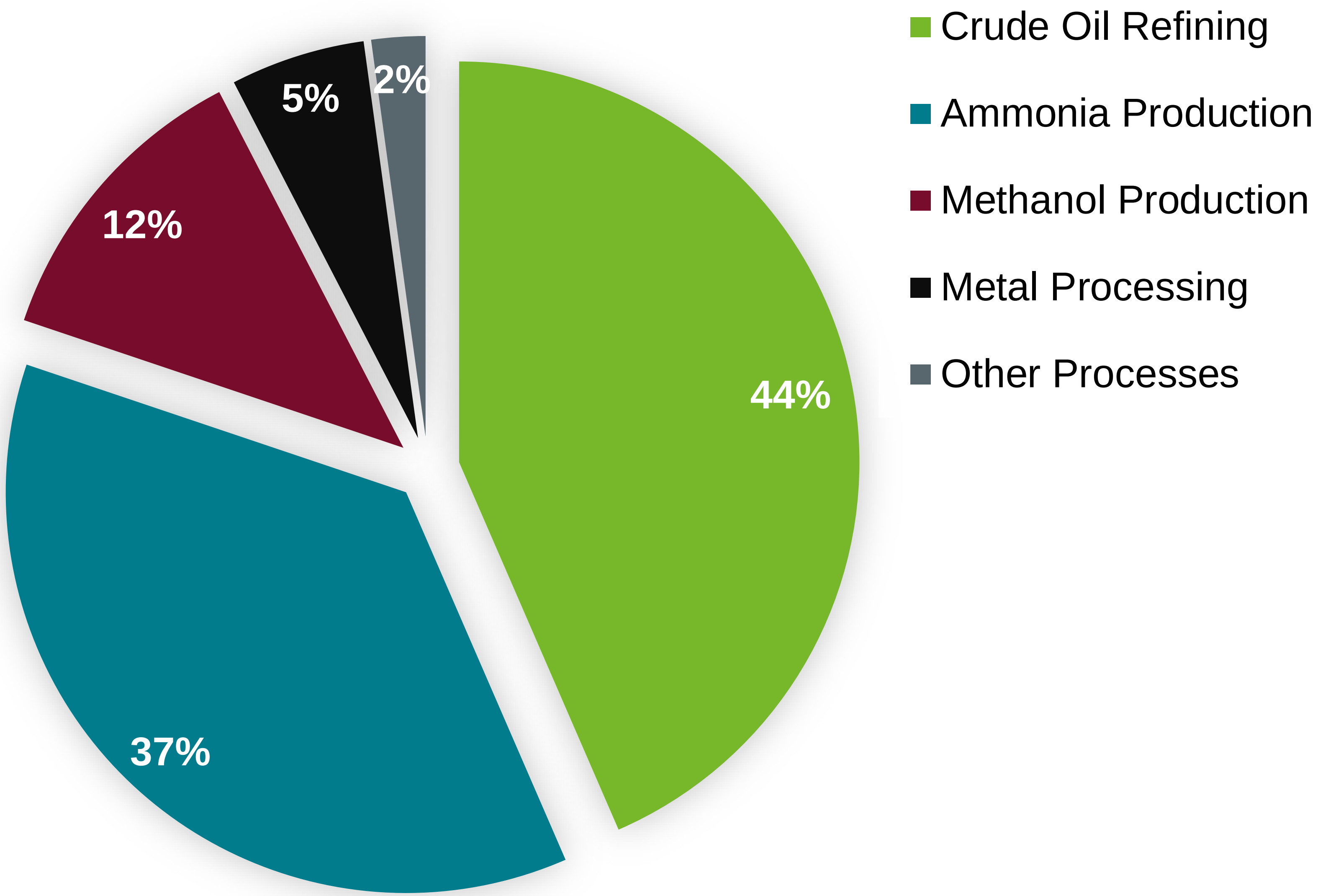
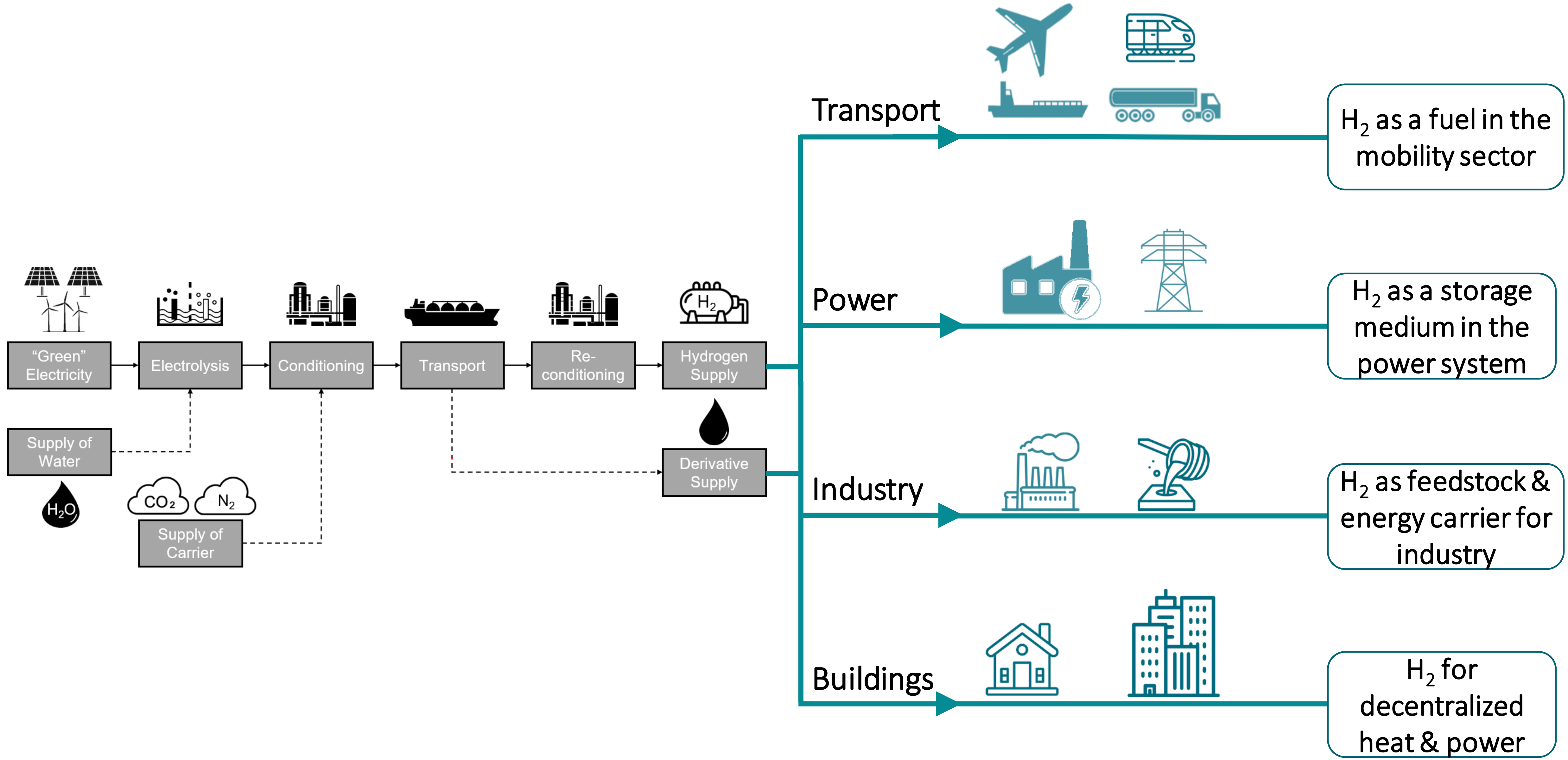
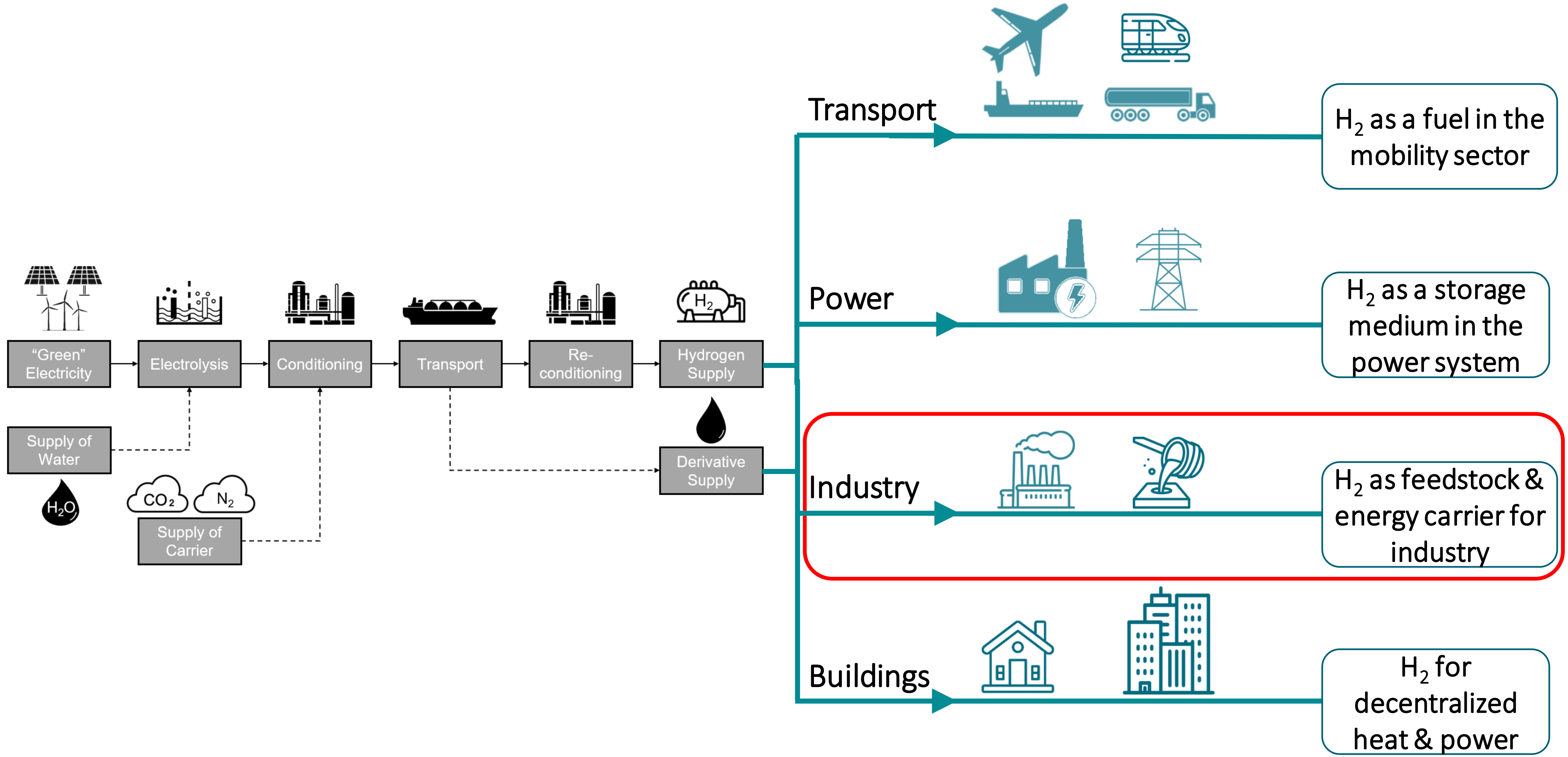
Hydrogen use today



