Alternative fuels and availability

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Decarbonizing gas turbines - Alternative Fuels & Carbon Capture

Zero or carbon neutral fuel

- **Green hydrogen**
- **Bio- / E-methane**
- **Ammonia**
- Sustainable liquid fuels (Bio-/E-**Methanol**, etc.)
- Biogas (→ local, distributed CHP applications)

Carbon capture & Storage

- blue hydrogen
- turquoise hydrogen

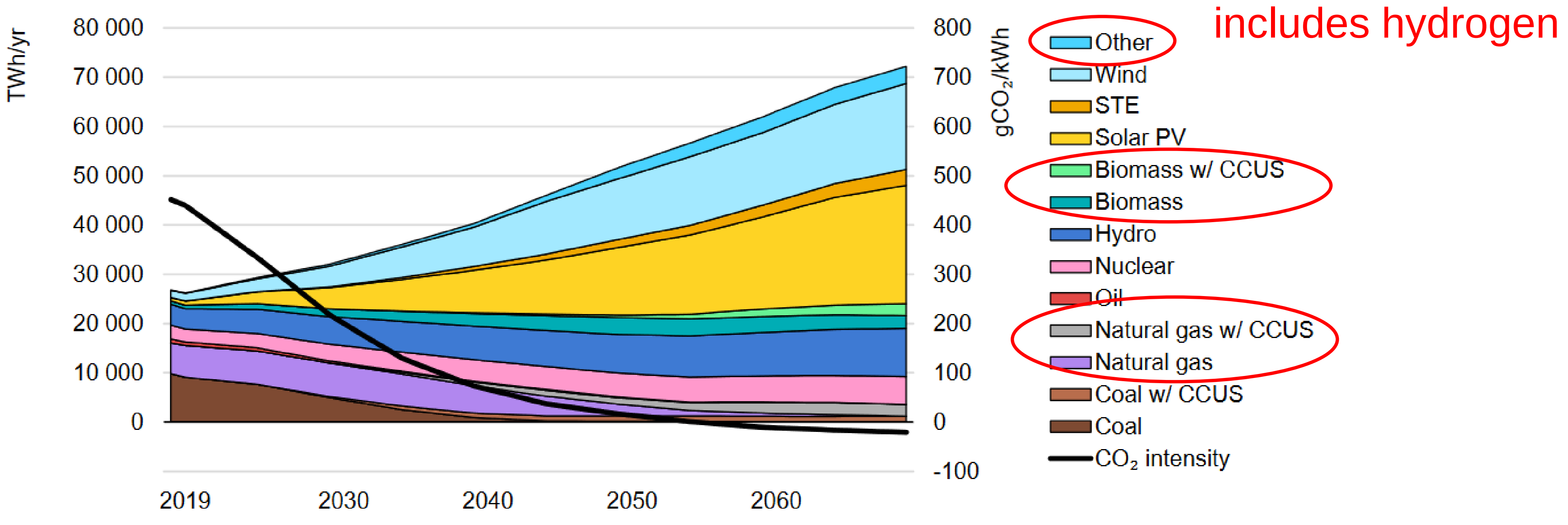
Carbon removal from exhaust

Natural gas (NG)/ liquefied natural gas (LNG) + CCUS (Carbon capture, Utilization and Storage)

- Solvents (liquid / solid)
- Oxy-fuel cycles

Production outlook for power generation

Global power generation by fuel/technology in the Sustainable Development Scenario, 2019-70



Notes: TWh = terawatt-hours; gCO_2/kWh = grammes of CO_2 per kilowatt-hour; STE = solar thermal electricity; PV = photovoltaic; CCUS = carbon capture, utilisation storage. Other includes geothermal power, ocean energy and hydrogen.

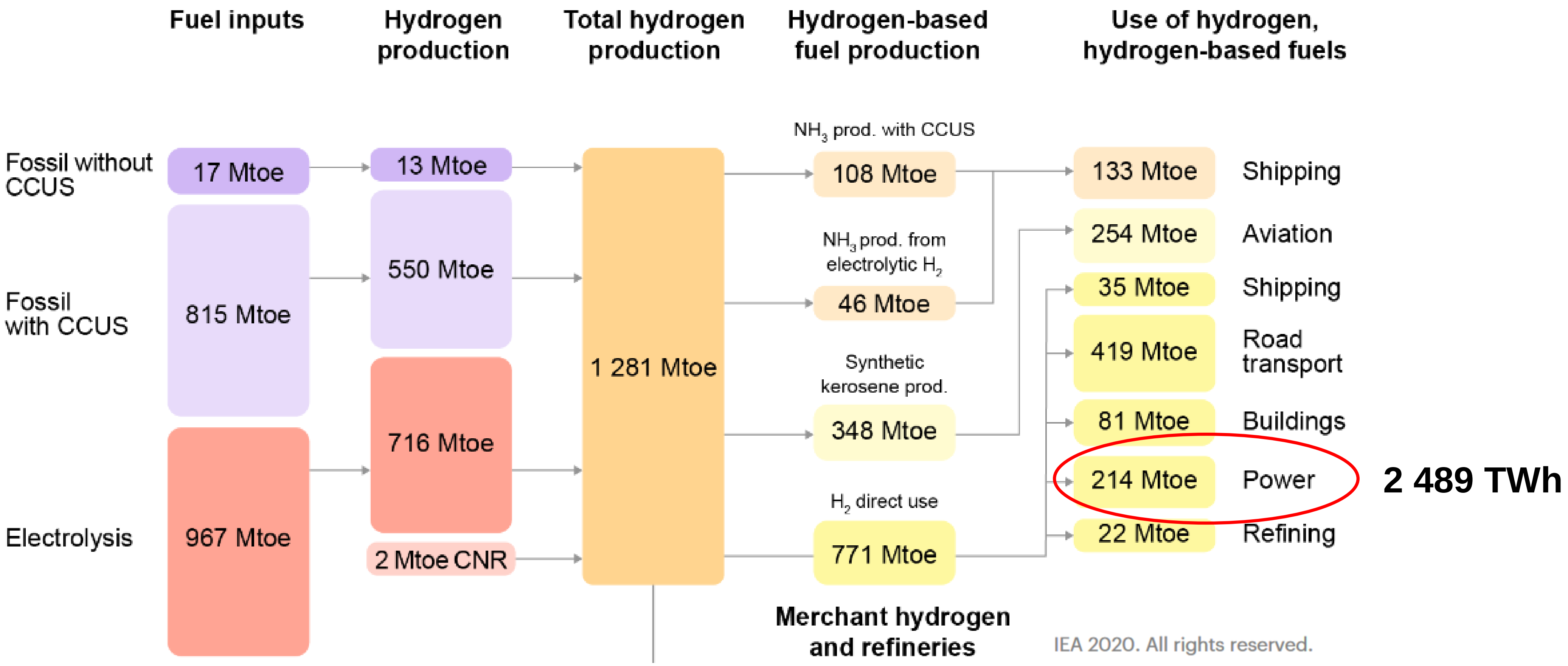
IEA (2020), *Energy Technology Perspectives 2020*, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2020

Green Hydrogen

Production	+ No carbon capture required (efficient production) + cost-effective production compared to synthetic methane or liquid fuels + proven technology - Ramp-up and cost-reduction of electrolyser production required
Transport and Infrastructure	- Installation of new EU gas infrastructure necessary / Repurposing natural gas networks to hydrogen - International long-distance transport difficult (cost-intensive transport of liquid hydrogen or hydrogen carrier required)
Applicability in gas turbines	+ Applicability in gas turbines possible / modifications necessary, new combustion systems required; good low load capability commitment of gas turbine industry to ensure 100 Vol.% H_2 capability by 2030

