Prioritising hydrogen for the most effective uses

An overview

Version 1.0

Agora Industry

icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

RAP
REGULATORY ASSISTANCE PROJECT

Key messages

1 **Achieving net zero requires climate-neutral hydrogen to decarbonise processes that are hard to electrify.** To meet this objective, global energy scenarios predict that clean hydrogen will need to represent 5 to 14 percent of final energy consumption by 2050. However, as hydrogen will be scarce, its use should be prioritised where it is most needed, while ensuring that the total emissions associated with its worldwide production decrease over time.

2 **A rapid scale-up of renewable hydrogen production and targeted use is key for climate neutrality.** “No-regret” applications include renewable molecules for industrial feedstocks and chemical processes, as well as high-energy-density fuels for aviation and shipping. Additionally, in some power systems, hydrogen will play a role in long-term seasonal storage to complement renewables and ensure energy security.

3 **Some hydrogen applications remain controversial, such as high-temperature industrial heat, which in most cases could be provided by electricity.** In transport, there is competition in the market between battery-electric and hydrogen-powered options for trucks and buses, short-haul aviation and shipping, trains and non-road mobile machinery. In the power sector globally, the role of hydrogen for long-term storage is still under debate, given the different seasonal demand patterns and competing flexibility options around the world.

4 **Hydrogen should not be used where more energy-efficient direct electrification technologies exist.** For example, low-temperature industrial heat and buildings are best served by heat pumps that deliver significantly more energy per unit of electricity. Likewise, for passenger cars and other light vehicles, battery-electric technology is the benchmark for energy efficiency.

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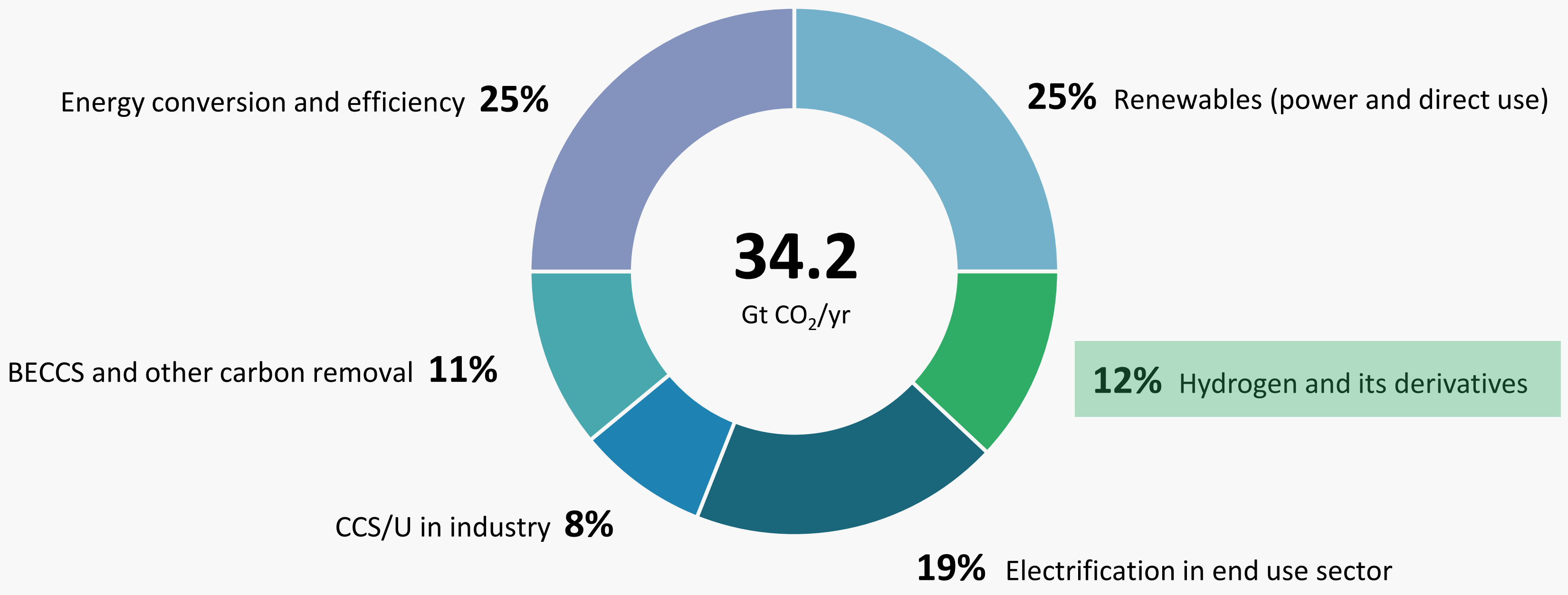
Introduction

Green hydrogen plays a key role in achieving climate neutrality goals but remains secondary to direct electrification

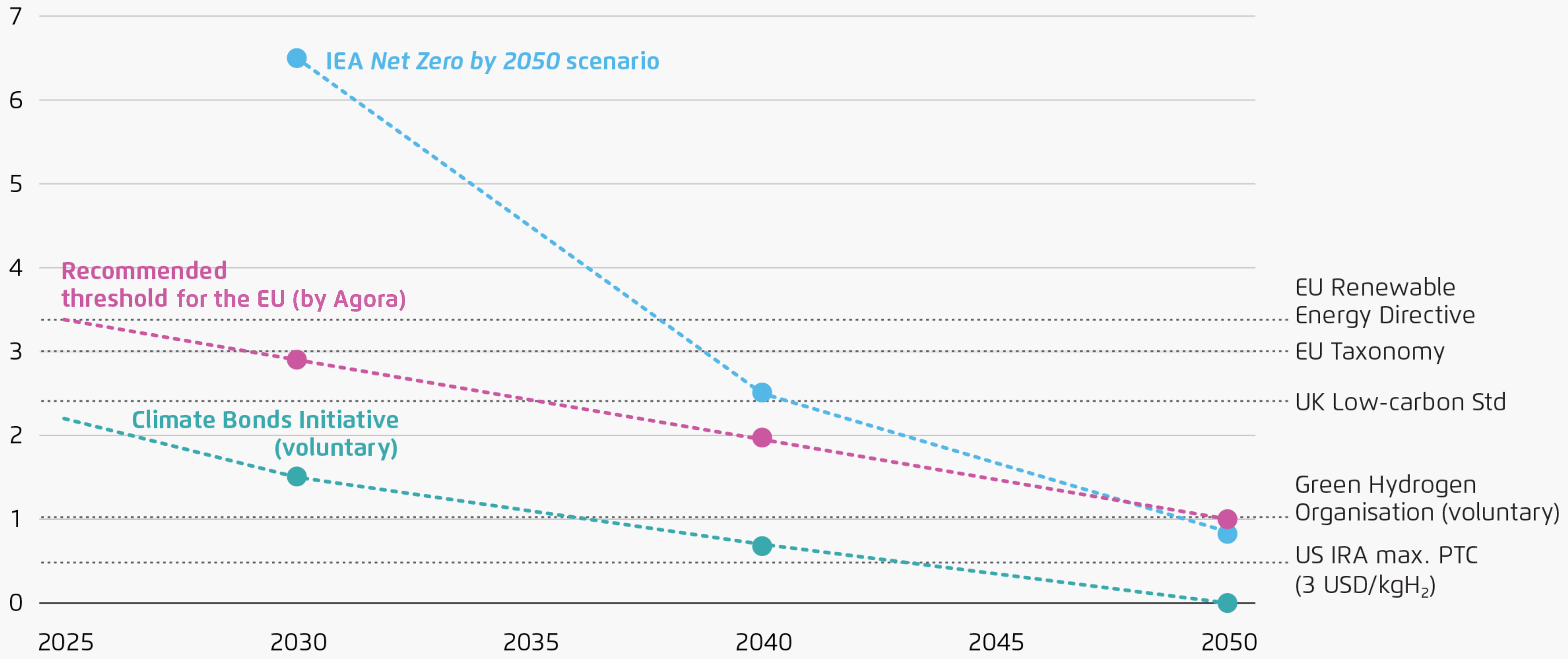
Carbon emissions abatement under the 1.5 °C scenario in 2050



 IRENA (2023): World Energy Transitions Outlook. Note: BECCS = bioenergy with carbon capture and storage; CCS/U = carbon capture and storage/utilisation

Hydrogen's actual contribution to climate change mitigation will depend on the extent to which its carbon footprint can be reduced over time

Greenhouse gas emissions intensity of hydrogen [kg CO_2eq/kg H_2]



 Agora Energiewende and Agora Industry (2024): Low-carbon hydrogen in the EU. Towards a robust definition in view of costs, trade and climate protection. Note: The system boundaries and implementation details of these standards and requirements differ.

A central disadvantage of electrolytic hydrogen is the loss of 20–30% of energy during the electrolysis process

Energy content

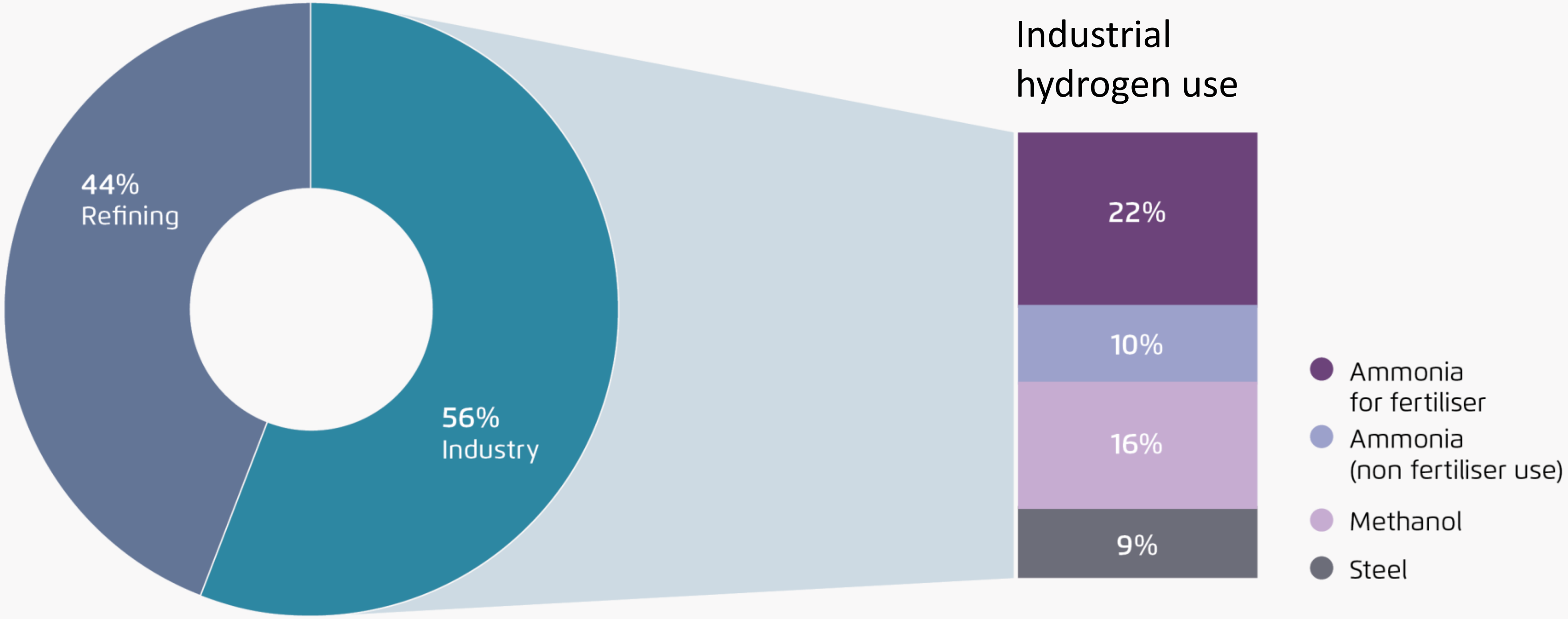
Electrical efficiency [%, LHV]	Alkaline	PEM	SOEC *
2019	63–70	56–60	74–81
Long-term	70–80	67–74	77–90

 | IEA (2019): The future of hydrogen. * requires high-temperature heat input

Hydrogen applications

Today, hydrogen is mainly used for non-energy applications in refining and industry, and is predominantly produced from unabated natural gas and oil

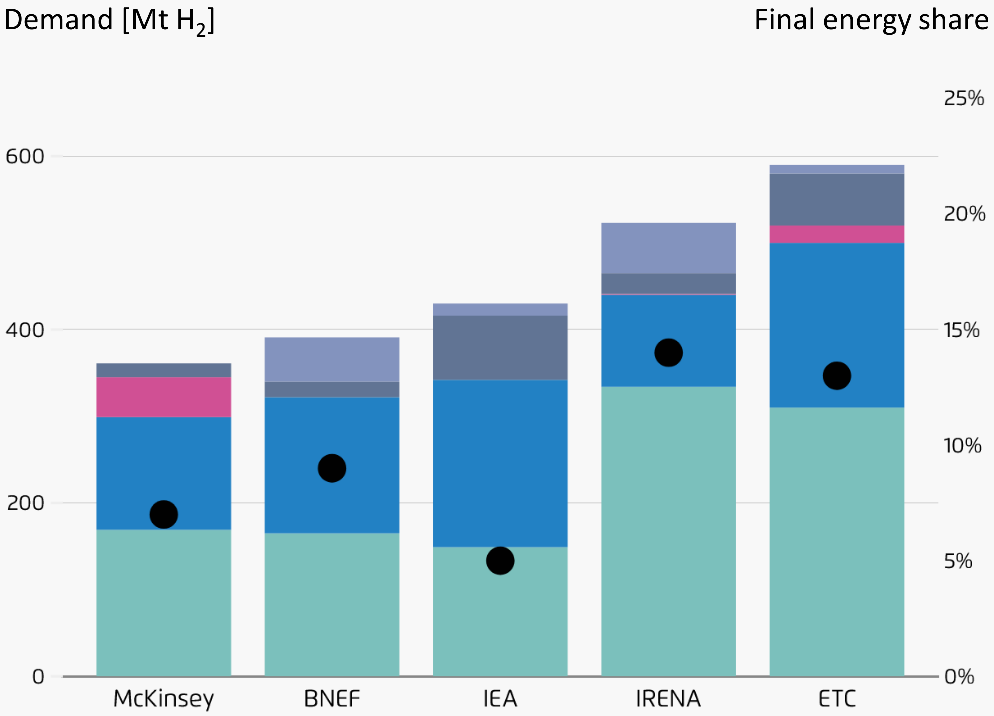
Hydrogen use in 2022
(95 Mt in total)

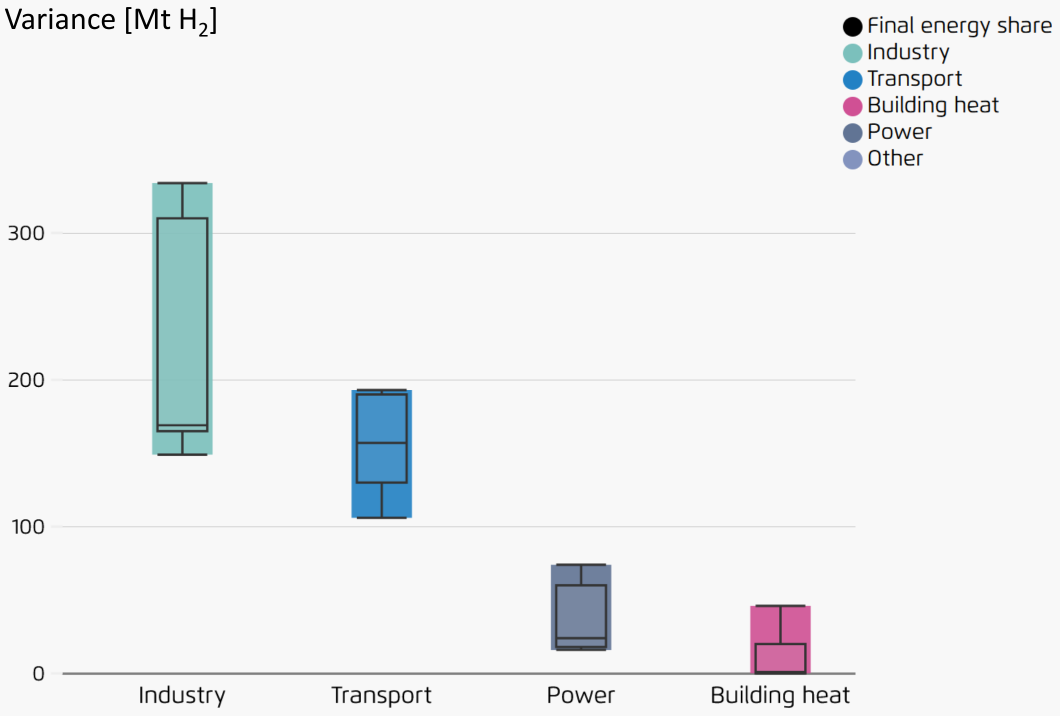


 | Agora Industry (2024): Global Green Fertiliser Tracker; based on IEA (2023) and IEA (2021)

Hydrogen's share in final energy demand is projected to increase to between 5% and 14% by 2050 in global energy scenarios

Estimates of global hydrogen demand in 2050: selected scenarios





 Agora Industry (2024) based on McKinsey (2024), BloombergNEF (2024), International Energy Agency (2023), International Renewable Energy Agency (2023), Energy Transitions Commission (2023). Note: Final energy does not include feedstocks and other non-energy use; final energy figures taken from respective sources

Policy should prioritise no-regret applications of hydrogen and derivatives with no/limited alternative pathways to achieve climate neutrality

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
No-regret	**Non-energy use:**[1] - Feedstock: ammonia, chemicals, fertilisers - Reaction agents: DRI steel	- Long-haul aviation - Maritime shipping	- Renewable energy back-up, depending on wind and photovoltaic share and seasonal demand structure	- Heating grids (residual heat load)[2]
Controversial	- High-temperature heat	- Trucks and buses[3] - Short-haul aviation & shipping - Trains[4] - Non-road mobile machinery	- Absolute size of need given other flexibility and storage options	–
Bad idea	- Low-temperature heat	- Cars - Light-duty vehicles - Two- and three-wheelers	–	- Building-level heating

Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen;
[1] Hydrogen may also be used as a reaction agent and/or feedstock in bio-refineries. [2] After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.[3] Series production currently more advanced on electric than on H_2 for heavy duty vehicles and buses. H_2 heavy duty to be deployed at this point in time only in locations with synergies (ports, mines, industry clusters),[4] depending on distance, frequency and energy supply options.

Policy should prioritise no-regret applications of hydrogen and derivatives with no/limited alternative pathways to achieve climate neutrality

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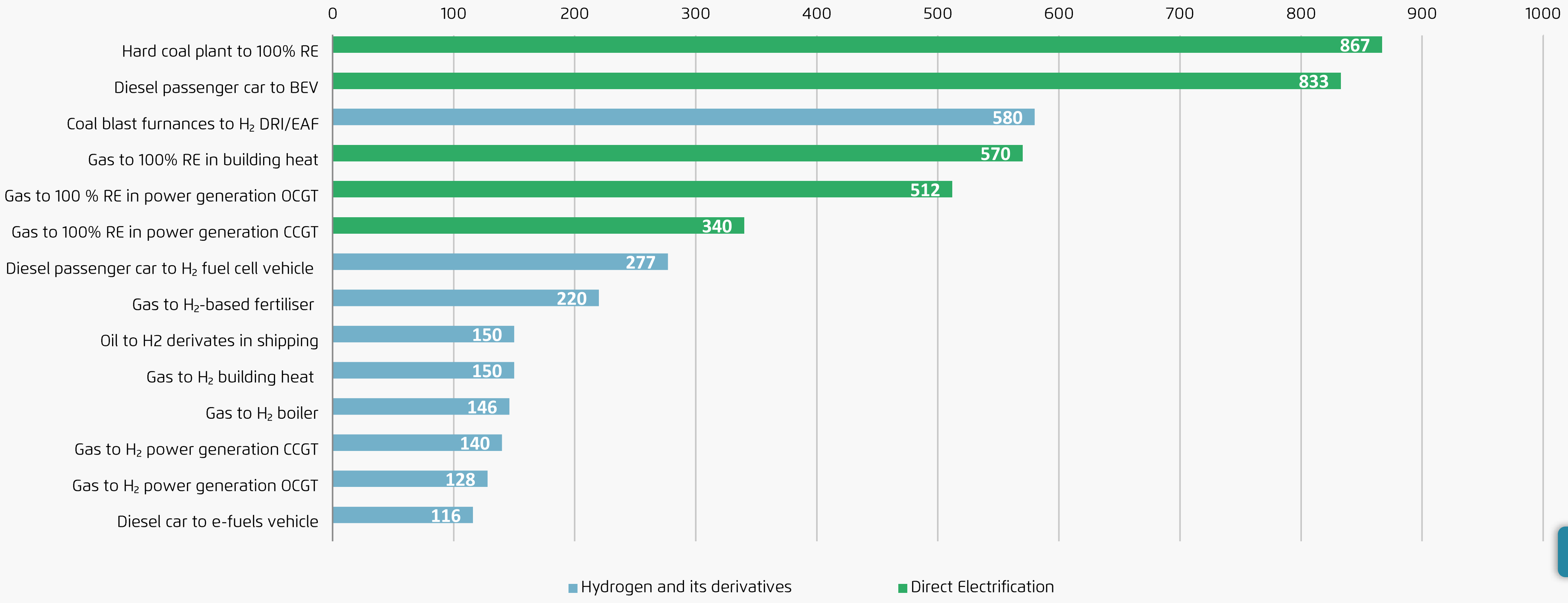
Hydrogen and its derivatives offer significant CO_2 mitigation potential, though often less than direct electrification, where feasible*

Greenhouse gas savings of renewable electricity [kg CO_2eq/MWh]



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Agora Energiewende (2023): Breaking Free from Fossil Gas; Agora Industry (2023): 15 Insights on the Green Steel Transformation ; Note: Hydrogen power plants cannot be substituted by direct electrification to the extent necessary to provide seasonal back-up for variable renewables.