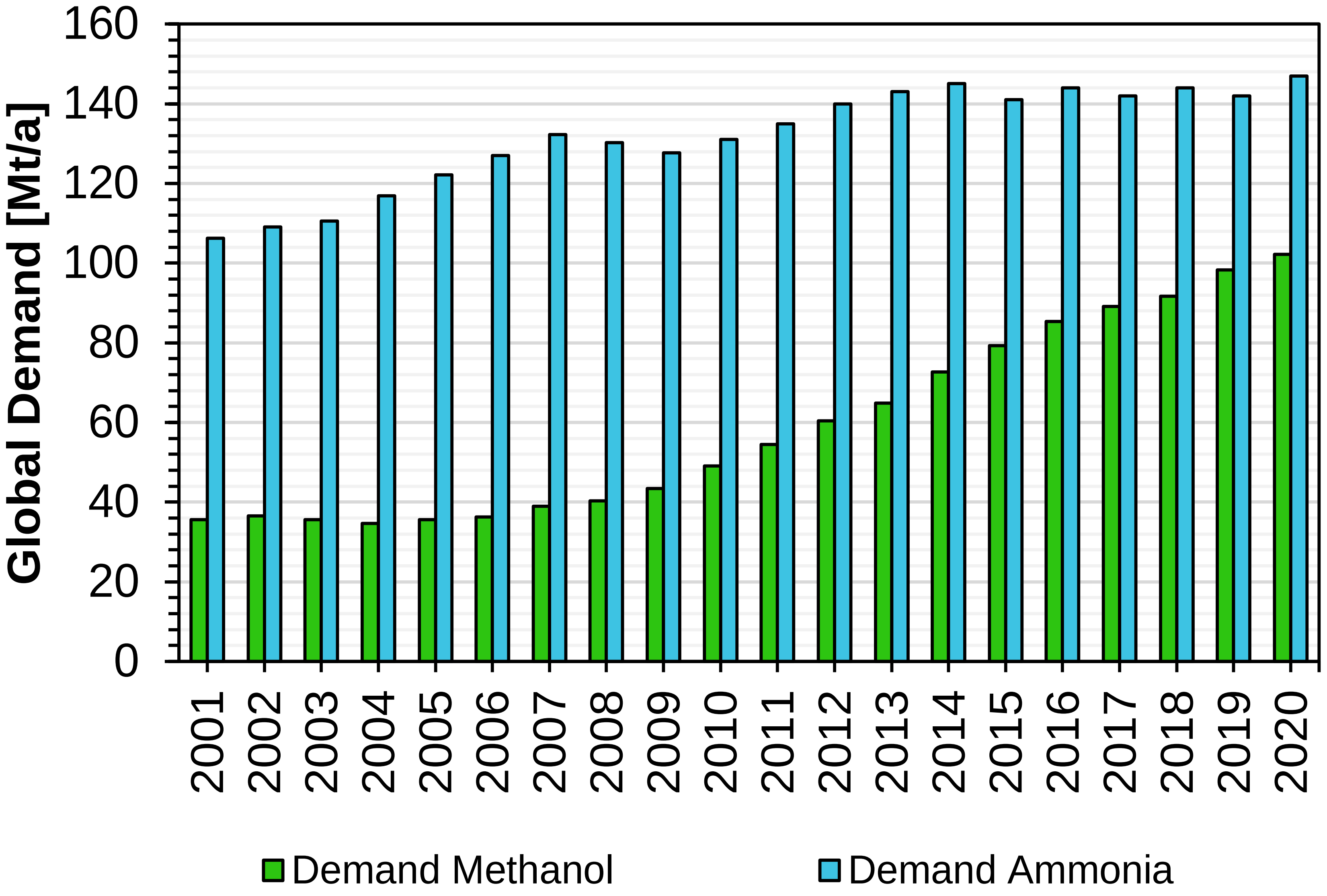
- Current global hydrogen demand of 75 Mt_{H2}/a and additional 45 $Mt_{H2\text{-}Mix}$/a (synthesis gas)
- H_2 almost entirely used in various industrial applications
- Largest share of demand covered by fossil based hydrogen (mainly from Steam Methane Reforming)

Potential markets for hydrogen in the future




"Green" Electricity
Electrolysis
Conditioning
Transport
Re-conditioning
Hydrogen Supply
Supply of Water
H_2O
CO_2
N_2
Supply of Carrier
Derivative Supply
H_2
Transport
Power
Industry
Buildings
H_2 as a fuel in the mobility sector
H_2 as a storage medium in the power system
H_2 as feedstock & energy carrier for industry
H_2 for decentralized heat & power

(Chemical) Industry – Ammonia and Methanol



Ammonia > 150 Mt/a$_{2020}$

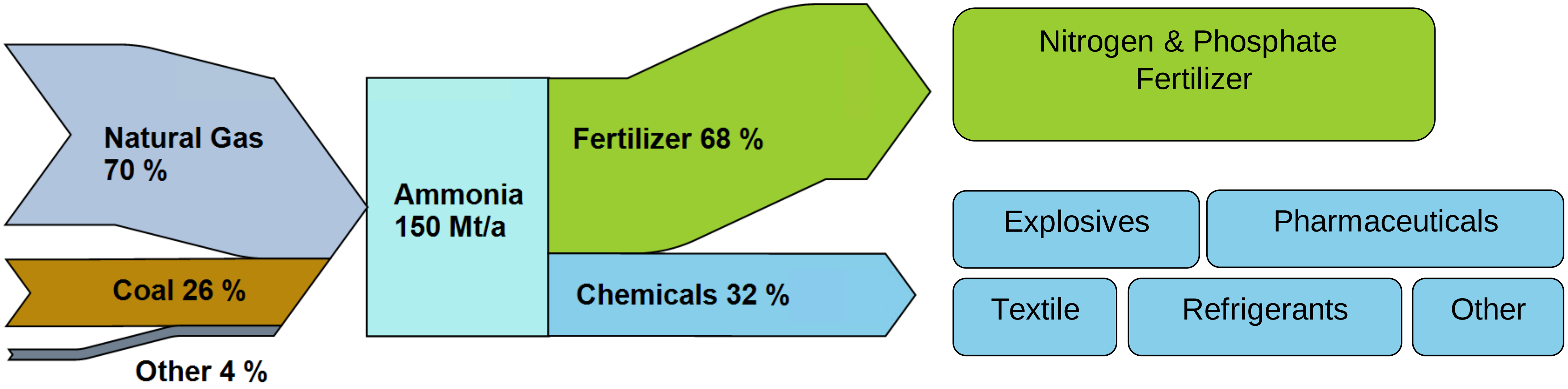
- Slight growth in demand (12 % in last decade)
- Increase broadly in line with rise in population

Methanol > 100 Mt/a$_{2020}$

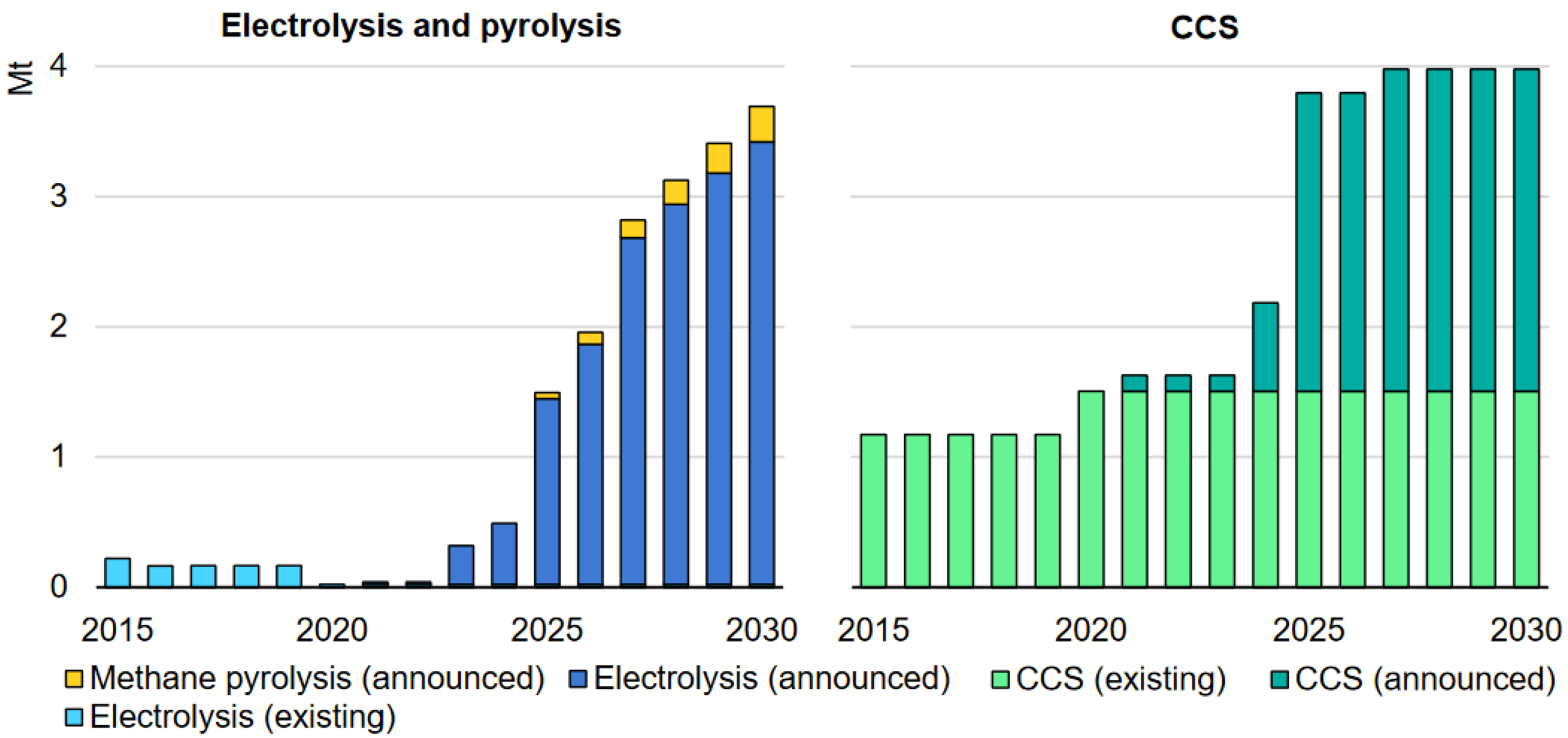
- Demand doubled within the last decade
- China's methanol economy is the main driver of this growth
- Very diverse use; mainly through chemical downstream processing

Source of data: https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary / https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol / https://www.ammoniaenergy.org/wp-content/uploads/2020/12/Oliver-Hatfield.pdf /