Green Hydrogen

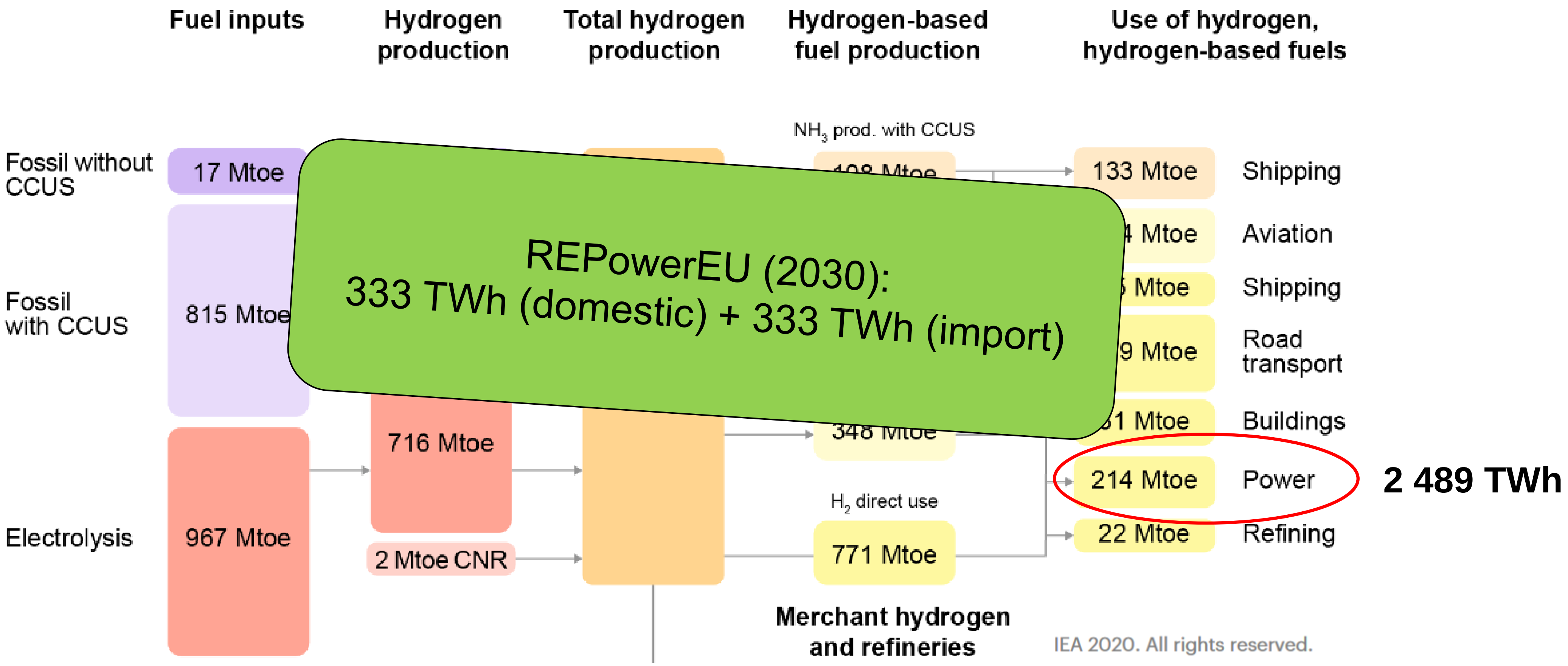
Global hydrogen production / demand in the Sustainable Development Scenario, 2070



IEA (2020), *Energy Technology Perspectives 2020*, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2020

Green Hydrogen

Global hydrogen production / demand in the Sustainable Development Scenario, 2070

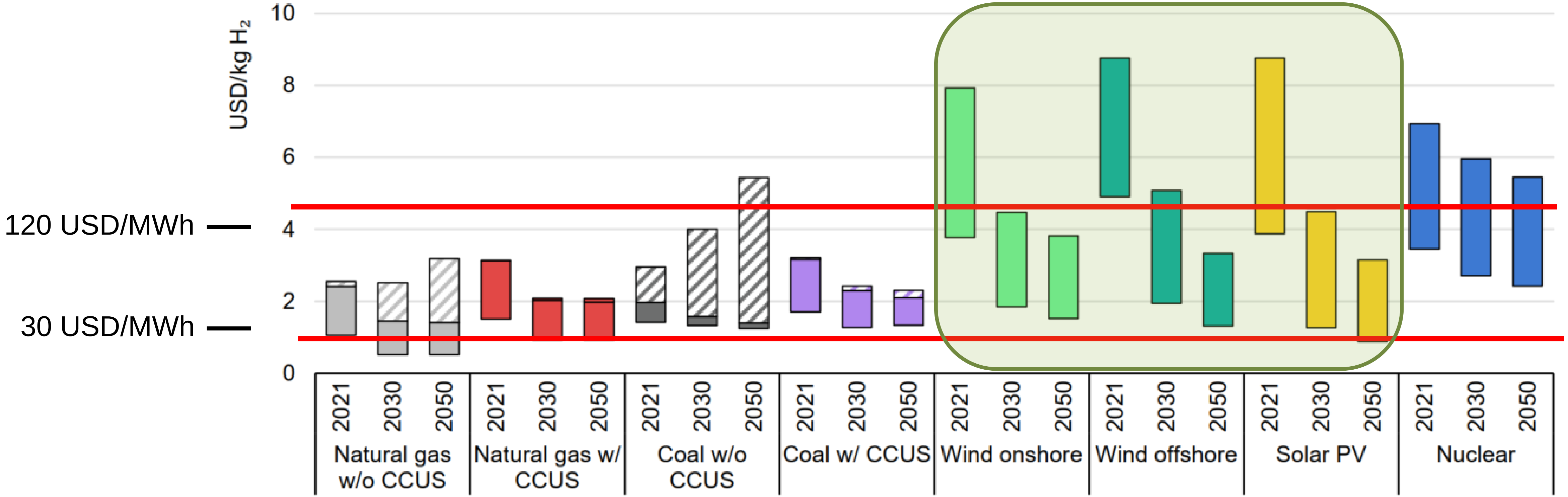


IEA (2020), *Energy Technology Perspectives 2020*, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2020

Green Hydrogen

Production costs outlook

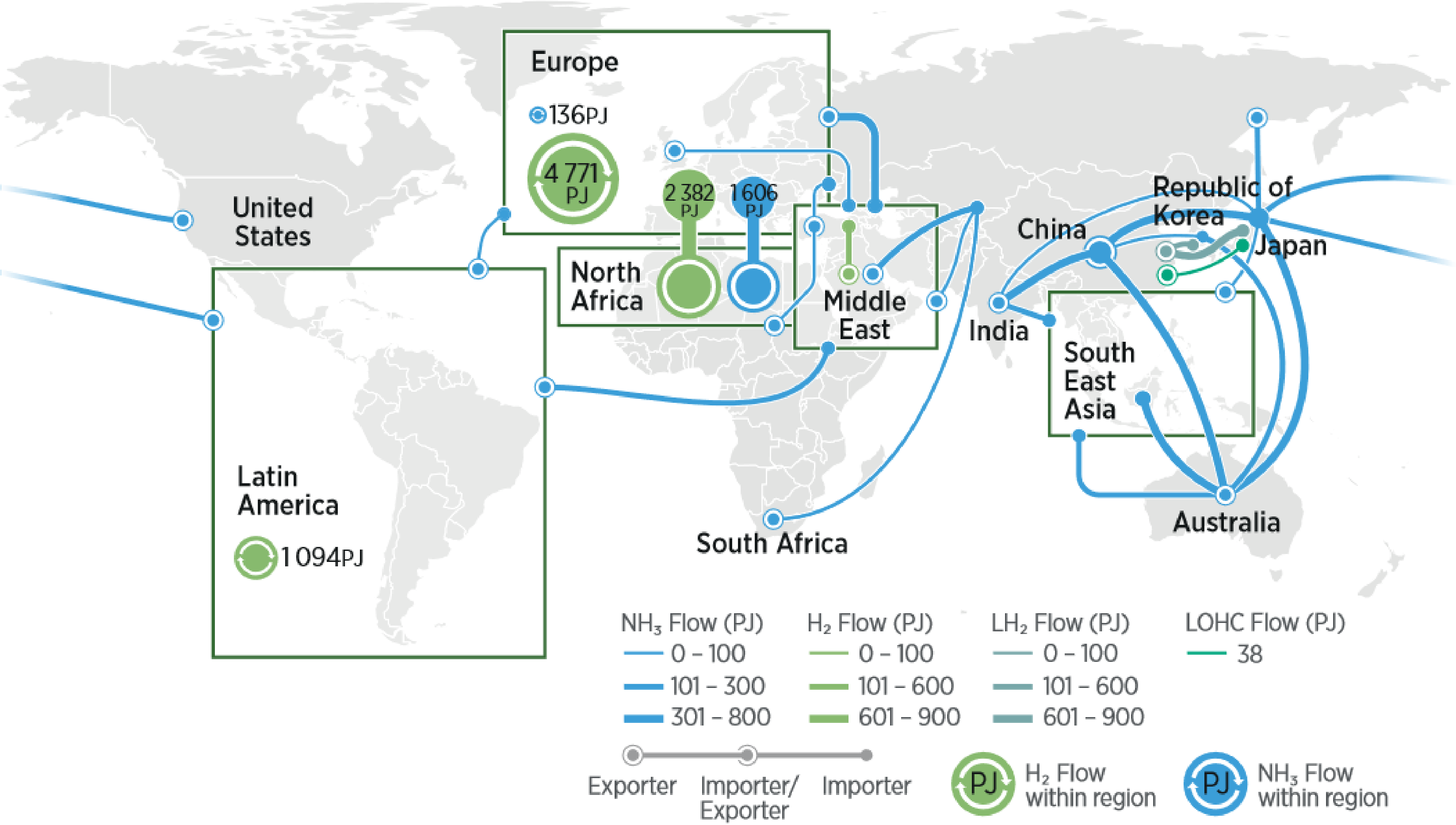
- Levelized cost of hydrogen production by technology in 2021 and in the Net Zero Emissions by 2050 Scenario, 2030 and 2050



