Modules prepared by the
International PtX Hub Berlin

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of the Federal Republic of Germany

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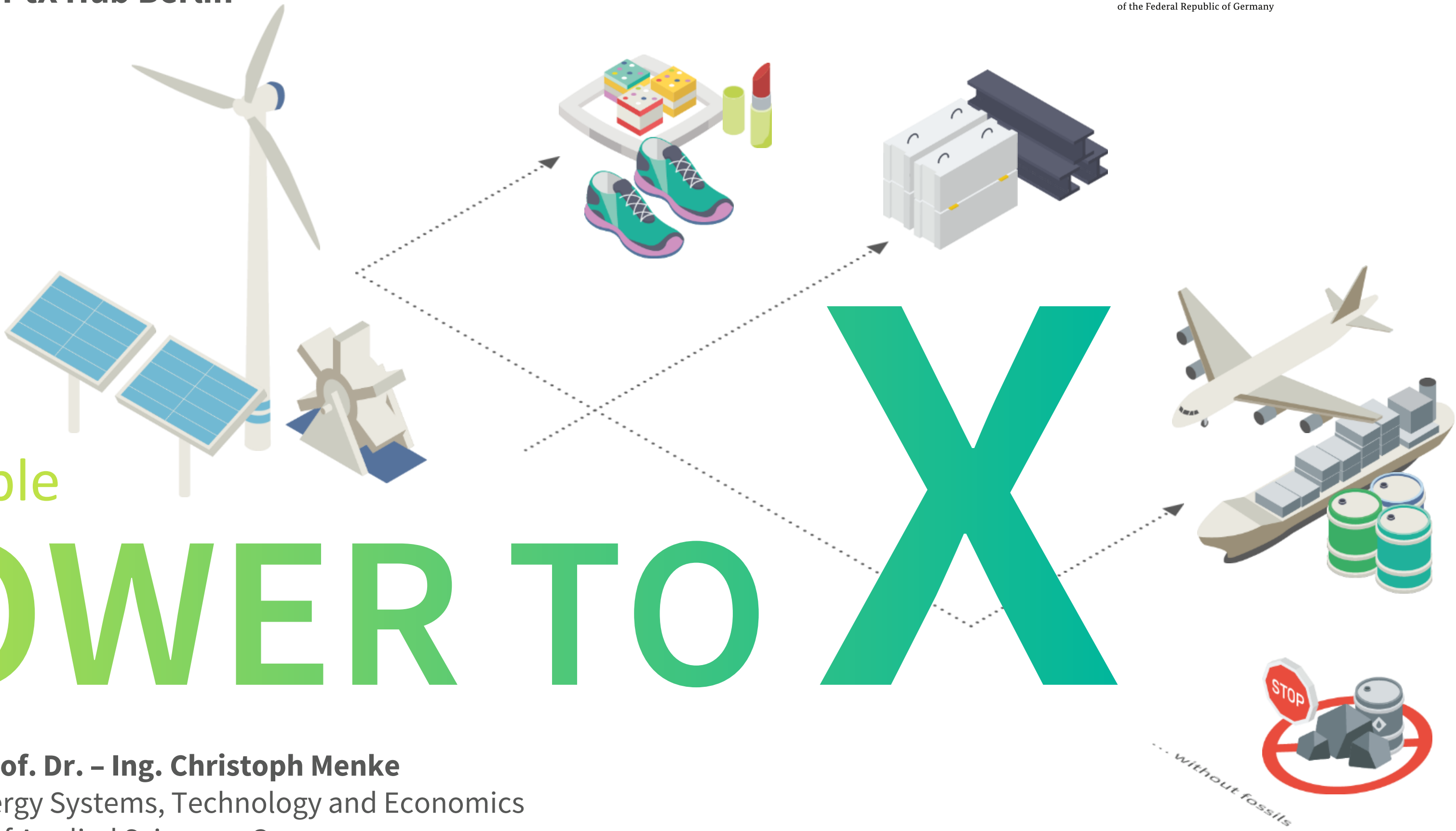

Renewable POWER TO X

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Trier University of Applied Sciences, Germany
Senior Energy Consultant

List of abbreviations

- **CAPEX**: Capital cost expenditures
- **CCfD**: Carbon contracts for difference
- **CCS**: Carbon Capture and Storage
- **DAC**: Direct Air Capture
- **FLH**: Full-load hours
- **GW**: Gigawatt
- **HVDC**: High voltage, direct current
- **LCOE**: Levelised cost of electricity
- **LOHC**: Liquid organic hydrogen carrier
- **LHV**: Lower heat value
- **OPEX**: Operating cost expenditures
- **PEM**: Proton Exchange Membrane
- **PtX / PtL / PtG**: Power-to-X / -Liquid / -Gas
- **PV**: Photovoltaic
- **RE**: Renewable Energy/ies
- **RES**: Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR**: Steam methane reforming
- **SOEC**: Solid Oxide Electrolyser Cell
- **TWh**: Terawatt hours
- **WACC**: Weighted average cost of capital

Key Conversion Data

- 1 kWh H_2= 3.6 MJ H_2
  1 MWh H_2 = 3.4 MMBTU H_2
  1 MJ H_2 = 0.277 kWh H_2

Conversion

- **kWh and kg H_2**:
  1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
  1 MWh H_2 = 30 t H_2
  1 Mio t H_2 = 33 TWh H_2
- Monetary value per weight or calorific value
- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2

Agenda

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1

Introduction to Renewable PtX
Why are we talking about renewable PtX now?

2

Production of Renewable PtX
What is needed to produce green hydrogen and PtX?

3

Renewable PtX Economics
How will the cost of renewable PtX and RE develop? What are the parameters to lower it?

4

PtX Infrastructure
How to transport and store hydrogen best?

5

Markets for Renewable PtX
How to determine where to start a PtX market in your country?

6

Sustainability Criteria for Renewable PtX
Which sustainability criteria will be applied for renewable PtX? Why are they so important?

7

Support Policies and Regulations for Renewable PtX
What policies and regulations are useful and necessary to start your national strategy? How to ramp up the market and business?

Module 1

Introduction

Energy Storage vs. Energy Source
- The Paris Delta
- Supporting pillars of the energy transition

Power-to-X (PtX)
- The concept behind hydrogen
- Sustainable carbon

Energy Efficiency and Electrification
- Efficiency and sufficiency
- Energy demand predictions

PtX Value Chain and Projects

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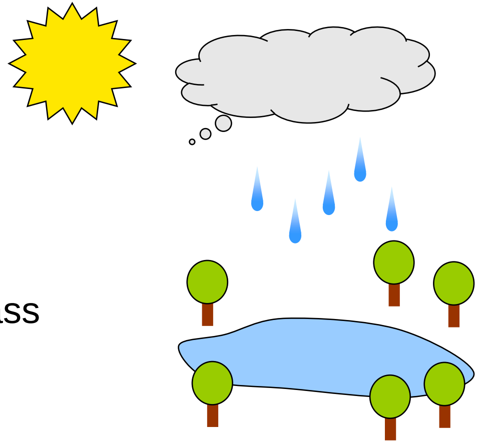
Mankind’s tragical misconception of energy sources

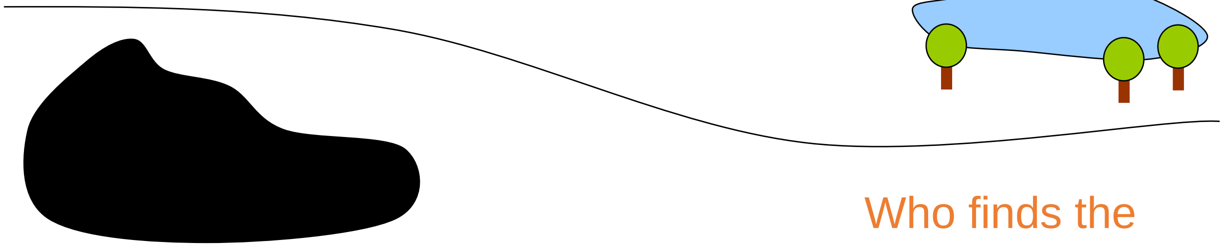
Fossil Energy Sources

Oil
Gas
Lignite
Coal

Renewable Energy Sources



Sun
Wind
Water
Biomass



Who finds the big mistake?

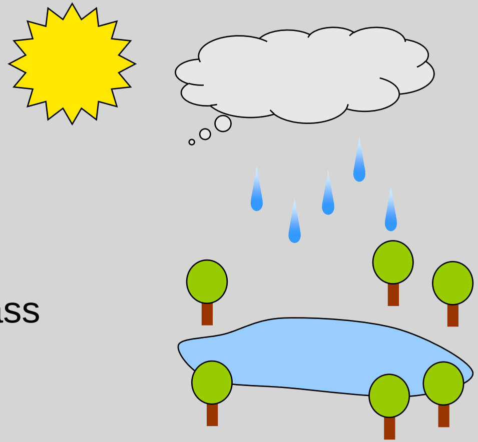
Mankind's tragical misconception of energy sources

Fossil
Energy ~~Sources~~
Storage

Oil
Gas
Lignite
Coal

Renewable
Energy Sources

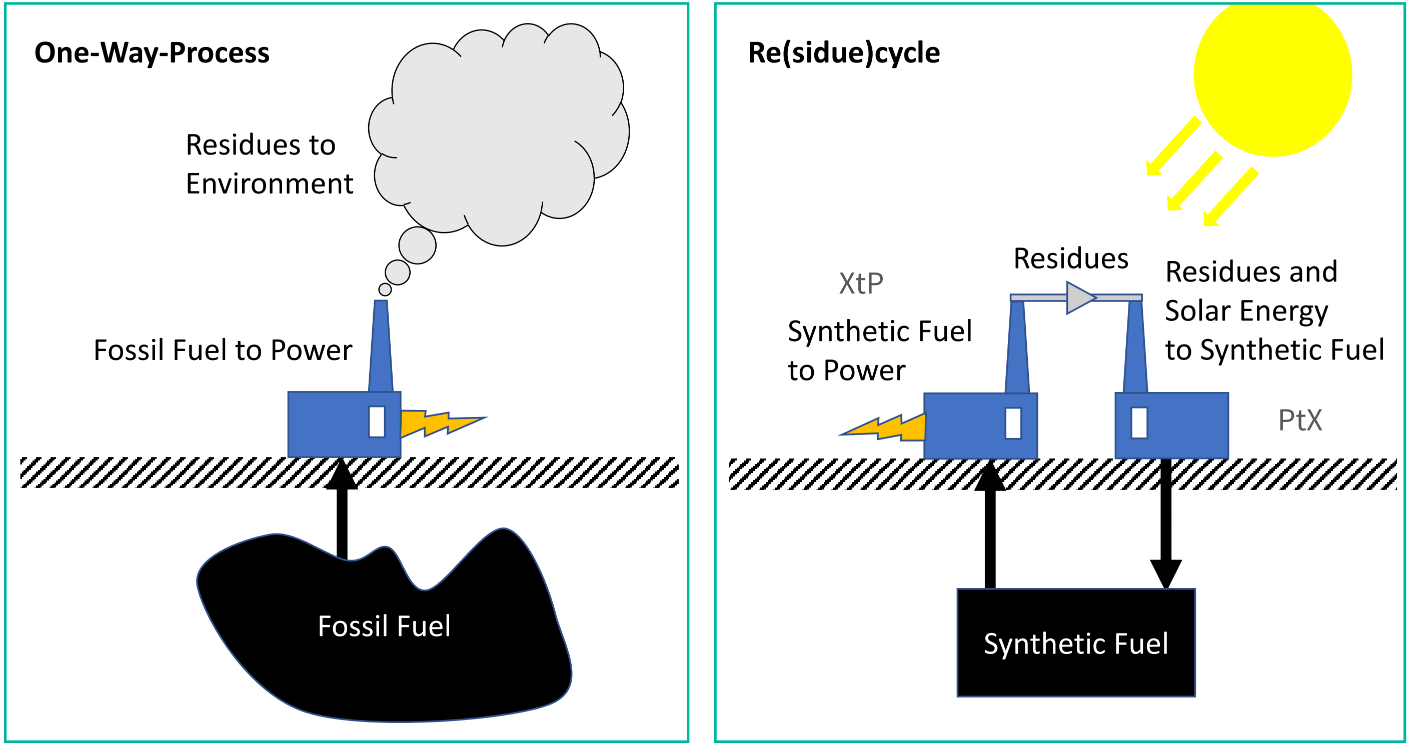
Sun
Wind
Water
Biomass



500 years later

Who finds the big mistake?