(Chemical) industry – Ammonia market

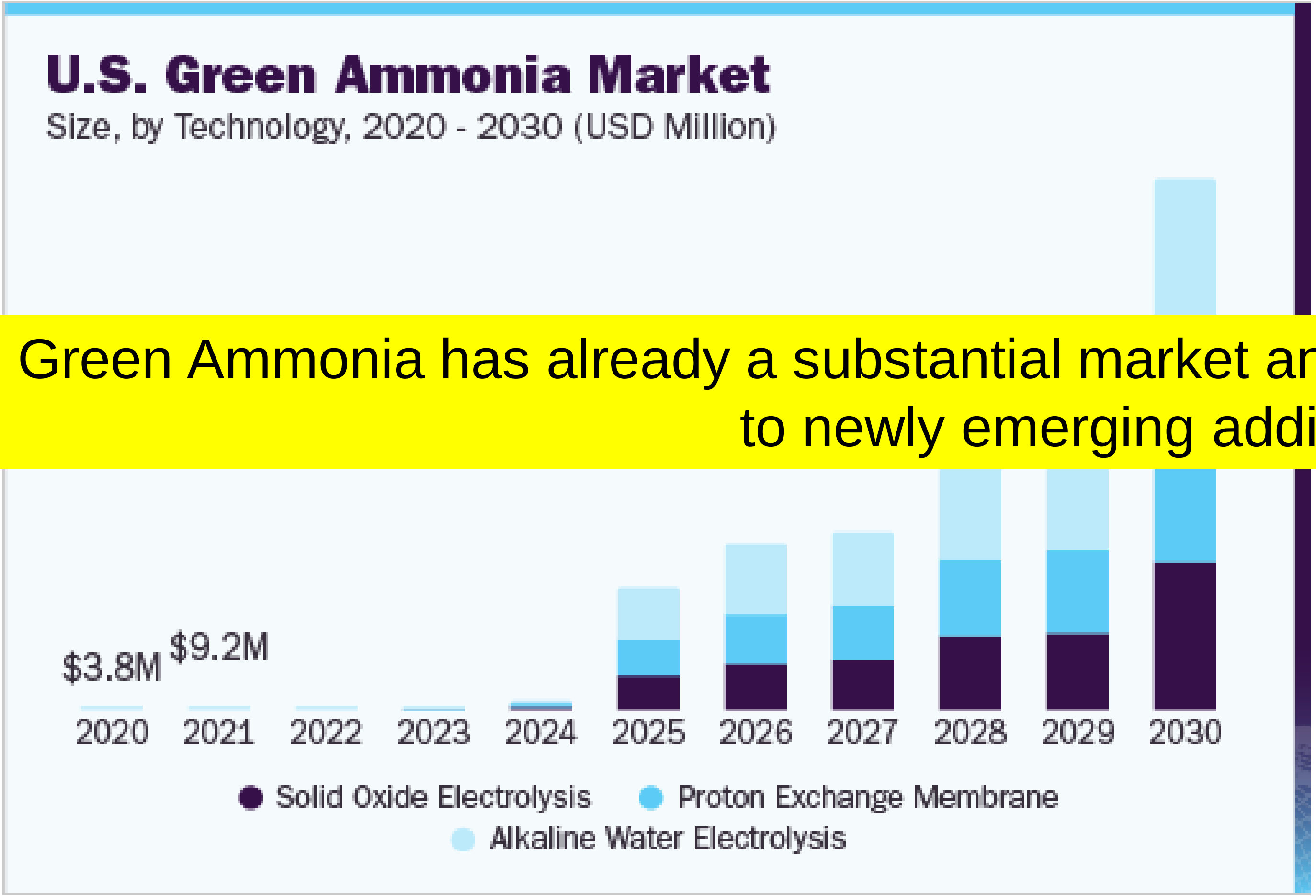


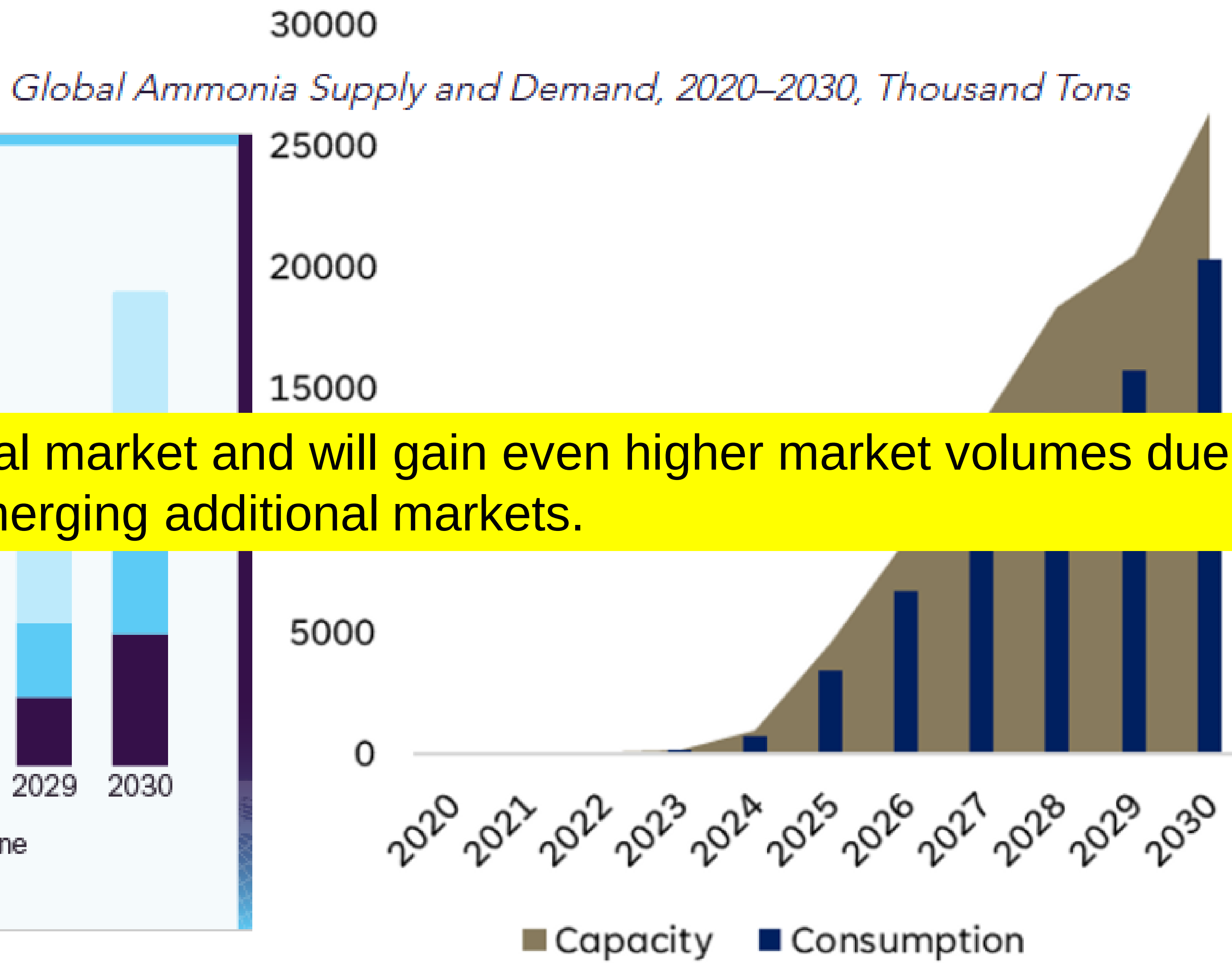
Current and announced projects for near-zero-emission ammonia production



Source: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

(Chemical) industry – Ammonia market

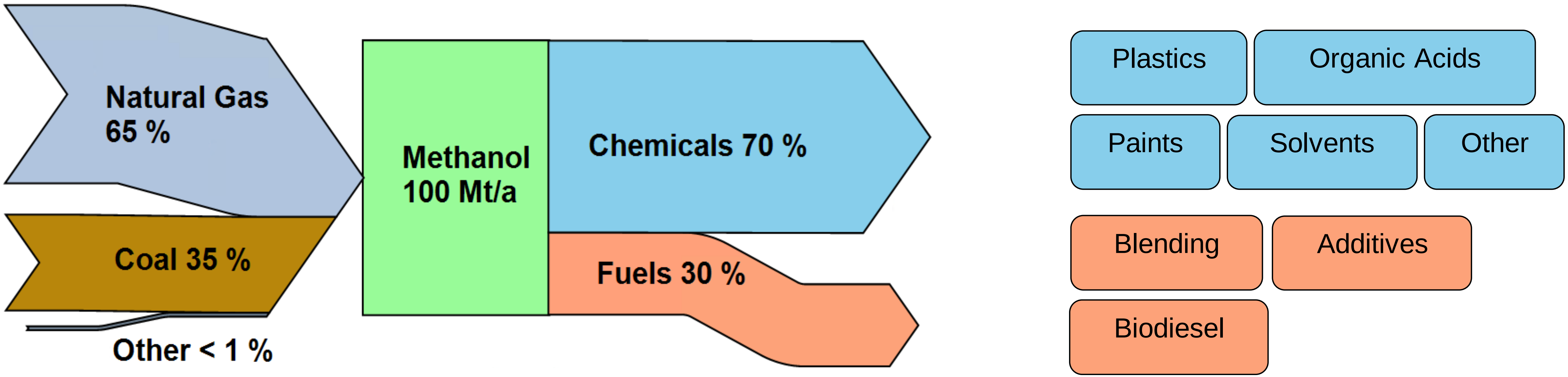




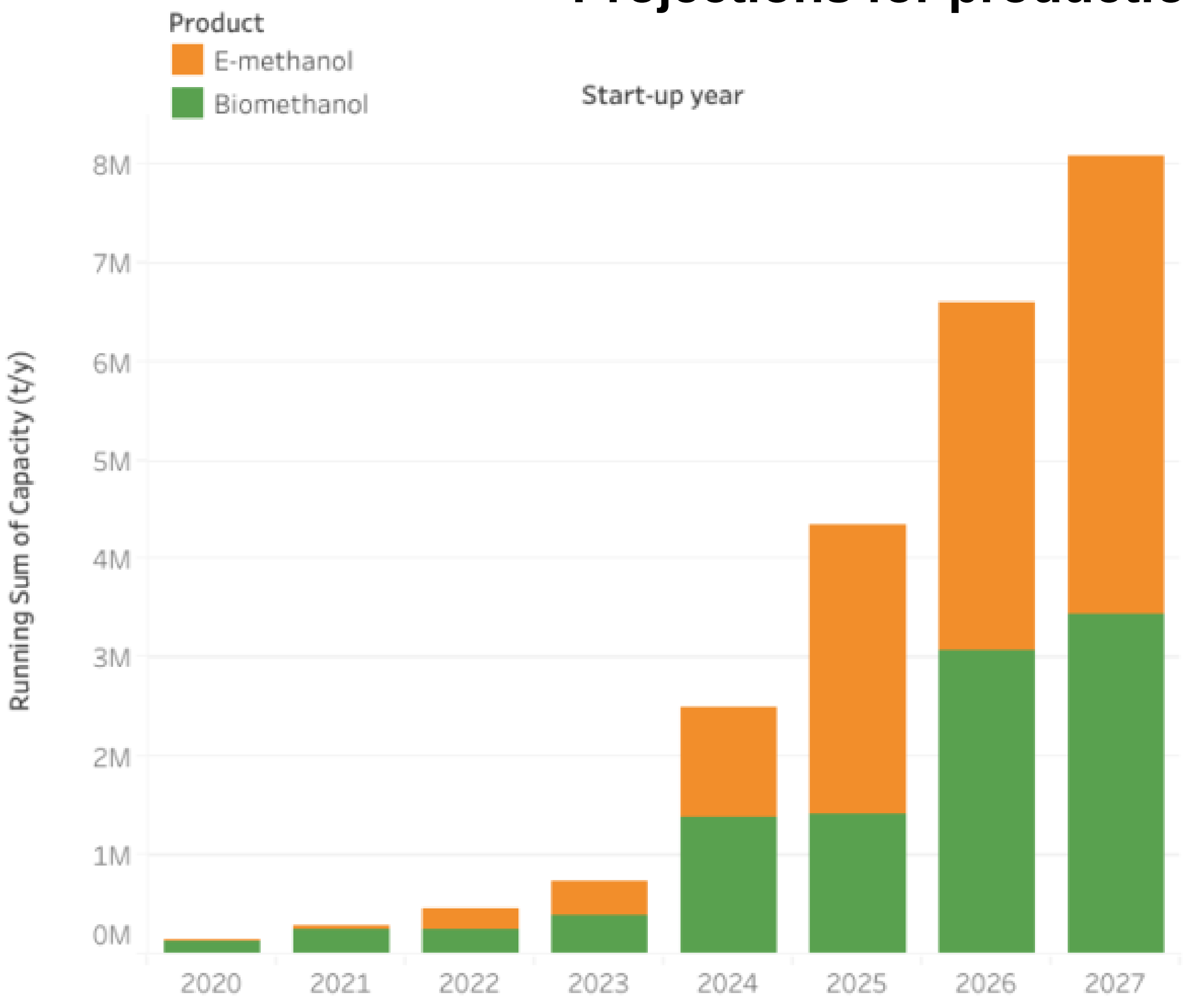
Green Ammonia has already a substantial market and will gain even higher market volumes due to newly emerging additional markets.