IEA (2022), *Global Hydrogen Review 2022*, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022

Green Hydrogen

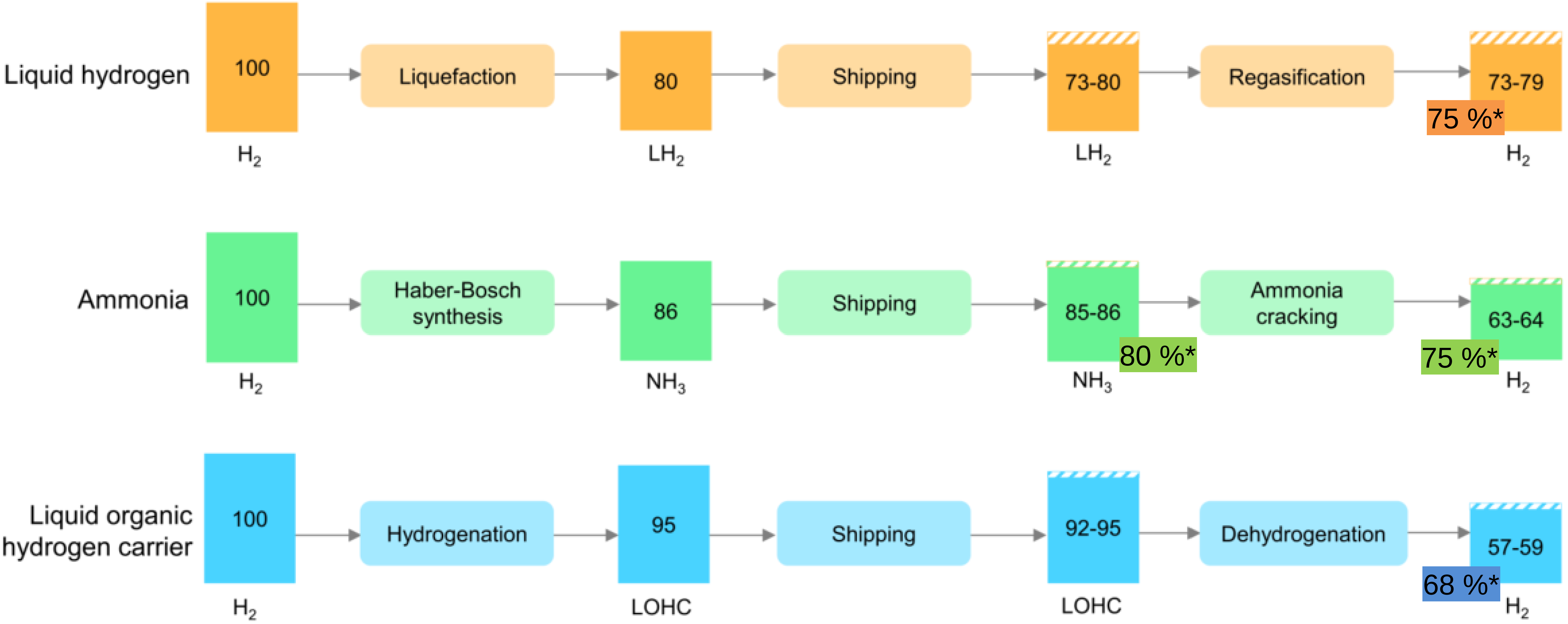
Global hydrogen trade map under optimistic technology assumptions in 2050



IRENA (2022), Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward, International Renewable Energy Agency, Abu Dhabi

Green Hydrogen

Conversion and transport chain in hydrogen equivalent terms, 2030



IEA (2022), *Global Hydrogen Review 2022*, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022

* Staiß, F. et al.: Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030, München 2022

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Green Hydrogen

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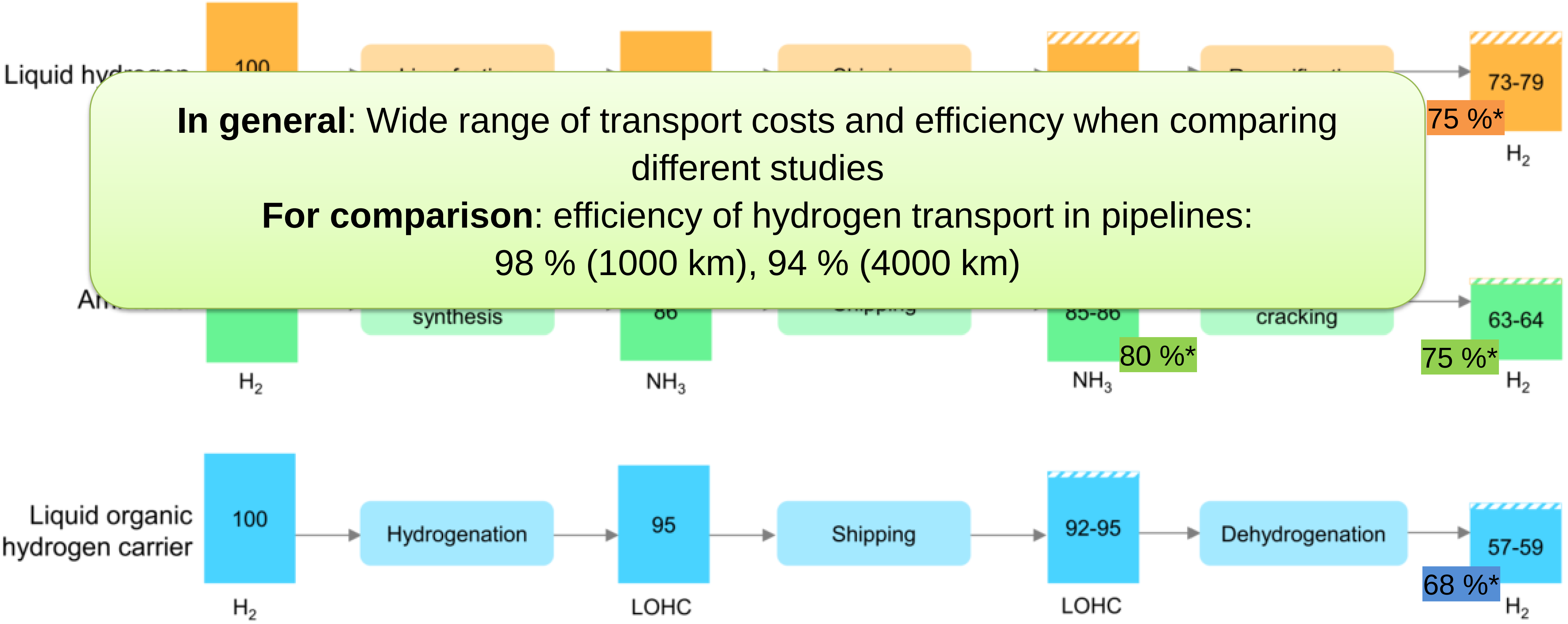