No-regret applications in industry include steel and ammonia production

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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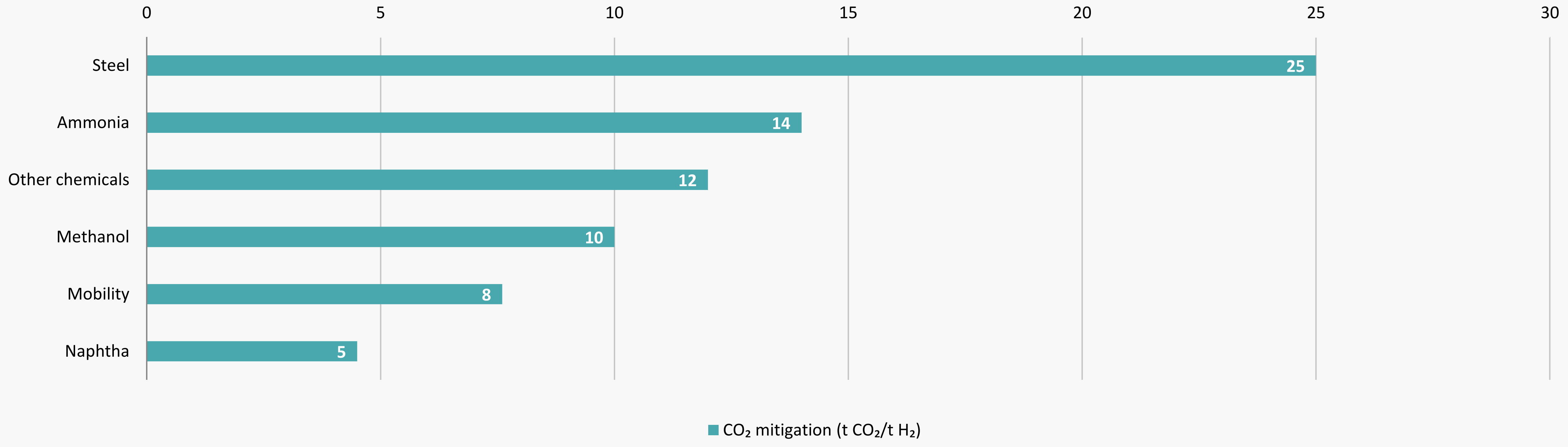
 Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen; [1] Hydrogen may also be used as a reaction agent and/or feedstock in bio-refineries.

Steel and chemicals have the largest CO_2 mitigation potential per tonne of hydrogen in projections for Germany

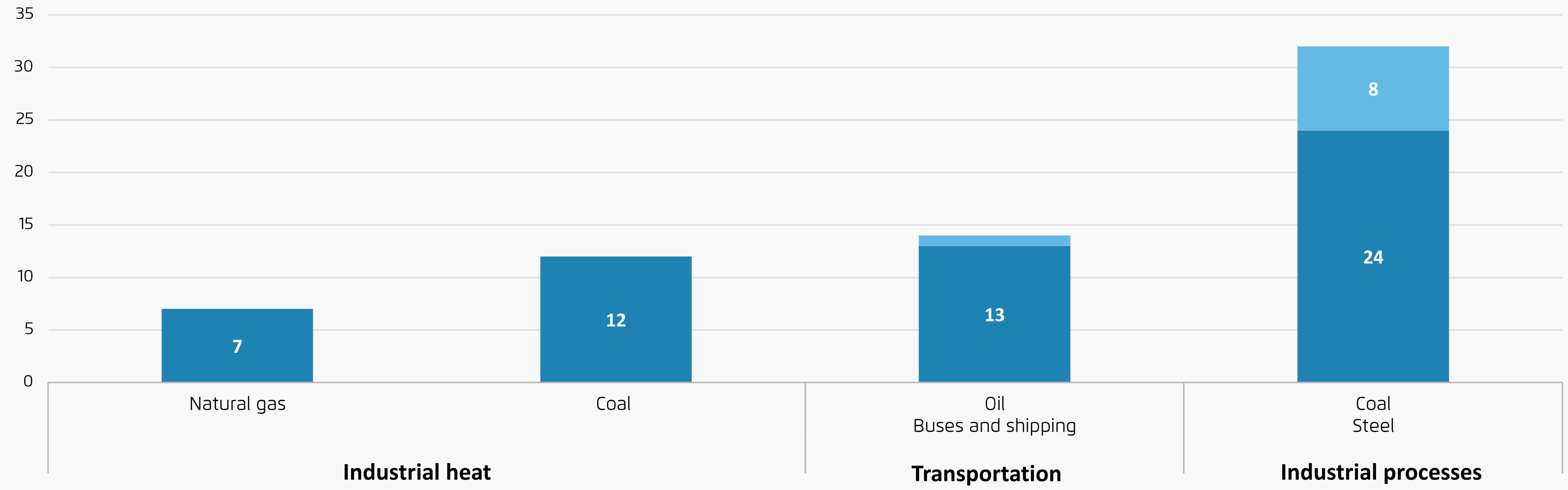
CO_2 mitigation via switching to H_2-based technologies (Germany, 2050)
[t CO_2/t H_2]



 | German National Hydrogen Council (2023): Grundlagenpapier Treibhausgaseinsparungen und der damit verbundene Wasserstoffbedarf in Deutschland

Greenhouse gas reductions from hydrogen depend on the fossil fuel substituted, with steel showing the greatest emission reduction potential

GHG emission reductions from substituting fossil fuels with hydrogen
[kg CO_2/kg H_2]



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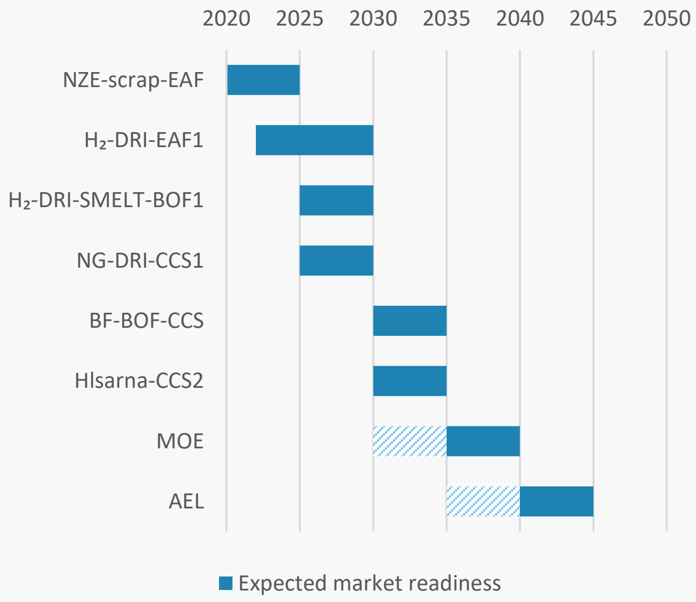
 | Adapted from Rocky Mountain Institute (2020): Hydrogen's Decarbonization Impact for Industry. Note: light blue bars represent ranges of values.

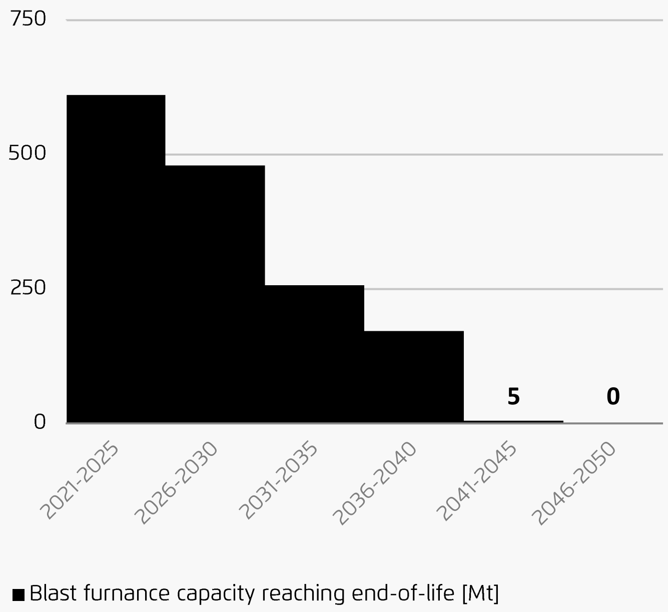
With over half of blast furnace capacity reaching end-of-life by 2030, it is important to prioritise decarbonisation technology available before this time

Comparing the TRL of breakthrough technologies and blast furnace reinvestment cycles

Expected market readiness of selected breakthrough technologies



Reinvestment cycles for current global blast furnance fleet – status quo



→ **Before 2030**, only the scrap-based EAF route and DRI-based routes will be available.

→ **Technologies**:
State-of-the-art DRI plants are 100% hydrogen-ready and thus compatible with climate neutrality but can be operated with natural gas initially if sufficient hydrogen is not available.

→ **Reinvestment cycles:**
By 2040, over 90% of existing blast furnaces could technically be phased out without an early shutdown.

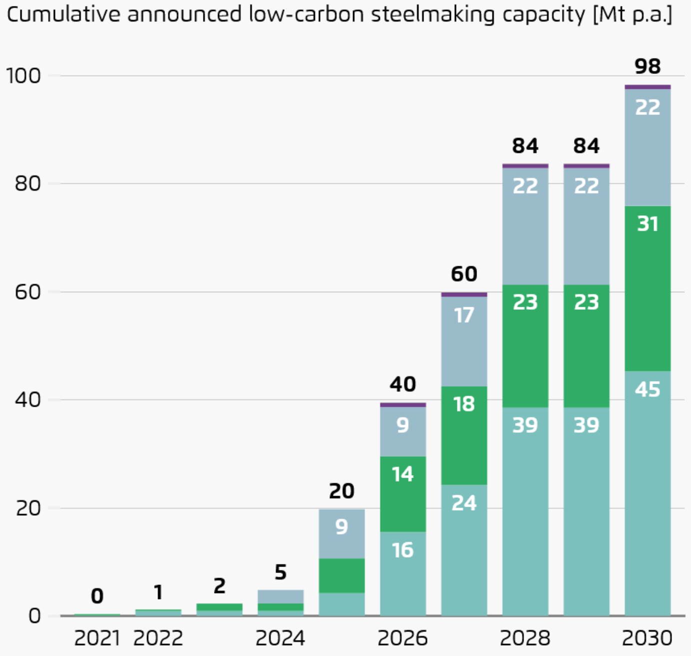
← Overview

Agora Industry and Wuppertal Institute (2024): Low carbon technologies for the global steel transformation
Note left: DRI plants running on natural gas can already blend high shares of H_2. Commercial DRI plants running on 100% H_2 are expected by 2025.
Note right: It is currently not clear what the TRL of the technology is and whether it is actively being developed further.

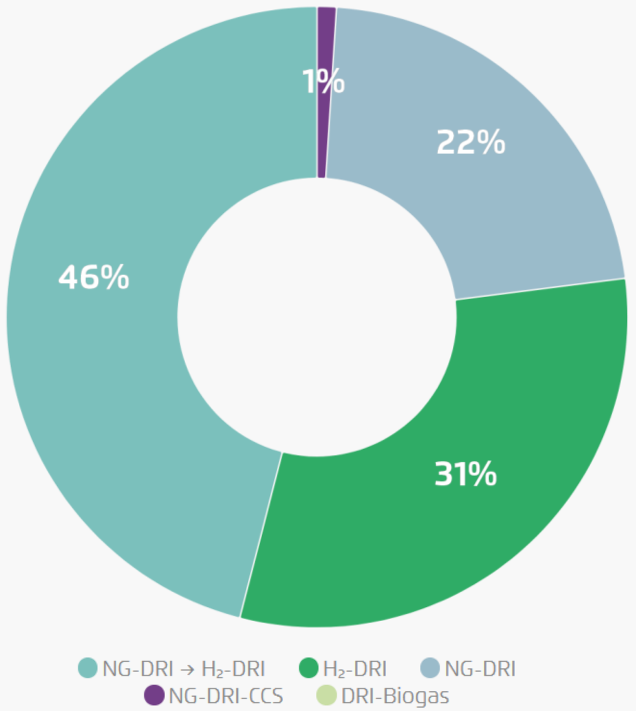
Hydrogen-ready Direct Reduced Iron plants will play an important role in the global steel transformation with 76 Mt of DRI projected to be produced in 2030

Where the global steel industry is heading: 2030 pipeline of low-carbon steelmaking announcements

DRI capacity additions by fuel type and year (cumulative)



Intended fuel used by 2030 in DRI pipeline



→ **Majority of steel companies** that plan to build low-carbon steelmaking capacity have opted for hydrogen-based or hydrogen-ready **DRI** plants.

→ 2030 project pipeline of hydrogen-ready DRI plants has grown to 76 Mt, Natural Gas-DRI with CCS amounts to just 1% of intended fuel used in the DRI pipeline.

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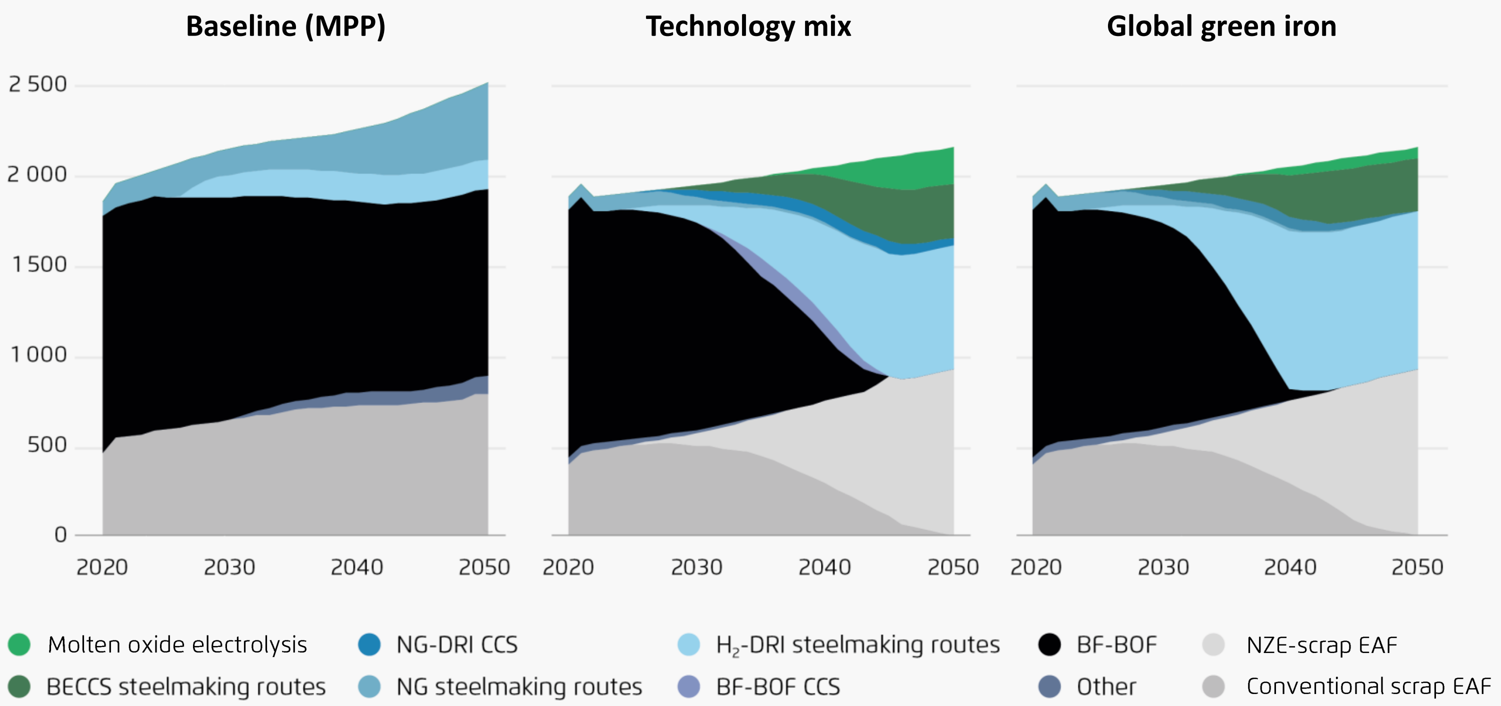
In the long run, direct electrification-based technologies for steelmaking could be a game changer, reducing the need for hydrogen in industry

Scenario comparison: steel production per route (2020–2050) [Mt/year]



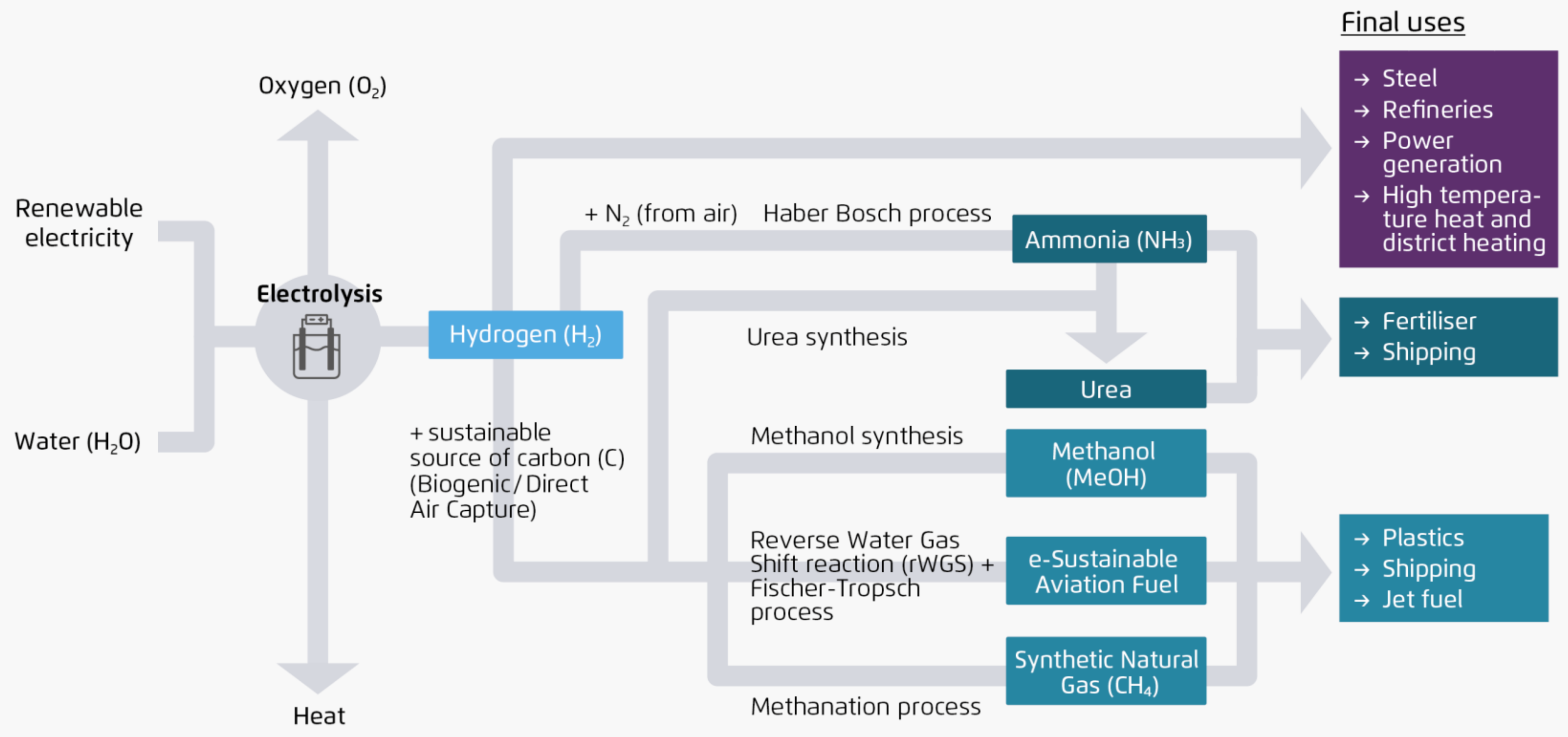
- → **Direct electrification-based technologies** like molten oxide electrolysis (MOE) or alkaline iron electrolysis (AEL) exhibit the **lowest CO_2 abatement costs** among the near-zero emissions steelmaking technologies, but have comparatively low technology readiness levels.
- → Availability of full-scale MOE plants expected in the 2030s.
- → Given the large uncertainties concerning if and when they will become commercially available, this **should not delay the deployment of hydrogen-based routes today**.