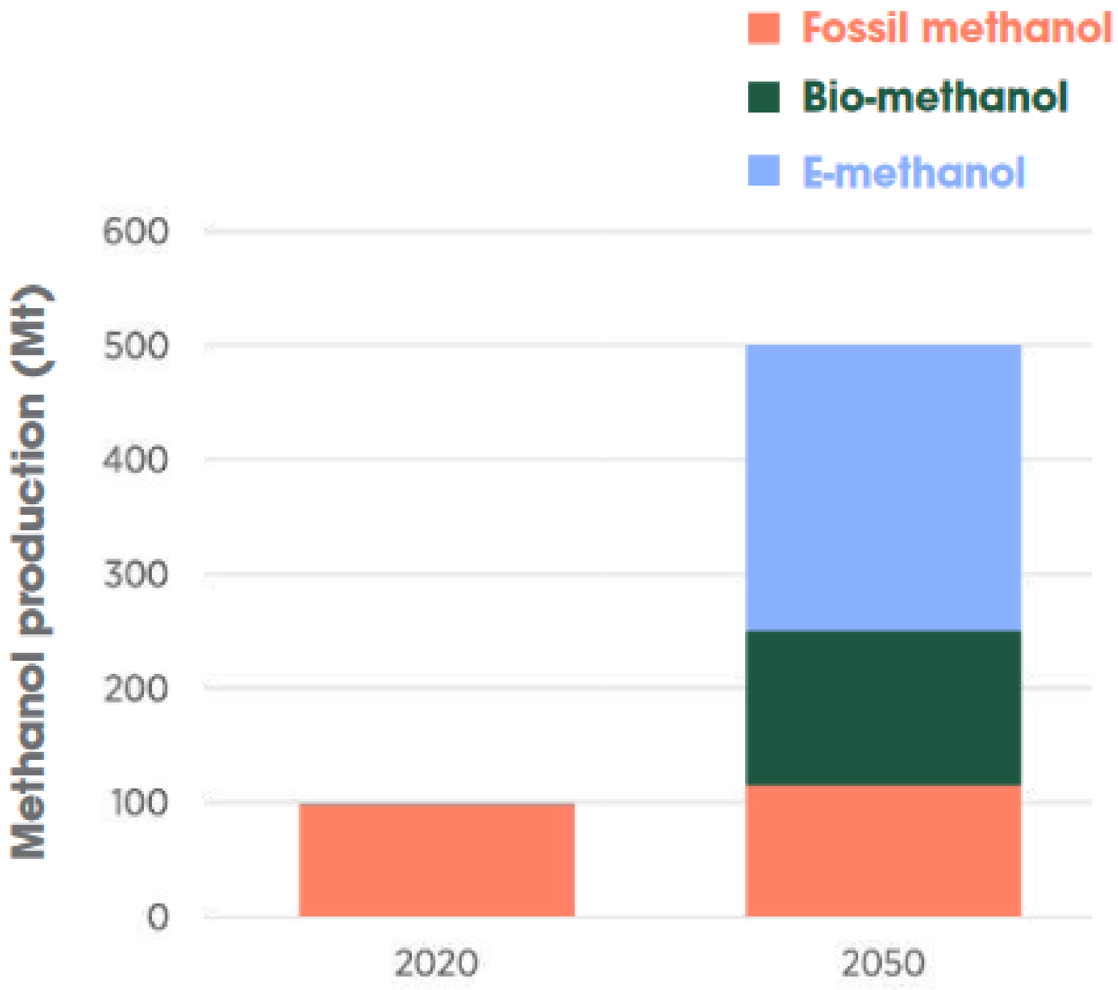
Source: https://www.grandviewresearch.com/industry-analysis/green-ammonia-market-report / https://www.insightutive.com/post/green-ammonia-market-outlook-to-2030

(Chemical) industry – Methanol market



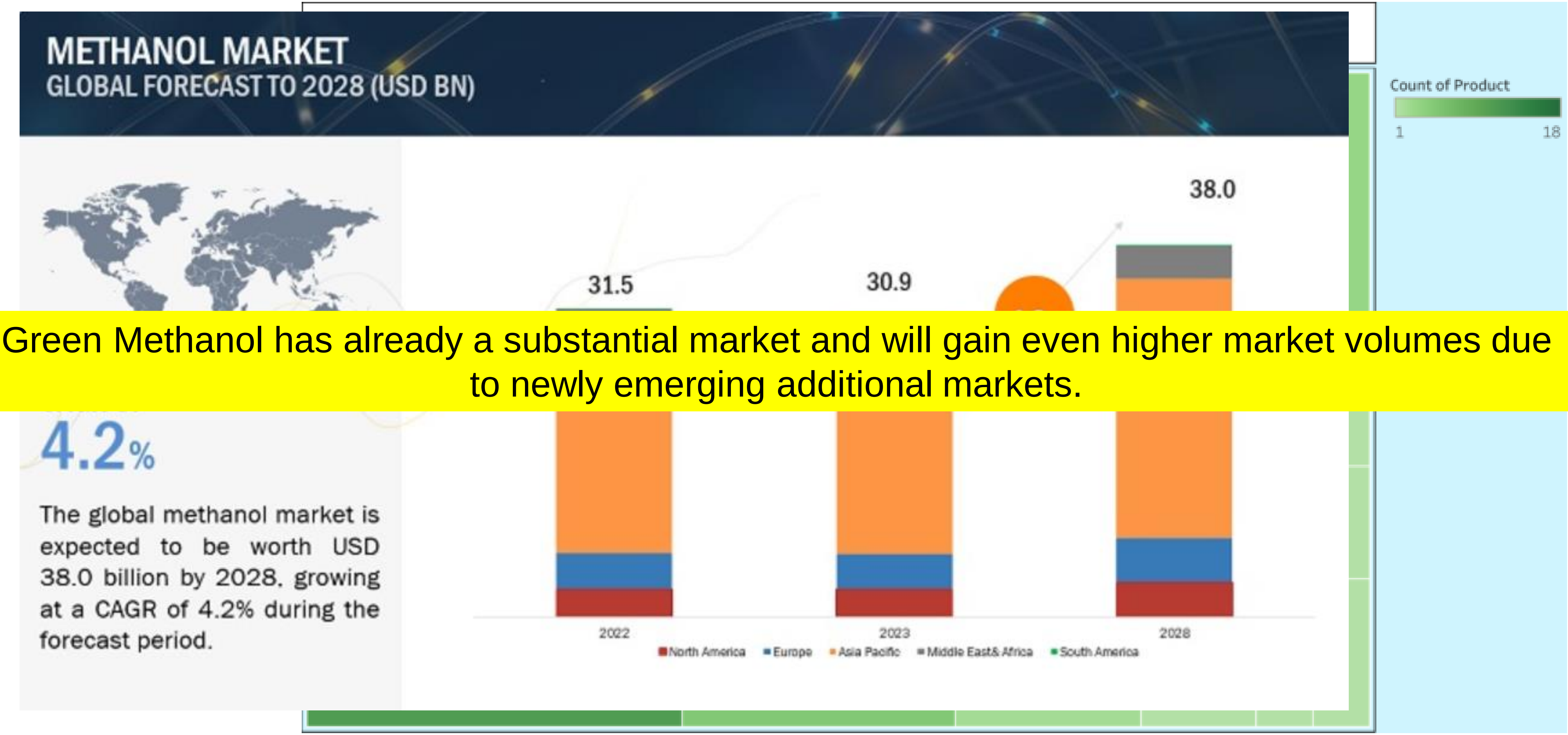
Projections for production of renewable methanol





Source : Methanol Institute Renewable Methanol Database of Current/Announced Projects

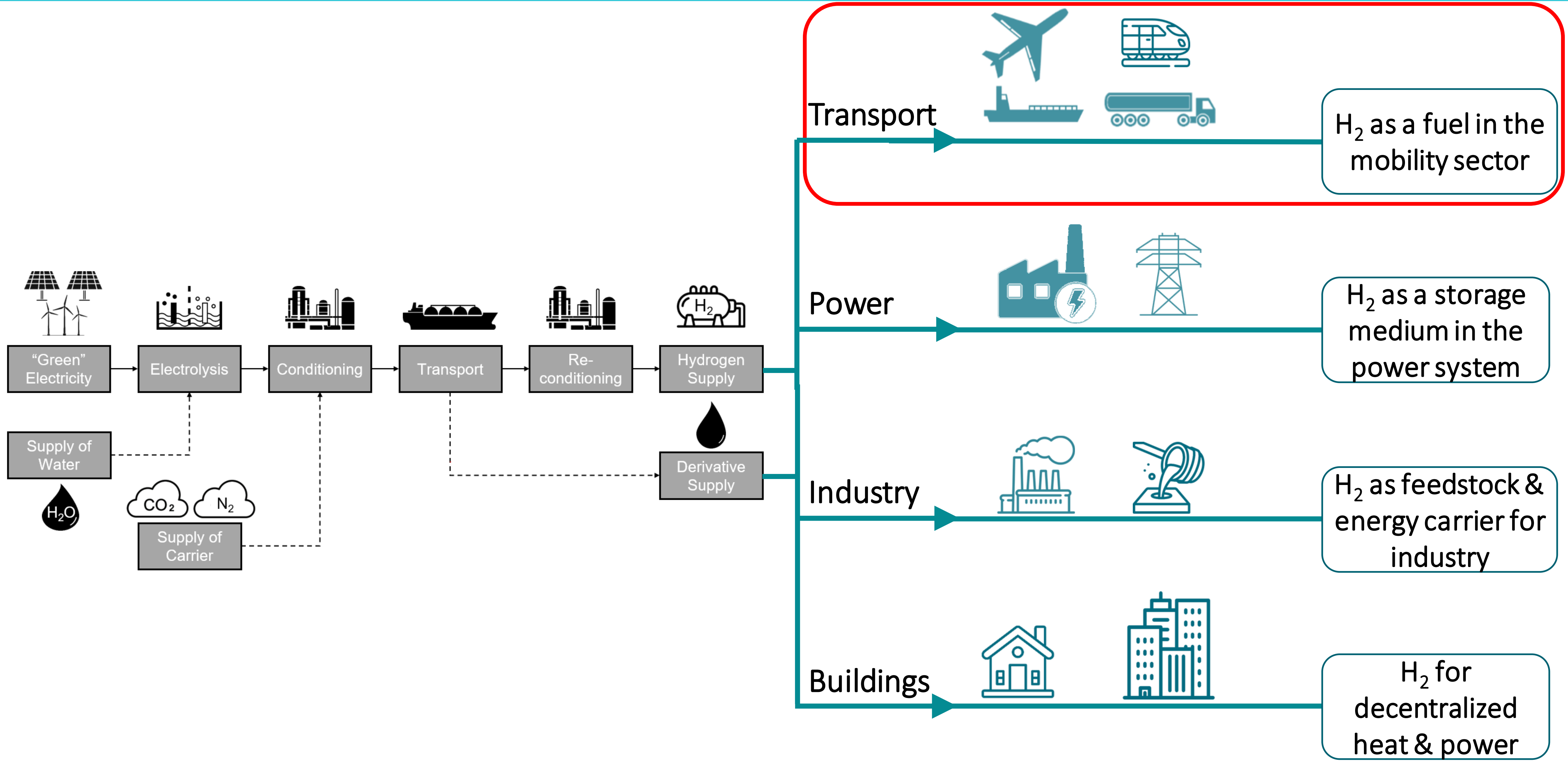
Source: https://www.methanol.org/renewable / https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf



Green Methanol has already a substantial market and will gain even higher market volumes due to newly emerging additional markets.

Source: https://www.methanol.org/renewable/

Potential use cases for hydrogen – Transport



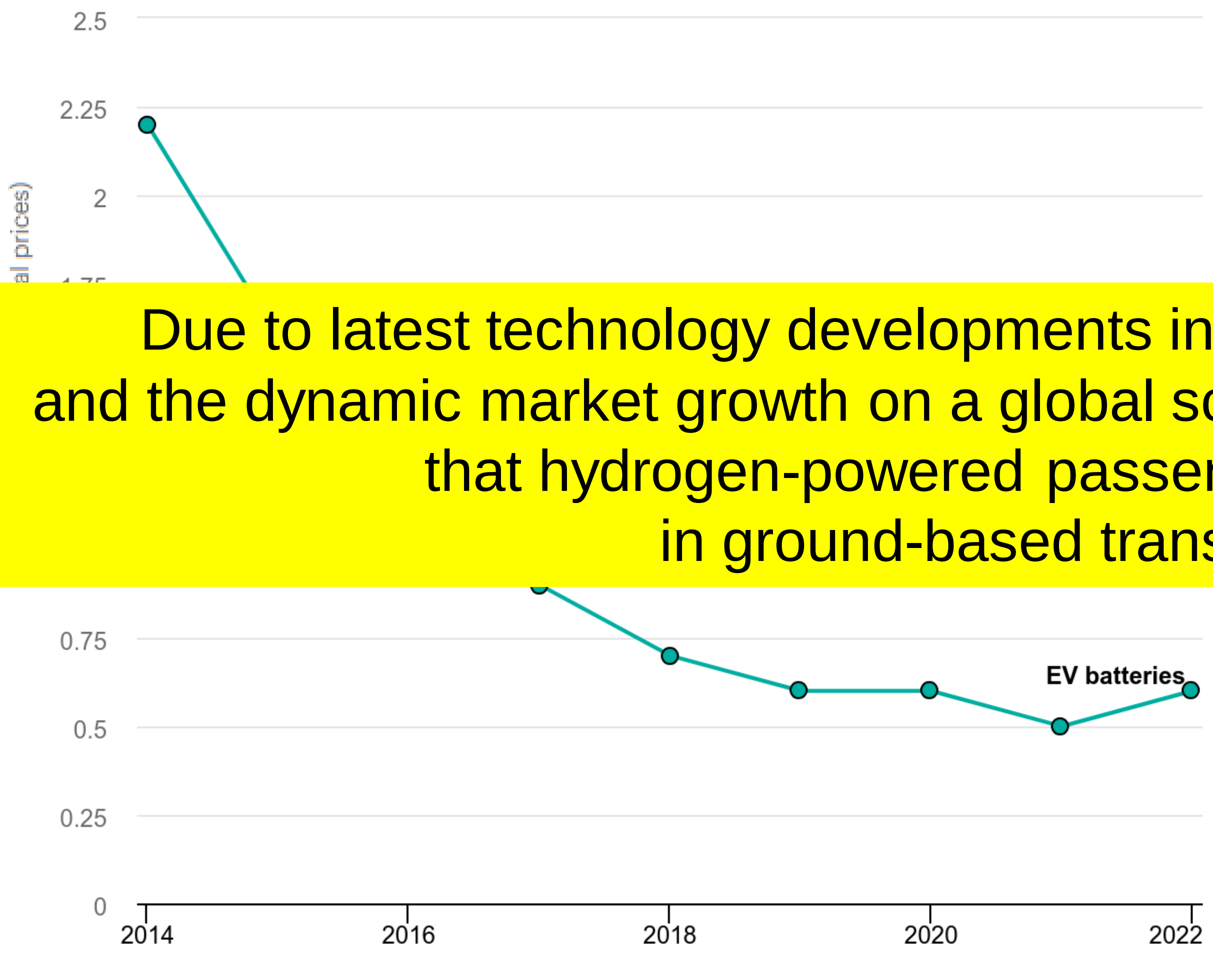
Hydrogen-powered vehicles – Renewable Energy Directive