In general: Wide range of transport costs and efficiency when comparing different studies

For comparison: efficiency of hydrogen transport in pipelines: 98 % (1000 km), 94 % (4000 km)

IEA (2022), *Global Hydrogen Review 2022*, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022

* Staiß, F. et al.: Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030, München 2022

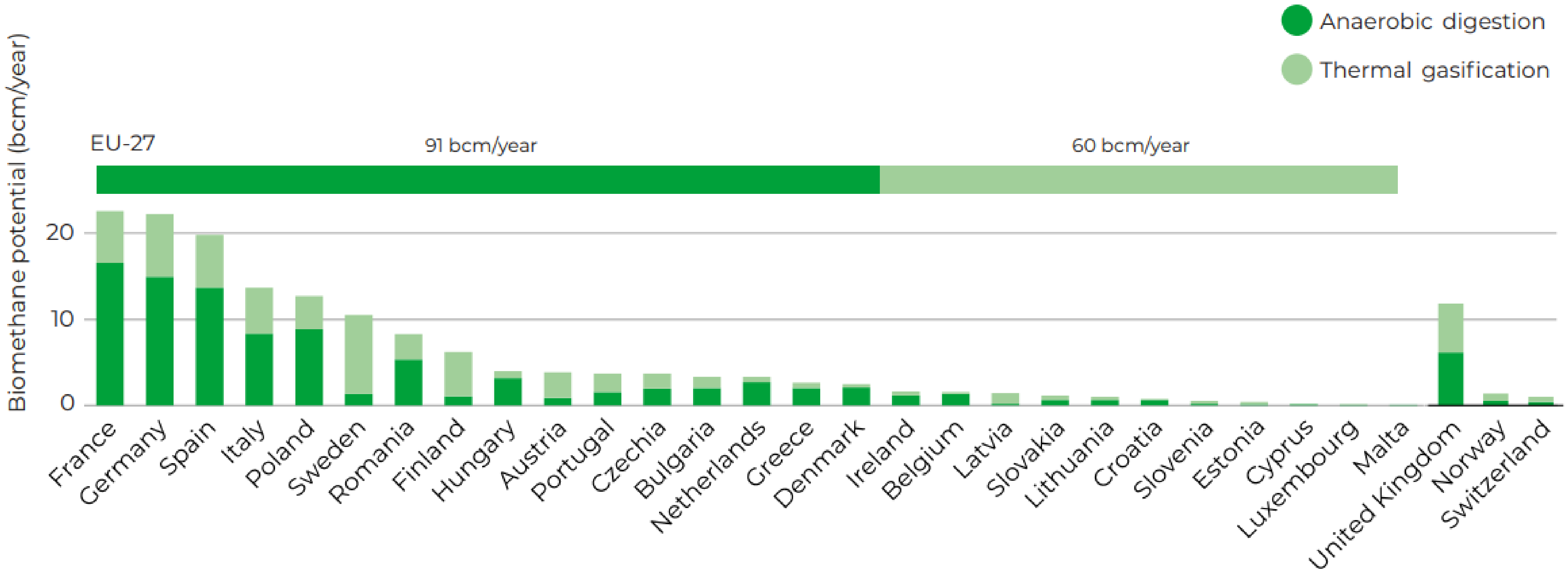
Bio-/ E-Methane

Production	○ Biological methanation: extraction of CO_2 from biogas plant / + injection of e-H_2 in reactor + proven technology ○ Catalytic methanation: e-H_2 + CO_2 (Carbon capture, point source (industry biogas plant)) - Higher production costs compared to hydrogen
Transport and Infrastructure	+ infrastructure available + direct feed into gas network possible + lower transport costs compared to hydrogen
Applicability in gas turbines	+ directly applicable

Bio-/ E-Methane

Biomethane potential in 2050 per technology and country

Biomethane potential: 41 bcm (2030), 151 bcm (2050) = **1505 TWh_{LHV}**



Gas for climate (2022), Biomethane production potentials in the EU, Guidehouse_GfC_report_design (gasforclimate2050.eu)

Bio-/ E-Methane

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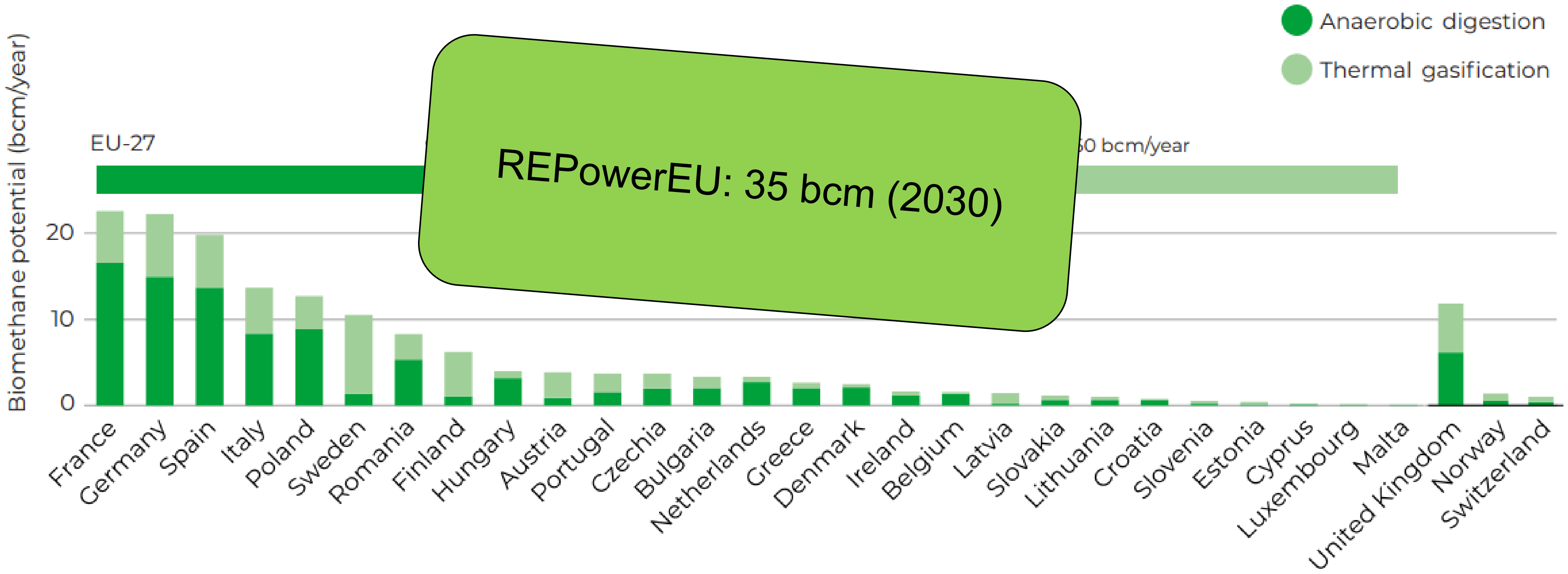
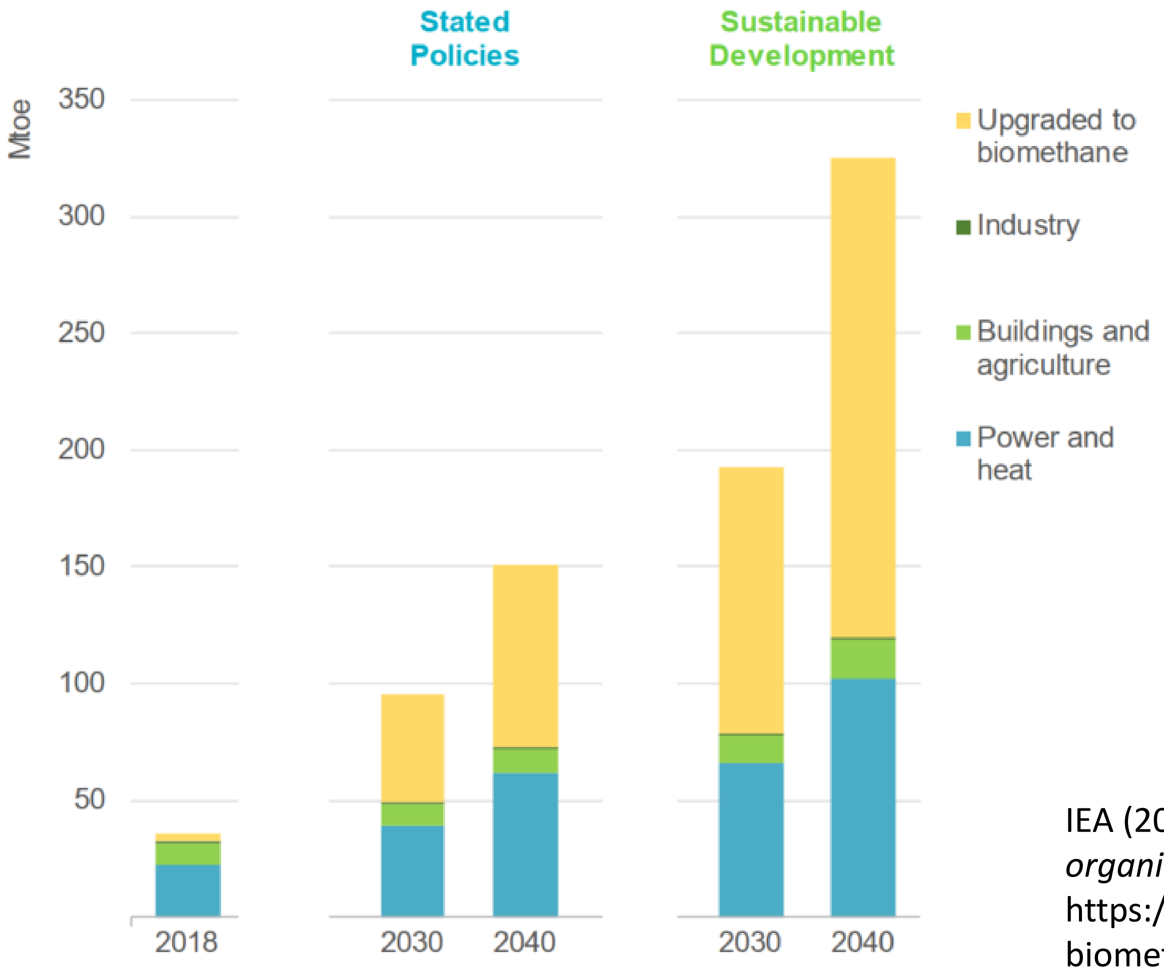