← Overview

Agora Industry and Wuppertal Institute (2023): 15 insights on the global steel transformation.
Note: The Baseline (MPP) scenario covers scope 1 and scope 2 emissions. NZE-scrap EAF stands for near-zero emissions scrap electric arc furnace which is defined as a scrap-EAF route with lower emissions than 0.01 tCO2 per t of crude steel. NG = natural gas; BECCS = Bioenergy and carbon capture and storage

Hydrogen can be transformed into various Power-to-X (PtX) products

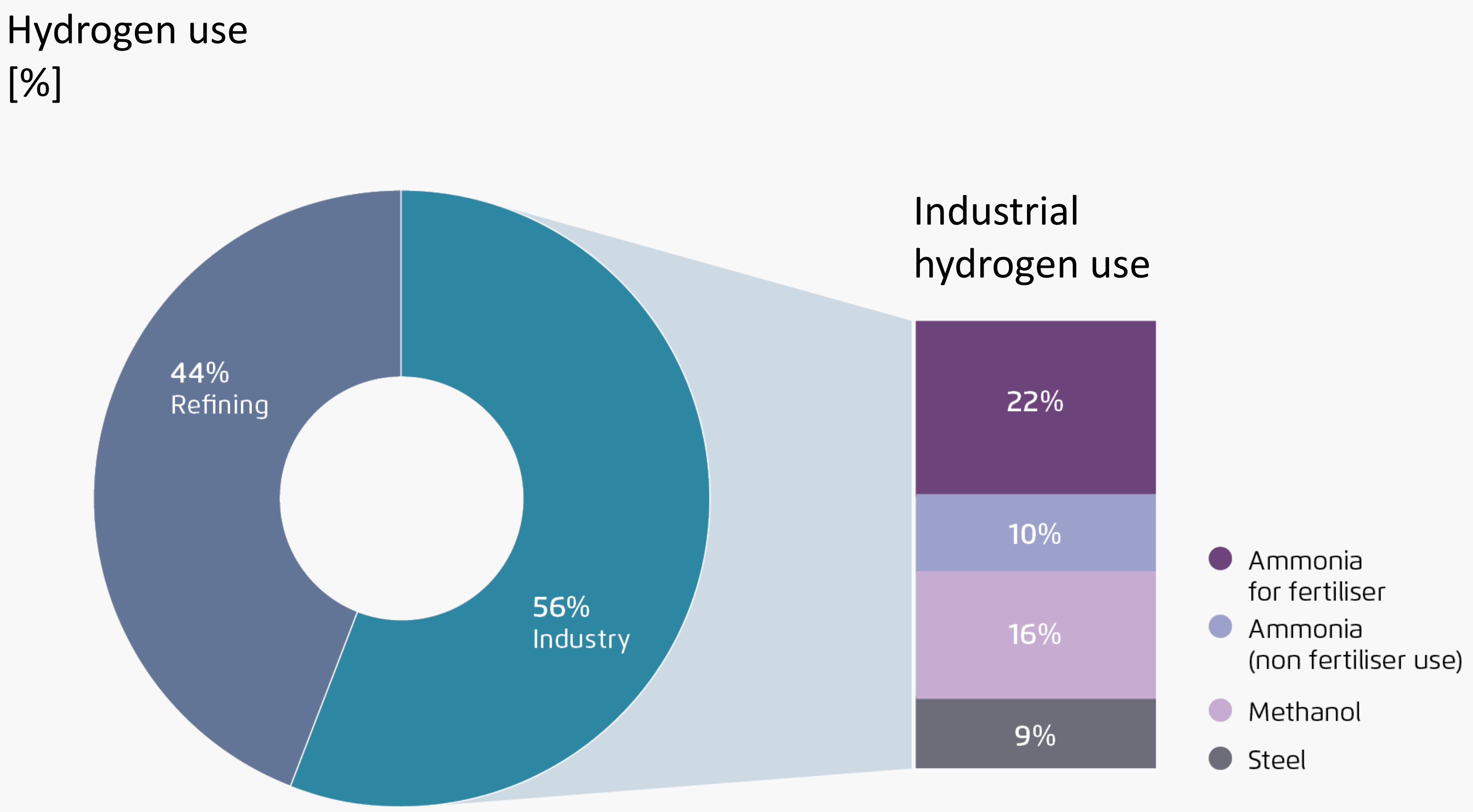
Paths for the production of PtX products



- Renewable hydrogen production needs renewable energy sources.
- Several PtX products **in addition need a source of carbon.**
- To produce these fuels at scale, carbon needs to come from sustainable biomass such as agricultural by-products or waste or be produced with Direct Air Capture (DAC).
- The purer the CO_2, the lower the costs of capture.

← Overview

Today, the second-largest use of hydrogen, after refining, is as a feedstock for ammonia production – the key component of nitrogen fertilisers

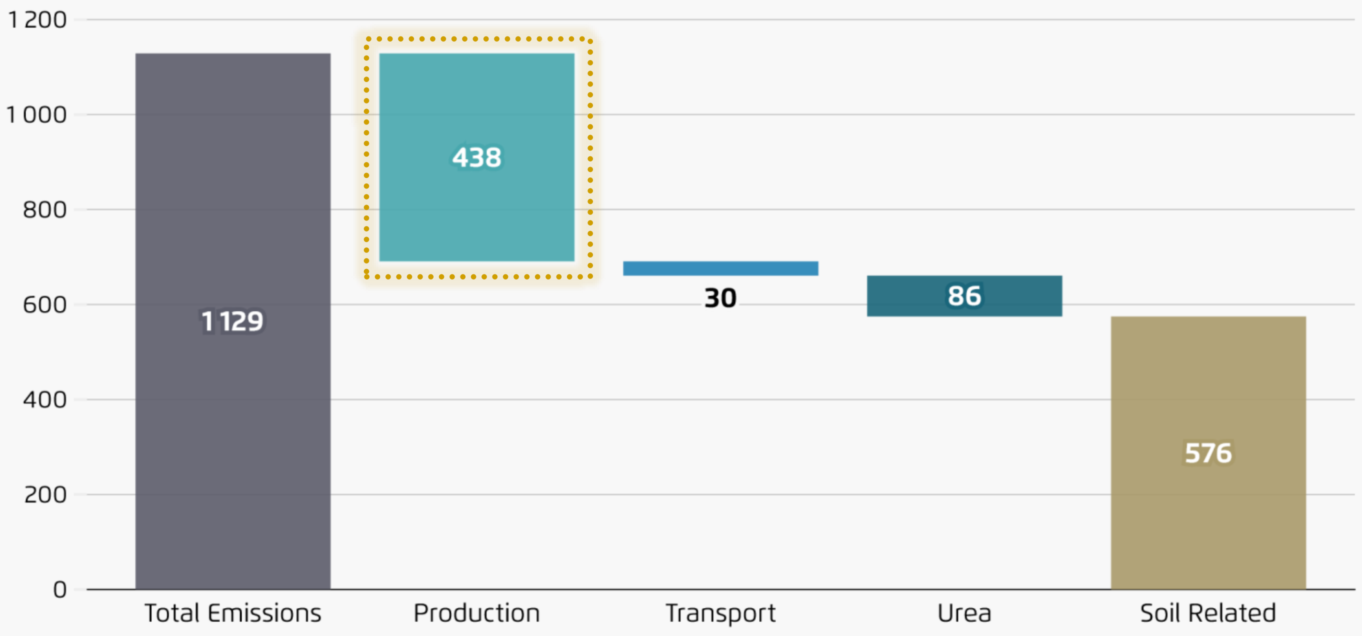


- Total hydrogen demand of 95 Mt in 2022.
- 22% of hydrogen used for ammonia production for **nitrogen fertilisers.**
- Hydrogen is predominantly produced from **unabated fossil natural gas and coal.**
- Production process emits about 1.8 tonnes of CO_2 per tonne of ammonia produced.

← Overview

Synthetic nitrogen fertiliser production is associated with more than 400 Mt of greenhouse gas emissions worldwide

Global GHGs related to nitrogen fertiliser production, transport and application
[Mt CO_2eq]



→ **70% of all annually produced ammonia** is used for nitrogen fertilisers.

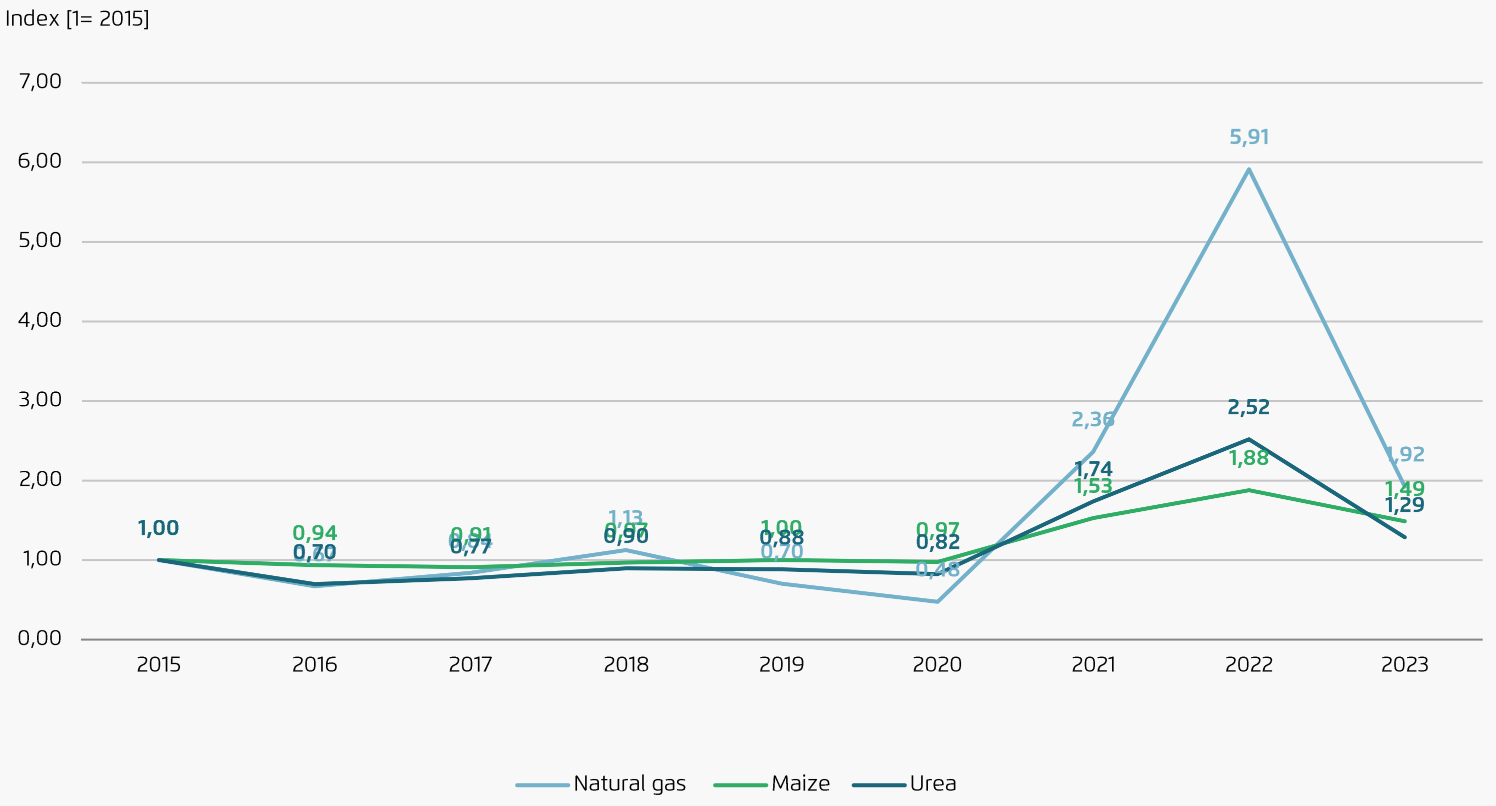
→ **Urea** markets differ according to world region.

→ **Urea and soil-related emissions** represent nearly 60% of total emissions associated with nitrogen fertiliser.

← Overview

Hydrogen can help to decouple fertilisers production from natural gas markets, thus easing pressure on global fertiliser markets

Natural gas, urea and maize price index

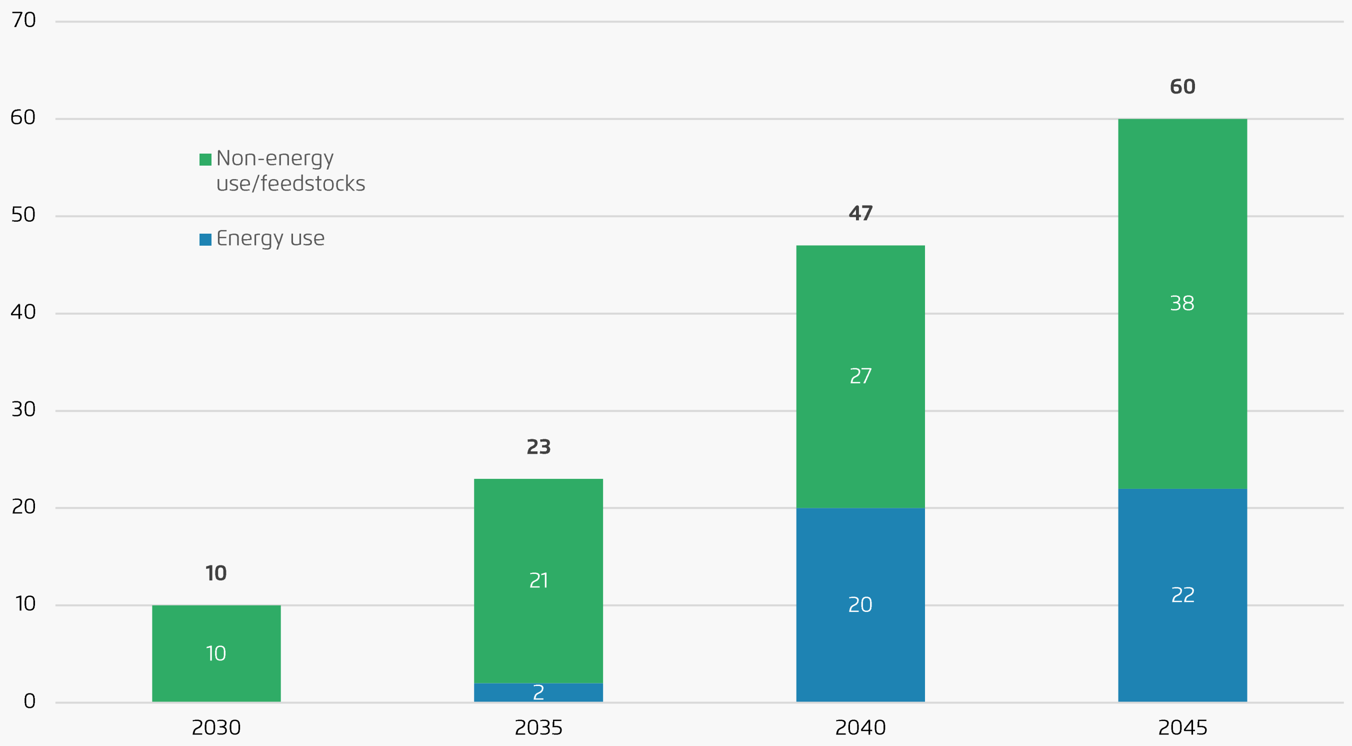


- → Producing fertilisers with hydrogen instead of fossil fuels increases the sector’s **resilience**.
- → **Food prices** increased massively due to fluctuations in the natural gas price.

← Overview

In a climate-neutral Germany scenario, hydrogen is particularly relevant as a feedstock and to back up industrial combined heat and power plants

Hydrogen use in the chemical industry
[TWh (LHV)/year]



→ The chemical industry transitions from fossil crude oil to renewable **methanol** as a **feedstock**, produced from biomass and hydrogen.

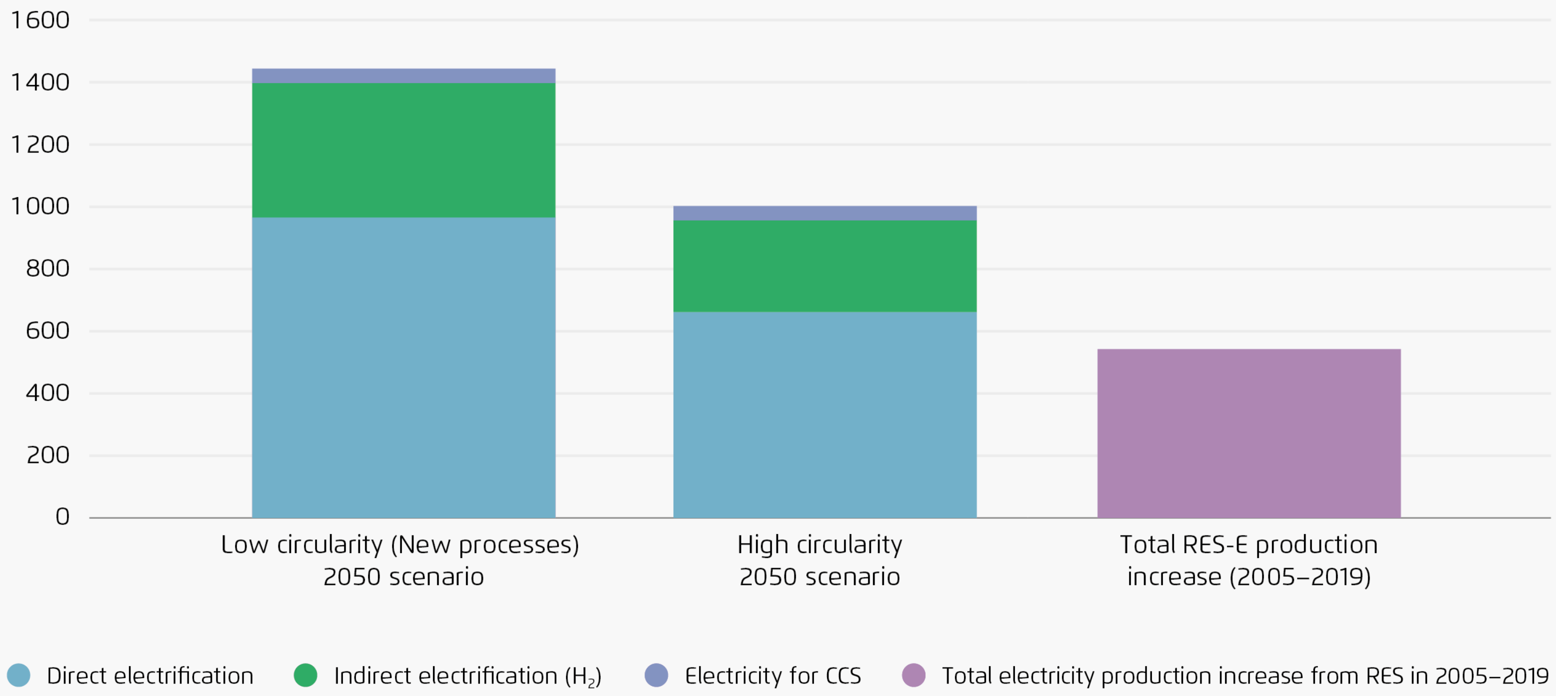
→ **Feedstocks**: Using hydrogen in biomass gasification increases the yield. More biogenic carbon is bound to methanol and less of it needs to be emitted or captured and stored geologically.

→ **Energy use**: Industry becomes a more integral and flexible part of the power system. Industrial power plants switch from natural gas and coal to renewable hydrogen to produce process heat and electricity.

← Overview

In the EU, a circular economy has the potential to reduce hydrogen demand in 2050 by one third, relative to a low circularity scenario

Additional power needs for the decarbonisation of steel, cement and chemicals, low- vs high-circularity scenarios [TWh/year]



→ Circular scenario would significantly reduce the need for hydrogen in the **cement, chemicals and steel** sectors.

→ **Low circularity** scenario estimates that 433 TWh of hydrogen are needed.

→ **High circularity** scenario suggests 293 TWh of hydrogen may be needed, a 33% reduction.

← Overview

Agora Industry (2022) based on data from Eurostat (2021) and Material Economics (2022): Mobilising the circular economy for energy-intensive materials. How Europe can accelerate its transition to fossil-free, energy-efficient and independent industrial production.

To achieve a climate-neutral transport sector, long-haul aviation and maritime shipping will require renewable hydrogen and its derivatives

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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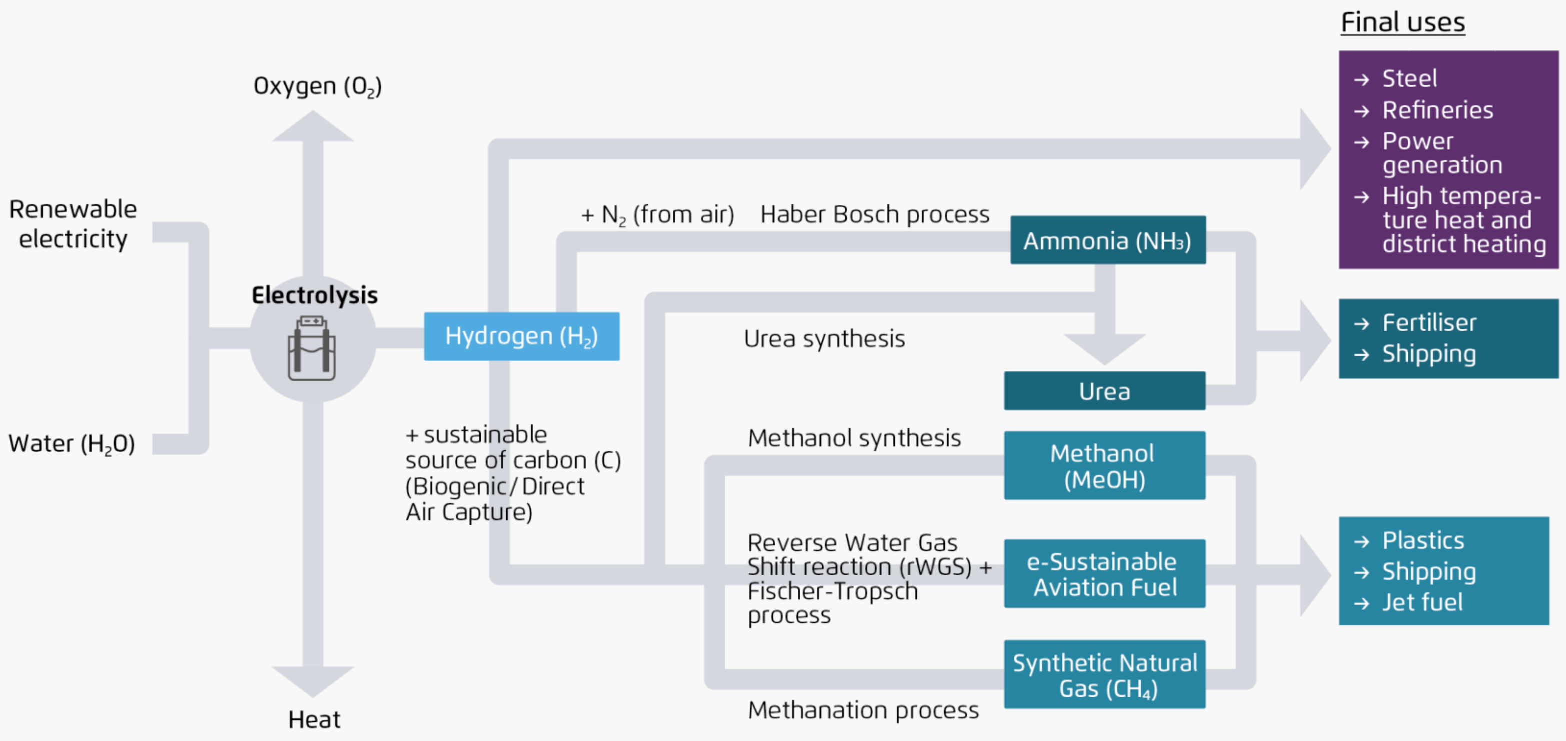
 Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen

Hydrogen can be transformed into various PtX products, including electric Sustainable Aviation Fuel (e-SAF), methanol and ammonia

Paths for the production of PtX products

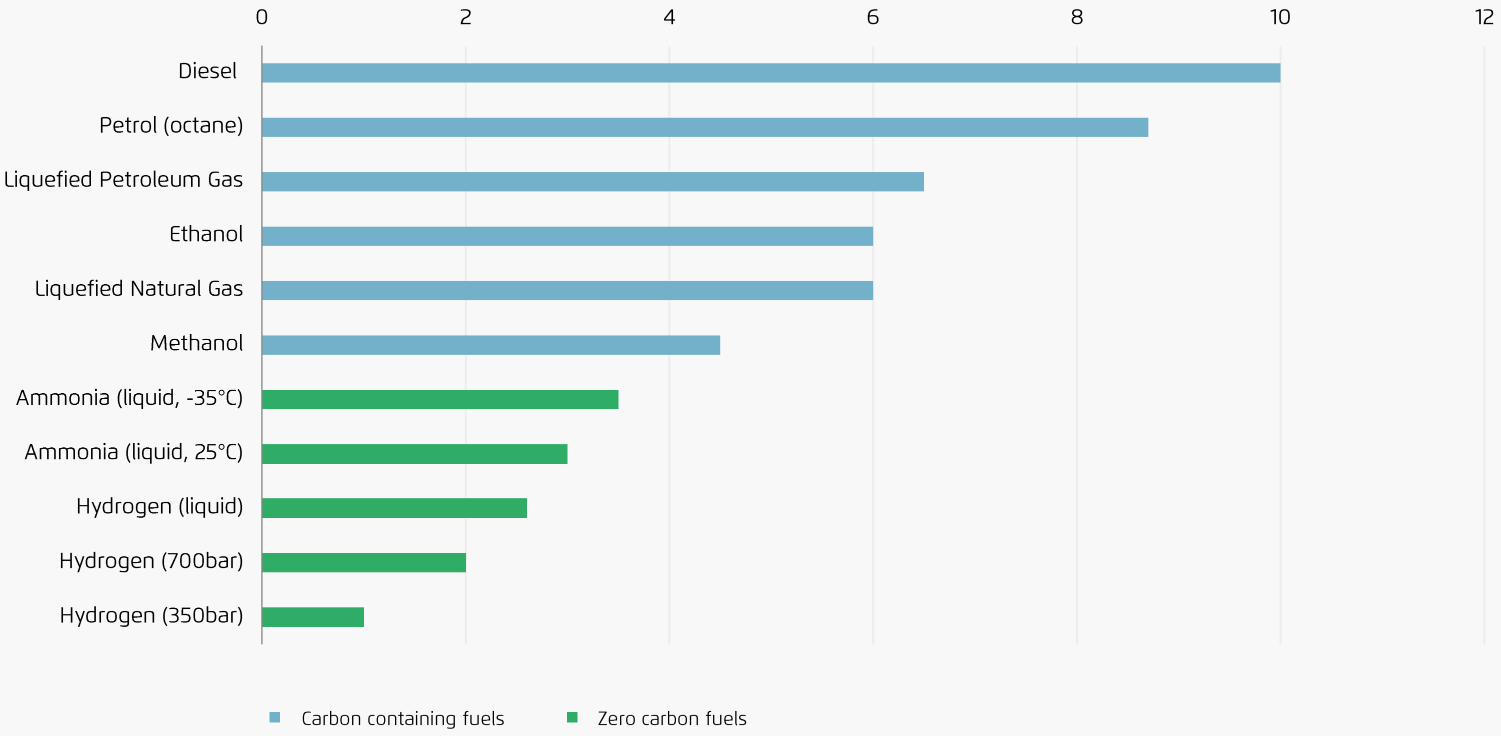


- → Renewable hydrogen production needs renewable energy sources.
- → Several PtX products **in addition need a source of carbon**.
- → To produce these fuels at scale, carbon needs to come from sustainable biomass such as agricultural by-products or waste or be produced with Direct Air Capture (DAC).
- → The purer the CO_2, the lower the costs of capture.

← Overview

In transport applications, energy density per volume is important, which is why derivatives outperform pure hydrogen

Volumetric energy density of various fuels [kWh/l]



→ Due to the **limited space** available in long-distance transport applications, fuels must have a high volumetric energy density.

→ **Carbon-containing fuels achieve the highest densities.**

→ Zero-carbon fuels have lower densities.

- For example: density of liquid hydrogen ≈ three times lower than density of diesel

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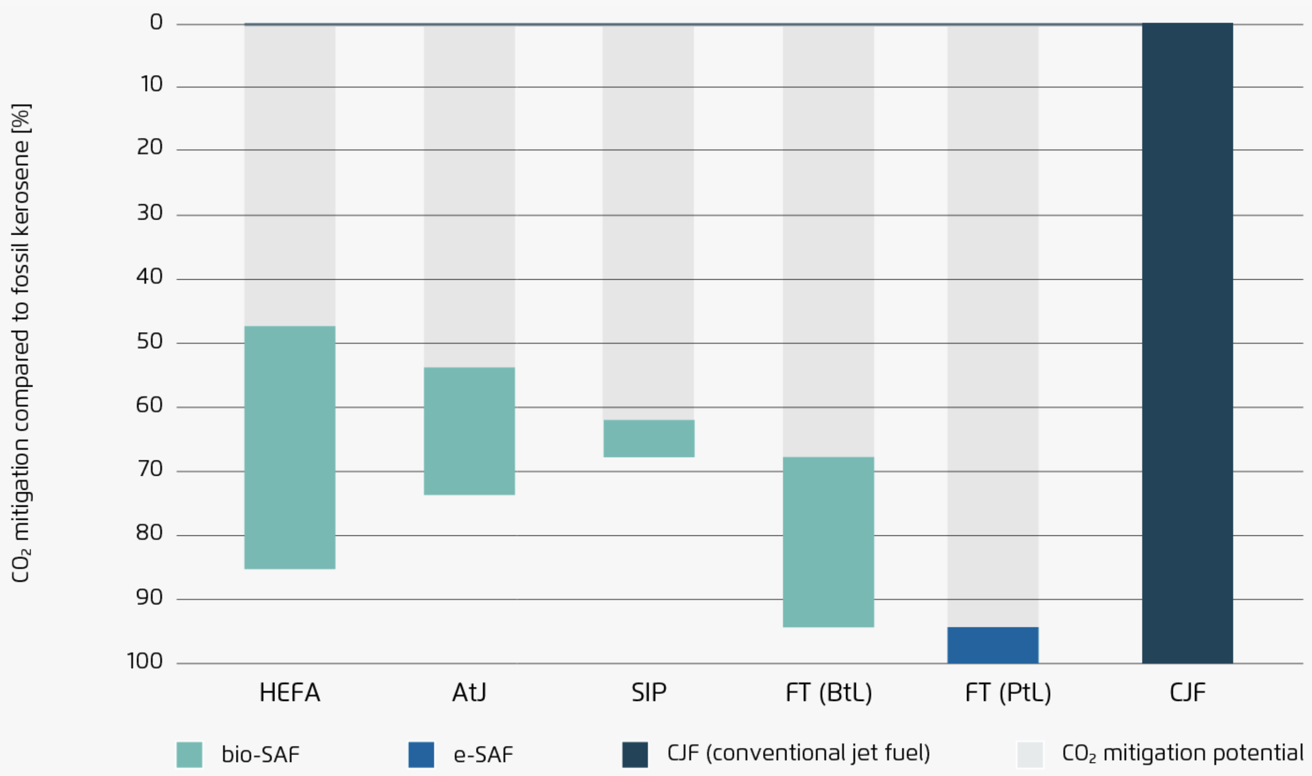
E-SAF has the highest CO_2 mitigation potential among SAF pathways compared to fossil kerosene

CO_2 mitigation potential of different SAF types compared to fossil kerosene



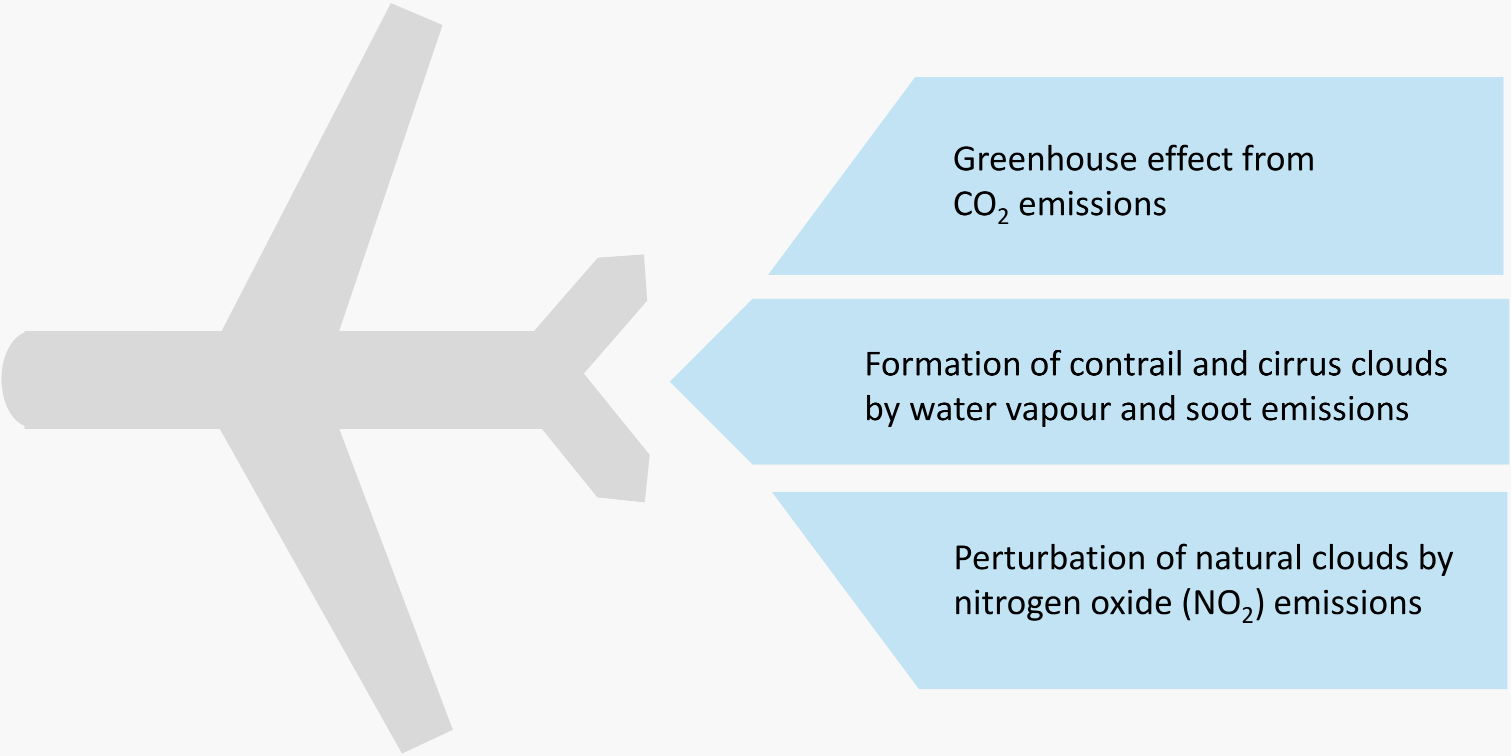
- → The overall **greenhouse gas emissions** of fuels are mainly affected by the feedstocks, process design and power mix.
- → Lowest greenhouse gas emissions profile is exhibited by e-SAF that is produced from renewable electricity and direct air capture.

← Overview

Agora Verkehrswende and International PtX Hub (2024): Defossilising aviation with e-SAF. HEFA = Hydroprocessed Esters and Fatty Acids; AtJ = Alcohol-to-Jet; SIP = Synthetic Isoparaffins; FT (BtL) = Fischer-Tropsch Biomass-to-Liquids; FT (PtL) = (Fischer-Tropsch Power-to-Liquids)

E-SAF alone cannot mitigate the non-CO_2 effects of aviation

The climate impact of non-CO_2 effects



- → Non-CO_2 effects account for **up to two thirds** of aviation's total climate impact.
- → Such effects may even occur when aircraft are fully powered by hydrogen.
- → However, synthetic fuels (e.g., e-SAF) have **high purity levels**, which reduces particulate emissions and may decrease the likelihood of cirrus cloud formation.

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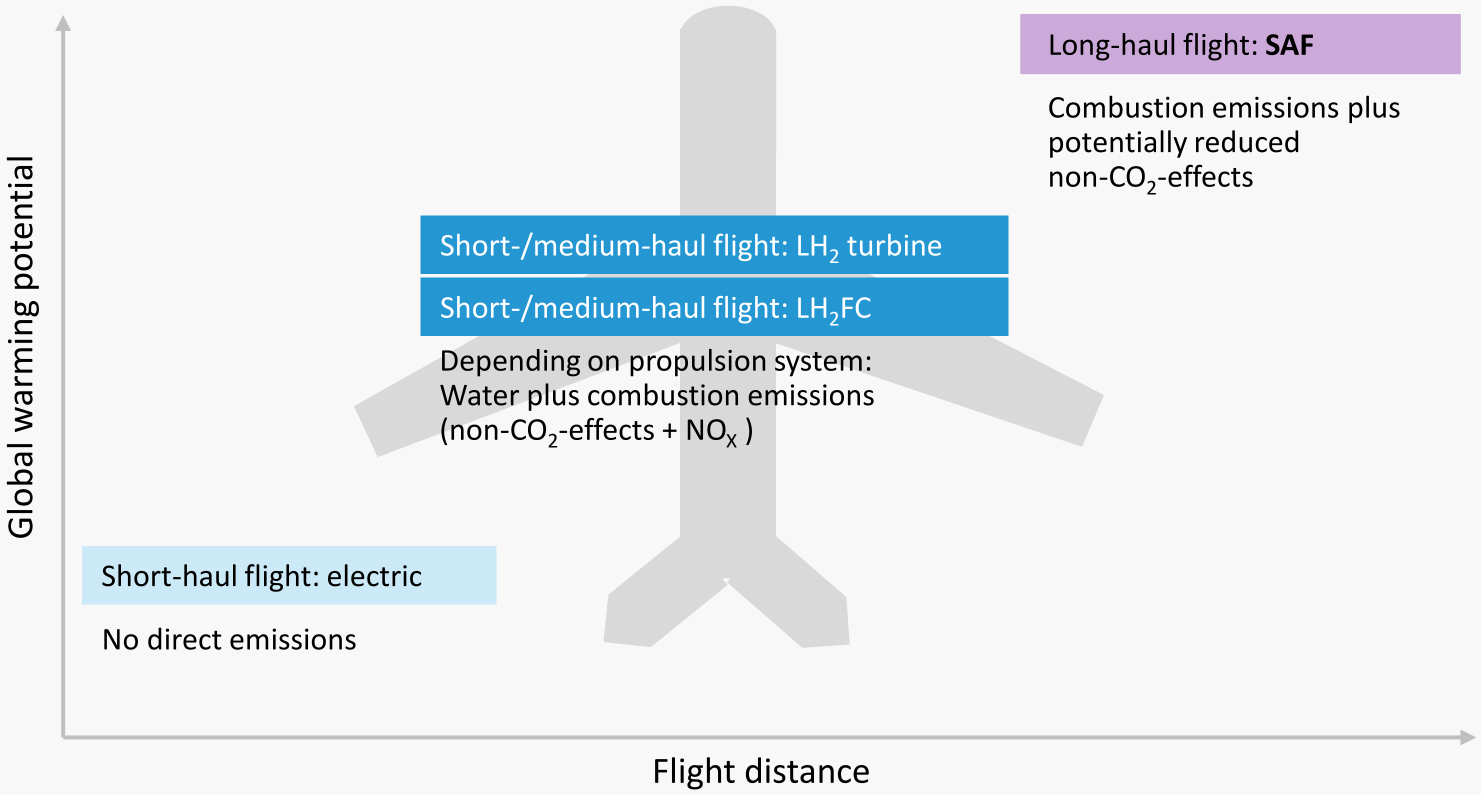
Long-haul flights need sustainable aviation fuels. For short- and medium-haul flights, however, hydrogen aircraft offer a potential advantage

Propulsion and energy transition options for aviation and their climate impacts



- → **Hydrogen aircraft** could be well-suited for short- to medium-haul flights but are **limited** by low energy density and storage challenges.
- → Drop-in e-SAF will be needed for long-haul flights due to a higher energy density.

← Overview

Agora Verkehrswende and International PtX Hub (2024): Defossilising aviation with e-SAF; ICCT (2022): Performance analysis of evolutionary hydrogen-powered aircraft
Note: FC = Fuel cell; LH_2 = Liquid hydrogen; SAF = Sustainable aviation fuel

The maritime sector will require renewable hydrogen or its derivatives to achieve decarbonisation

Expected environmental performance by fuel compared with marine gas oil (MGO)

Fuel	Air pollution				GHGs	
	SO_x	NO_x	CO	PM	TTW	WTW
Diesel alternatives	+	o		+	o	+ (soy bio); ++ (UCO renewable)
Synthetic FT diesel	+	o	o	+	o	++ (miscanthus /corn stover gasification) - - (captured CO_2 and grid electricity) ++ (captured CO_2 and renewable electricity)
Hydrogen	++	++ FC o ICE	++	++	++	++ renewable electricity; - SMR of natural gas o SMR of natural gas with CCS; - - grid electricity
Ammonia	++	++ FC o ICE	++ FC + ICE	++ FC + ICE	++ FC + ICE	++ renewable electricity - - SMR of natural gas / grid electricity
Methanol	++	++ FC o ICE	++ FC + ICE	++	++ FC o ICE	++ DAC and renewable electricity ++ (miscanthus/corn stover gasification) o SMR of natural gas - - ethanol CO_2 / DAC CO_2 and grid electricity
Dimethyl ether	++	++ FC o ICE	++ FC + ICE	++ FC + ICE	++ FC o ICE	o SMR of natural gas ++ (miscanthus/ corn stover gasification´)
LNG	++	++ FC +LPDF o HPDF	-	++	++ FC + HPDF - LPDF	- - ethanol CO_2 and grid electricity - - DAC CO_2 and grid electricity ++ DAC and renewable electricity + landfill gas (LPDF); ++ landfill gas (HPDF)
Electricity	++	++	++	++	++	+ grid electricity; ++ renewable electricity

- → Like SAF for aviation, using hydrogen and its derivatives produced from 100% renewable electricity for the marine sector can provide **deep reductions in life-cycle greenhouse gas emissions compared to other pathways.**
- → Two potential hydrogen derivatives for use in the marine sector are methanol and ammonia.

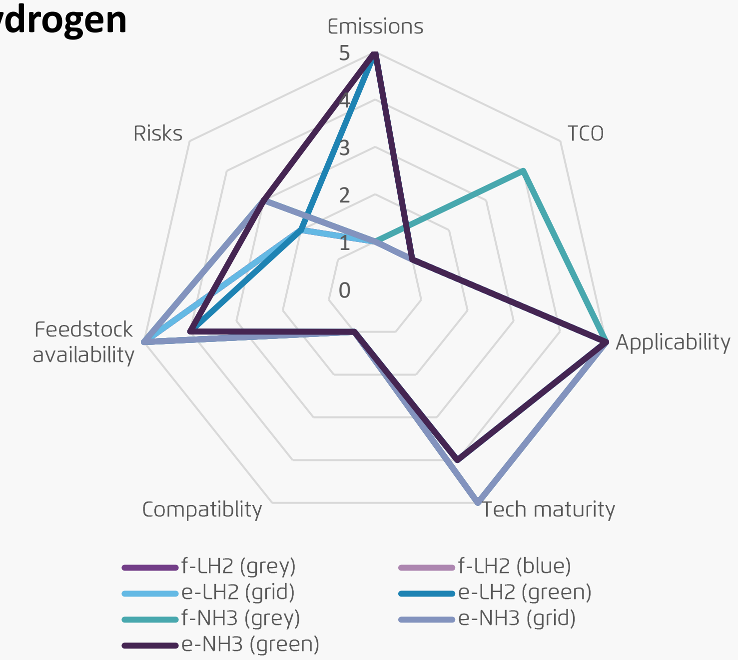
← Overview

ICCT (2024): Feasibility Study of Future Energy options for Great Lake Shipping
++ much better than MGO; + better than MGO; o same as MGO; - worse than MGO; -- much worse than MGO;
TTW = tank-to-wake; WTW = well-to-wheel emissions; FC = fuel cell; ICE = internal combustion engine; LPDF = low-pressure dual-fuel ICE; HPDF = high-pressure dual-fuel ICE

Renewable ammonia and methanol are the main options for decarbonising shipping and come with different pros and cons

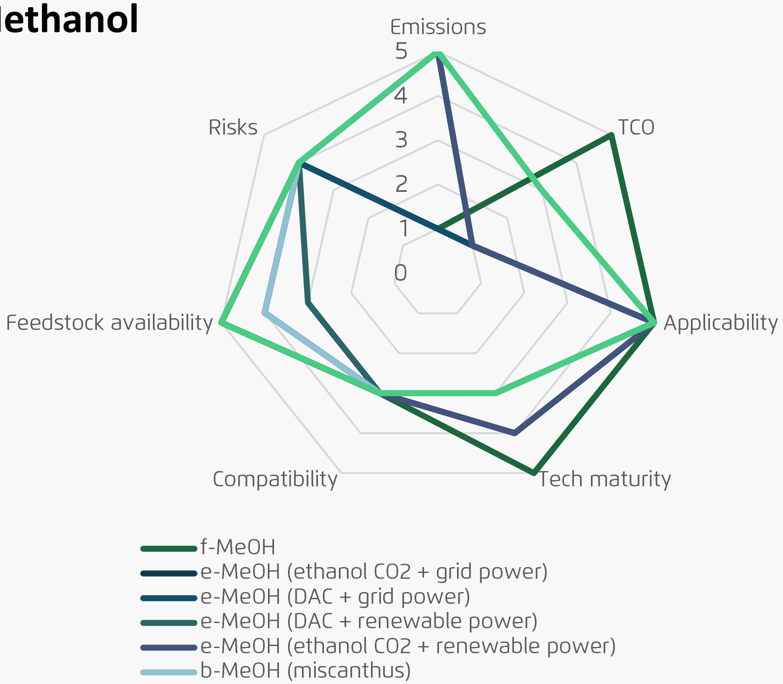
Renewable hydrogen and renewable ammonia are two fuels with low GHG emissions and good scalability; both present some safety concerns but are relatively technologically mature.