- The Renewable Energy Directive ("RED") sets binding targets for the Member States that must be achieved by 2030 → Each member state must implement these targets in its national legislation
- In future, “RED III” (2023/2413) introduces sub-quota(s) for RFNBO in transport sector to be achieved by 2030:
  - 1.0 % of final energy in whole transport sector
  - 1.2 % of final energy in maritime sector*
- RFNBO can generally be used in the entire transport sector
- For target “29 % share of renewable energy”: RFNBO incentivised by accounting factors (but: other fuel options as well!)

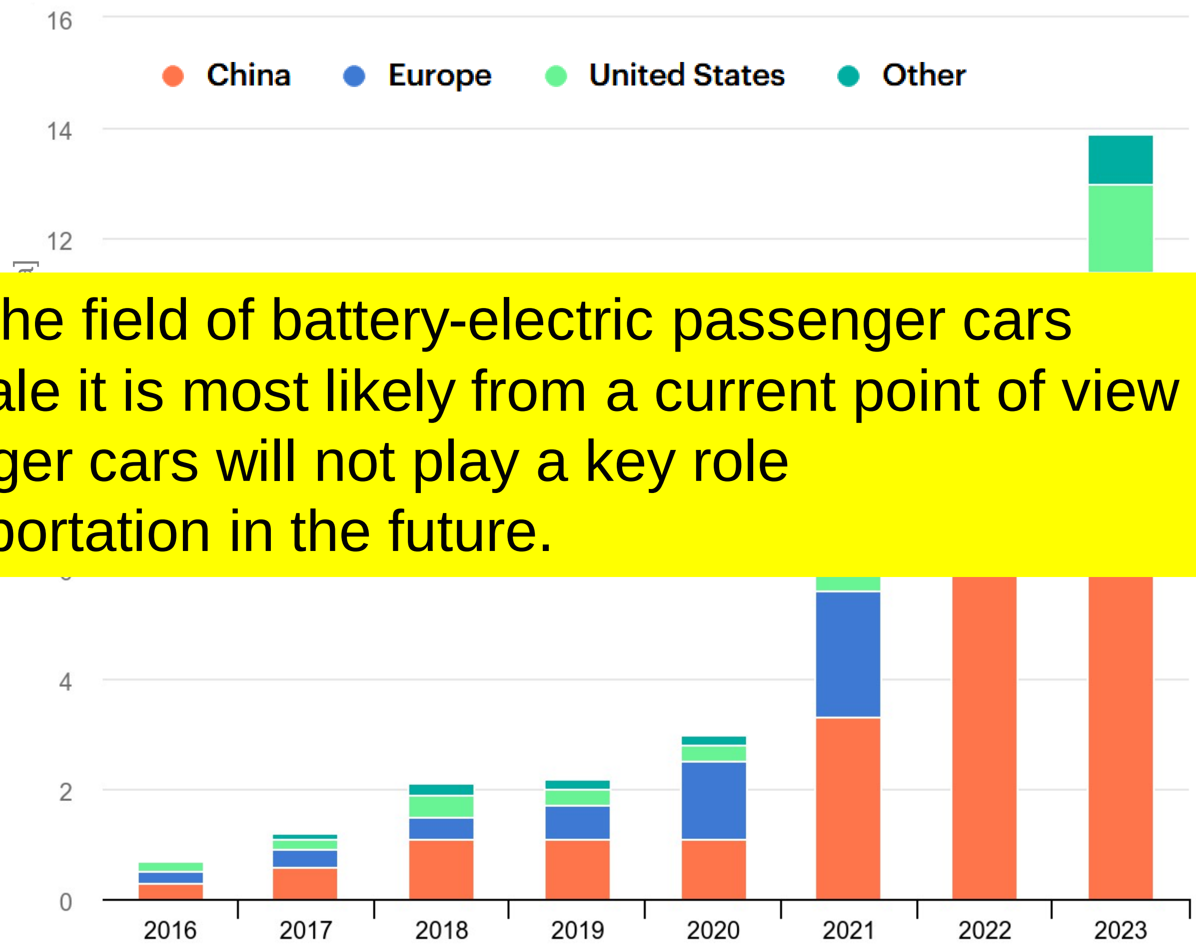
Possible overall targets	GHG-Quota	Share of Renewable Energies
Target to reach (%)	14.5	29
Sub-Quota for RFNBO (% of final energy consumption)	1	1
Accounting factor (-)	X	2
Accounting factor for RFNBO in maritime or aviation sector (-)	X	1.5

* Non-Mandatory; Member states shall “endeavour to ensure“ that the share of RFNBO supplied to the maritime sector is at least 1.2 % in 2030 (Directive 2023/2413 („RED III“))

Battery costs



Worldwide sales of battery-electric vehicles



Due to latest technology developments in the field of battery-electric passenger cars and the dynamic market growth on a global scale it is most likely from a current point of view that hydrogen-powered passenger cars will not play a key role in ground-based transportation in the future.

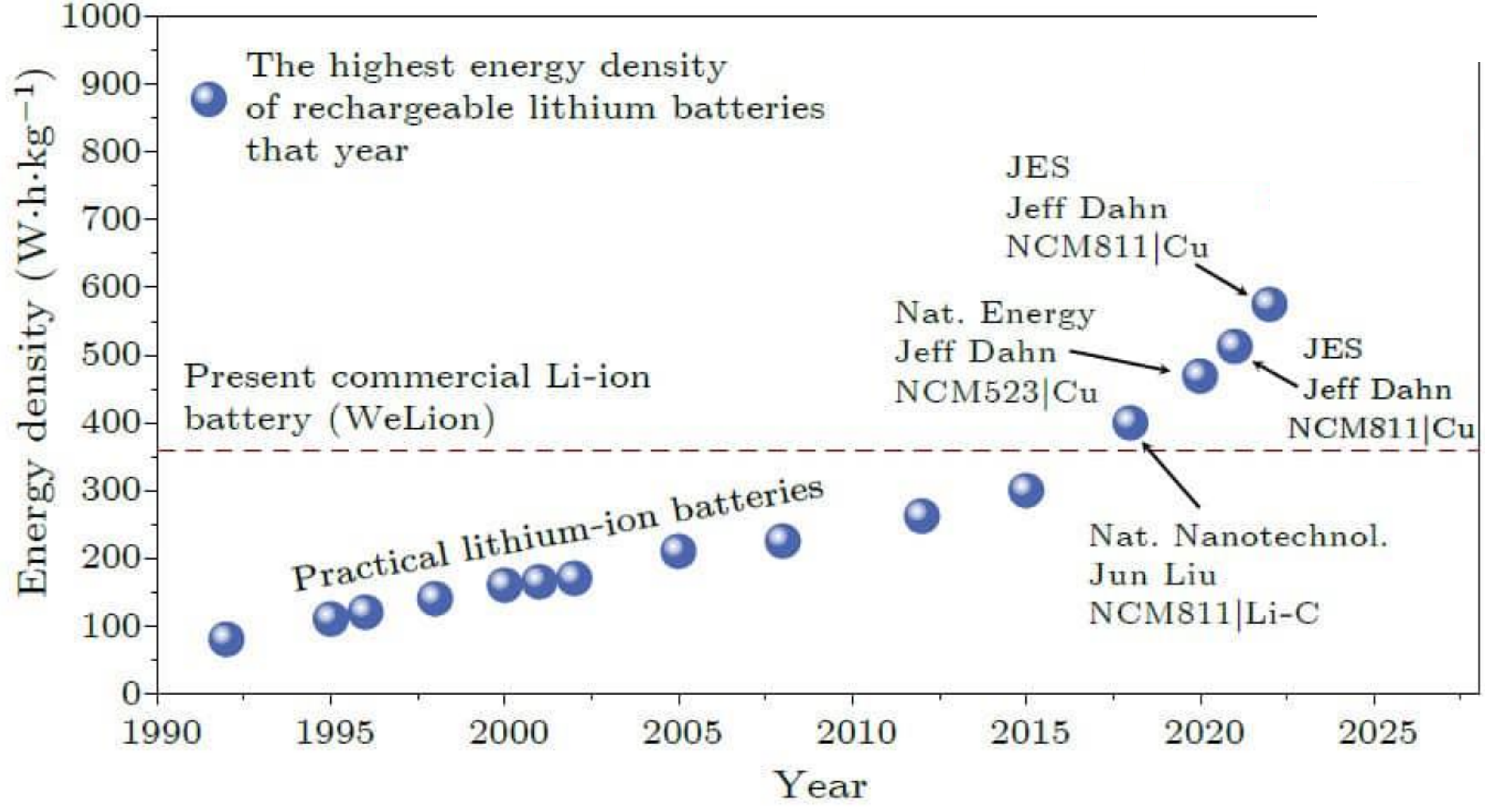
Source: https://www.iea.org/data-and-statistics/charts/average-prices-for-selected-technologies-2014-2022 / https://www.iea.org/data-and-statistics/charts/electric-car-sales-2016-2023

Hydrogen-powered vehicles – Road transport

FINANCIAL TIMES

Northvolt in new sodium-ion battery breakthrough

Swedish start-up has developed an energy storage technology with no critical minerals including lithium which could minimise reliance on China [26]