Recycling energy commodities
=> Need to move to "Re(sidue)cycling of energy and materials"



Power-to-X: The concept beyond hydrogen

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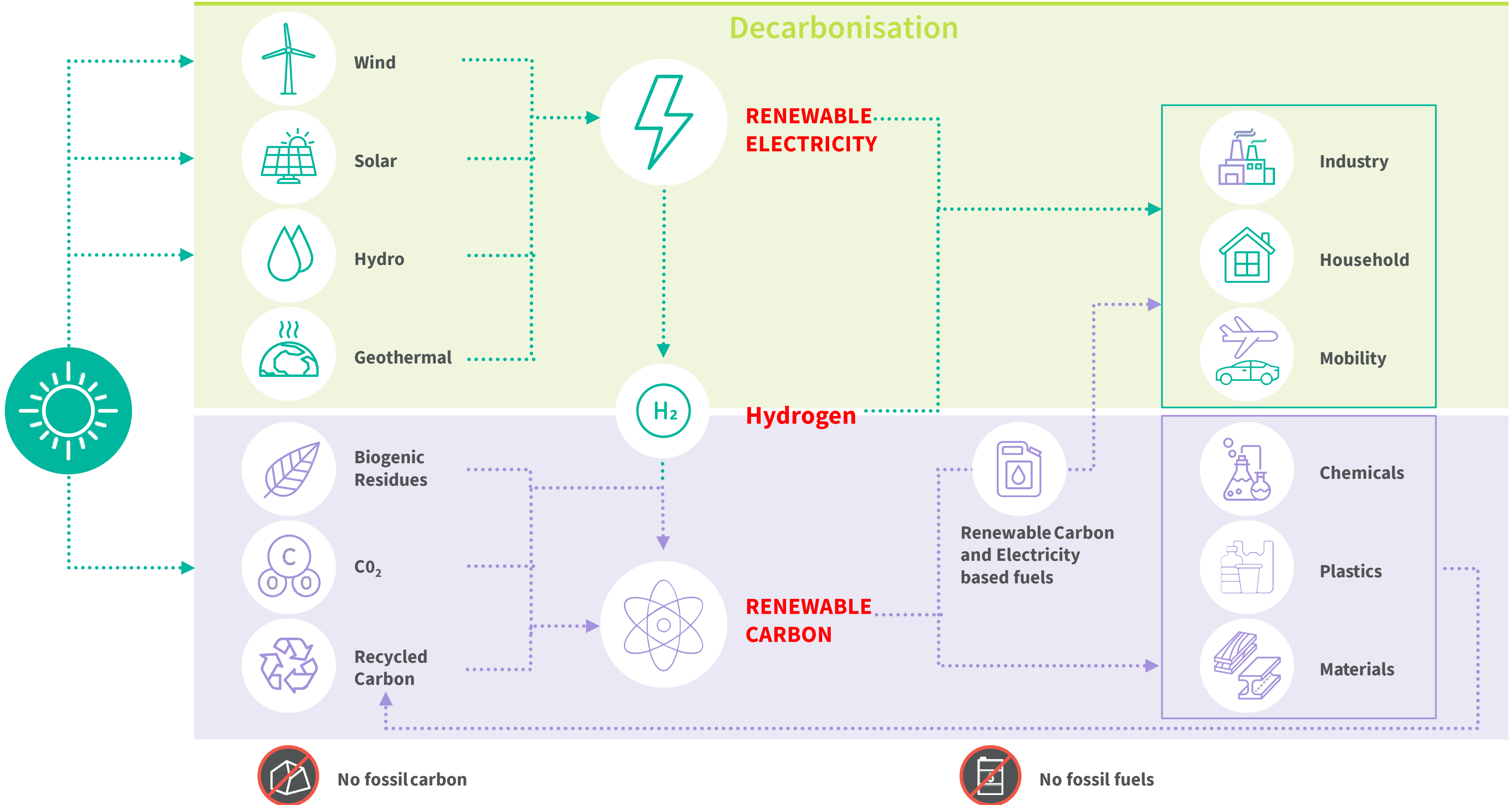
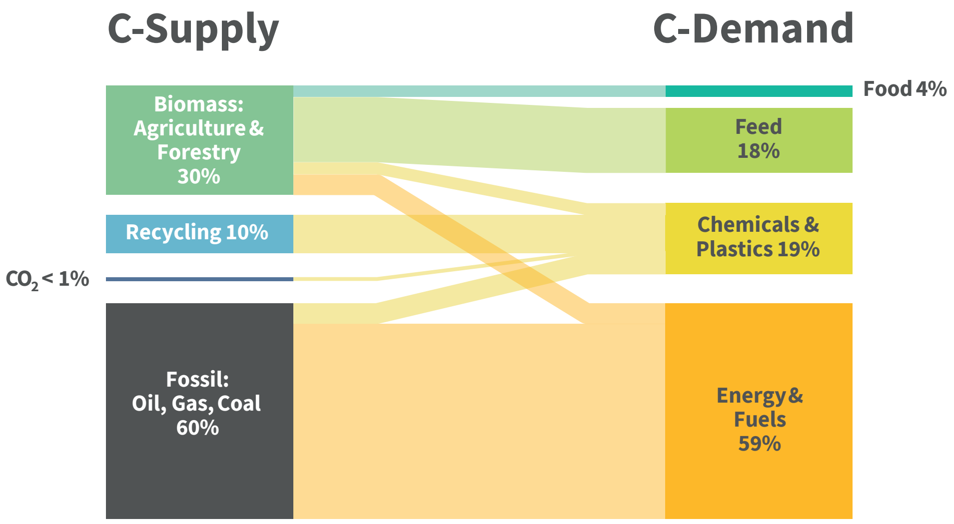


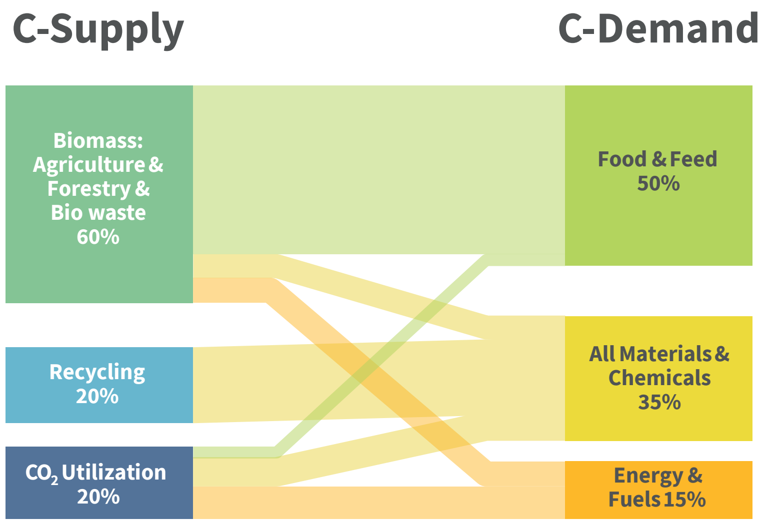
Based on nova-Institut 2020 (nova-Paper #12 on renewable carbon 2020-09)

Power-to-X: focusing on the right element: Carbon

World C-flows today



World C-flows 2050 electric mobility + no fossil



Based on nova-Institut 2020 (nova-Paper #12 on renewable carbon 2020-09)

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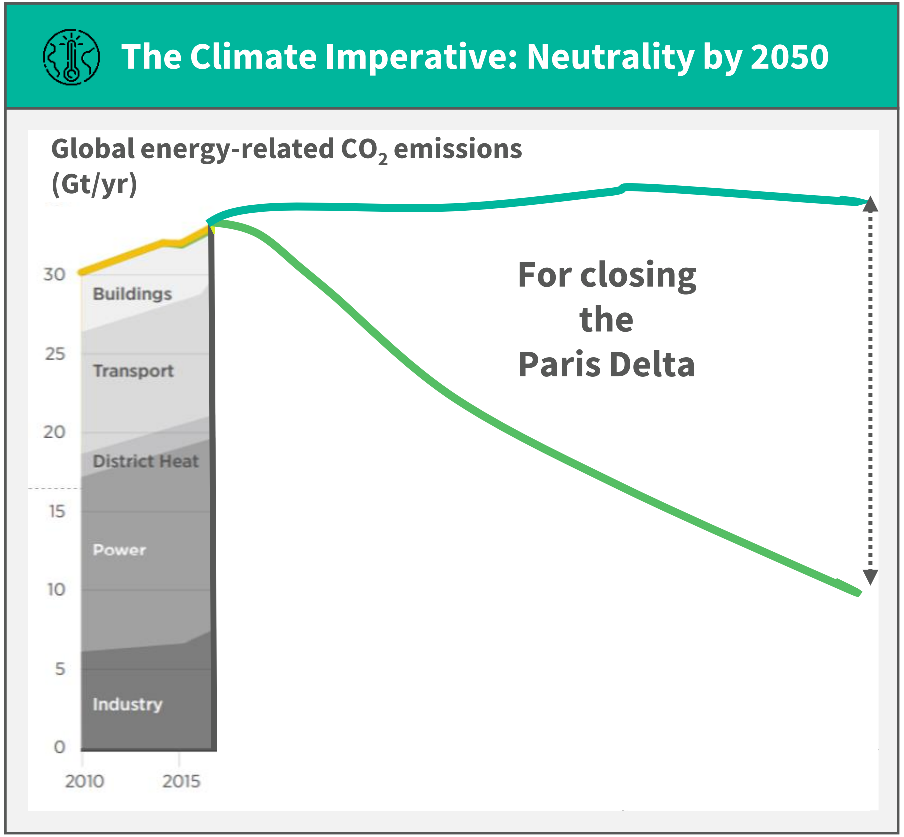
How to close the Paris Delta



… and remaining loop-holes?

We need:

ENERGY EFFICIENCY

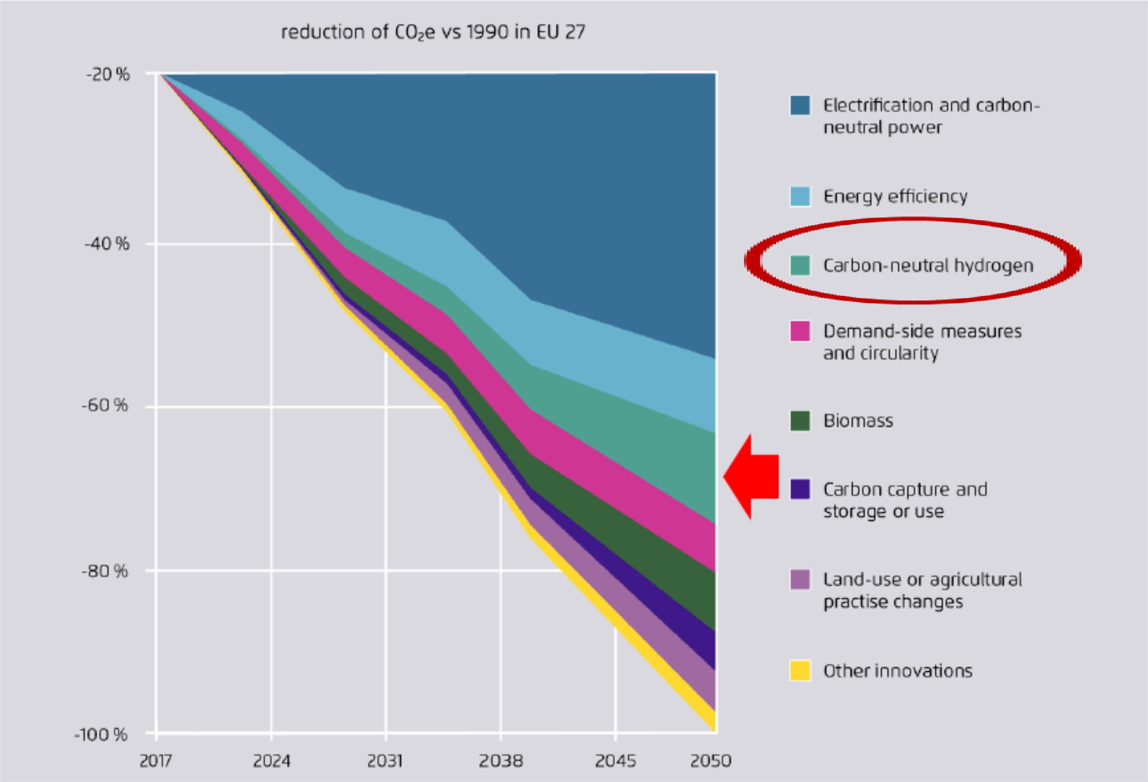
RENEWABLE ENERGY

ELECTRIFICATION

POWER-TO-X

Source: International Renewable Energy Agency Hydrogen From Renewable Power Technology Outlook For The Energy Transition, 2018, p.10/1.