Ammonia and hydrogen



Renewable methanol overall performs well in risk, compatibility and applicability.

Methanol



← Overview

Power and district heat generation require seasonal storage to ensure reliability during low production periods from wind and solar

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
No-regret	**Non-energy use:**[1] - Feedstock: ammonia, chemicals, fertilisers - Reaction agents: DRI steel	- Long-haul aviation - Maritime shipping	- Renewable energy back-up, depending on wind and photovoltaic share and seasonal demand structure	- Heating grids (residual heat load)[2]
Controversial	- High-temperature heat	- Trucks and buses[3] - Short-haul aviation & shipping - Trains[4] - Non-road mobile machinery	- Absolute size of need given other flexibility and storage options	–
Bad idea	- Low-temperature heat	- Cars - Light-duty vehicles - Two- and three-wheelers	–	- Building-level heating

← Overview

Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen;[2] After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.

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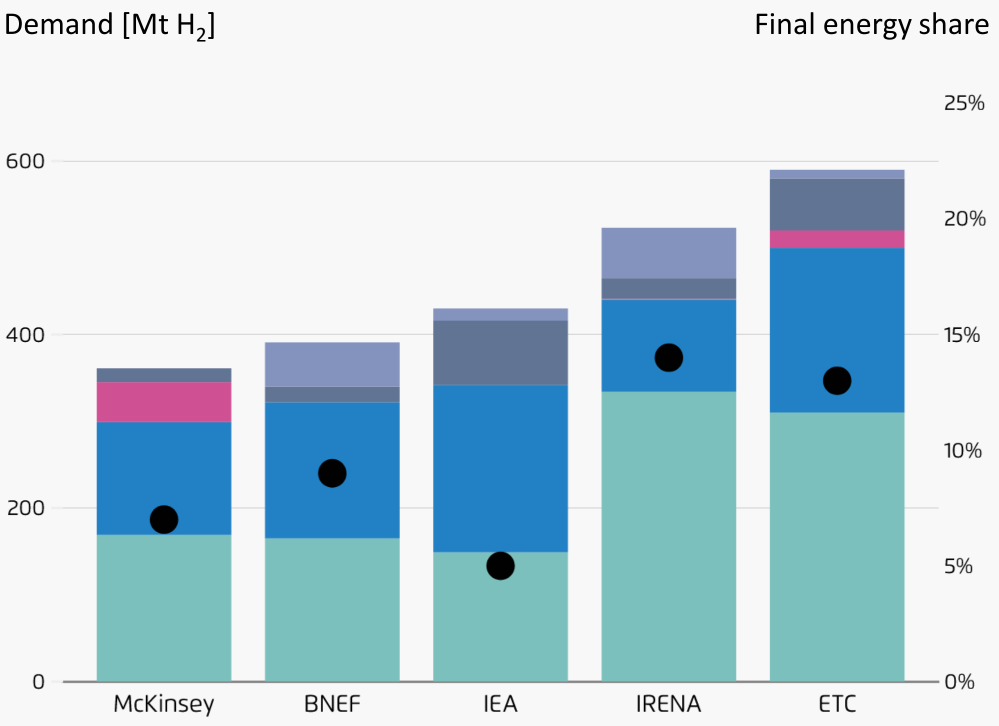
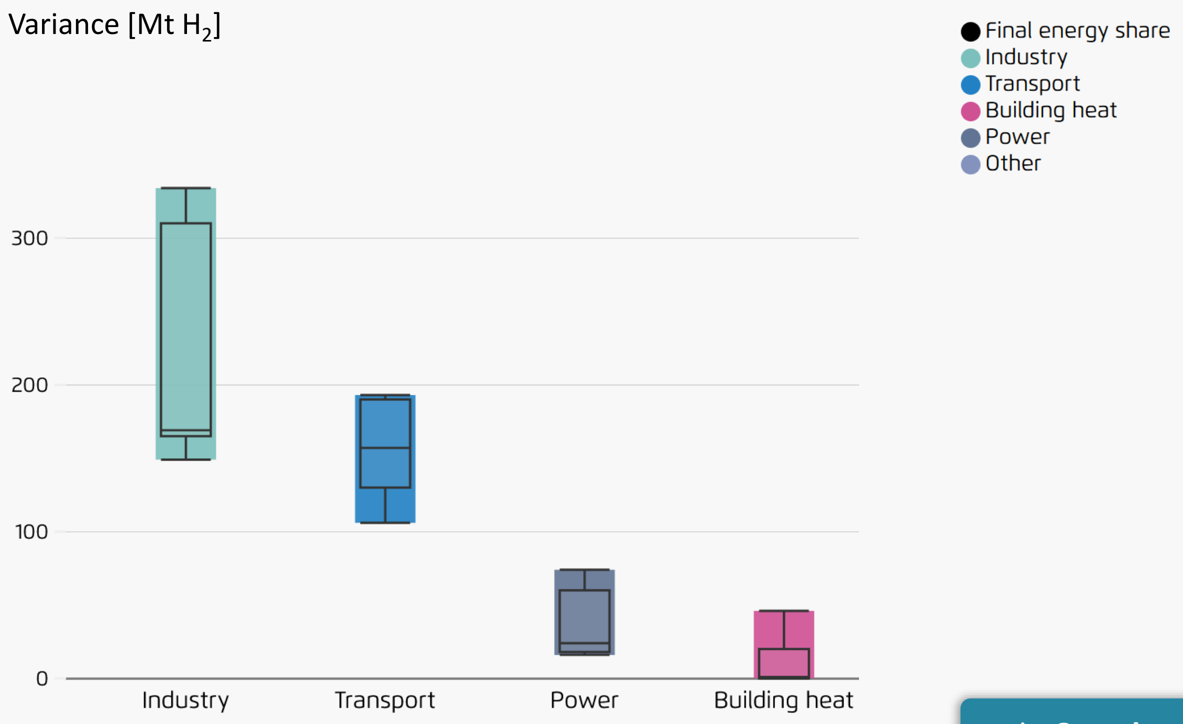
Hydrogen use in the power sector is the second smallest use of all sectors in global energy system scenarios for 2050

Estimates of global hydrogen demand in 2050: selected scenarios



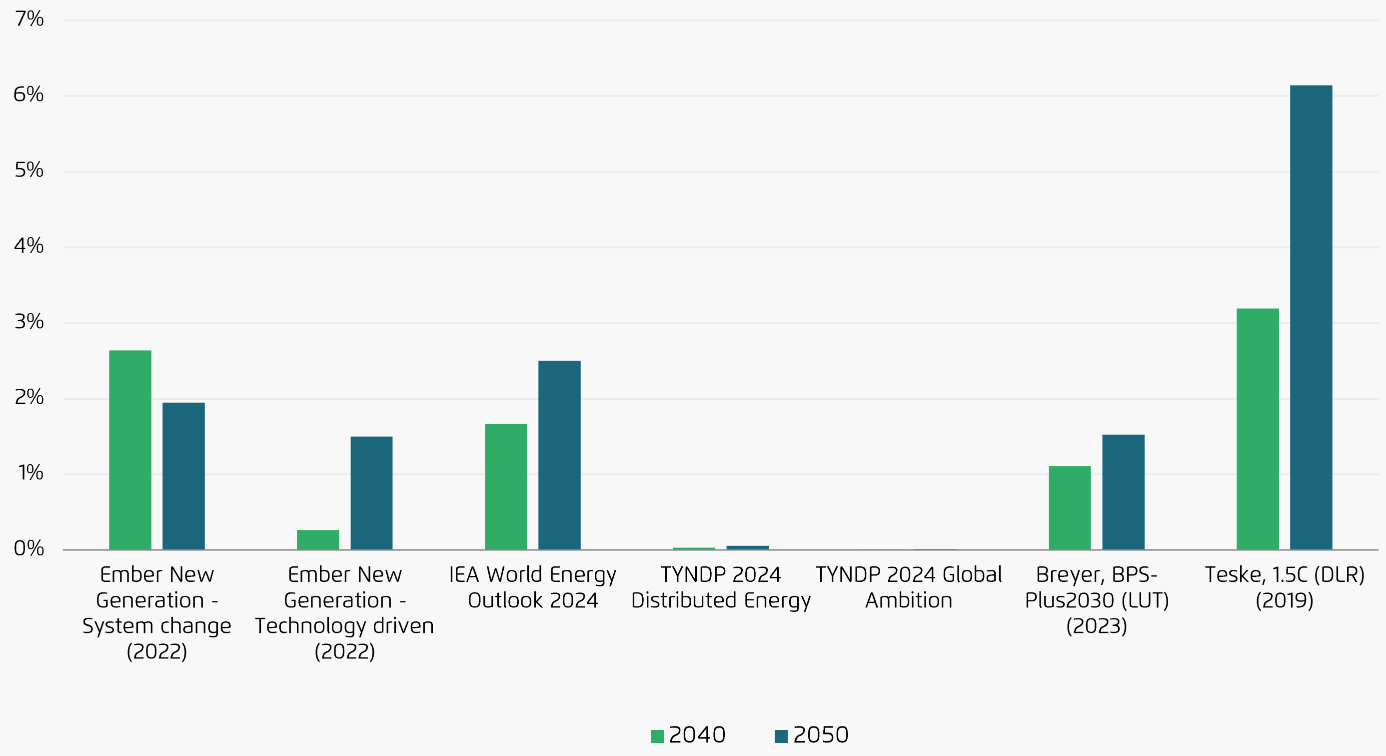


← Overview

 Agora Industry (2024) based on McKinsey (2024), BloombergNEF (2024), International Energy Agency (2023), International Renewable Energy Agency (2023), Energy Transitions Commission (2023). Note: Final energy does not include feedstocks and other non-energy use; final energy figures taken from respective sources

Hydrogen can help to decarbonise the energy system by enabling flexibility and securing sufficient energy supply

Share of H_2-to-power in total electricity generation

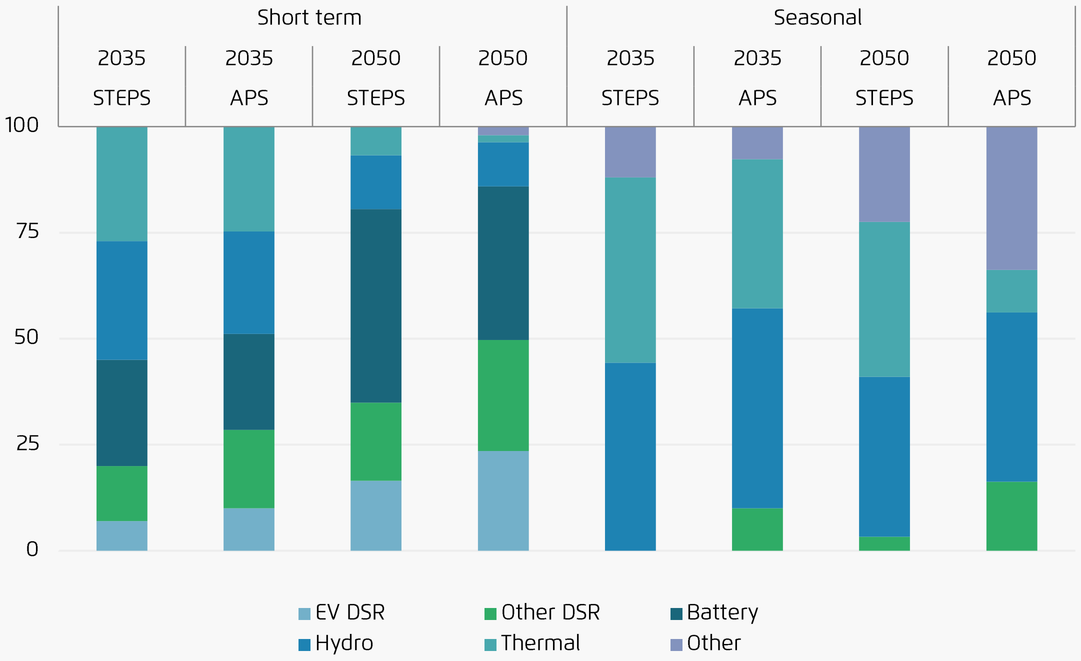


- Power to hydrogen in times of RES abundance, and hydrogen back to power
  in times of scarcity, offers **long-duration storage** opportunity.
  - Energy losses along the way amount to round-trip efficiency of about 40%
- Independent research estimates **contribution of hydrogen to power generation.**
  - 0-3% in 2040, 0-6% in 2050
- **Large variability**, in part related to constraints on technology choice: technology neutrality tends to result in lower hydrogen contribution.

← Overview

Seasonal flexibility needs are driven by electricity demand patterns and variability in the renewable energy sources

Power system flexibility supply in Stated Policies Scenario (STEPS) and Announced Pledges Scenario (APS) [%]



→ **Drivers**

- Electricity demand patterns, mitigated by energy efficiency, e.g., winter heating in Europe, cooling demand in India
- Seasonality of solar and wind

→ **Seasonal flex providers**

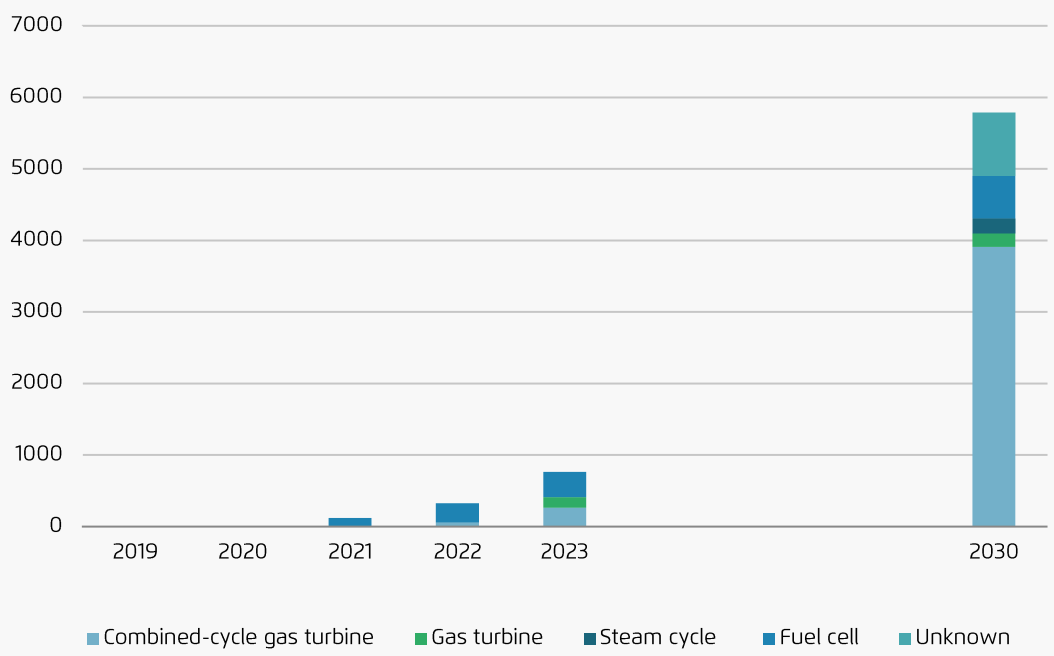
- Thermal power plants and hydro (until 2035)
- Renewables curtailment and demand-side response
- Interconnections (all timescales, incl. long) (JRC, 2023)
- Electrolysers producing **hydrogen for long-duration storage**

← Overview

IEA (2024): World Energy Outlook; JRC (2023): Flexibility requirements and the role storage in future European power systems
EV DSR = electric vehicle smart charging; Other DSR = other types of demand-side response, including operation of electrolysers;
Thermal = fossil fuels, nuclear, bioenergy, hydrogen and ammonia; Other = other types of demand-side response including the operation of electrolysers

A range of technologies are available for hydrogen electricity production, but need to be scaled up further

Total installed capacity by technology [MW]



→ **Available today**: technology for 100% hydrogen electricity generation

- Fuel cells, internal combustion engines, gas turbines
- NH_3 instead of hydrogen also an option (in gas turbines)
- Still **small units**: MW scale

→ **TRL[1] in 2024 increased to 8** for pure hydrogen. First-of-a-kind commercial

- Projects in Austria, France, Portugal, UK, USA, China, Japan…

→ **NOx air pollution** remains concern: R&D needed

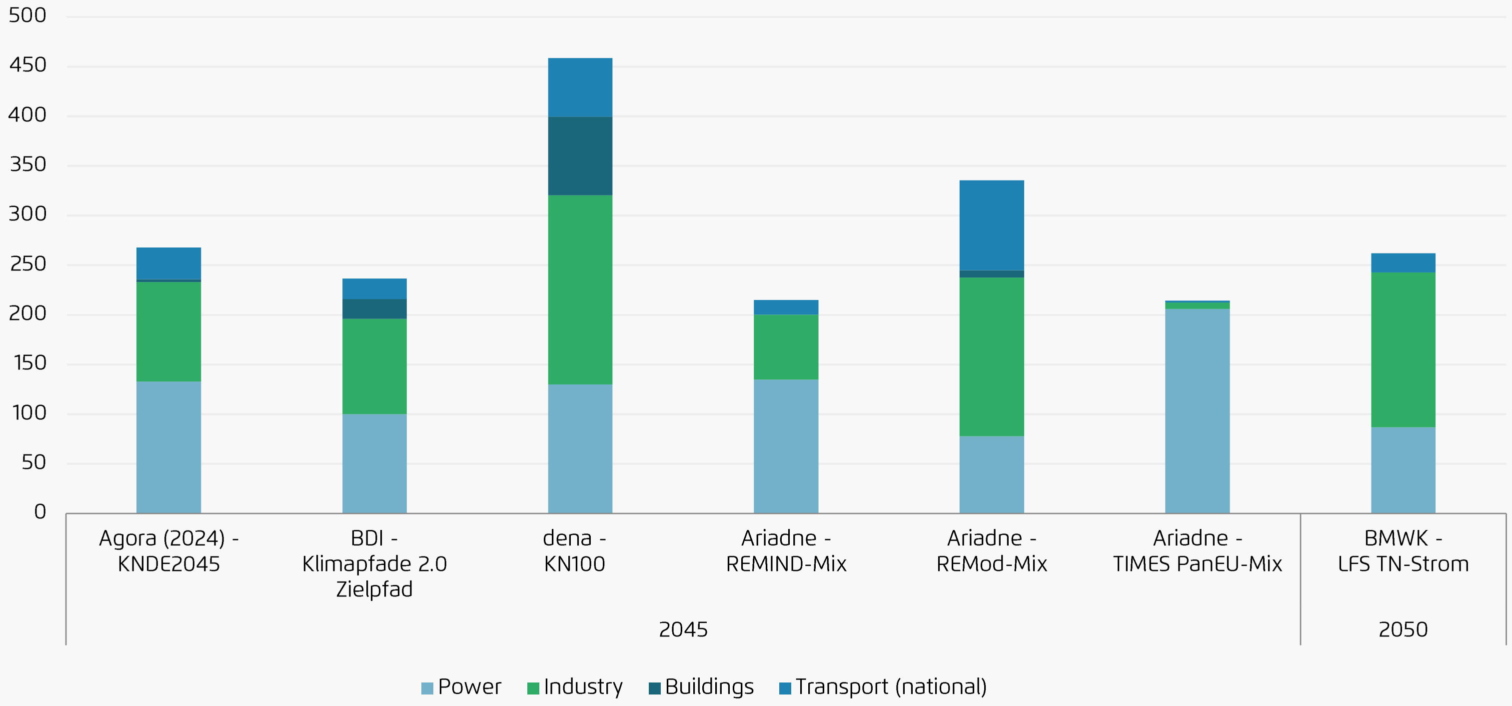
- Barrier in areas vulnerable to eutrophication (e.g., in Northwestern Europe)

← Overview

IEA (2023): Global Hydrogen Review; IEA (2023): ETP Clean Energy Technology Guide
Note: Values for 2023 are estimates, assuming plants with an announced start date in 2023 actually start operation in 2023. [1] Technology Readiness Level

For Germany, prominent energy system scenarios expect large hydrogen demand from the power sector, including district heating, due to need for seasonal storage

Use of CO_2-free hydrogen [TWh/yr]



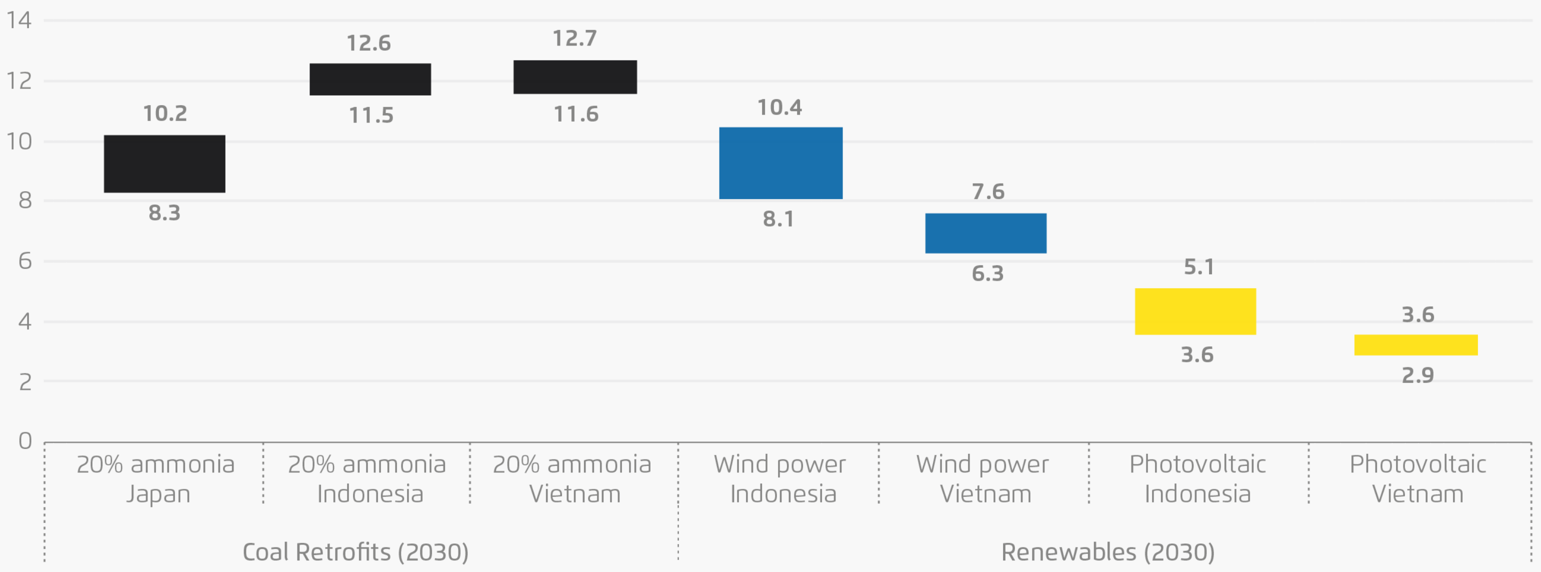
- → All scenarios indicate a strong increase in demand until 2045.
- → The biggest demand is projected in the power (light blue) and industry (green) sectors.
- → **Power sector: ≈ 80–200 TWh**
- → These scenarios were **commissioned by diverse stakeholders:** Federation of German Industries, the Germany energy agency, independent researchers, German Federal Ministry for Economic Affairs and Climate Action, think tanks

← Overview

Climate Neutrality Foundation (2022): Vergleich der „Big 5“ Klimaneutralitätsszenarien;
Agora (2024): Agora Think Tanks et al.: Klimaneutrales Deutschland. Von der Zielsetzung zur Umsetzung – Vertiefung der Szenariopfade.
Note: BDI = Federation of German Industries; dena = Germany energy agency; Ariadne = Independent research consortium; BMWK = German energy and climate ministry

Co-firing green ammonia in coal power plants is inefficient and costly

Levelised cost of electricity for different technologies including ammonia co-firing in selected countries [USD cents/kWh]



- Recent interest in Southeast Asia for ammonia co-firing to decarbonise young coal power plants fleet.
- **Economically inefficient**: high retrofitting costs.
- High emissions: ammonia used as a 20–50% co-firing in SEA leads to **higher CO_2 emissions than existing gas-fired plants**.
- Green ammonia should be prioritised for decarbonising the fertiliser and shipping industries, rather than being used in the power sector.