Gas for climate (2022), Biomethane production potentials in the EU, Guidehouse_GfC_report_design (gasforclimate2050.eu)

Bio-/ E-Methane

The outlook for global biogas consumption by sector

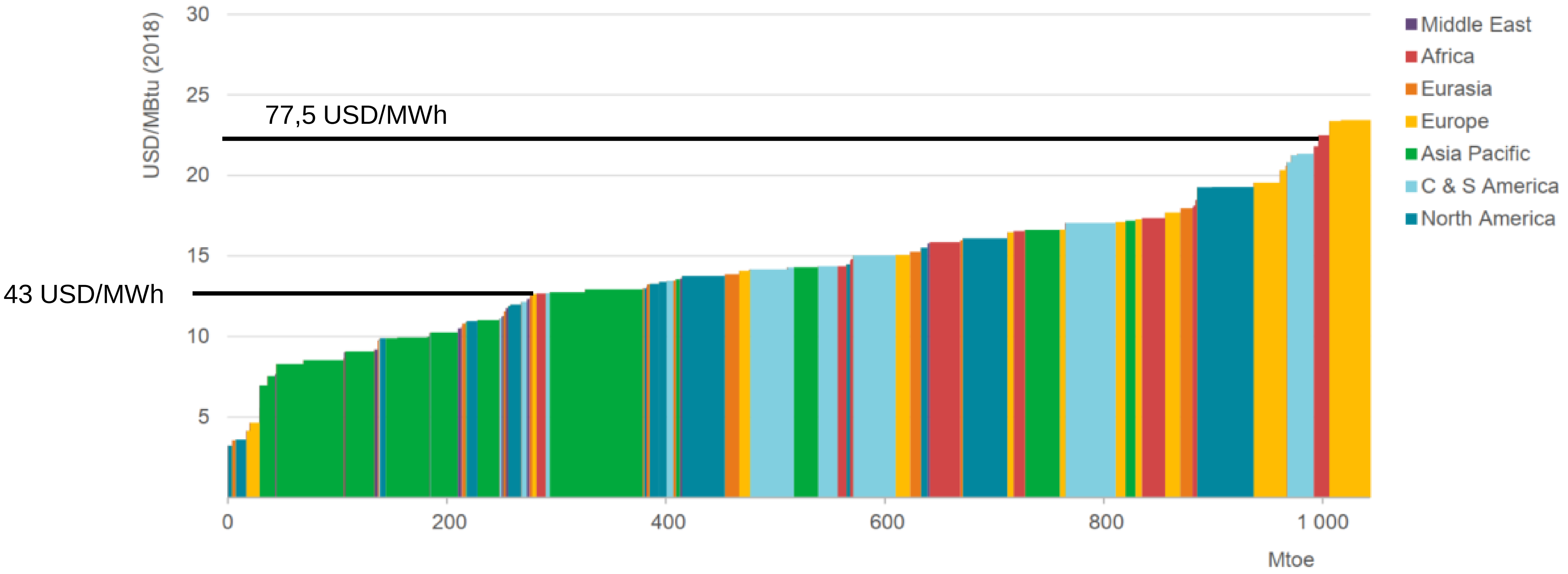


100 Mtoe = 1163 TWh

IEA (2020), *Outlook for biogas and biomethane: Prospects for organic growth*, IEA, Paris https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

Bio-/ E-Methane

Cost curve of potential global biomethane supply by region, 2040



Notes: C & S America = Central and South America. The curve integrates technology and feedstock costs; injection costs are not included. The chart incorporates all the biogas potential that can be upgraded to biomethane. 1 MBtu = 0.29 MWh.

IEA (2020), *Outlook for biogas and biomethane: Prospects for organic growth*, IEA, Paris https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

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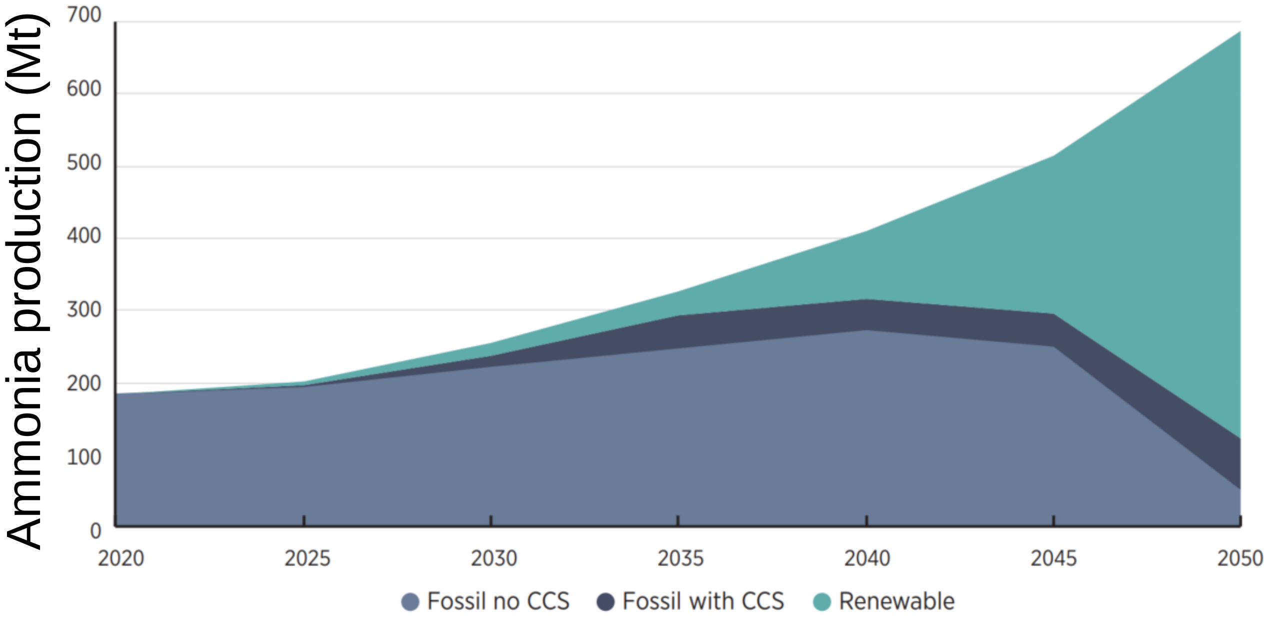
Ammonia