Share of GHG abatement in the EU by mitigation measures



→ Carbon-neutral hydrogen is 3rd largest component in achieving carbon neutrality by 2050!

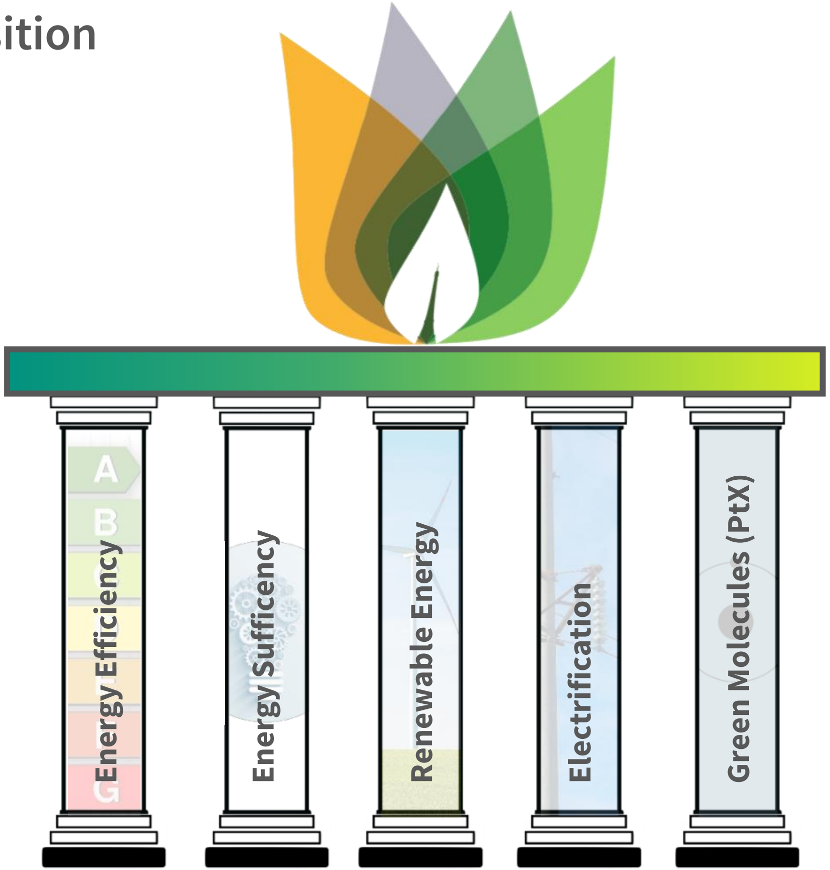
Source: Agora Energiewende, Agora Industry (2021): 12 Insights on Hydrogen

The supporting pillars of the energy transition

Sufficiency and energy efficiency is a mandatory start

Considering the total demand, for the rest of the energy demand:

- Renewable energy and its use in further **electrification of demand**
- For **hard to abate sectors: PtX (incl. green H_2)**



Energy efficiency comes first, then electrification of demand

For example for mobility by cars

Battery-electric vehicles

Renewable Power 100%

Transmission (95%)

Battery use 86%

Electric motor (85%)
Mechanical (95%)

69% Total

Fuel cell vehicles with H_2

Renewable Power 100%

Transmission (95%)
Electrolysis (70%)

Hydrogen 67%

Compression / transport (80%)

32% **Fuel cell 60%**

E-motor (85%)
Mechanical (95%)

26% Total

Internal combustion engine vehicles with PtL from H_2

Renewable Power 100%

Transmission (95%)
Electrolysis (70%)

Hydrogen 67%

PtL (70%)
Transport (95%)

44% **Liquid fuel**

Internal combustion engine (30 %), Mechanical (95 %)

13% Total

Source: (illustration adapted) Agora Verkehrswende, Agora Energiewende and Frontier Economics, The Future Cost of Electricity-Based Synthetic Fuels, 2018, p.12/fig.2.

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Energy content per unit **volume**

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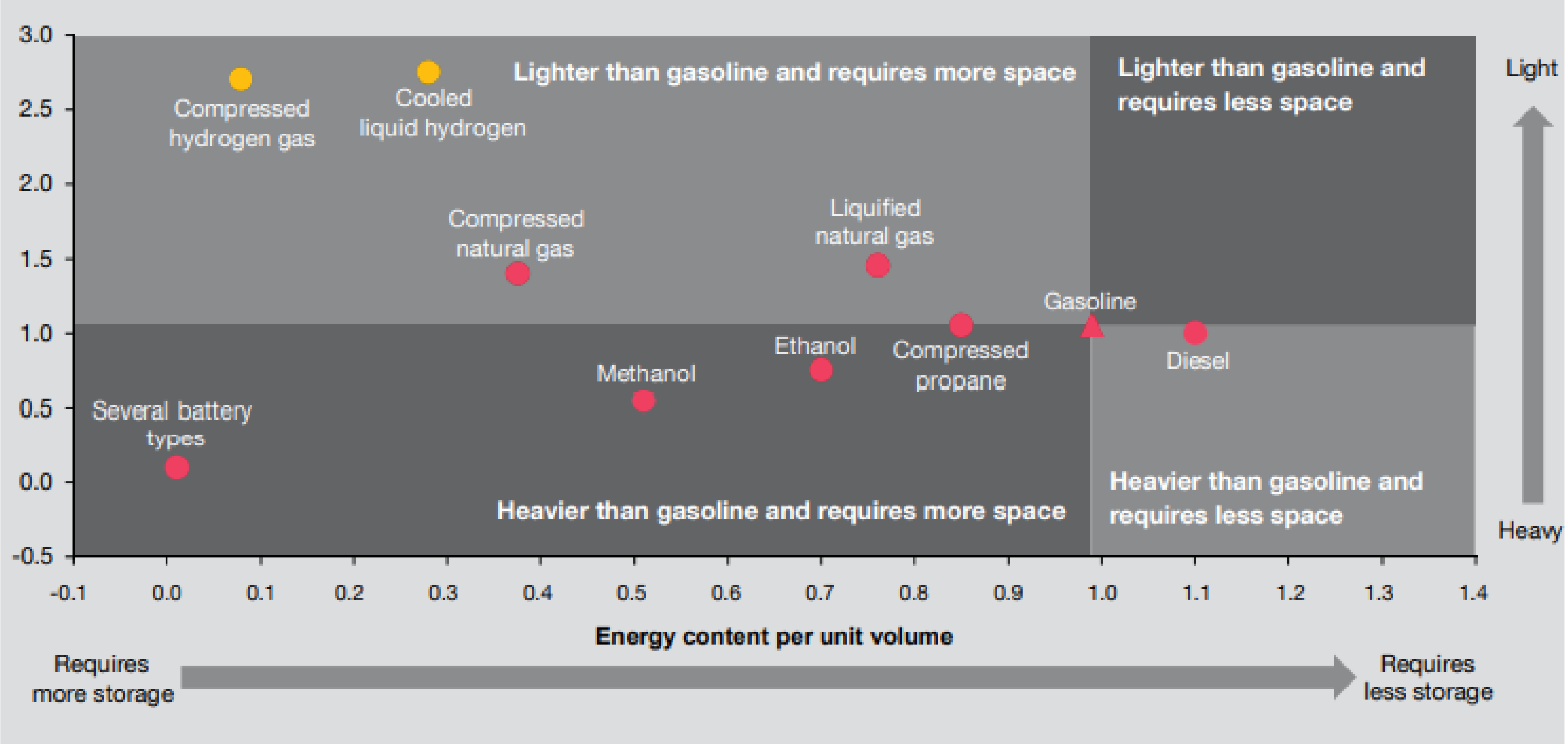
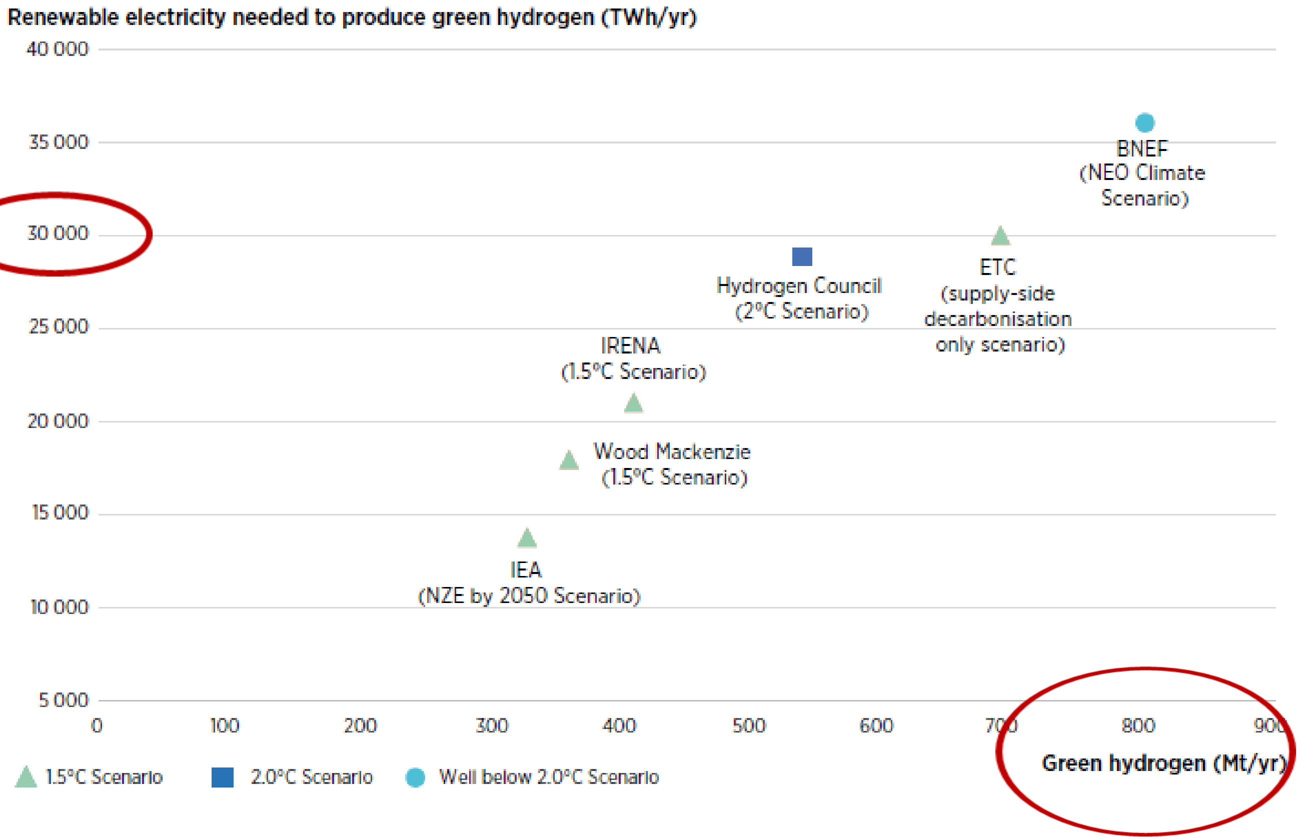


Source: strategy&, Unlocking South Africa’s Hydrogen Potential, 10/2020, p.6/exhibit 2.