← Overview

Controversies around hydrogen use are due to technology competition with direct-electric approaches

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
No-regret	**Non-energy use:**[1] - Feedstock: ammonia, chemicals, fertilisers - Reaction agents: DRI steel	- Long-haul aviation - Maritime shipping	- Renewable energy back-up, depending on wind and photovoltaic share and seasonal demand structure	- Heating grids (residual heat load)[2]
Controversial	- High-temperature heat	- Trucks and buses[3] - Short-haul aviation & shipping - Trains[4] - Non-road mobile machinery	- Absolute size of need given other flexibility and storage options	–
Bad idea	- Low-temperature heat	- Cars - Light-duty vehicles - Two- and three-wheelers	–	- Building-level heating

← Overview

Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen;[3] Series production currently more advanced on electric than on H_2 for heavy duty vehicles and buses. H_2 heavy duty to be deployed at this point in time only in locations with synergies (ports, mines, industry clusters),[4] depending on distance, frequency and energy supply options

High-temperature heat is controversial because direct-electric approaches could provide any required temperature within real-world constraints

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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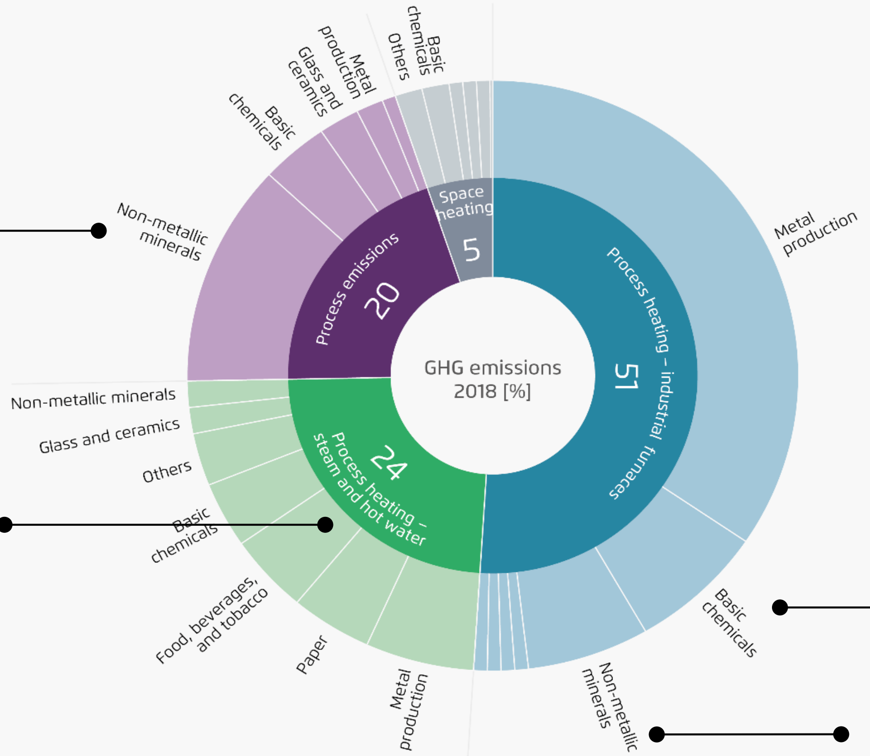
← Overview

In the EU, 75% of greenhouse gas emissions from industry result from process heat generation

Approximate structure of GHG emissions in the European industry sector, 2018

Chemical reactions releasing CO_2 – regardless of heat generation

Low-to mid-temperature (steam and hot water)



High-temperature reheating, smelting, melting

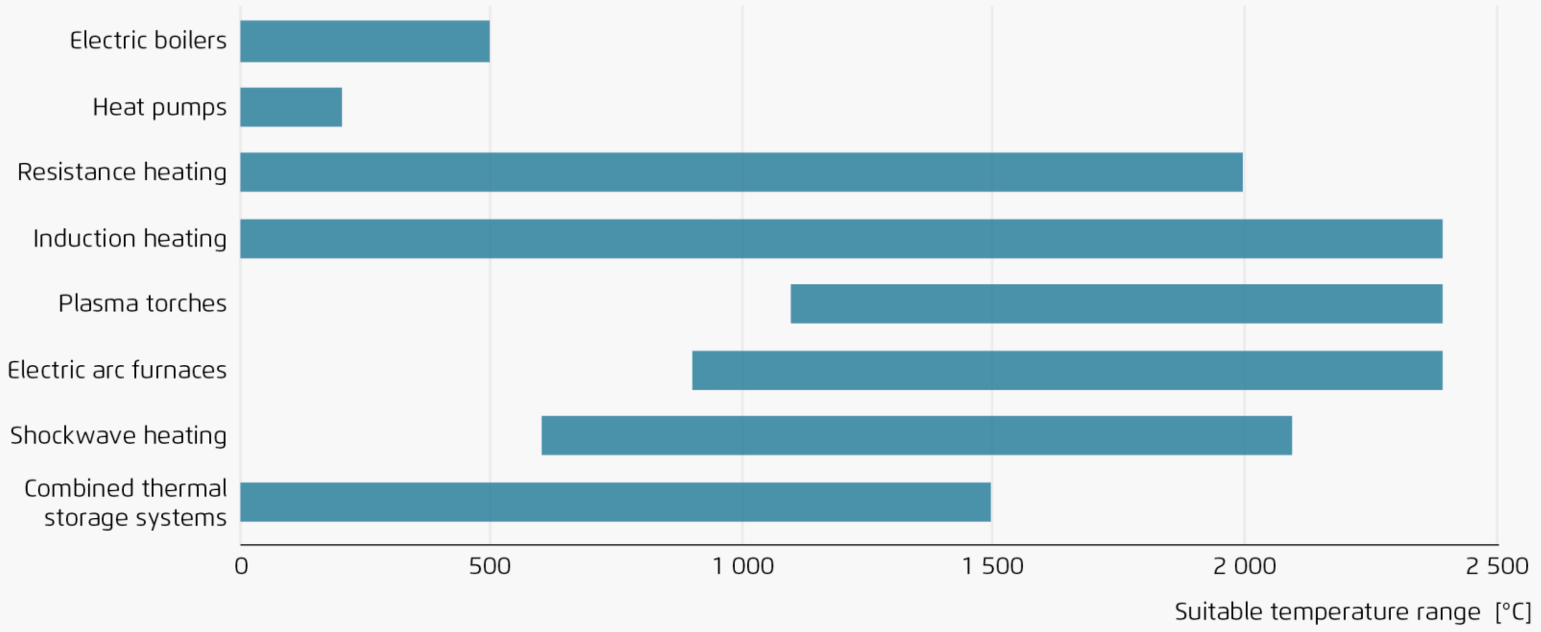
Cracking, reforming

Calcination, sintering

← Overview

Direct electric supply options exist over a broad range of the temperature levels

Potential development of suitable temperature range of electric heating technologies until 2035

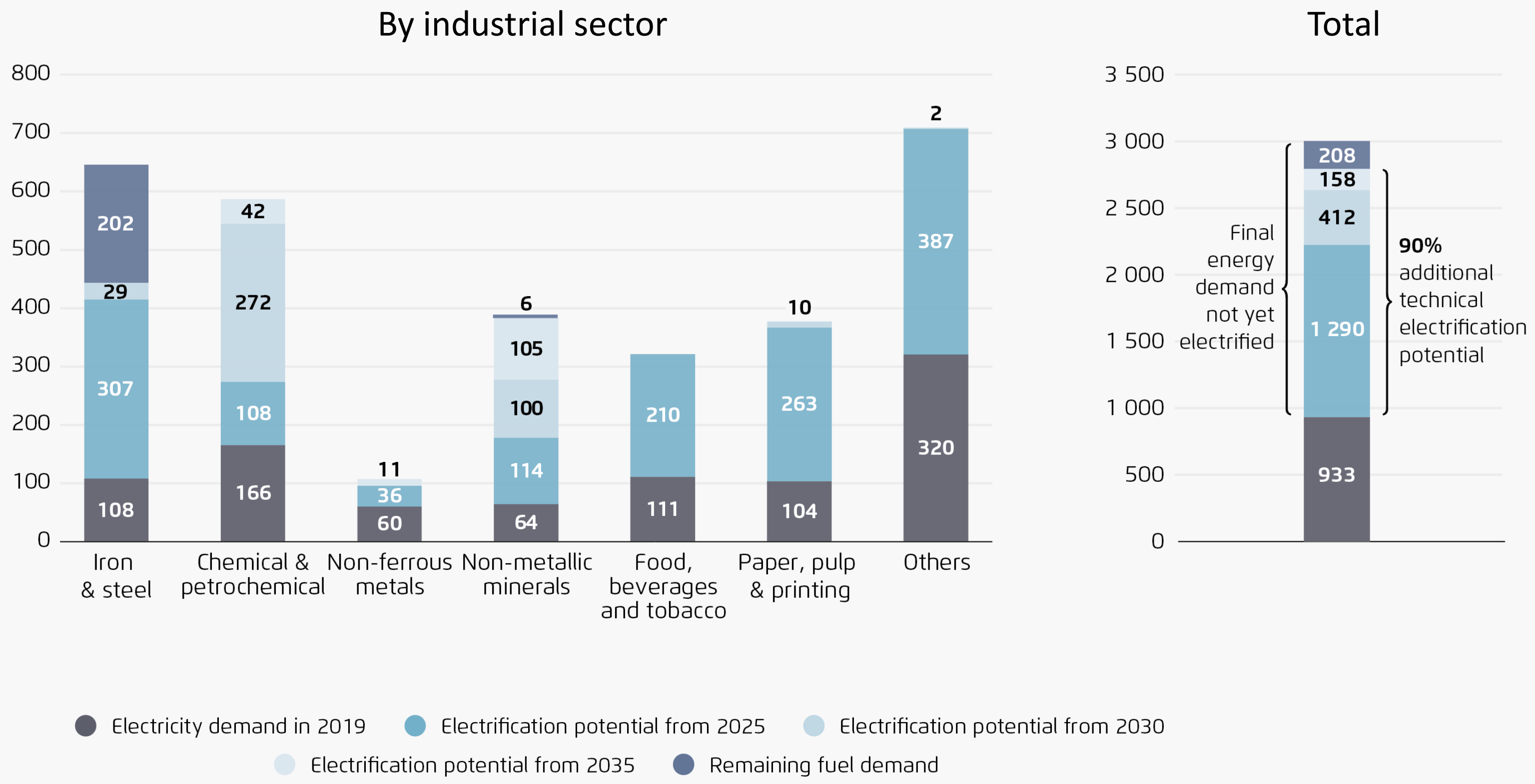


- → Electric boilers and heat pumps mostly target steam generation at **lower heat levels**.
- → Plasma torches, electric arc furnaces and shockwave heating address **high temperature levels**, e.g., in smelting processes
- → Resistance and induction heating provide solutions over a broad range of temperate levels.

← Overview

90% of the EU's remaining industrial final energy demand can be electrified with already existing or imminently mature technologies

Technical potentials for direct electrification in the EU27 [TWh]



- → Electricity already accounts for one third of the industrial final energy demand (933 TWh).
- → Of the remaining final energy demand (2,067 TWh), 90% can be electrified with technologies we expect to be mature before 2035.
- → Of this remaining final energy demand, **60% could already be electrified** with technologies that exist at large scale **today**.

← Overview

Many short-haul transport applications face competition with batteries, and it is questionable whether hydrogen infrastructure will be built in parallel

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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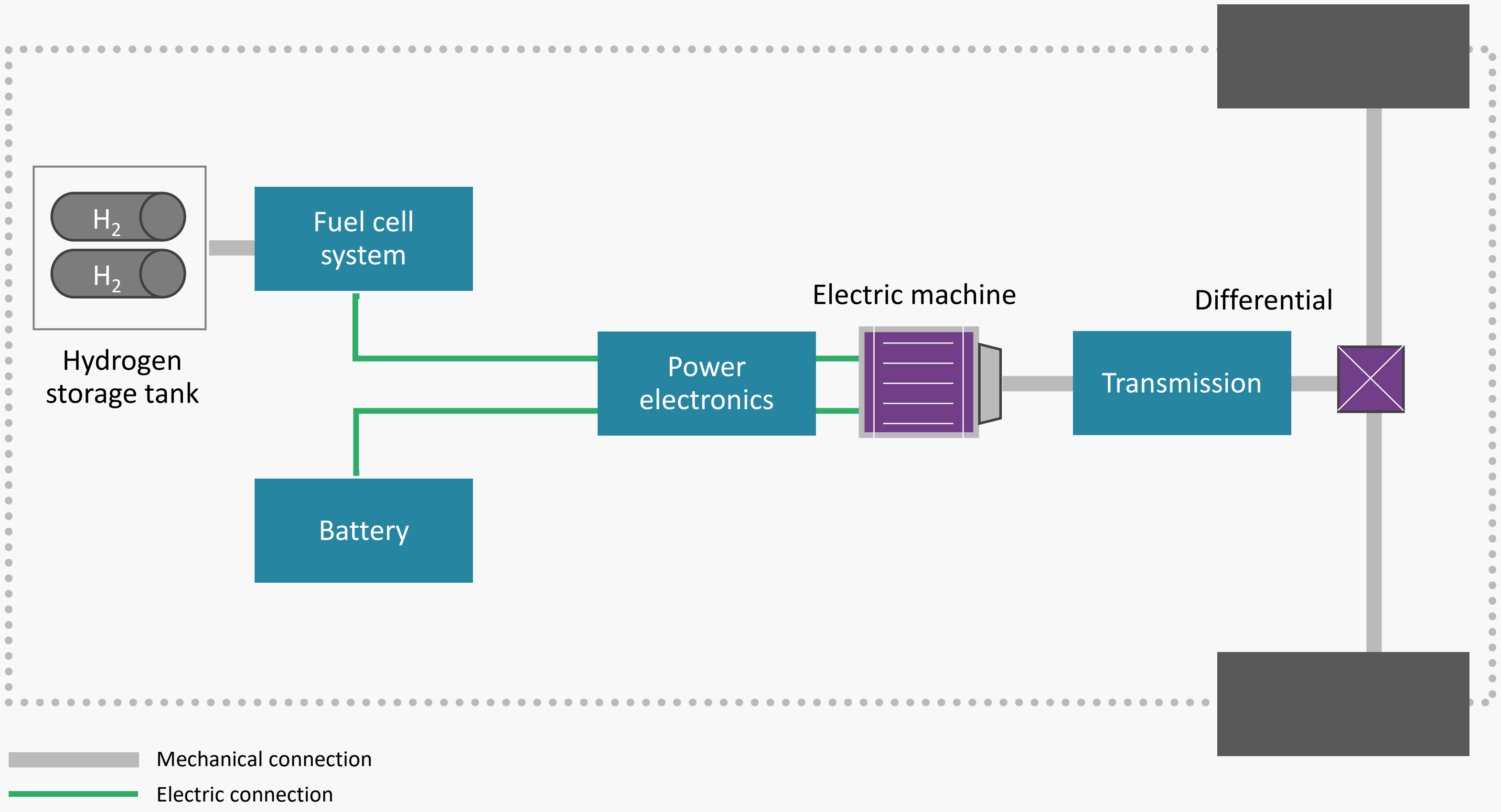
Fuel cell electric trucks include as main energy carrier hydrogen storage tanks and energy conversion devices

Fuel cell electric vehicle powertrain architecture

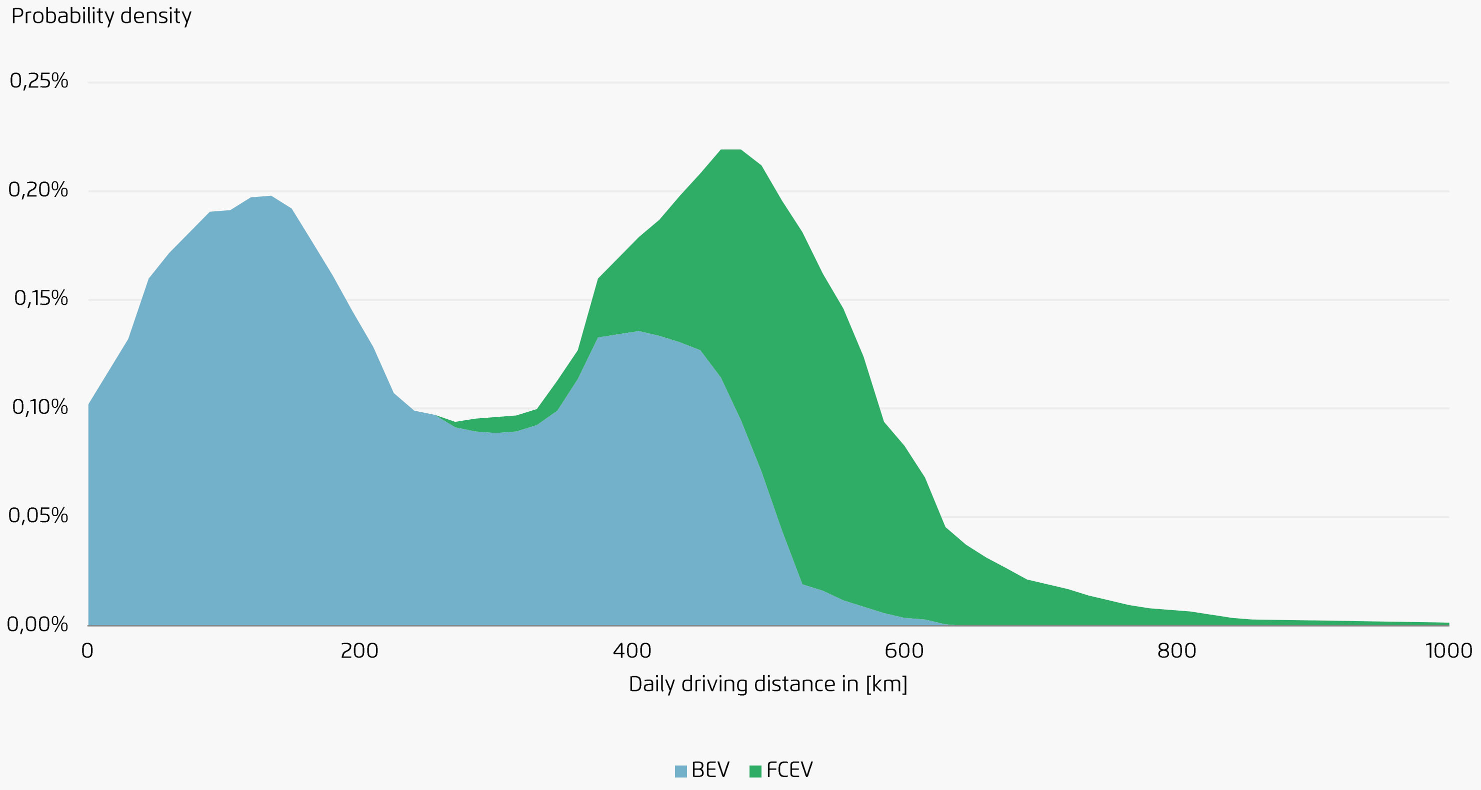


→ **Fuel cell electric trucks are hybrid trucks** composed of two main energy carriers – hydrogen storage tanks and batteries – and various energy conversion devices, such as fuel cells and electric motors.