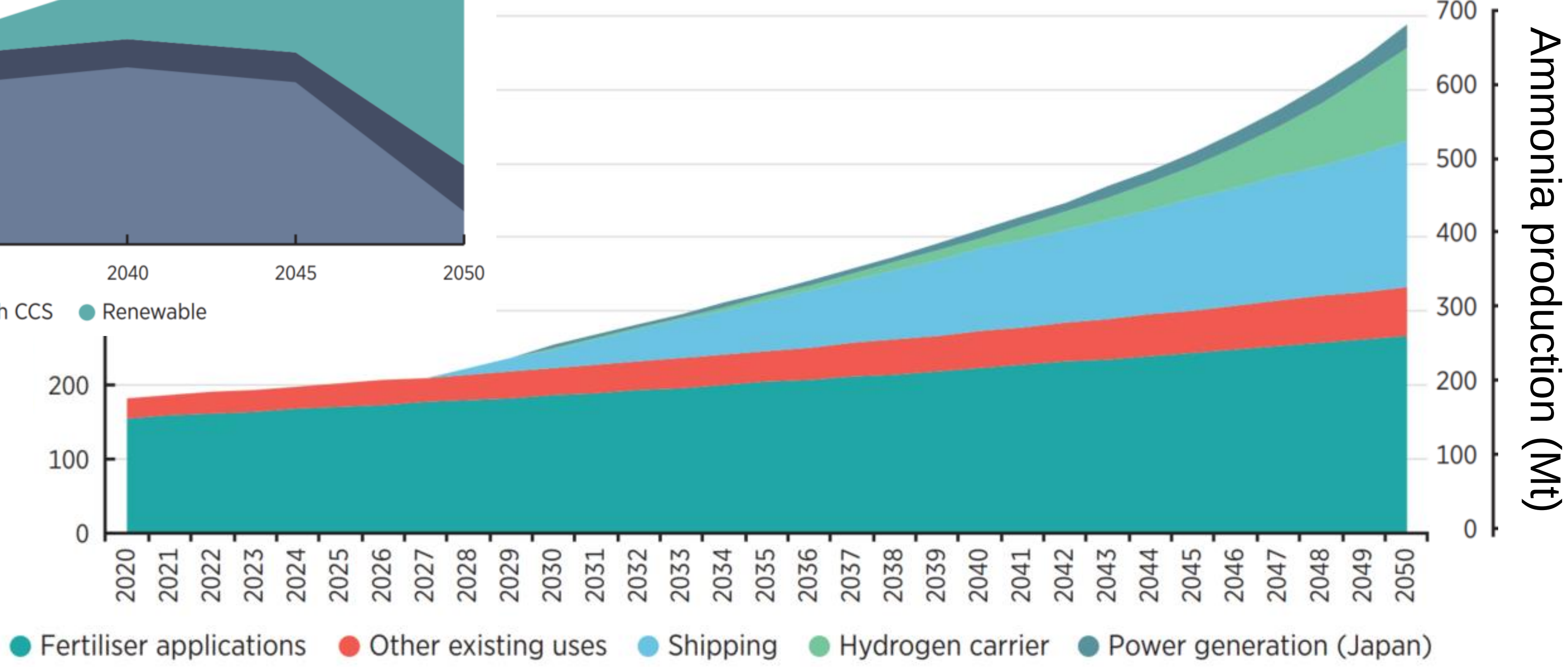
Ammonia is key for all mineral nitrogen fertilizers and for a wide range of industrial applications, including explosives, synthetic fibers and specialty materials

Production	+ Non-carbon fuel → no carbon-capture required + proven technology
Transport and Infrastructure	+ High energy density → efficient option for long-distance transport + Important basic chemical → internat. transport infrastructure (tanks, pipelines, ships) and regulations available ○ Installation of additional infrastructure necessary - Toxicity (health and safety impact)
Applicability in gas turbines	– Poor combustion characteristics (flame speed; ignition; flammability limits, etc.) → research / new combustor-development required – High NO_x-emissions (exhaust gas treatment necessary) – Low load capability, load flexibility ? – Materials impact to be clarified

Ammonia
Expected demand up to 2050 for the 1,5°C scenario



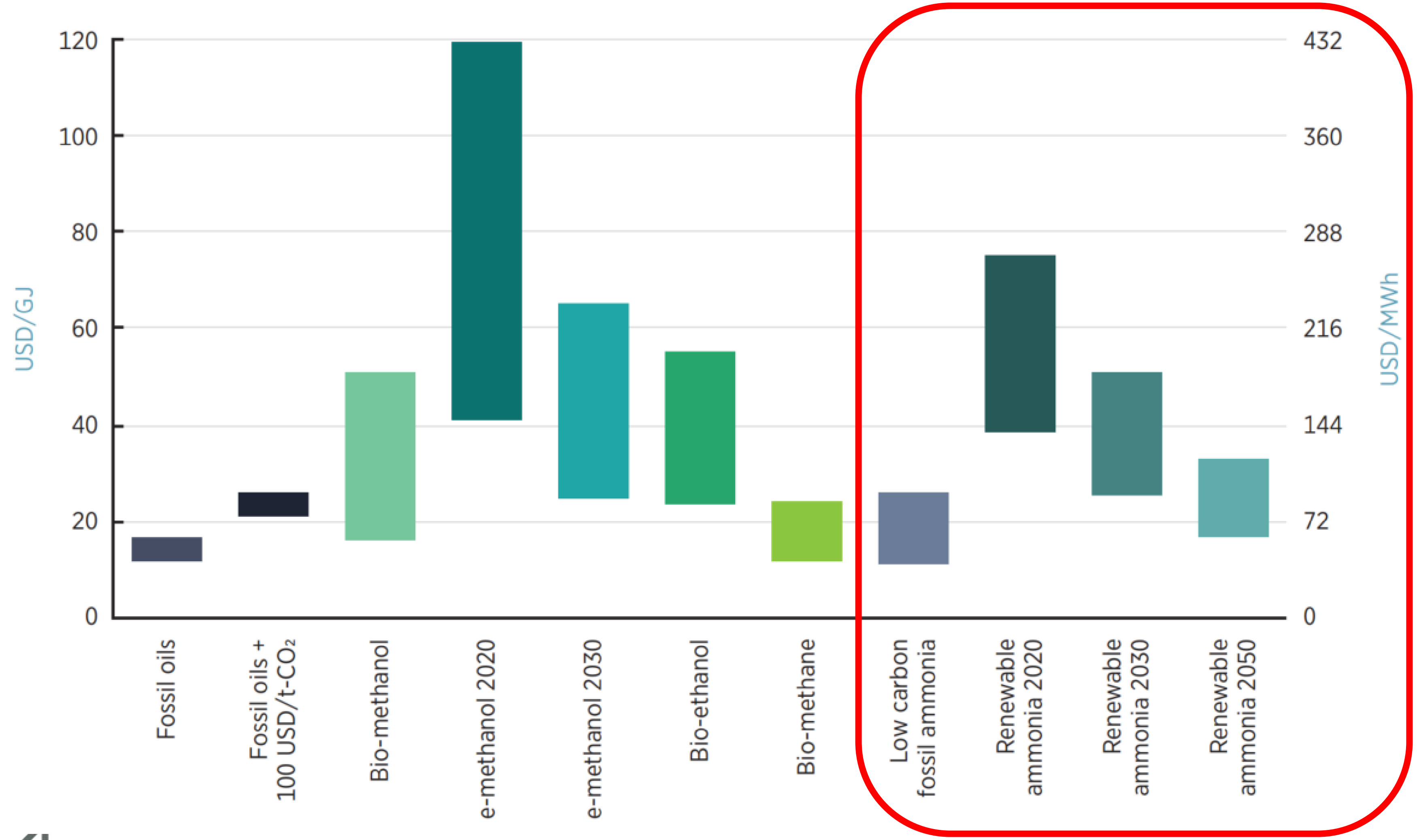
100 Mt = 52,2 TWh_{LHV}



IRENA and AEA (2022), *Innovation Outlook: Renewable Ammonia*, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn.