Global demand for renewable electricity to produce green hydrogen by 2050



Compare:
In 2021 around 8,000 TWh renewable electricity were produced word wide

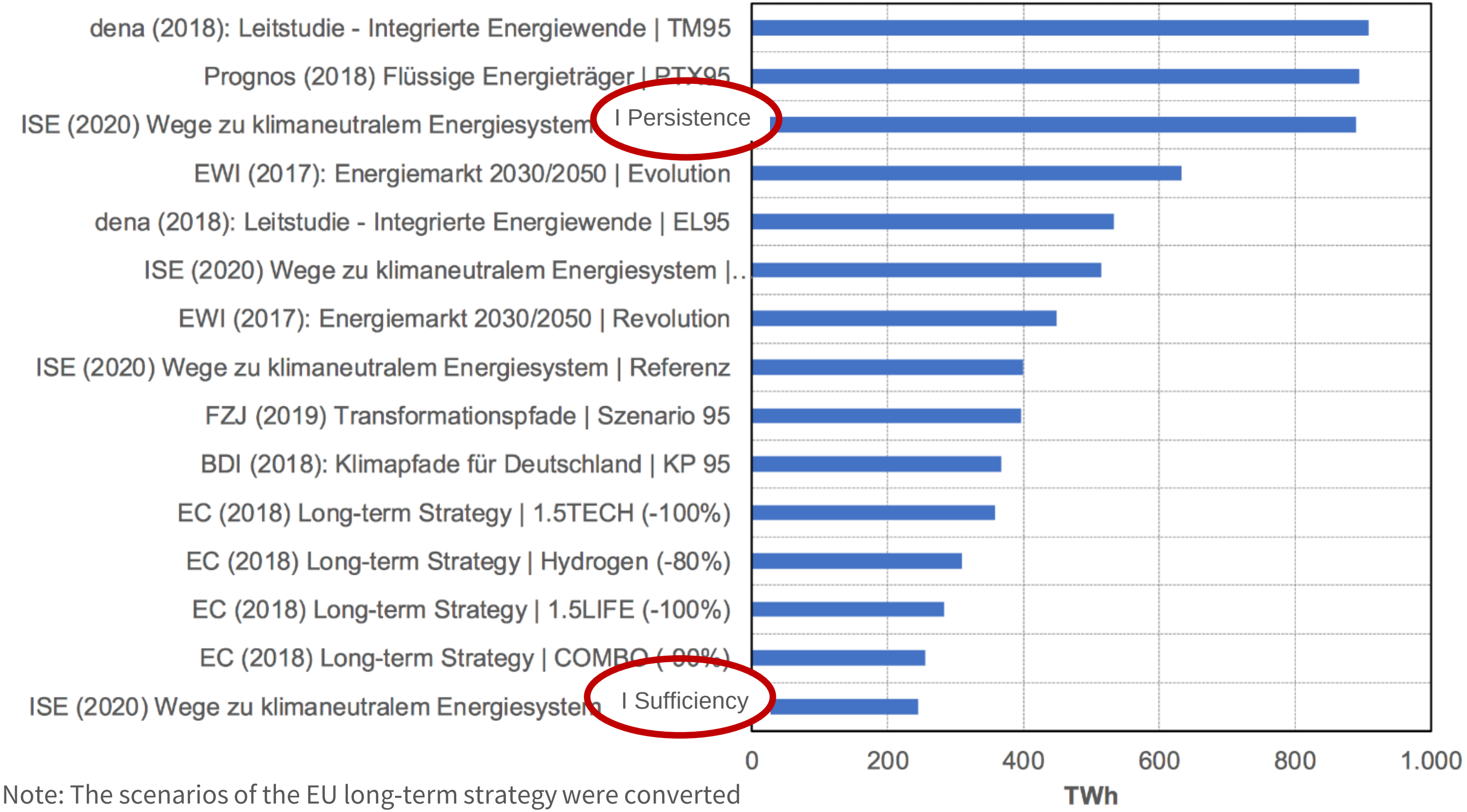
- **PV around 1,000 TWh/a**
- **Wind around 2,000 TWh/a of that amount.**

Source: IEA: Global energy review 2021

Note: The ETC supply-side decarbonisation only scenario is an illustrative scenario considering 2050 final energy demand without application of energy productivity levers. This scenario assumes green hydrogen will make up 85% of total hydrogen production in 2050.

Source: IRENA Coalition for Action, Decarbonising end-use sectors: Practical insights on green hydrogen, 2021, p.11/fig.2.

PtX demand in Germany in 2050 depends on our behavior!



Note: The scenarios of the EU long-term strategy were converted with a 20% share of Germany in the values for the EU-28.

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Source: Öko-Institut e.V., Wasserstoff und wasserstoffbasierte Energieträger bzw. Rohstoffe, 2020, p.80/3-1.

Additional renewable energy capacity to cover oil demand in Germany by PtX?

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Electricity demand and necessary capacity expansion of renewable electricity generation at different efficiency levels of the production of liquid synthetic hydrocarbons in Germany.

		Efficiency 48% (today)			Efficiency 57% (long-term)		
	C_xH_y-Production	Electricity Demand	Full load hours	Capacity expansion	Electricity Demand	Full load hours	Capacity expansion
	TWh	TWh	h/a	GW	TWh	h/a	GW
Wind-Onshore	100	208	1.936	108	175	1.936	91
Wind-Offshore	100	208	4.032	52	175	4.032	44
PV	100	208	903	231	175	903	194

Note: Data on production of synthetic hydrocarbons and efficiency related to the lower heating value of the synthetic hydrocarbons.

In Germany, approx. 100 million tons of mineral oil were used in 2019 → 1,163 TWh CxHy.

If we want to cover this with synthetic crude, the demand for RE electricity would be the last column **11-fold**.

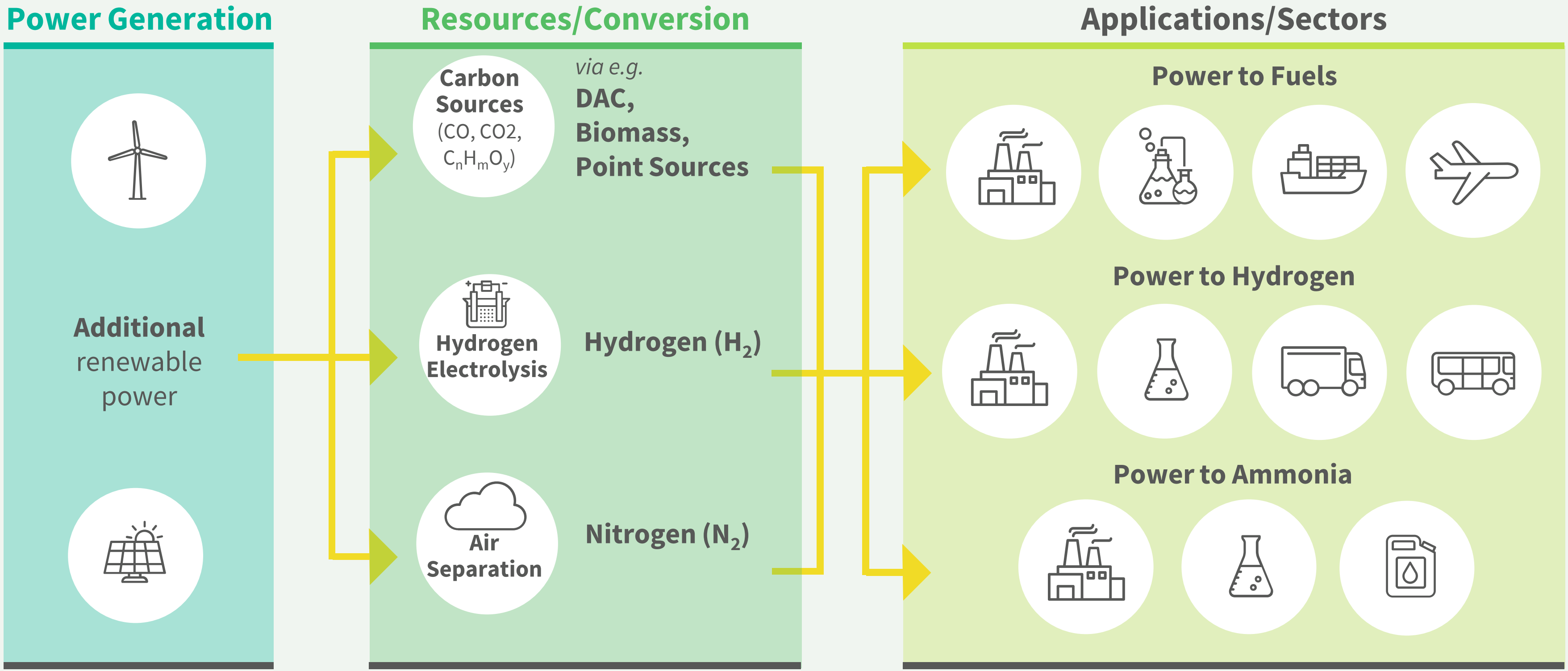
We need either:

- **1,000 GW on-shore wind,**
- **500 GW off-shore wind *or***
- **2,200 GW PV**

to satisfy German Oil demand

Source: Öko-Institut e.V., Wasserstoff und wasserstoffbasierte Energieträger bzw. Rohstoffe, 2020, p.64/abb.2-6.

Power-to-X: Steps from renewable energy to feedstock/fuel supply



Source: Own illustration based on: Frontier Economics/Word Energy Council, International aspects of a Power-to-X Roadmap, 2018, p.15/4.

Power-to-X value chain

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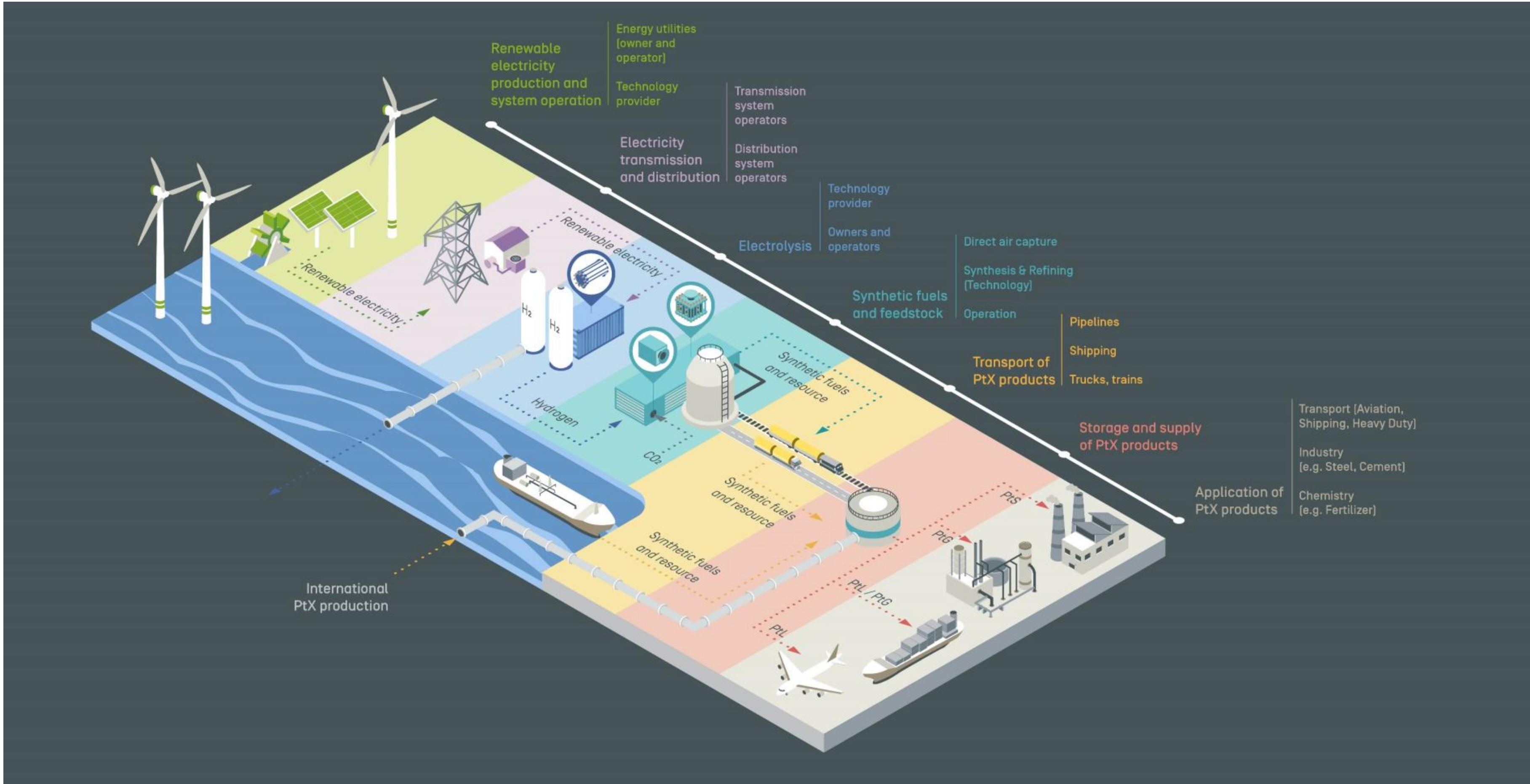