REUTERS® World Business Markets Sustainability Legal Breakingviews Technology

Autos & Transportation | Sustainable & EV Supply Chain

VW masters dry-coating battery process with potential to slash cell costs

Reuters

June 16, 2023 3:00 PM GMT+2 · Updated 7 months ago

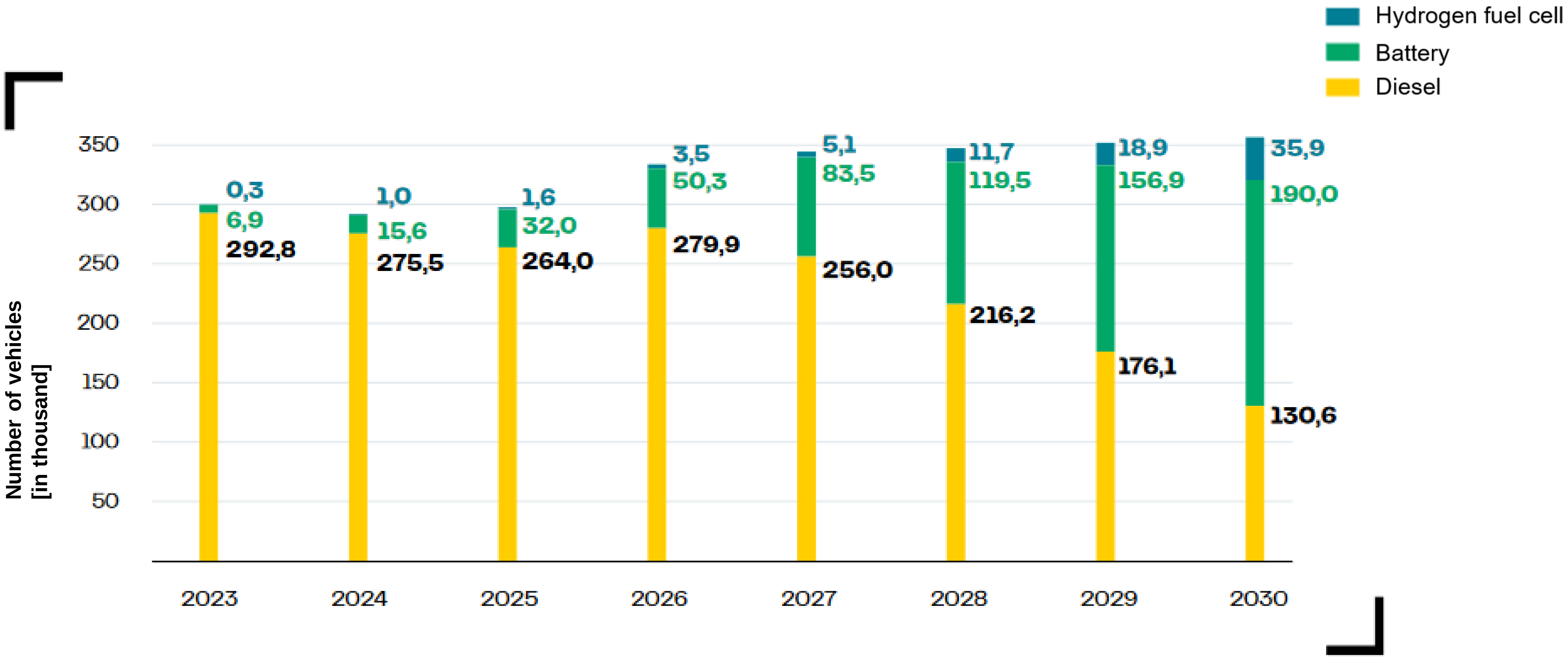
[27]

[28]

Mercedes-Benz Trucks celebrates world premiere of the battery electric long-haul truck eActros 600

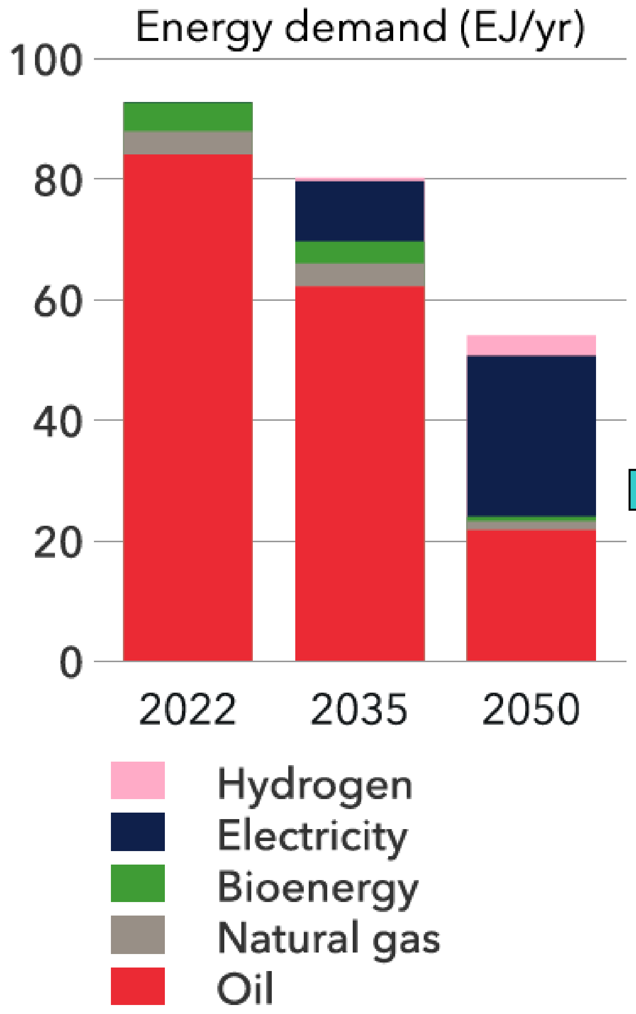
Source: https://physicsworld.com/a/lithium-ion-batteries-break-energy-density-record/

Forecasted sales of heavy duty vehicles (> 12 t) in Europe



Source: NOW (2023) - Marktentwicklung klimafreundlicher Technologien im schweren Straßengüterverkehr

Forecasted demand of hydrogen and hydrogen derivatives in road transport



In the defossilized road transport of the future, battery electric vehicles will in all likelihood be predominantly used. Hydrogen and hydrogen derivatives will only be used in niche applications.

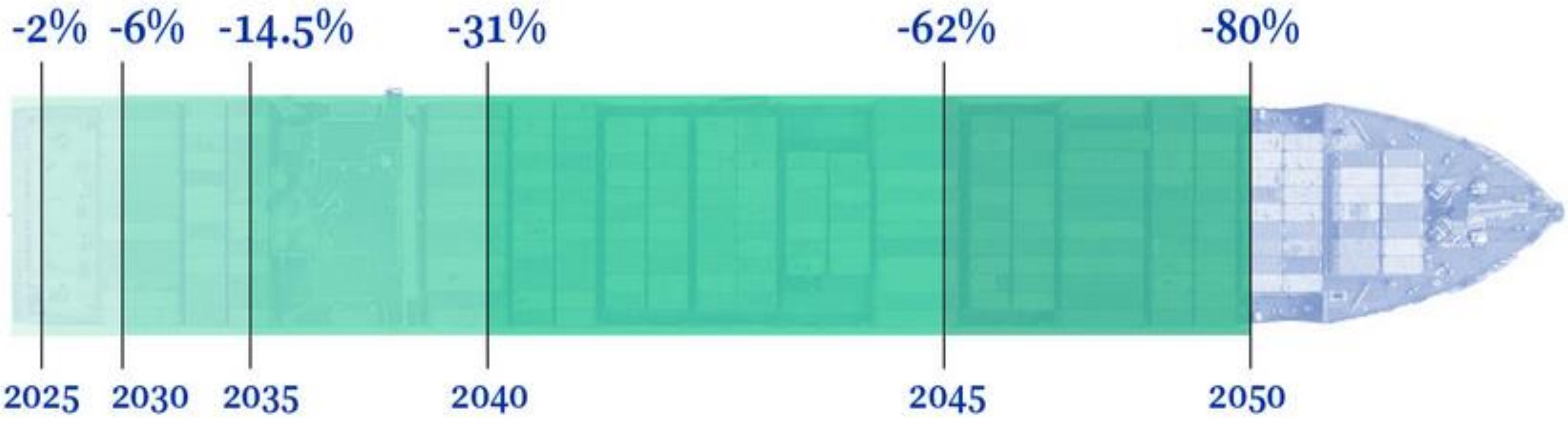
Source: DNV (2023) – Pathway to net-zero emissions. Energy Transition Outlook 2023

Hydrogen-powered vehicles – Maritime transport

The FuelEU maritime regulation will oblige vessels above 5000 gross tonnes calling at European ports (with exceptions such as fishing ships):

→ to **reduce** the **greenhouse gas intensity** of the energy used on board as follows

Annual average carbon intensity reduction compared to the average in 2020



Source: https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu/

Hydrogen-powered vehicles – Maritime transport

Press releases

Maersk to deploy first large methanol-enabled vessel on Asia - Europe trade lane

07 December 2023

Ocean Transport | Decarbonisation | Share

[28]

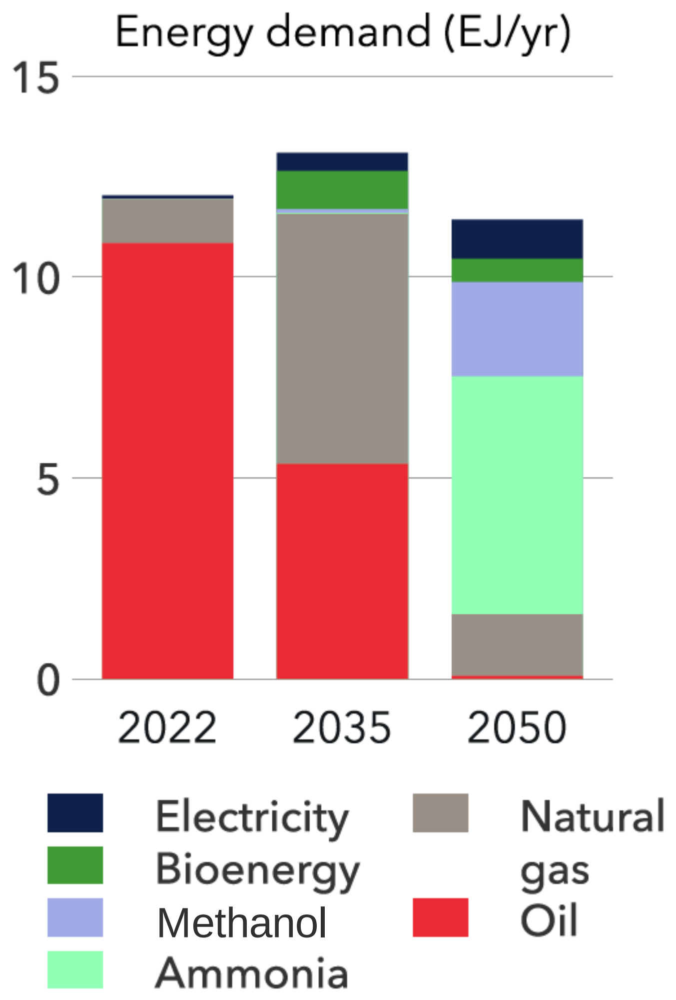
COSCO Shipping Energy picks methanol for six new tankers [29]

Wärtsilä solutions chosen for world's first methanol fuelled hybrid RoRo vessels

Wärtsilä Corporation, Press release 13 September 2023 at 10:00 UTC+2

[30]

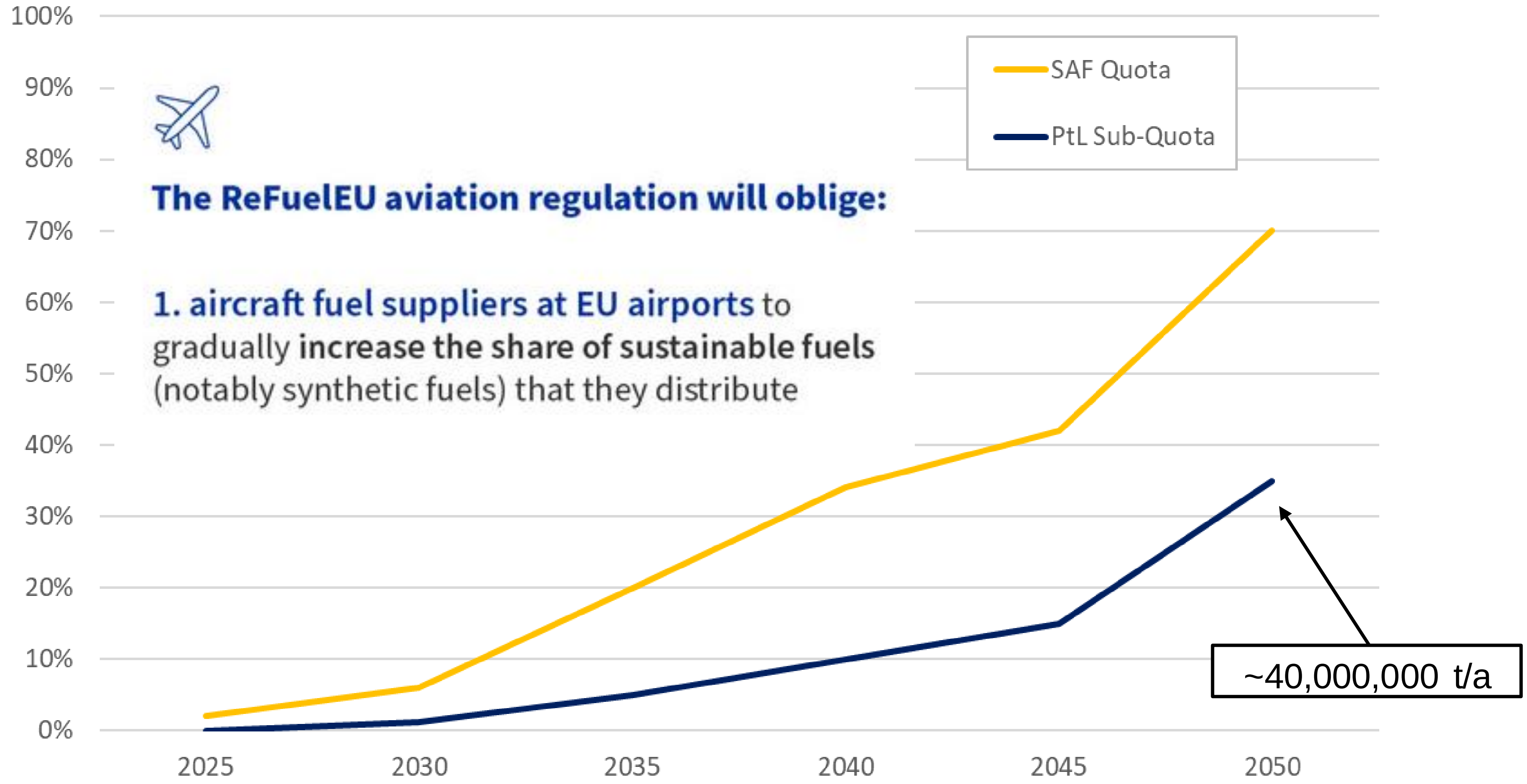
Forecasted demand of hydrogen and hydrogen derivatives in maritime transport