Ammonia

Comparison of fuels based on the price per unit of energy



IRENA and AEA (2022), *Innovation Outlook: Renewable Ammonia*, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn.

Ammonia
GE and IHI sign agreement to develop fuels roadmap across asia

First Ammonia Gas Turbine Engine, MHI (H25), 40 MW Power
[https://power.mhi.com/news/20210301.html]

2,000-kilowatt-class gas turbine co-firing liquid ammonia and natural gas at IHI Yokohama Works
[https://www.ihi.co.jp]

Bio-/E-Methanol

Second-largest industrial hydrogen application - intermediate product to produce other chemicals

Production	- CO_2 source required + proven technology
Transport and Infrastructure	+ High energy density → efficient option for international transport + international transport infrastructure and regulations available ○ installation of additional infrastructure necessary + Easy to handle + raw material: chemical conversion to “high-quality” synthetic fuels
Applicability in gas turbines	+ Superior turbine fuel: low emissions - Modification of fuel systems due to higher mass and volume fuel flow - Low flash point (flashback, explosion proofing necessary); start-up with secondary fuel - Retrofit of gas turbines necessary

Bio-/E-Methanol

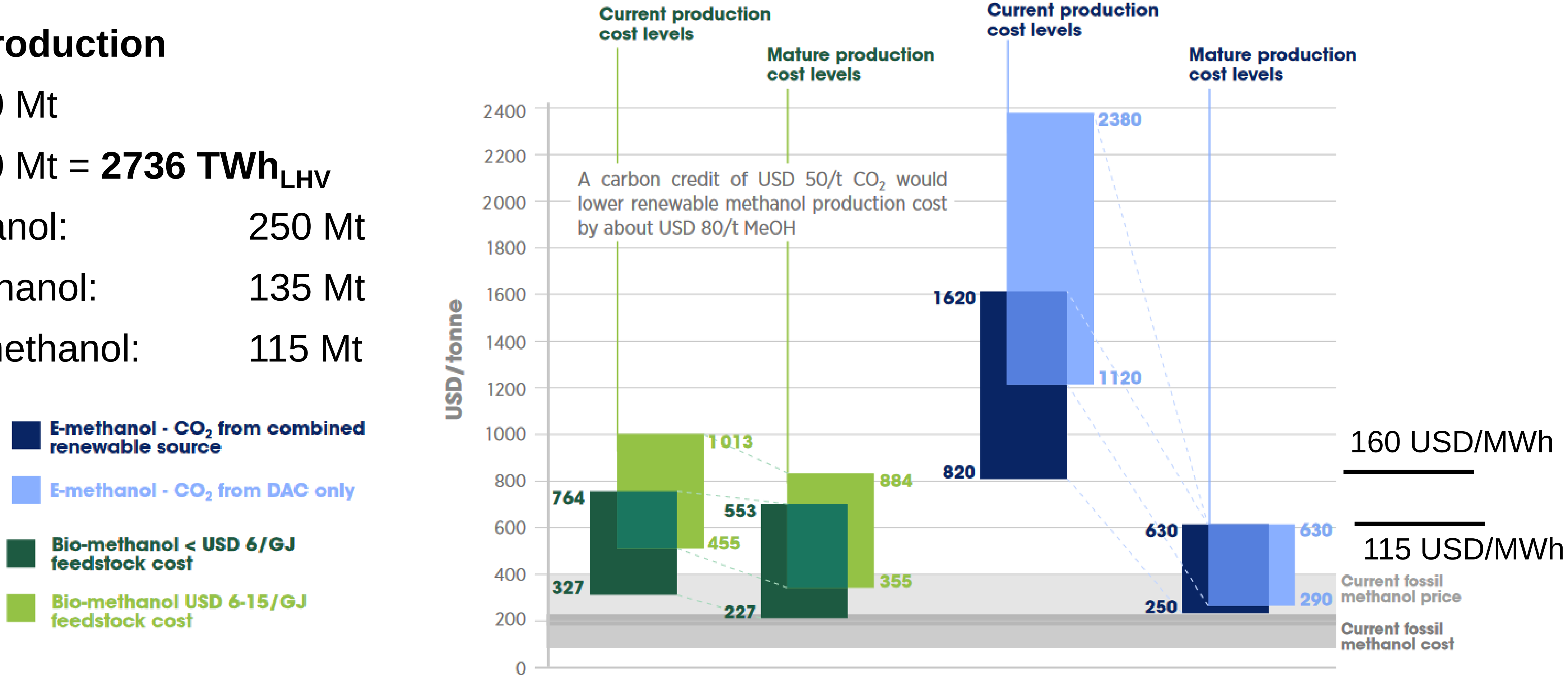
Production & costs of bio- and e-methanol (2021 and 2050)