PtX in practice: Westküste100, Germany

Upscaling PtL

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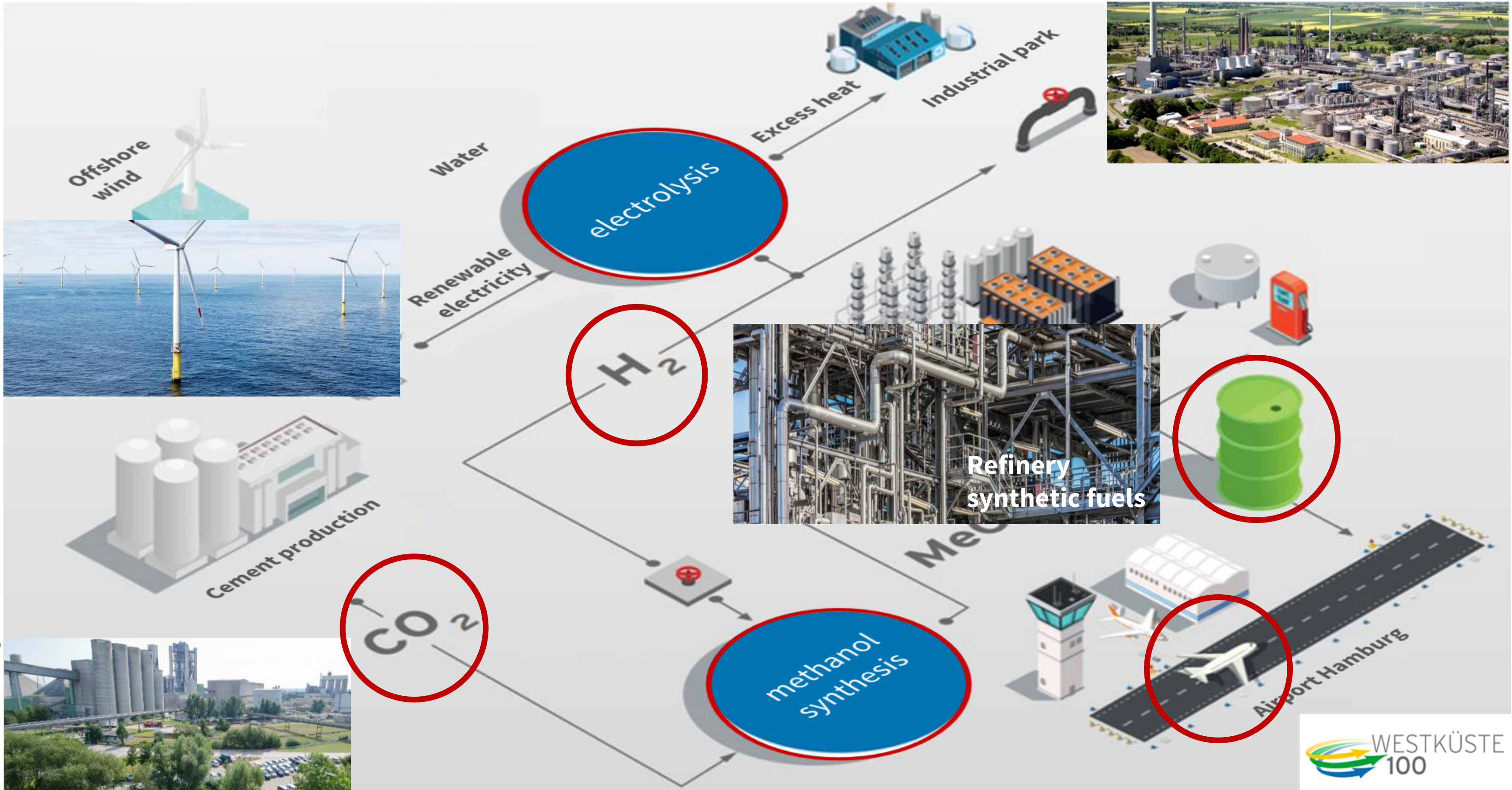

Source: Westküste 100, Grüner Wasserstoff und Dekarbonisierung im industriellen Maßstab, 2020.

Clean hydrogen projects and investment (as of November 2021)

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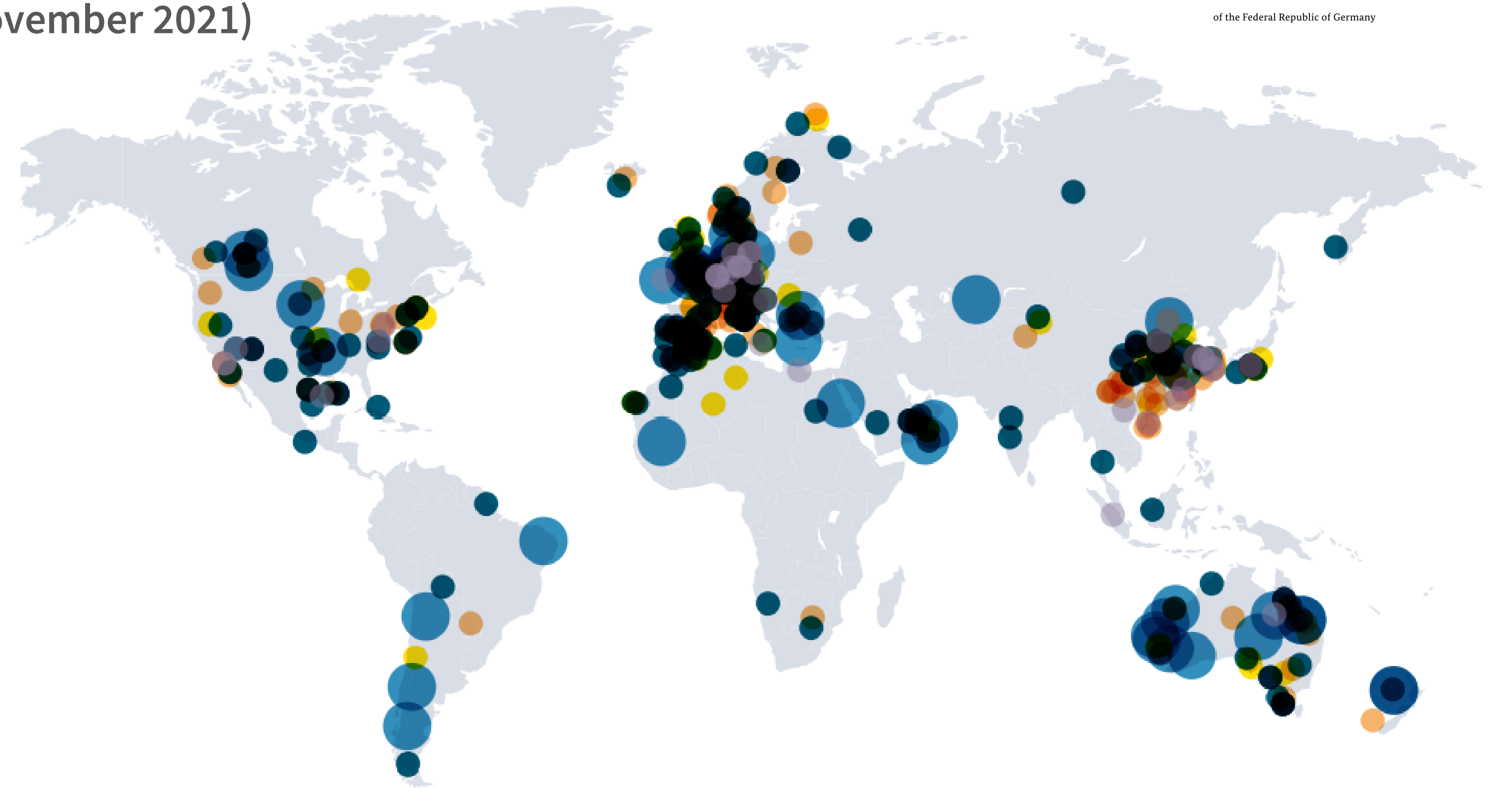


221 large-scale industrial usage
Refinery, ammonia, methanol, steel and industry feedstock

133 transport
Trains, ships, trucks, cars and other hydrogen mobility applications

74 integrated H_2 economy
Cross-industry and projects with different types of end uses

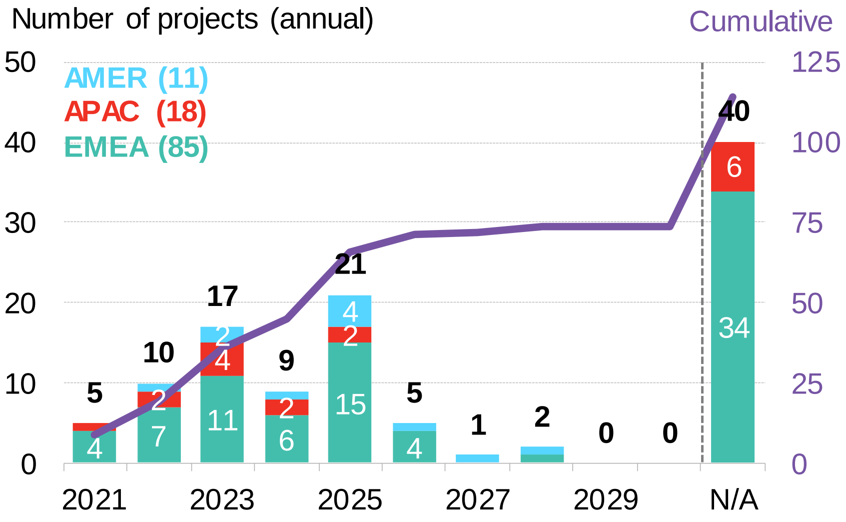
51 infrastructure projects
H_2 distribution, transportation, conversion and storage

43 giga-scale production
Renewable H_2 projects >1 GW and low-carbon H_2 projects > 200 ktpa

Source: IRENA, Geopolitics of the Energy Transformation The Hydrogen Factor, p.42/fig.3.3.

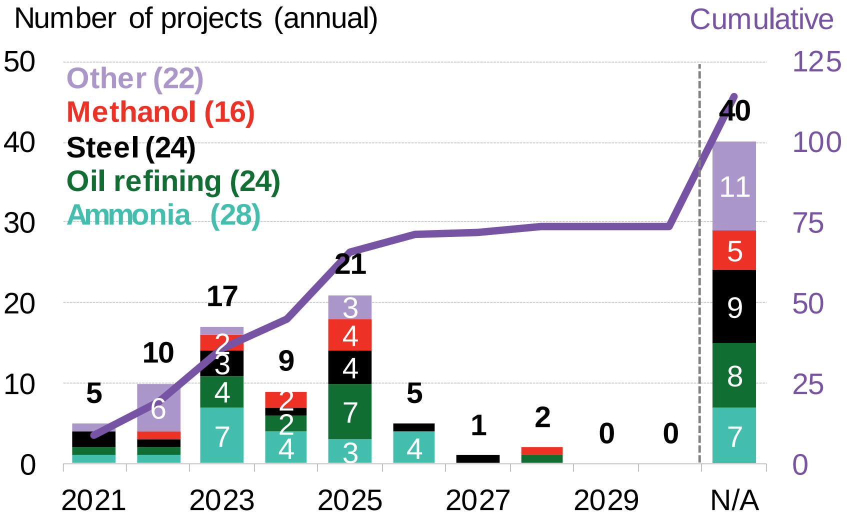
Announced pipeline of industrial hydrogen projects

By region



Source: BloombergNEF

By industry



Source: BloombergNEF

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Summary of introduction

Why do we need PtX?