"Green" methanol and/or ammonia are expected to be the predominant renewable marine fuels in the future. The first developments in the market for converting propulsion systems to these fuels can already be seen today.

Source: DNV (2023) – Pathway to net-zero emissions. Energy Transition Outlook 2023

Hydrogen-powered vehicles – Aviation

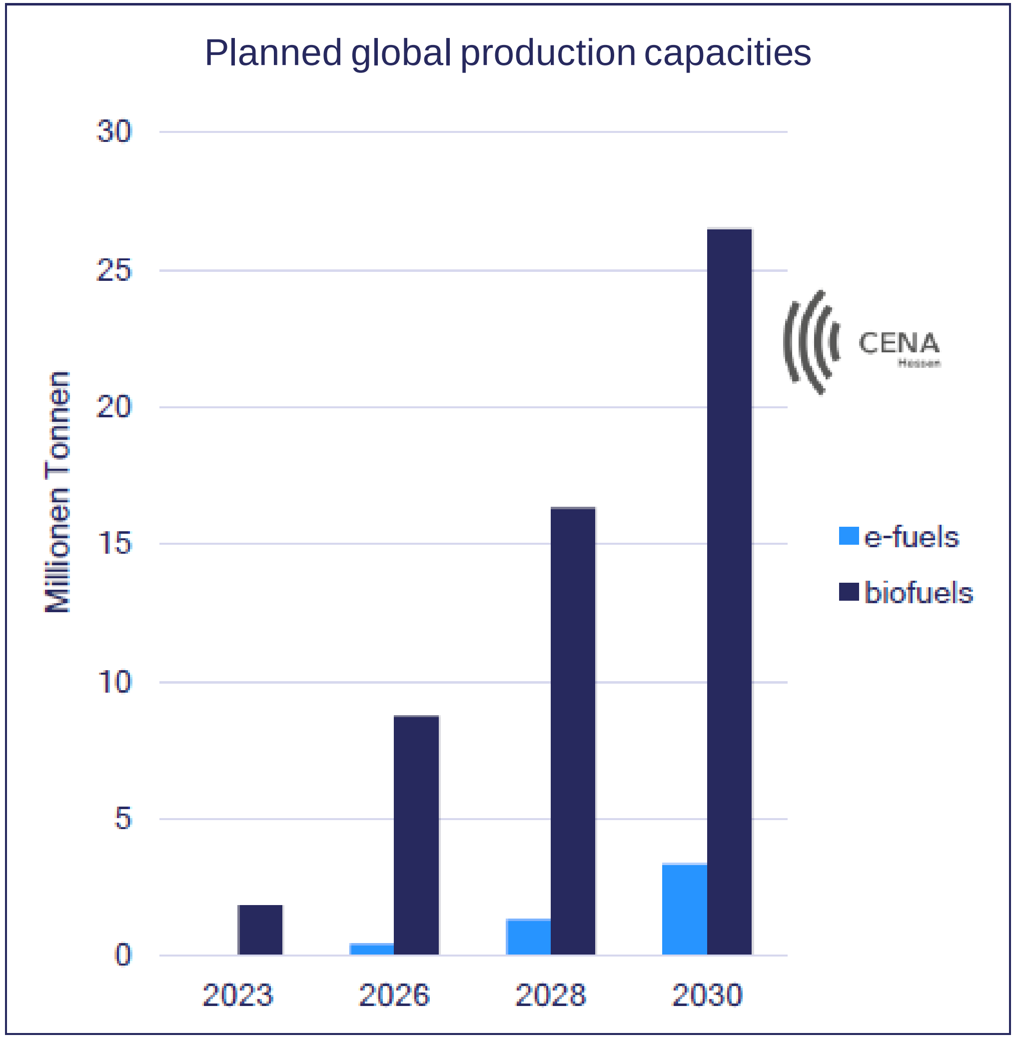


Biogenic or synthetic (PtL) kerosene is the only sustainable option for the foreseeable future to decarbonize aviation. This is especially true for medium- to long-haul flights where novel propulsion systems (e.g., based on liquid hydrogen) are technologically too challenging.

Source: https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu/

Hydrogen-powered vehicles – Aviation

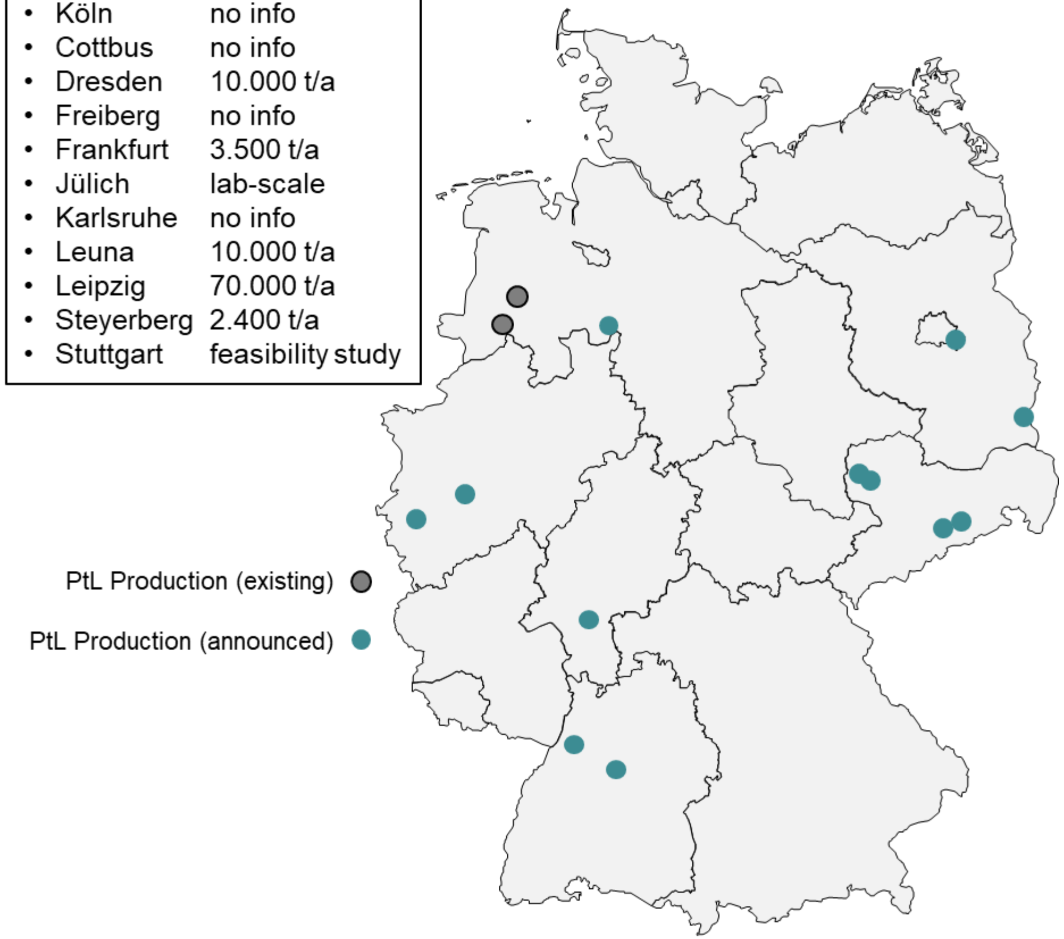
Global → Focus on biogenic kerosene



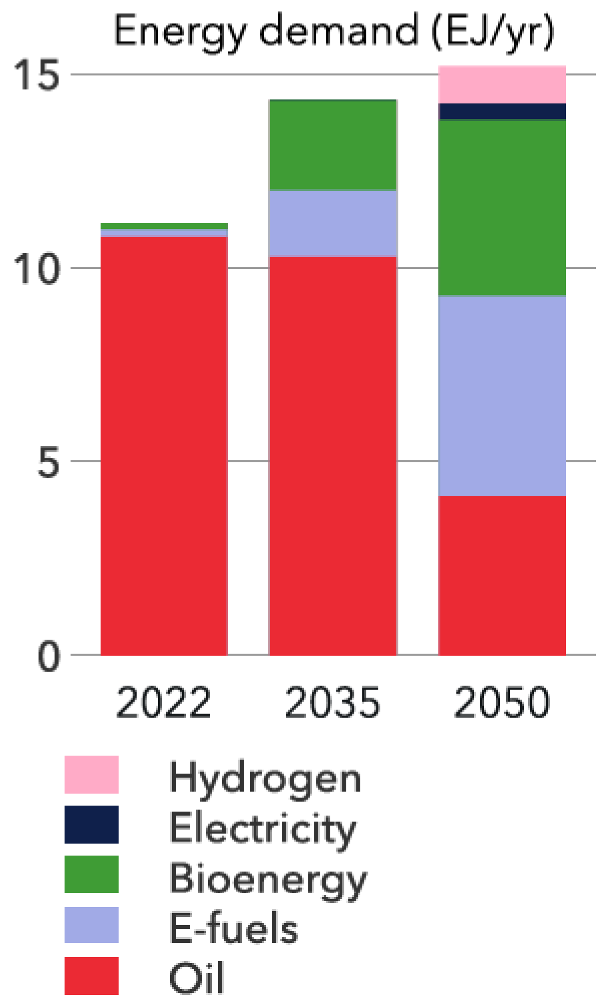
Germany → Focus on PtL kerosene

Announced PtL Produktion

• Berlin	15.000 t/a
• Köln	no info
• Cottbus	no info
• Dresden	10.000 t/a
• Freiberg	no info
• Frankfurt	3.500 t/a
• Jülich	lab-scale
• Karlsruhe	no info
• Leuna	10.000 t/a
• Leipzig	70.000 t/a
• Steyerberg	2.400 t/a
• Stuttgart	feasibility study