Global Production

2020: 100 Mt

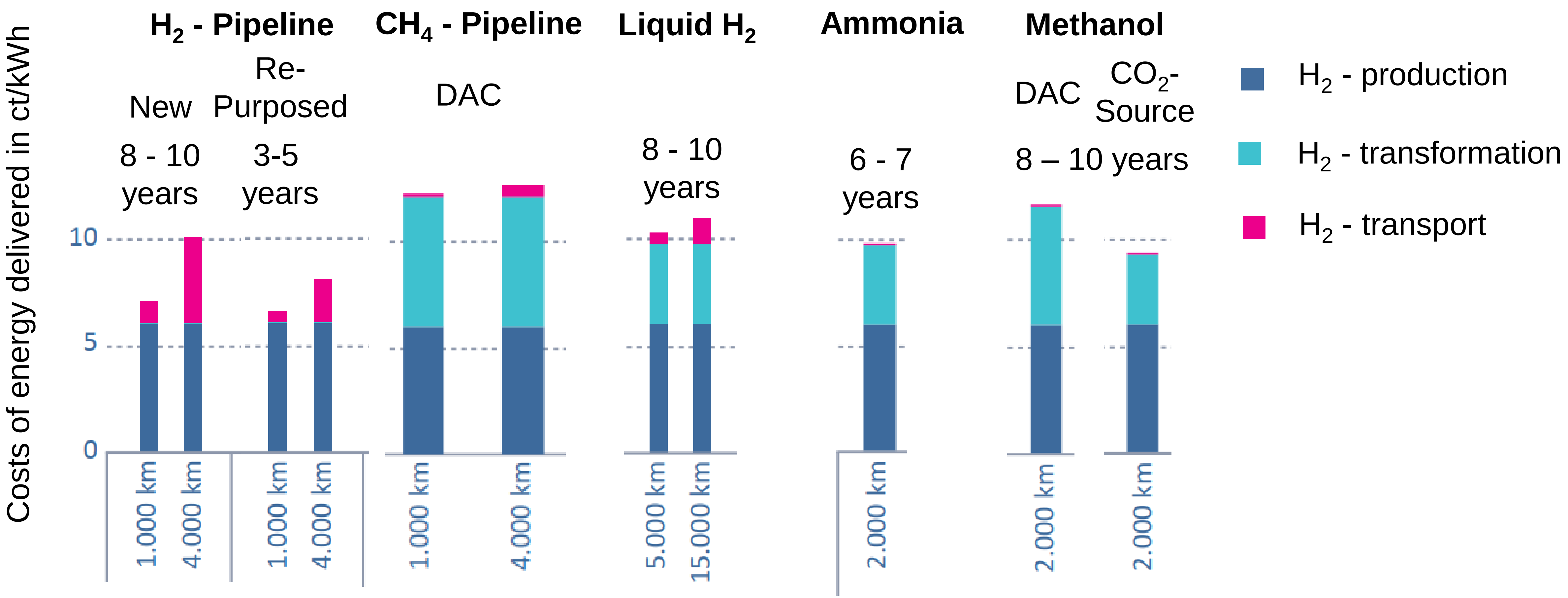
2050: 500 Mt = **2736 TWh_{LHV}**

- E-methanol: 250 Mt
- Bio-methanol: 135 Mt
- Fossil methanol: 115 Mt



IRENA and methanol institute (2021), Innovation Outlook : Renewable Methanol, International Renewable Energy Agency, Abu Dhabi

Comparison of costs of different fuels based on hydrogen (2 €/kg)



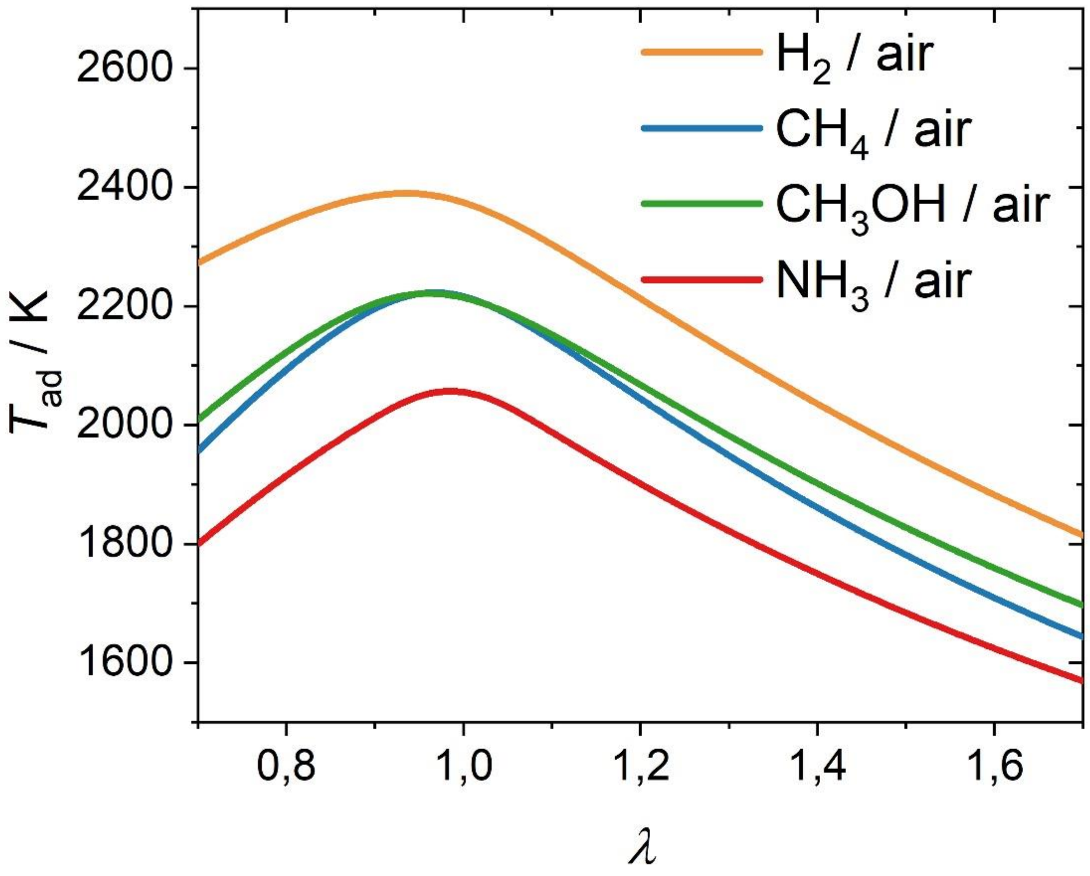
Staiß, F. et al.: Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030, München 2022

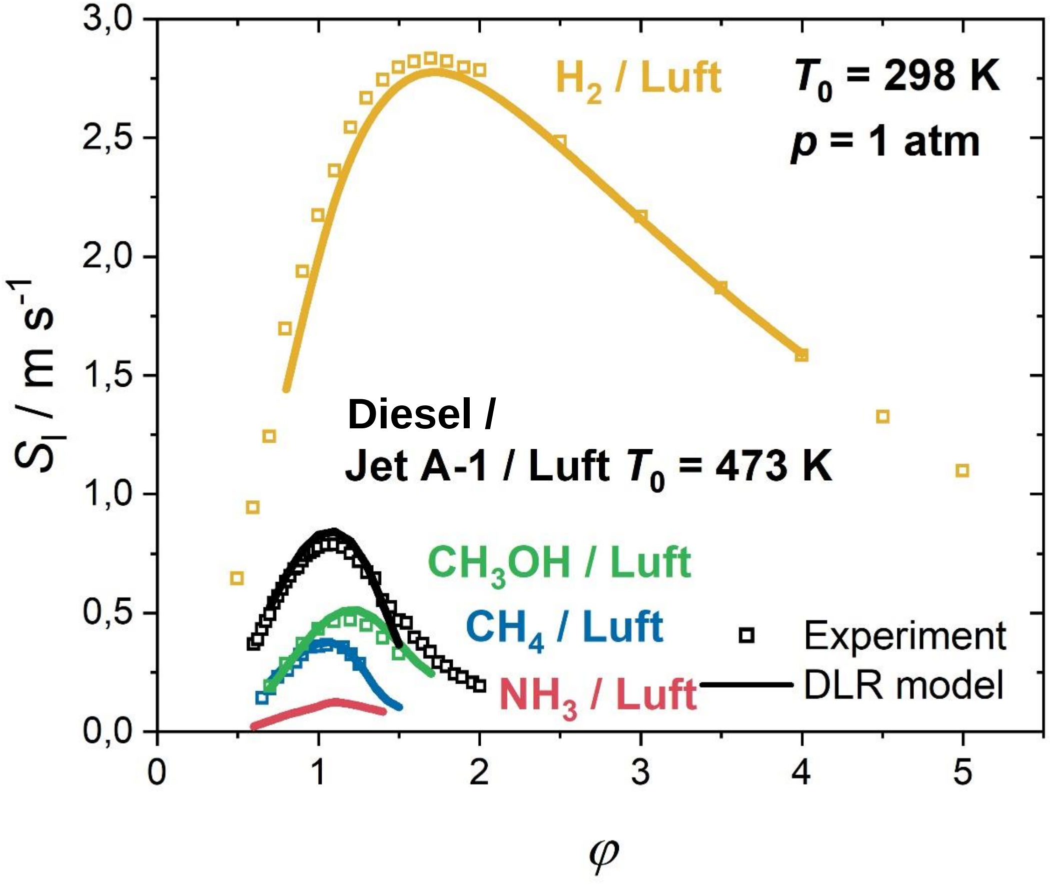
Combustion properties

	Methane	Hydrogen	Propane	Ammonia	Diesel	Methanol
LHV [MJ/kg]	50	120,1	46,4	18,8	42,5	19,7
Flammability limit [equivalence ratio]	0,5 – 1,7	**0,1 – 7,1**	0,51 – 2,5	**0,63 - 1,4**	0,6-5,5 (vol.%)	0,55 – 2,9
Auto-ignition temperature [K]	810	844	723	**924**	498	743
Minimum ignition energy [mJ]	0,28	**0,011**	0,25	**8**	0,24	0,14

Combustion properties

Adiabatic flame temperatures & Flame speeds





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