- Complementary energy carrier to limit global warming < 2°C
- Absolute necessary energy carrier to achieve “climate neutrality” by 2050, especially for indirect electrification of hard to abate sectors
- Enable conversion of renewable electricity into materials and energy carriers (hydrogen, platform chemicals, synthetic fuels etc.)
- Use global RE potential: PtX can be transported and traded globally

Key questions:
Where to start?
Focus on which sectors?

MODULE 1: Key messages

Energy Storage vs. Energy Source

- Fundamental **difference between fossil fuels as energy storage**, being emptied by humans at very fast pace, **and renewables as energy sources. Burning fossil fuels for winning energy is a one-way process**

Power-to-X (PtX)

- **Hydrogen is mainly an energy carrier**, based on renewable energy sources and renewable carbon
- Closing the Paris Delta requires **full decarbonization of energy systems and economies** – for hard to abate sectors renewable PtX as solution, incl. green H2

Energy Efficiency and Electrification

- To use liquid fuels (synthetic fuels) for mobility services rather than using electricity directly, **5x more renewable energy** is needed to provide the same service
- The overall PtX efficiency is low, but **energy efficiency is situationally.**
- PtX is **most suitable for sectors in which direct use of electricity is not (yet) feasible**
- Green Hydrogen and PtX is only **one of five pillars of the whole energy transition**, the other pillars are a precondition for the use of PtX and green hydrogen
- **Global demand** for renewable electricity to produce green hydrogen by 2050 **is very high**

PtX Value Chain and Projects

- PtX refers to the complex conversion from renewable electricity to other forms of energy carriers (PtL, PtG, PtC) and **requires knowledge from up- and downstream markets**, like in oil and gas business

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Test your knowledge

“Where do you see opportunities for PtX in your country?”

“What are the biggest challenges to achieve them?”

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Module 2

Production of Renewable PtX

Hydrogen Production
- Ways of producing H2
- Blue vs. green H2
- Applications of H2

Electrolysis
- Alkaline Electrolyser
- Proton-Exchange-Membrane Electrolyser (PEM)
- Solid Oxide Electrolysis Cell (SOEC)

Carbon Capture
- Sustainable carbon sources
- Direct-Air-Capture (DAC)

PtX product sourcing, production of:
- Green hydrogen
- Methanol
- Green ammonia

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Test your knowledge

"What do you think – how is hydrogen currently being produced around the world?"

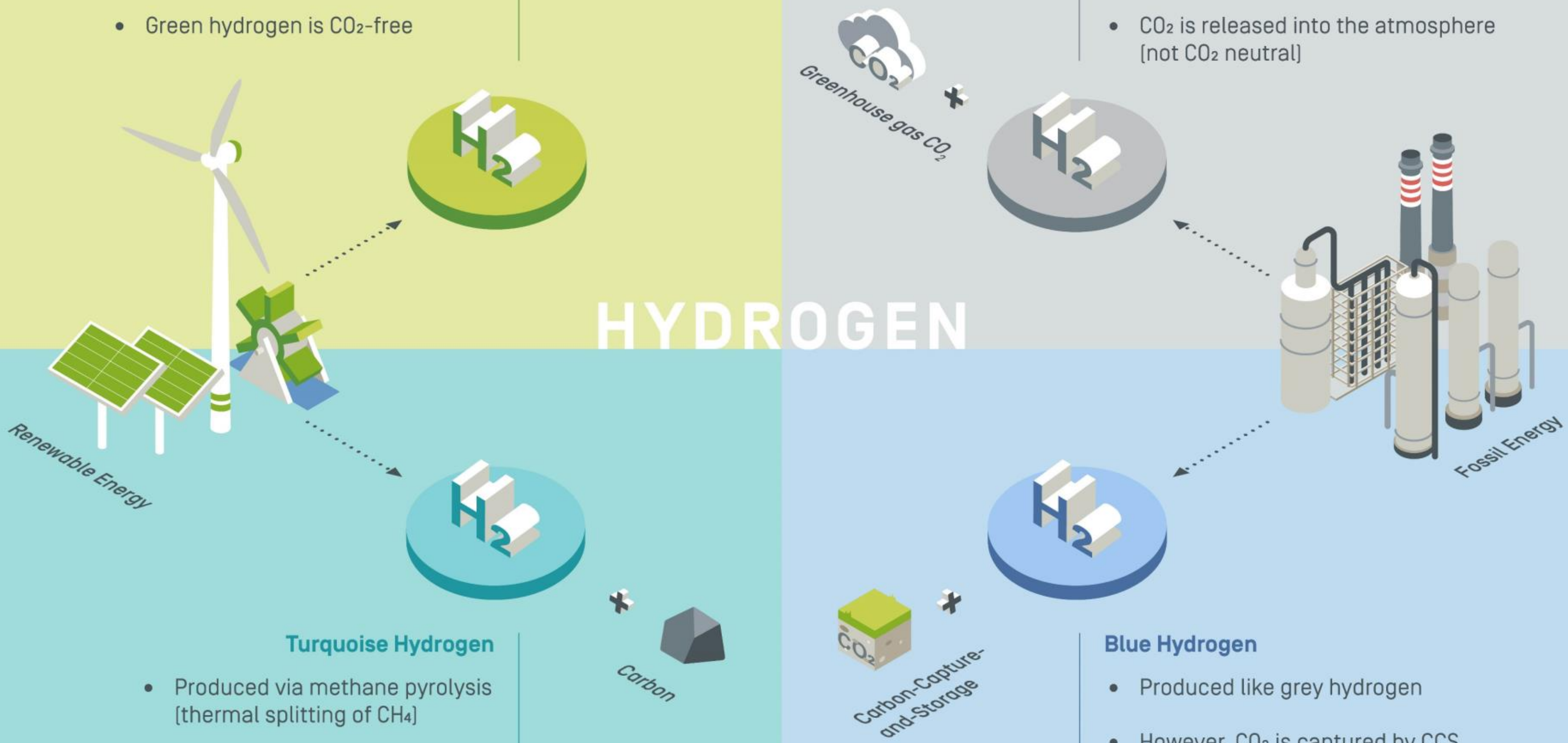
"Which colours of hydrogen do you consider sustainable?"

Green Hydrogen

- Produced via hydrogen electrolysis from renewable energies
- Green hydrogen is CO_2-free

Grey Hydrogen

- Produced from fossil fuels via steam reforming (CH_4 -> H_2 + C)
- CO_2 is released into the atmosphere (not CO_2 neutral)



Turquoise Hydrogen

- Produced via methane pyrolysis (thermal splitting of CH_4)
- CO_2-neutral if heat supply for reactors from RES

Blue Hydrogen

- Produced like grey hydrogen
- However, CO_2 is captured by CCS and stored underground

Options for hydrogen production (colours of H_2)

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Feedstock and energy source		Process of hydrogen production	By-product of the process		Designation of the hydrogen
Water	+E	Electrolysis with nuclear power	Oxygen	+	Pink hydrogen
Water	+E	Electrolysis with electricity mix	Oxygen	+	Yellow hydrogen
Water	+Solar /Wind	Electrolysis	Oxygen	+	Green hydrogen
Water	+Solar /Wind	Thermolysis	Oxygen	+	Green hydrogen
Water	+Solar /Wind	Photolysis	Oxygen	+	Green hydrogen
Biomass	Solid	Gasification	CO_2	+	Green hydrogen**
Biomass	Biogas	Reforming*	CO_2	+	Green hydrogen**
Natural gas/ methane		Pyrolysis	Solid Carbon	+	Turquoise hydrogen
Natural gas/ methane		Reforming*	CO_2 (with CCS)	+	Blue hydrogen
Natural gas/ methane		Reforming*	CO_2	+	Grey hydrogen
Coal		Gasification	CO_2	+	Black hydrogen

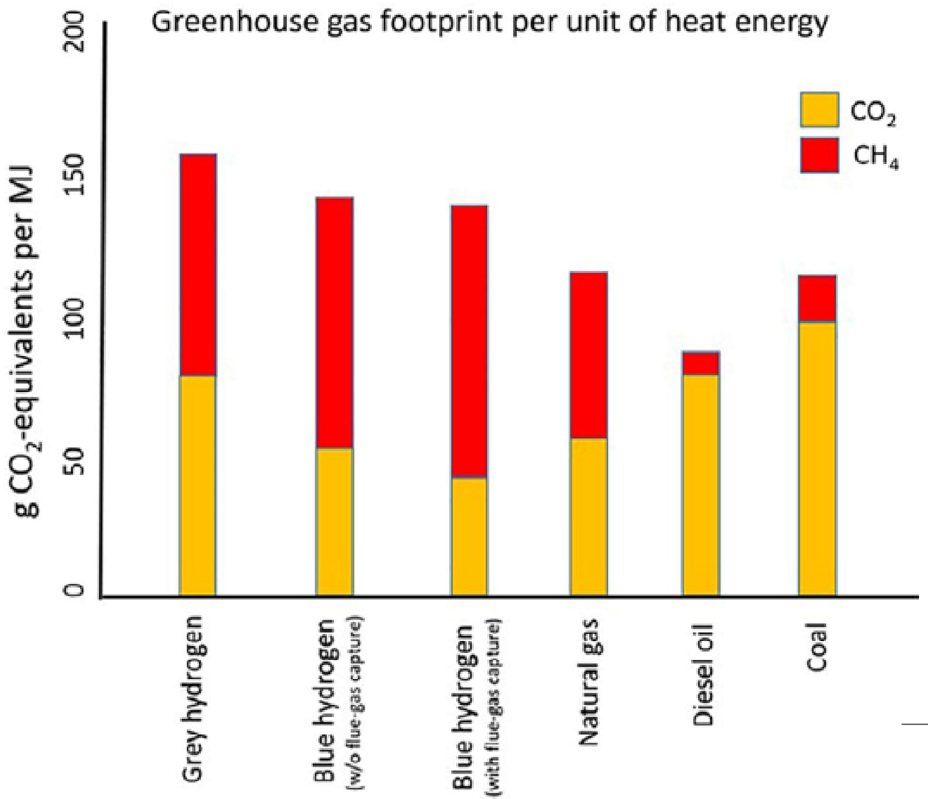
E: energy; RE: renewable energy

* Steam reforming / autothermal reforming; ** With restrictions, see *notes*.

Source: Sachverständigenrat für Umweltfragen, Wasserstoff im Klimaschutz: Klasse statt Masse, June 2021, p.16/fig.4.

How green is blue hydrogen?

Lifecycle GHG emission analysis of blue H_2 compared to natural gas, diesel and coal



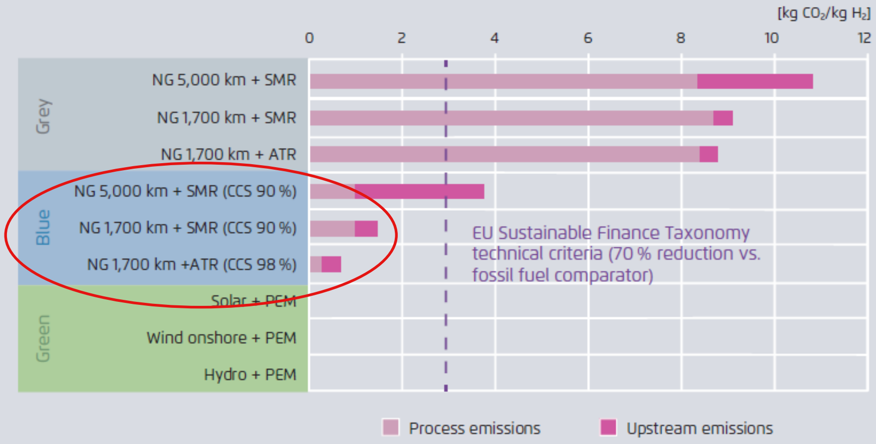
CO_2 and fugitive methane emissions for blue H_2 can be higher than those from natural gas!
→ Blue H_2 is only 10% better than grey H_2!

CH_4 emissions from gas leakage must be considered!
→ In some cases, it may be better to use natural gas directly than producing blue H_2!

Source: Howarth/Jacobson, How green is blue hydrogen?, 2021, p.8/fih.1.