← Overview

Hydrogen-fuelled transport could play a role for distances exceeding 400 km

Distribution of heavy trucks by daily driving distances, 2050

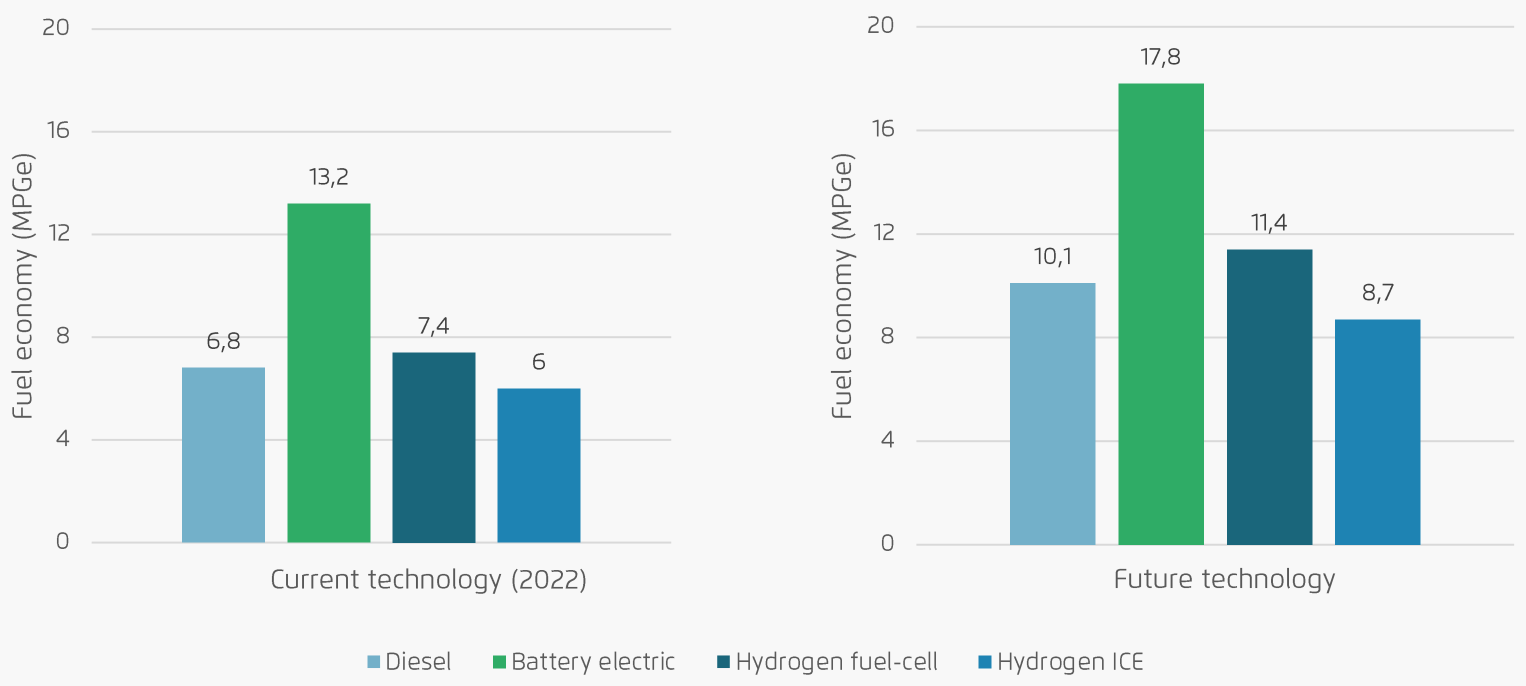


- → The IEA has projected heavy truck driving distances for 2050.
- → Hydrogen could be used to fuel **long-range** (> 400 km) and specialist vehicles.
- → **Shorter** driving distances will be covered by battery-electric vehicles.
- → Around 80% of driving distances can be covered by BEV.

← Overview

Trucks powered by battery electric technology are more efficient in terms of fuel economy

Trucks' fuel economy for current and future vehicles technologies expressed in miles per gallon diesel equivalent [MPGe]

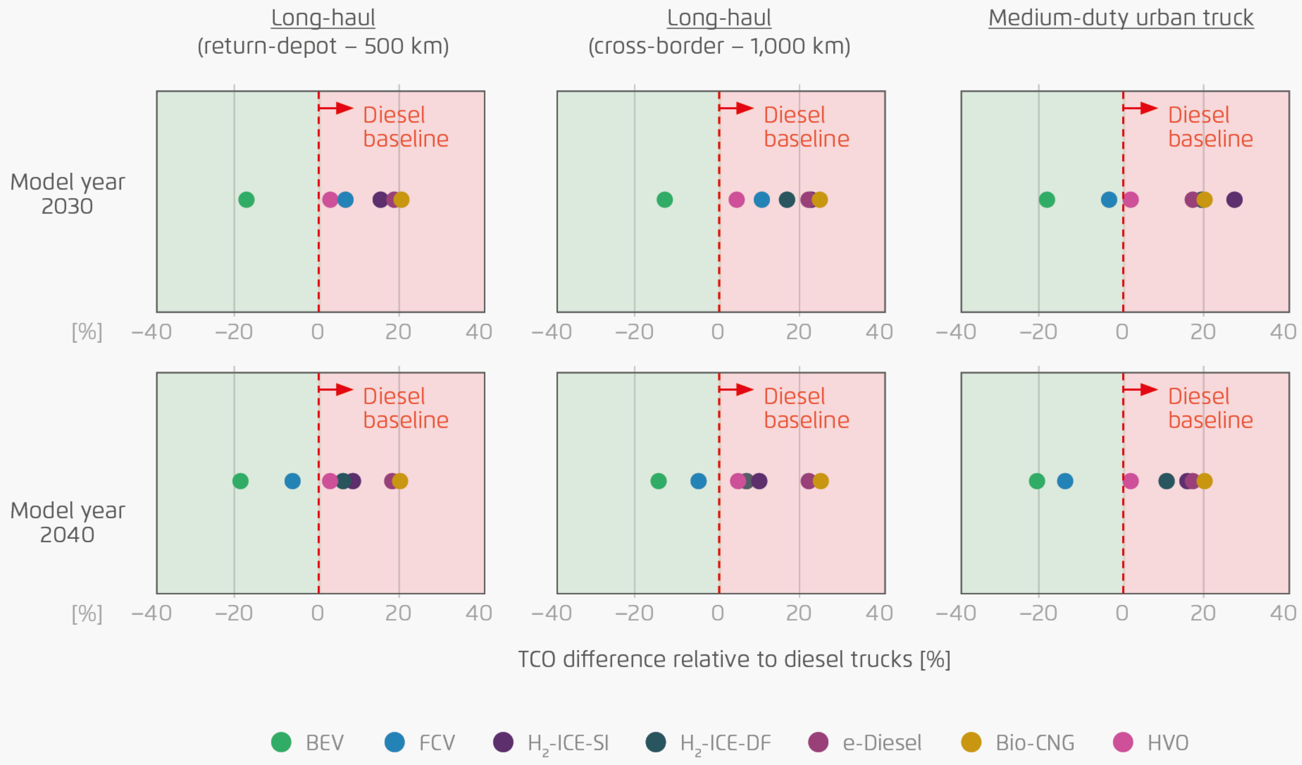


- → **Battery electric** is the most energy-efficient technology.
- → **Hydrogen fuel cell** trucks offer about 10% improvement in fuel economy relative to their diesel counterparts for current vehicle technologies.

← Overview

Battery electric trucks are likely to be the most cost-effective decarbonisation pathway

Total cost of ownership (TCO) percentage difference relative to diesel trucks for selected truck classes in Europe in 2030 and 2040

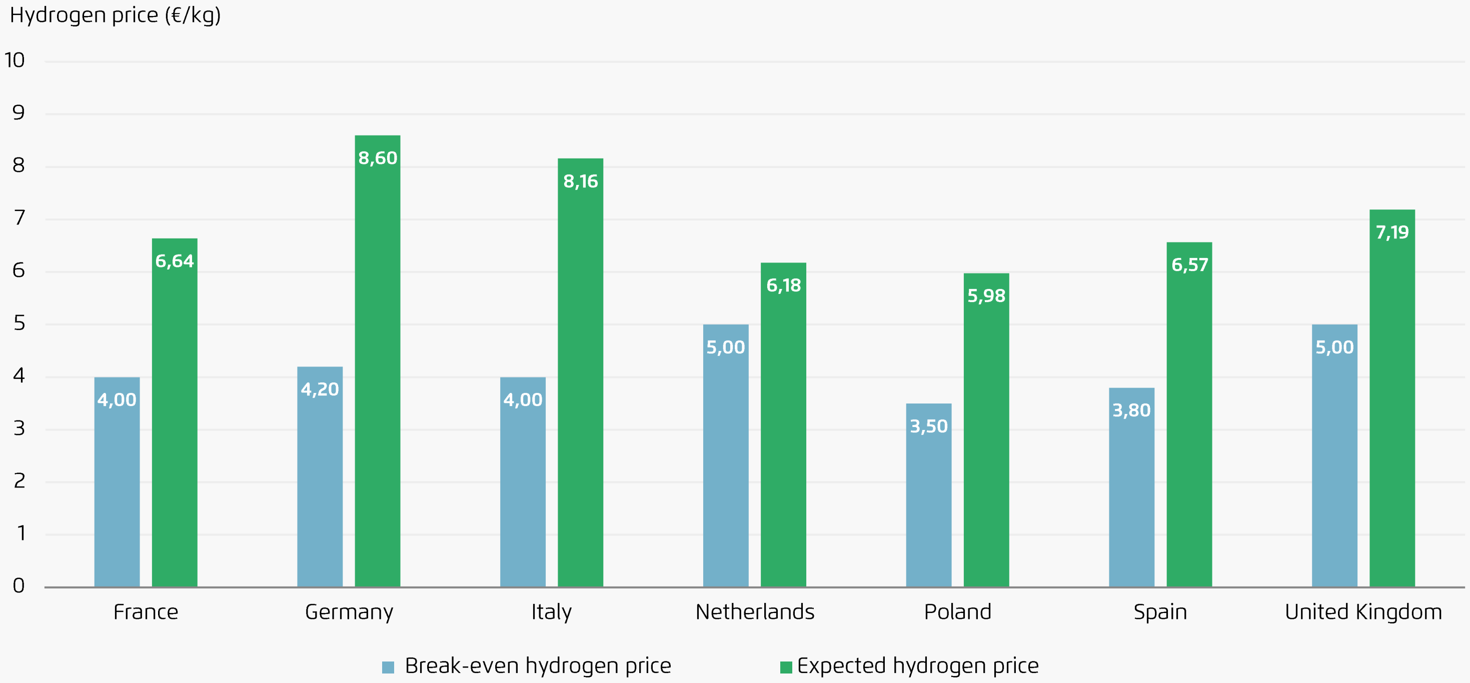


- → The **total cost of ownership** (TCO) considers the costs of owning and operating a truck fleet, by considering the truck's retail price, residual value at its end-of-life, finance costs, infrastructure costs, and all operational expenses, including fuel and energy, mainte-nance, labour, insurance and taxes
- → **Battery electric trucks** are projected to be the least-cost decarbonisation pathway for most truck classes
- → **Fuel-cell trucks** powered by renew-able hydrogen are expected to become cost-competitive with diesel later than BET, if at all

← Overview

Hydrogen fuel subsidy is required to make fuel cell electric trucks competitive with diesel trucks in Europe

Gap between expected hydrogen price and break-even price to achieve total cost of ownership parity between renewable hydrogen-powered fuel cell electric trucks and diesel trucks by 2030



- → **High renewable hydrogen cost** is the main reason that prevents fuel cell trucks reaching cost parity with diesel trucks.
- → **Subsidy** for renewable hydrogen is needed to achieve total cost of ownership parity by 2030.
- → The **hydrogen price gap** in different EU countries ranges from ≈ EUR 1/kg H_2 to EUR 4/kg H_2

← Overview

Several clear bad end-use cases for hydrogen exist across all sectors

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
No-regret	**Non-energy use:**[1] - Feedstock: ammonia, chemicals, fertilisers - Reaction agents: DRI steel	- Long-haul aviation - Maritime shipping	- Renewable energy back-up, depending on wind and photovoltaic share and seasonal demand structure	- Heating grids (residual heat load)[2]
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← Overview

 Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen

Low-temperature heat can be produced more efficiently with heat pumps

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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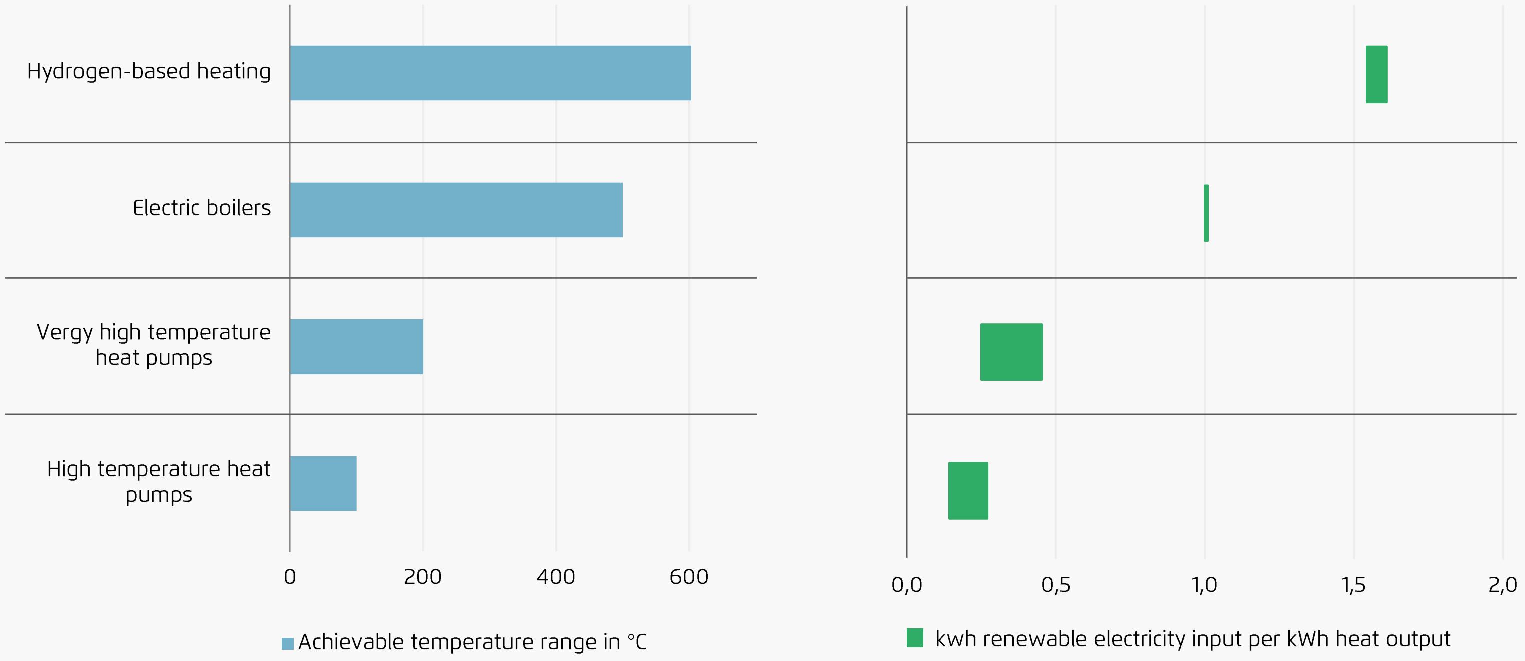
← Overview

Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen

Heat pumps can deliver up to 200 °C, electric boilers up to 500 °C. Their flexible use should facilitate overall decarbonisation

Achievable temperature ranges and electricity requirements of electricity-based technology options for climate-neutral heat

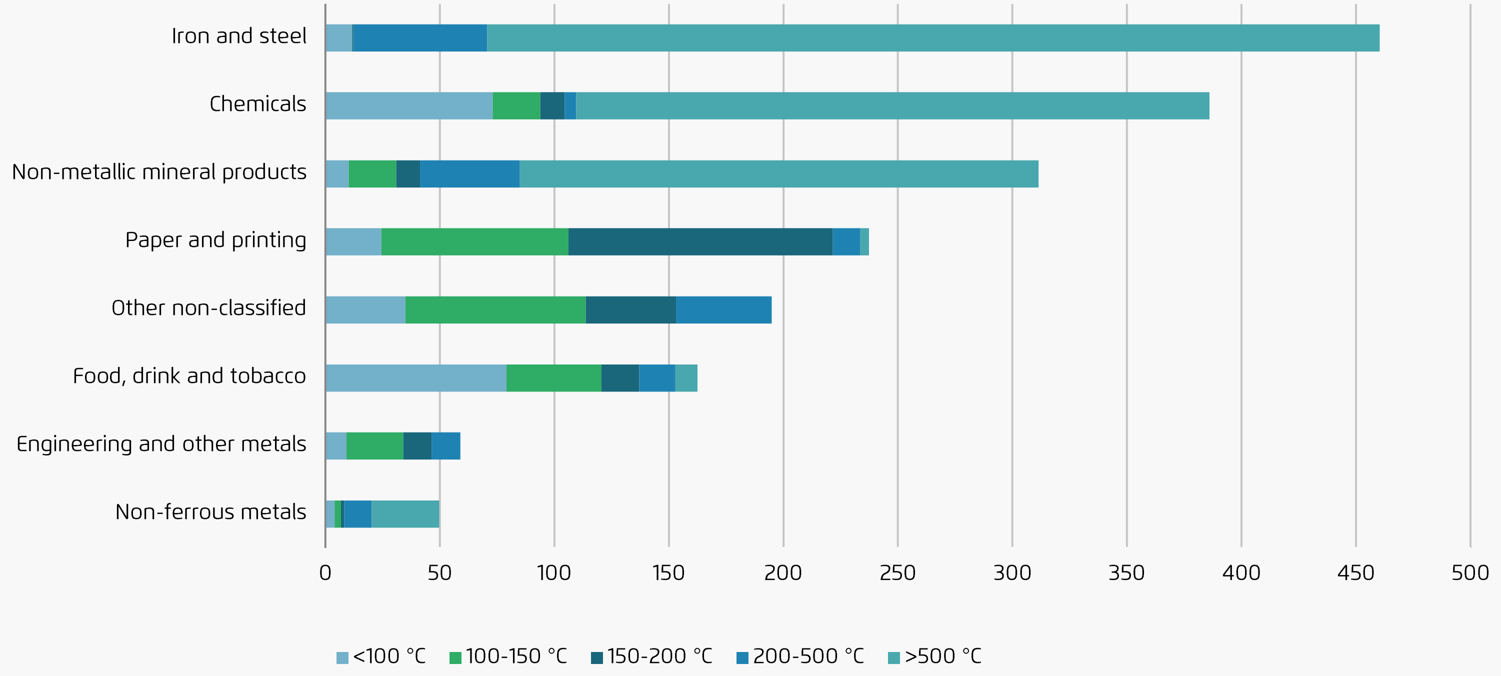


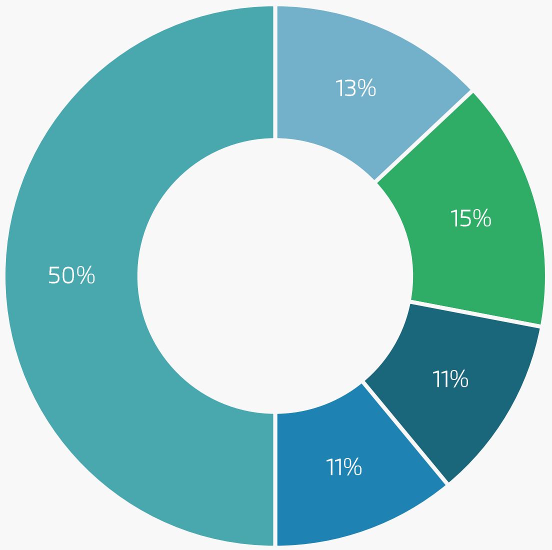
- → **Flexible electricity use** that adapts to production needs can support the expansion of renewables and overall electrification.
- → In periods when the power feed-in from sun and wind is high, flexible consumers can generate **additional loads**.
- → When renewable electricity is scarce, flexible consumers can **reduce loads**.

← Overview

Around 40% of all process heating in the EU needs temperatures of 200 °C or less – which can be supplied by heat pumps

Estimated total final energy demand for process heating in 2019 by temperature and energy carrier in the EU27 countries





← Overview

Fraunhofer ISI (2024): Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU.