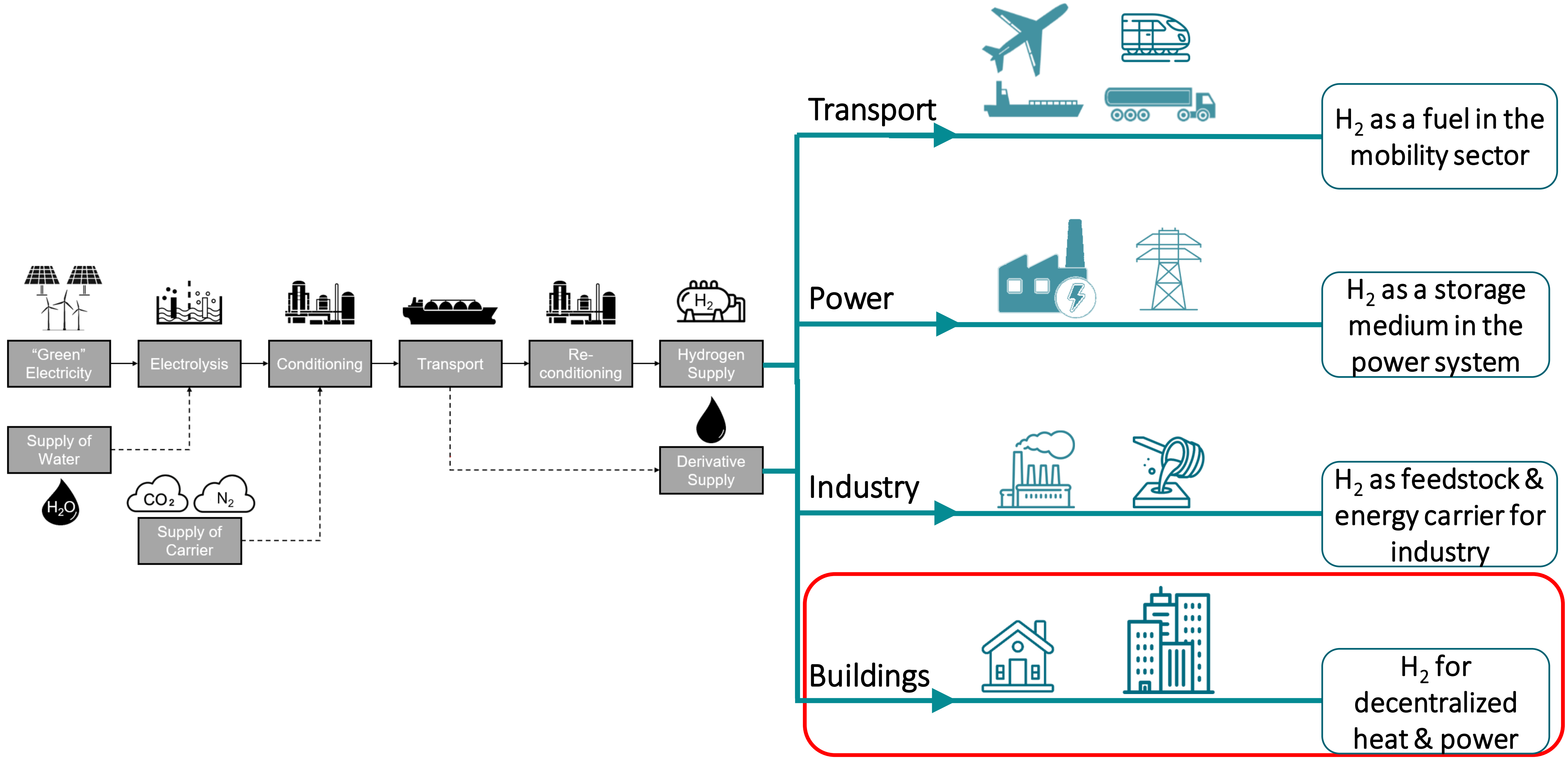
Forecasted demand of hydrogen and hydrogen derivatives in aviation

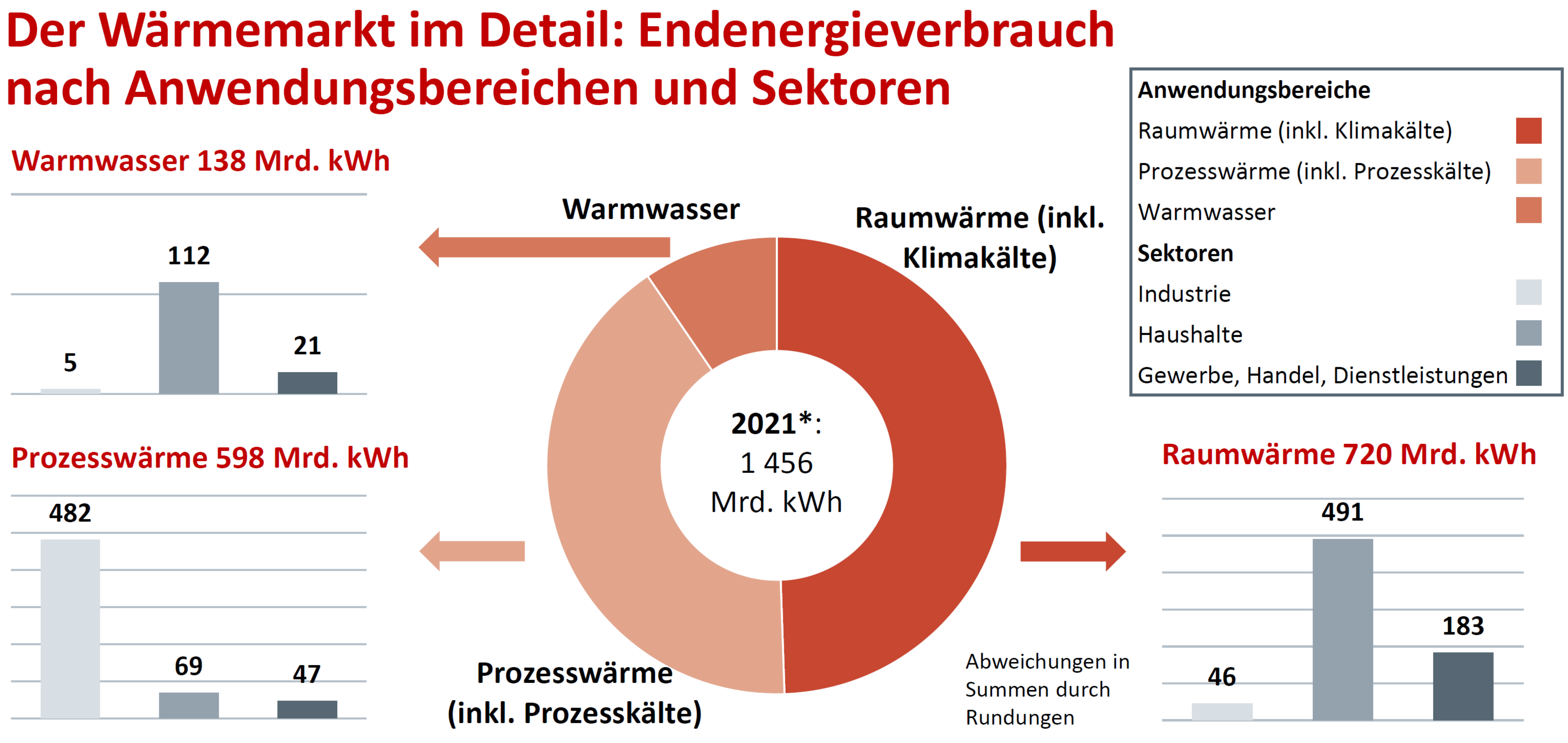


PtL kerosene (*E-fuel*) made from (green) hydrogen will play a pivotal role in the defossilization of aviation. It has almost identical properties to fossil. The emergence of an international market is therefore likely.

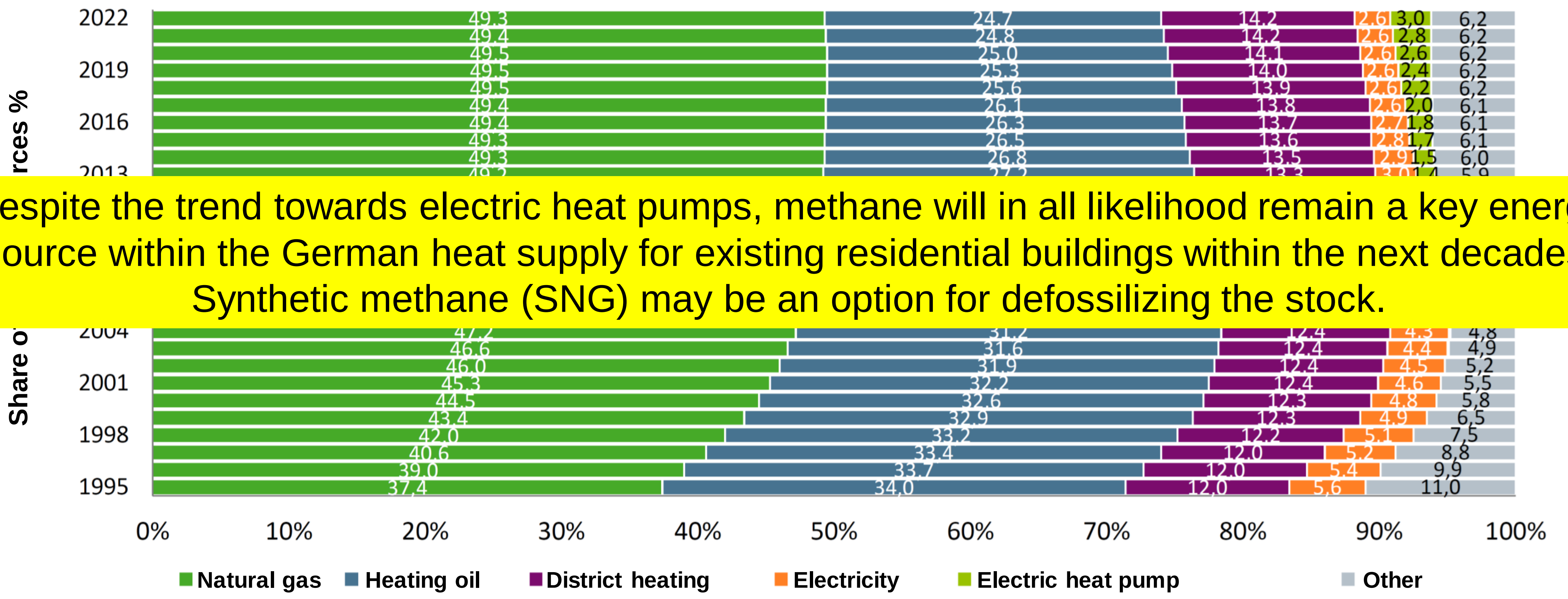
Source: DNV (2023) – Pathway to net-zero emissions. Energy Transition Outlook 2023

Potential use cases for hydrogen in the future – Heat for buildings




Der Wärmemarkt im Detail: Endenergieverbrauch nach Anwendungsbereichen und Sektoren
Warmwasser 138 Mrd. kWh
5
112
21
Prozesswärme 598 Mrd. kWh
482
69
47
Warmwasser
Raumwärme (inkl. Klimakälte)
2021*: 1 456 Mrd. kWh
Prozesswärme (inkl. Prozesskälte)
Abweichungen in Summen durch Rundungen
Anwendungsbereiche
Raumwärme (inkl. Klimakälte)
Prozesswärme (inkl. Prozesskälte)
Warmwasser
Sektoren
Industrie
Haushalte
Gewerbe, Handel, Dienstleistungen
Raumwärme 720 Mrd. kWh
46
491
183

Energy sources for the heat supply of buildings in Germany



Despite the trend towards electric heat pumps, methane will in all likelihood remain a key energy source within the German heat supply for existing residential buildings within the next decades. Synthetic methane (SNG) may be an option for defossilizing the stock.

Source: https://www.bdew.de/media/documents/Statusreport_Waerme_Stand_17_11_2023_final.pdf

Conclusion

- Hydrogen-based molecules are an indispensable part of our overall global economy; we use them as a raw material as well as an energy carrier – and so far these molecules are fossil-based.
- Due to the need to transform our highly integrated global energy system towards more climate-compatibility, "green" molecules must be used. Taking technological, economic and systemic aspects into consideration the following developments can be observed.
  - The chemical industry demands today already substantial amounts of ammonia and methanol; these bulk chemicals will become more increasingly "green".
  - Within the transport sector mainly the maritime and the aviation sector are demanding "green" molecules; for ship propulsion mainly ammonia and methanol and for long-haul flights FT-based PtL fuels are under discussion. Additionally, minor markets might emerge for special-purpose vehicles.
  - For heat provision within existing residential buildings synthetic natural gas (SNG) might be a promising option due to the extensively developed infrastructure. This is also true for selected applications in industry and commerce.
- Related to the already existing and most likely emerging markets "green" ammonia, "green" methanol, "green" methane and FT-crude are the most important hydrogen derivates – and at least for a transition period these end-consumer markets are clearly bigger compared to the pure hydrogen markets.

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