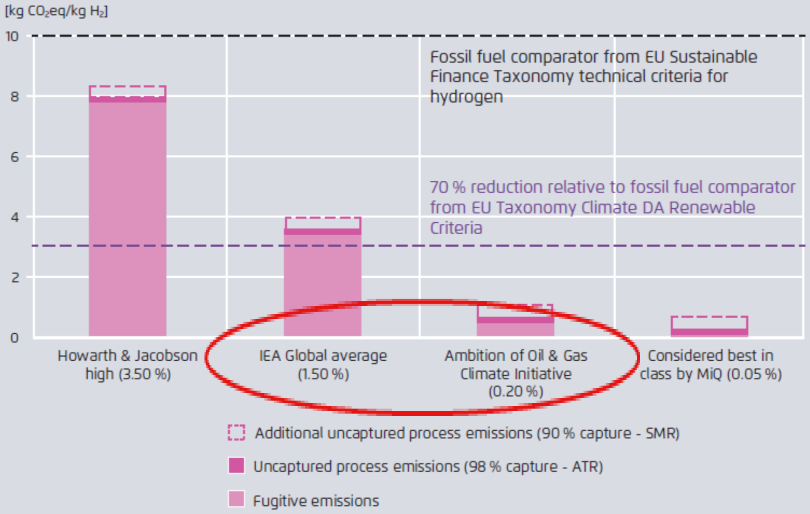
Lifecycle GHG emissions of hydrogen
Using blue hydrogen requires substantial reduction of methane leakage!

Lifecycle GHG emissions of hydrogen production pathways on a GWP 20 basis, 2050 — Figure 26



ETC (2021), Hydrogen Council & LBST (2021), COM (2021a)
Note: The energy production includes upstream methane emissions and has leakage rates of 0.15–1.2 % based on fossil gas source and transport distance. H_2 production refers to process emissions from SMR/ATR. GHG emissions for capex are due to carbon emissions associated with grid electricity used to manufacture equipment. Embedded emissions in renewables are assumed to be zero due to the complete decarbonisation of production process, including electricity, steel and concrete. NG = Fossil gas; ATR = Autothermal reforming; SMR = Steam methane reforming; PEM = Polymer electrolyte membrane electrolysis. A GHG emissions factor of 84 is used to reflect the global warming potential of methane over 20 years. OGCI = Oil and Gas Climate Initiative.

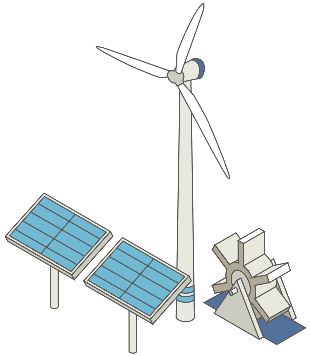
Total GHG emissions on a GWP 20 basis from fossil-based hydrogen with CCS (methane leakage as percentage of consumed gas in brackets) — Figure 27



ETC (2021), IPCC (2021), Robert W. Howarth, Mark Z. Jacobson (2021)
Note: The figure assumes GHG emissions factor of 82.5 used to reflect the global warming potential of methane over 20 years based on IPCC AR6. Note that the most commonly used GWP is GWP100. With GWP100, the GHG effect of fugitive emissions would be considerably smaller. OGCI = Oil and Gas Climate Initiative; DA = Delegated Act.

Source: Agora Energiewende, Agora Industry, 12 Insights on Hydrogen, 2021, p. 43f.

Options for hydrogen production



- **Hydrogen Production Methods**
  - **Fossil Fuels**
    - Hydrocarbon Reforming
      - Steam Reforming
      - Partial Oxidation
      - Autothermal Reforming
    - Hydrocarbon Pyrolysis
  - **Renewable Sources**
    - **Biomass Process**
      - Biological
        - Bio-photolysis
        - Dark Fermentation
        - Photo Fermentation
      - Thermochemical
        - Gasification
        - Pyrolysis
        - Combustion
        - Liquefaction
    - **Water Splitting**
      - Thermolysis
      - Photolysis
      - Electrolysis
        - Alkaline
        - PEM
        - Solid Oxide

Source: S. Shiva Kumar, V. Himabindu (Materials Science for Energy Technologies), Hydrogen production by PEM water electrolysis – A review, 2019, p.443/fig.1.

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How does an electrolyser work?

Electrolysers consist of an **anode and a cathode separated by an electrolyte / membrane**

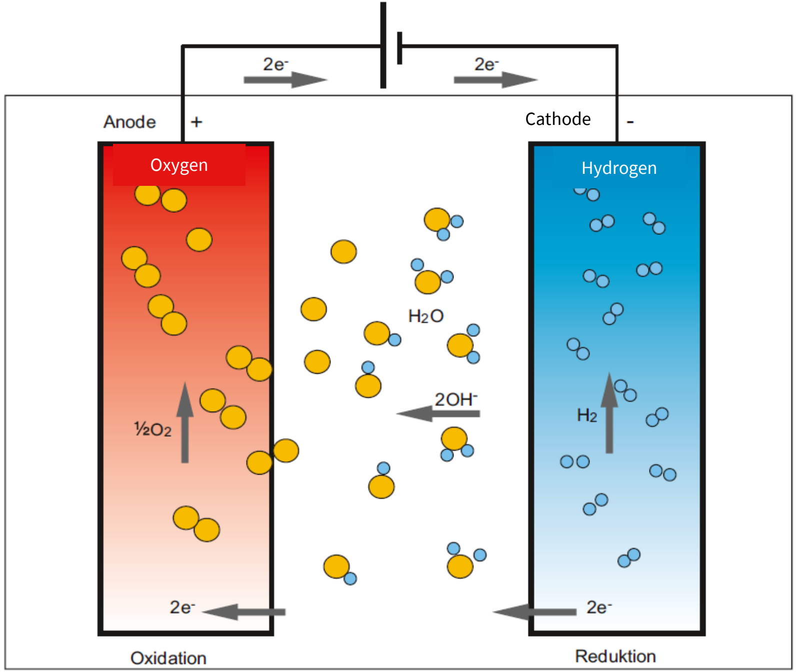
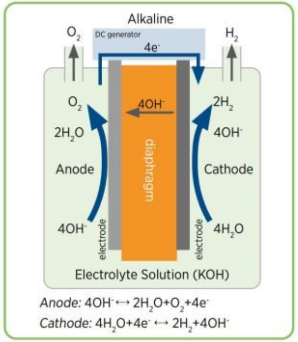


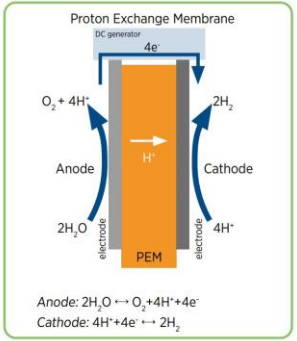
Bild 5.20 Das Grundprinzip der Wasserelektrolyse

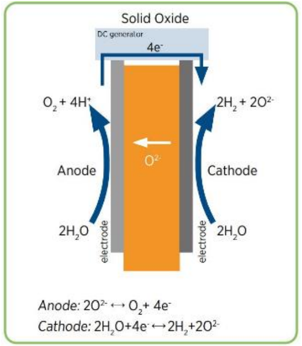
- Due to different types of electrolyte material used and the ionic species it conducts, different electrolysers function differently:
  - Alkaline and Alkaline-Exchange-Membrane (AEM)
  - Proton-Exchange-Membrane (PEM)
  - Solid-Oxide-Electrolyser-Cell (SOEC)

Source: Thomas Schmidt, Wasserstofftechnik, 2020, p.257f.

Key parameter of different electrolyser technologies





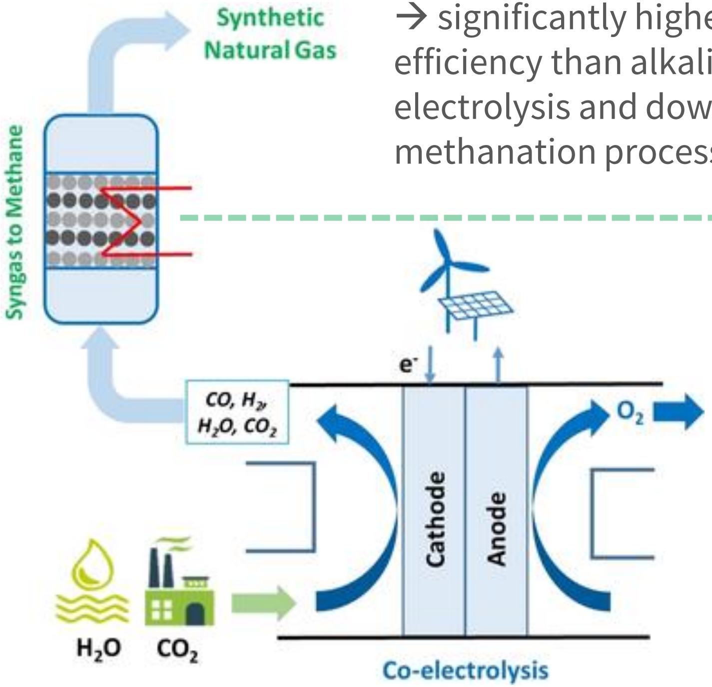


		Alkaline	PEM	SOEC
Operating Temperature		60-80°C	50-80°C	650-1.000°C
Voltage Efficiency		62-82%	67-82%	< 110%
Stack Lifetime		20.000-90.000 h	60.000-90.000 h	< 10.000 h
Operating Pressure		approx. 30 bar	< 50 bar	approx. 1 bar
Efficiency in %	**Current**	63-70[3]; 62-82[5]	56-60[3]; 65-82[5]	74-81[3]; 65-85[5]
	Long-term	70-80[3]; 78-84[5]	67-74[3]; 75-84[5]	77-90[3]; 87-95[5]

Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.31/figure 6.
Frontier Economics/Word Energy Council, International Aspects of a Power-to-X Roadmap, 2018, p.62/1.

Solid-Oxide-Electrolysis-Cell (SOEC): Co-SOEC

Generates H_2+CO in 1 process step
→ significantly higher degree of efficiency than alkaline or PEM electrolysis and downstream FT or methanation processes



Source: European Chemistry Society Publishing, 2021.

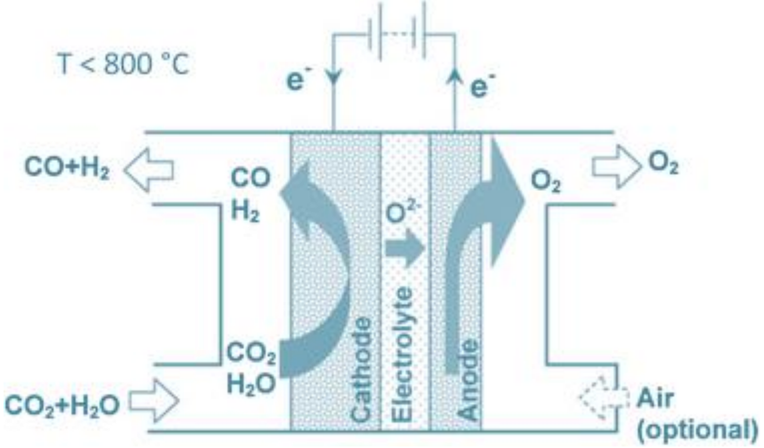
SOEC avoids RWGS

High-temperature co-electrolysis (Co-SOEC)

a) **In SOEC cell: H_2 production**
$CO_2 + H_2O = CO + H_2 + O_2$

b) **plus RWGS reaction in SOEC:**
$CO_2 + H_2 = CO + H_2O$

c) ***(potentially) Methanation reactions in fixed bed reactor:***
$CO_2 + 4H_2 = CH_4 + 2H_2O$ and
$CO + 3H_2 = CH_4 + H_2O$