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Global markets highlight the shift towards battery-electric passenger cars

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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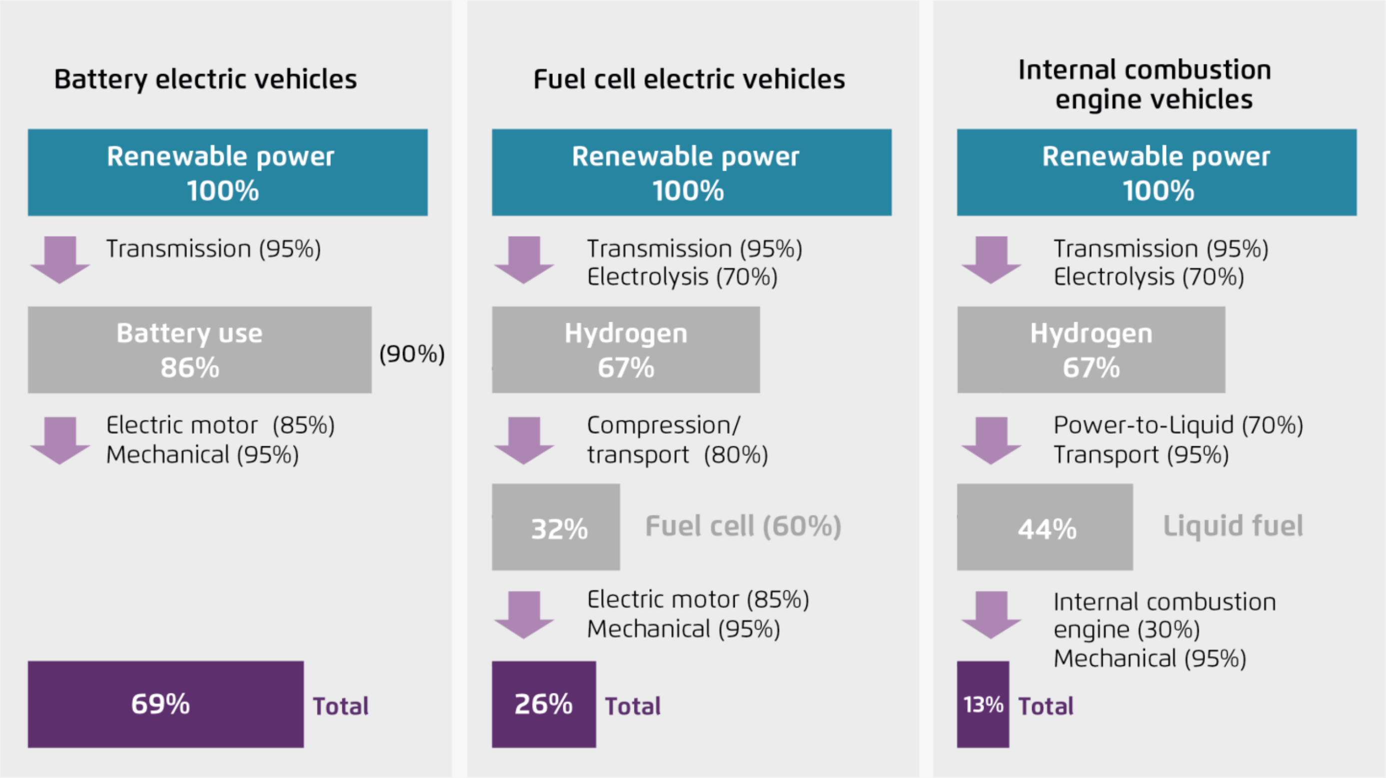
Overview

 Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen

For passenger cars, battery-electric vehicles are the energy efficiency benchmarks

Individual and overall efficiencies for cars with different vehicle drive technologies, based on renewable electricity



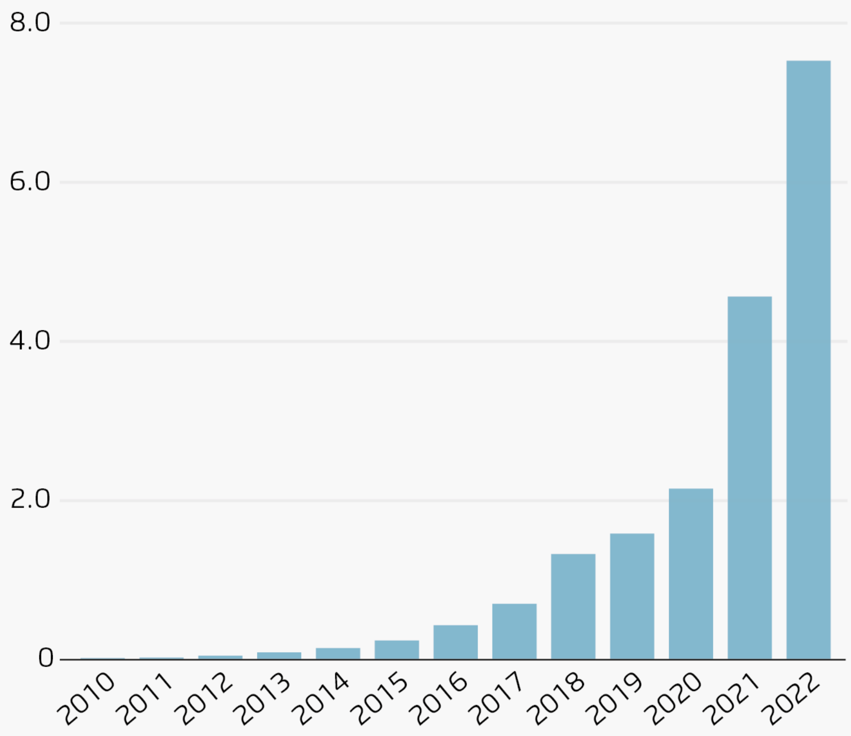
- → To travel the same distance, a **combustion-engine vehicle** powered by a liquid hydrogen derivative would need about **five times as much renewable electricity** as a battery-driven vehicle.
- → A **fuel cell vehicle** needs about two and a half times as much electricity.

← Overview

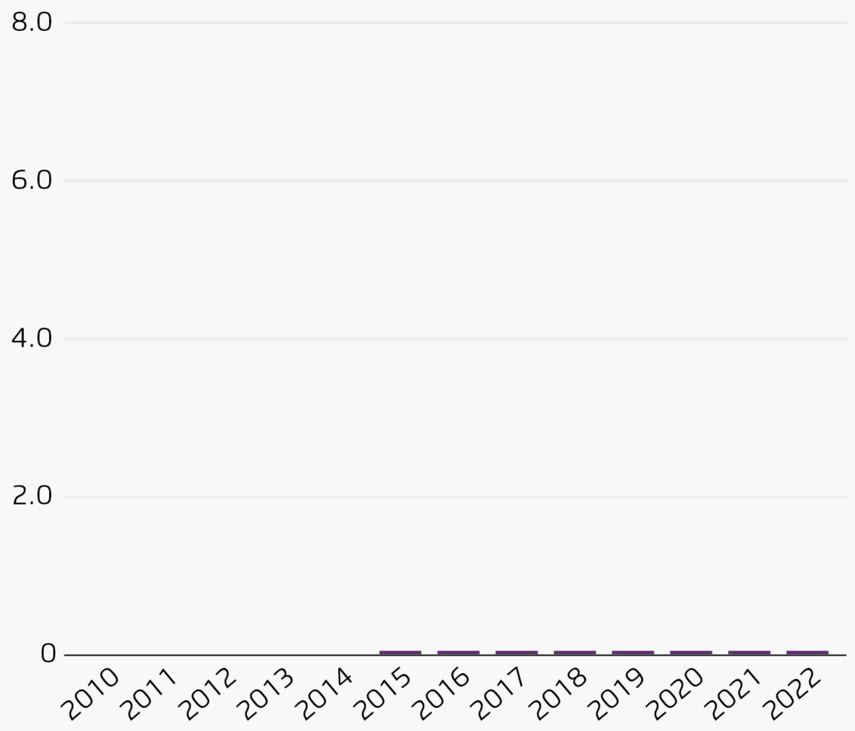
Agora Industry (2023): 9 Insights on Hydrogen - Southeast Asia Edition
Note: Individual efficiencies are indicated in parentheses. Multiplied together, the individual efficiencies yield the overall cumulative efficiencies in the boxes.

Battery-electric versus fuel cell electric vehicle annual sales globally (passenger vehicles)

Battery-electric vehicles (BEV)
[millions]



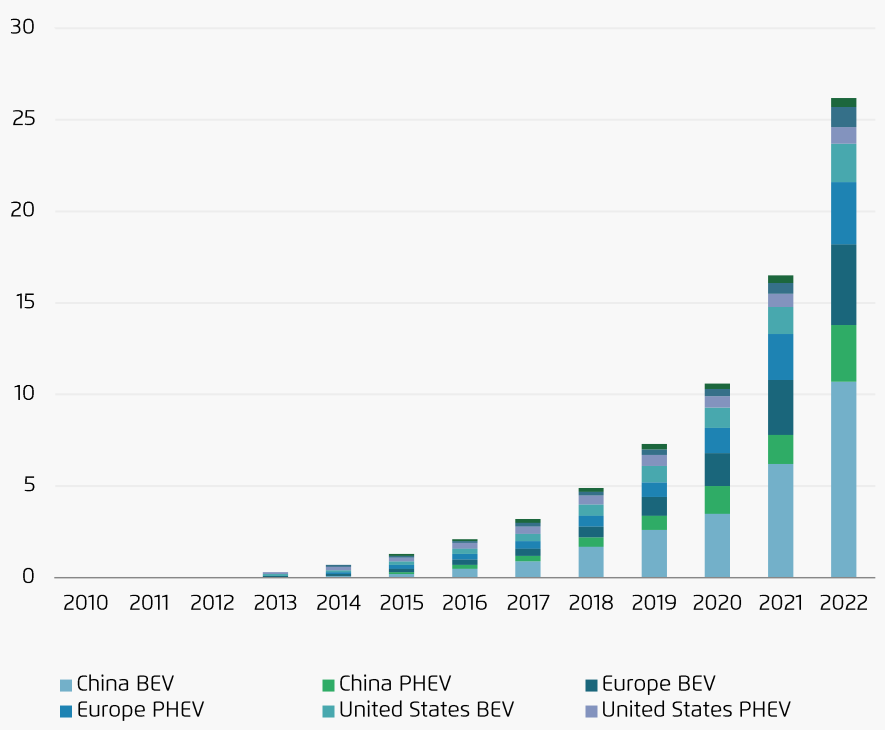
Fuel cell electric vehicles (FCEV)
[millions]



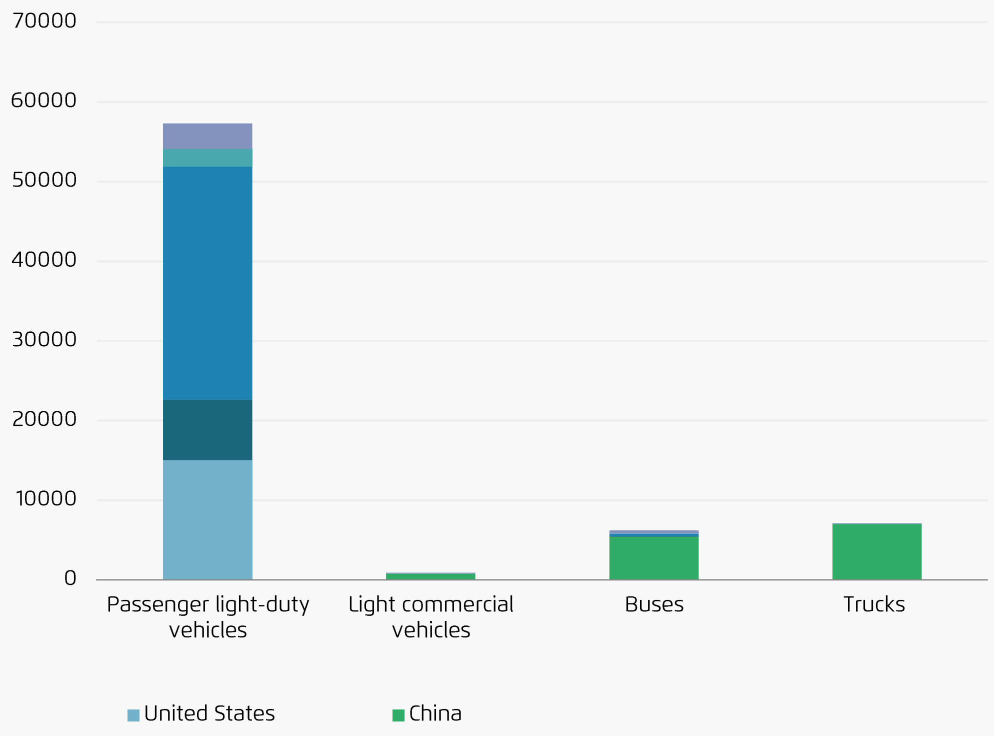
← Overview

Global stock of battery-electric vehicles vs fuel cell electric vehicles: millions versus thousands

Global electric vehicle stock 2010–2022 [millions]



Fuel cell electric vehicle stock 2022 [thousands]



← Overview

Building-level heating happens at low temperatures around 20 °C, for which heat pumps or – where applicable – heat grids are more suitable

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
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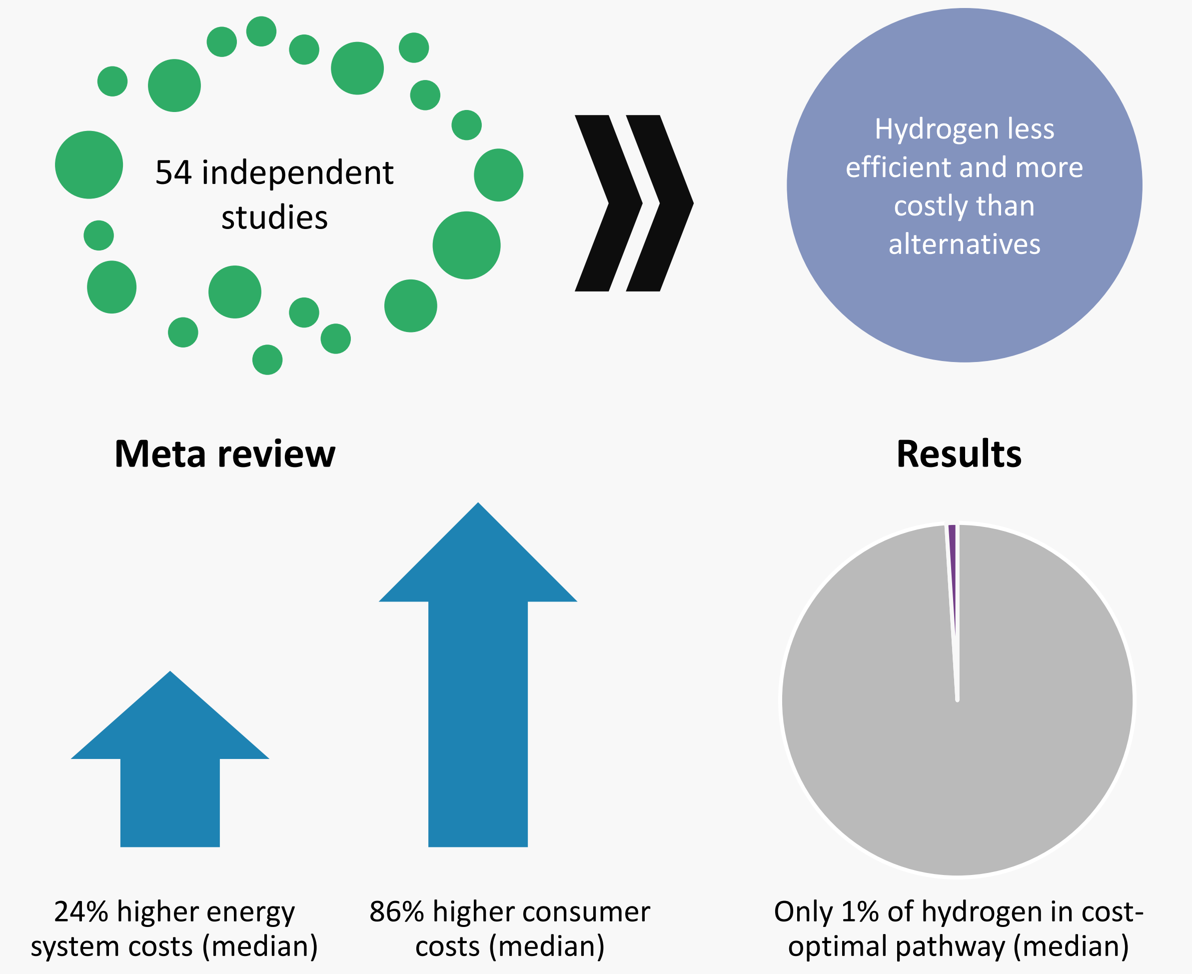
← Overview

 Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen

Independent studies do not support hydrogen for heating

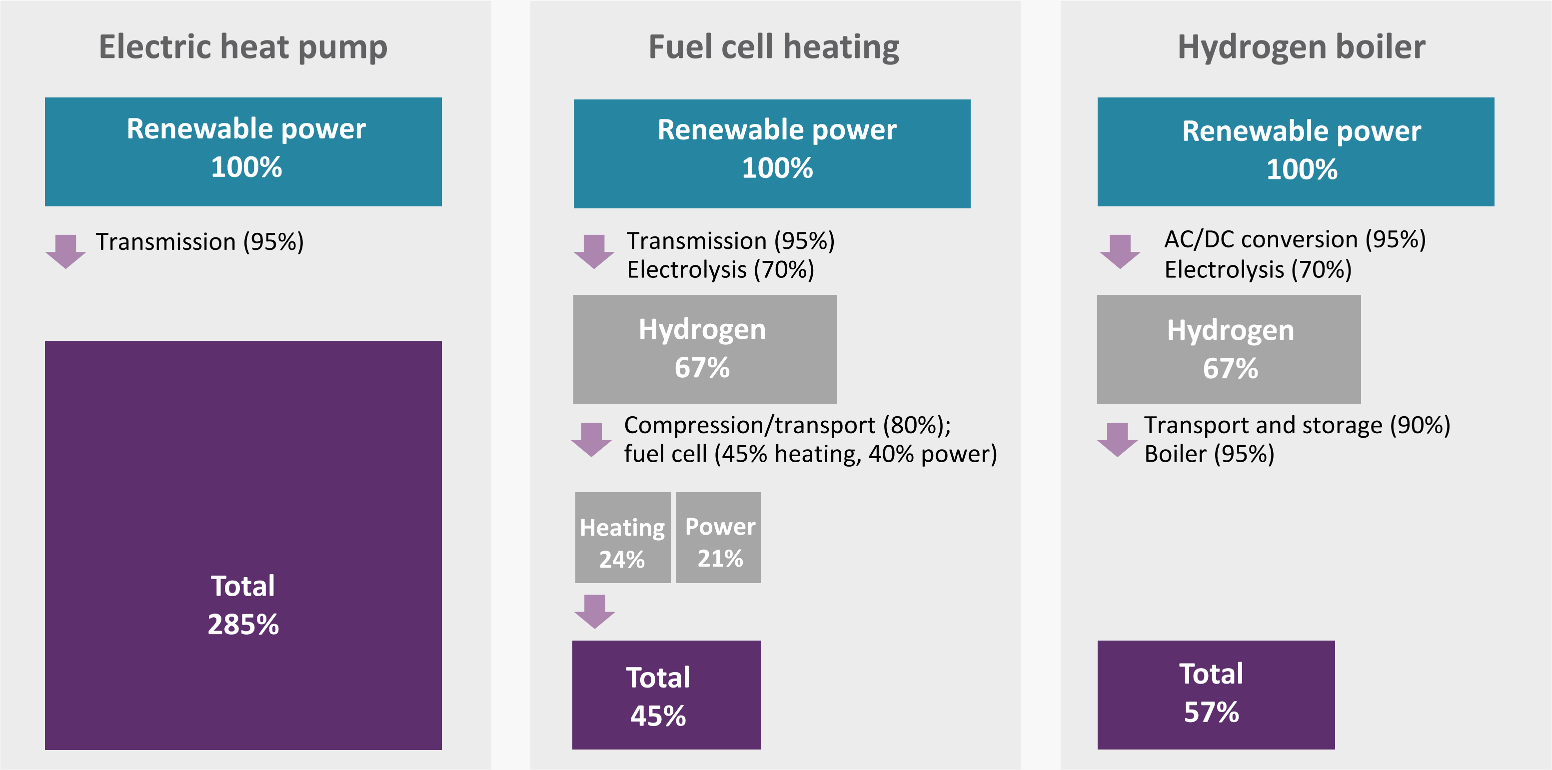


- → No independent studies support heating with hydrogen at scale.
- → Median of **consumer cost increase** compared to heat pumps and district heating is +86%, ranging from 27% to 670%.
- → The median of all studies for the **share of hydrogen** in future scenarios is 1% with a range of 0–10%.
- → This suggests that there may be a very **limited role for hydrogen for heating** but only as a complementary technology, with the bulk of heating provided by other means.

← Overview

Heat pumps make particularly efficient use of renewable electricity

Individual and overall efficiencies for different heating systems, starting from renewable electricity



The electric heat pump withdraws more **energy from the environment** (air, soil or water) than required in terms of operational power, which is why it can have an efficiency rating over 100%.

← Overview

Agora Energiewende and Agora Verkehrswende (2018): The Future Cost of Electricity-Based Synthetic Fuels;
Agora Energiewende, Agora Industry (2021): 12 Insights on Hydrogen. Note: The efficiency of electrolysis was adjusted to 70% for consistency reasons. Individual efficiencies are indicated in parentheses. Multiplied together, the individual efficiencies yield the overall cumulative efficiencies in the boxes. For heat pumps, we have assumed an annual performance factor of 3.

Policy should prioritise no-regret applications of hydrogen and derivatives with no/limited alternative pathways to achieve climate neutrality

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Bad idea	- Low-temperature heat	- Cars - Light-duty vehicles - Two- and three-wheelers	–	- Building-level heating

← Overview

Agora Energiewende and Agora Industry (2024): 9 Insights on Hydrogen – Southeast Asia Edition, based on Agora Energiewende and Agora Industry (2021): 12 Insights on Hydrogen;
[1] Hydrogen may also be used as a reaction agent and/or feedstock in bio-refineries. [2] After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector. [3] Series production currently more advanced on electric than on H_2 for heavy duty vehicles and buses. H_2 heavy duty to be deployed at this point in time only in locations with synergies (ports, mines, industry clusters),[4] depending on distance, frequency and energy supply options.

Imprint

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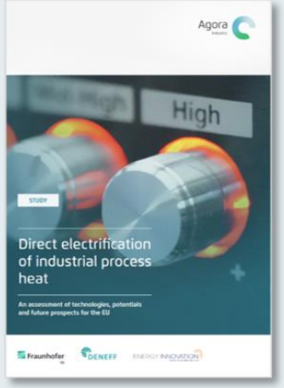
Publications and tools on electrons and molecules by Agora Industry

Electrons

Power-2-Heat
[Impulse]



Direct electri-fication of industrial process heat
[Study]

EU map with production cost of electrons and molecules
[Tool]

Molecules

Low-carbon hydrogen in the EU
[Impulse]

Hydrogen imports to Germany
[Study (DE)]

Insights on hydrogen (publication series)
[Global (EN)],
[Argentina (ES)],
[Brasil (PT)],
[SEA (EN)],
[Tool]

Industrial value chain trans-formation
[Impulse]
[PtX cost tool]

Global Green Fertiliser Tracker
[Tool]

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