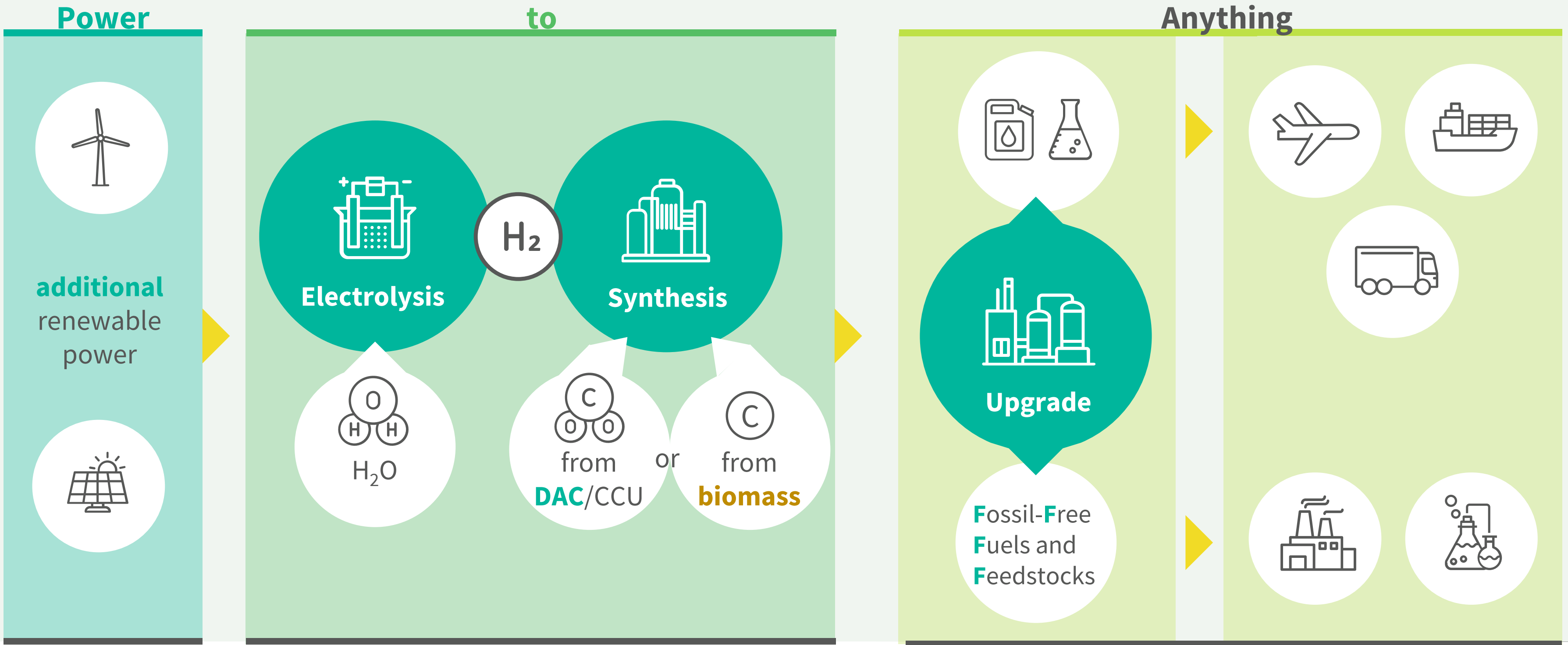


Source: Oxidaion of Metals, 06/2017.

How to produce PtX products?

We need as well SUSTAINABLE CARBON

If you have CO_2 and water you can **convert power to nearly anything**



CCU: Carbon capture and utilisation
DAC: Direct Air capture

Source: Own illustration.

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Test your knowledge

"How can you obtain the CO_2 for the production of renewable PtX ?"

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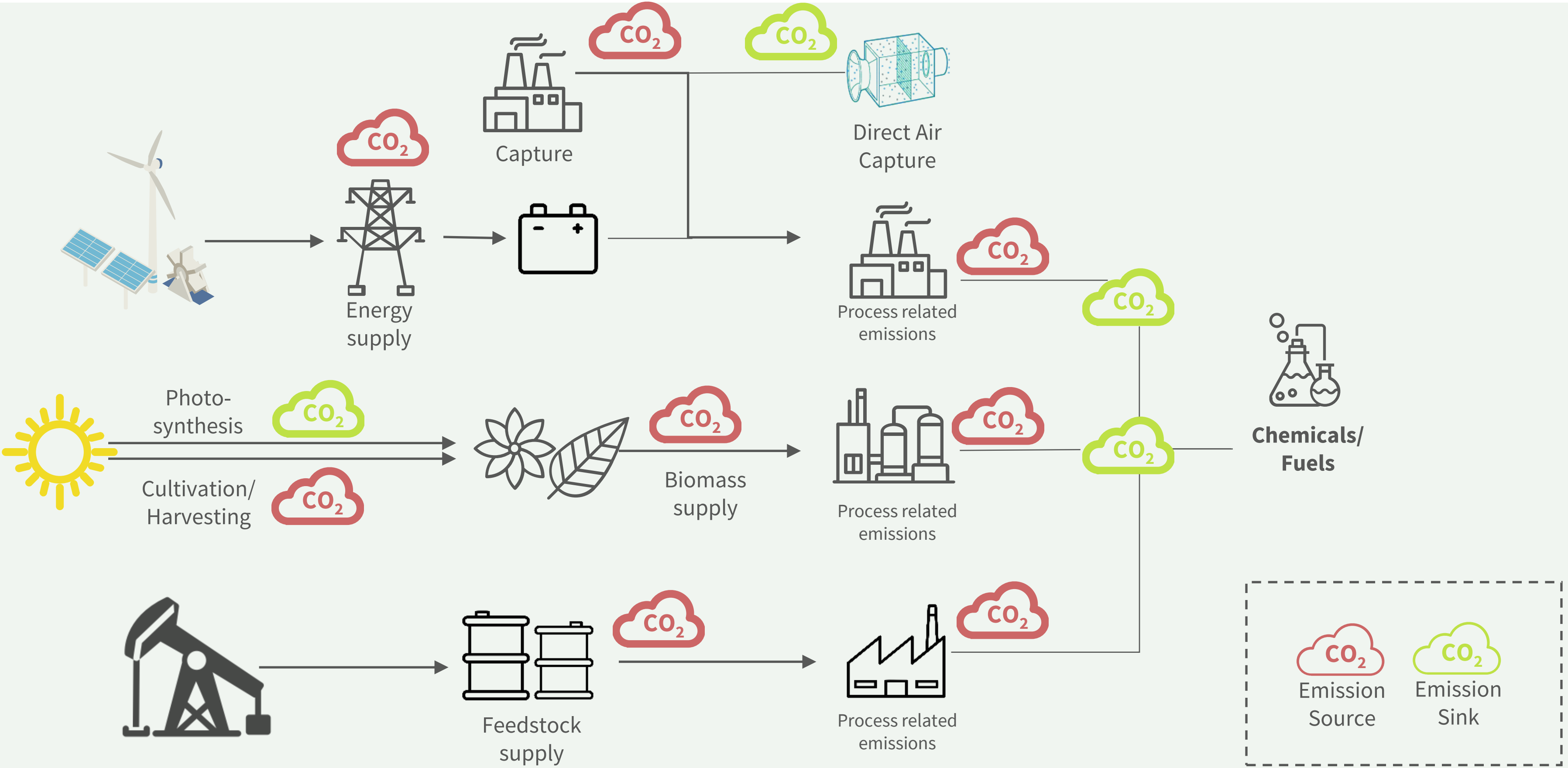
Potential CO_2 routes – only some are sustainable!



Source: WEC 2018; Dechema 2017; Global CCS Institute 2011.

CO_2 capture by Direct Air Capture (DAC)

Challenge CO_2 costs:

- Biomass ($90€/tCO_2$)
- Industrial emissions ($30\text{-}50€/tCO_2$)
- Direct Air Capture ($150\text{-}180€/tCO_2$)
  - Currently around $400\ €/tCO_2$

Direct Air Capture is the one always available and sustainable CO_2 source.

In some places biomass can be an option.

Image Source: Climeworks.com

Where is hydrogen currently used? Its applications in different sectors:

HYDROGEN

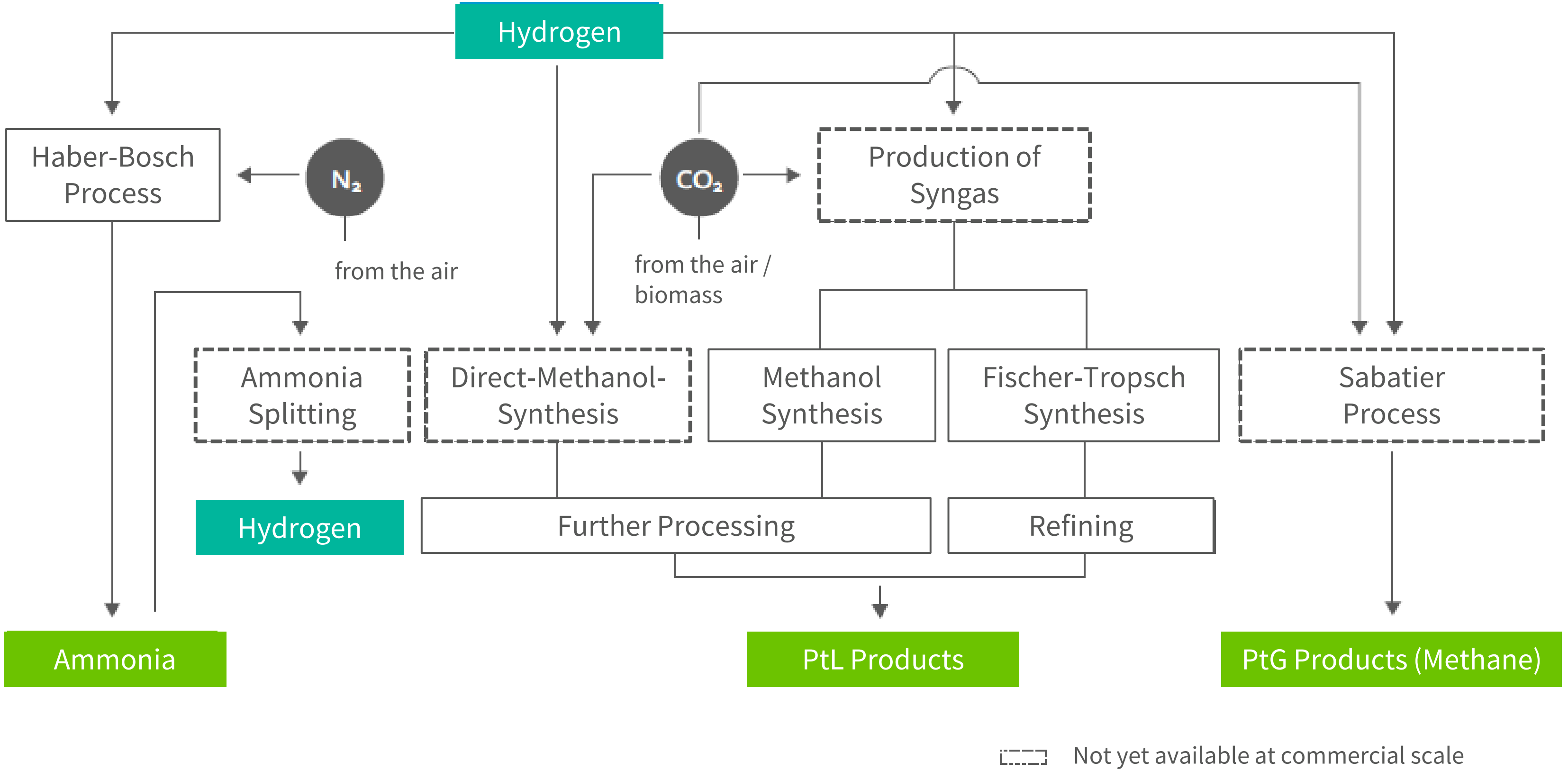
Chemical Industry
- Reduction Gas
- Hydrogenation
- Methane
- Methanol
- Fischer-Tropsch
- Ammonia
- Alcohols

Energy Applications
- Natural Gas Substitute
- Energy Storage
- Combustion Engine
- Gas Turbine
- Fuel Cell

Refining
- Hydroformulation
- Hydrotreating
- Hydrocracking

Source: Own illustration based on: Prof. Dr.-Ing. B. Epple, Innovative Energieumwandlungsprozesse – Energy Systems and Technology, TU Darmstadt.

Converting power to anything with hydrogen and CO2



Source: adapted: SRU, Wasserstoff im Klimaschutz: Klasse statt Masse, 2021, p.23/Abb.5.

Syngas for production of hydrocarbons, alcohols, and dimethyl ether (DME)

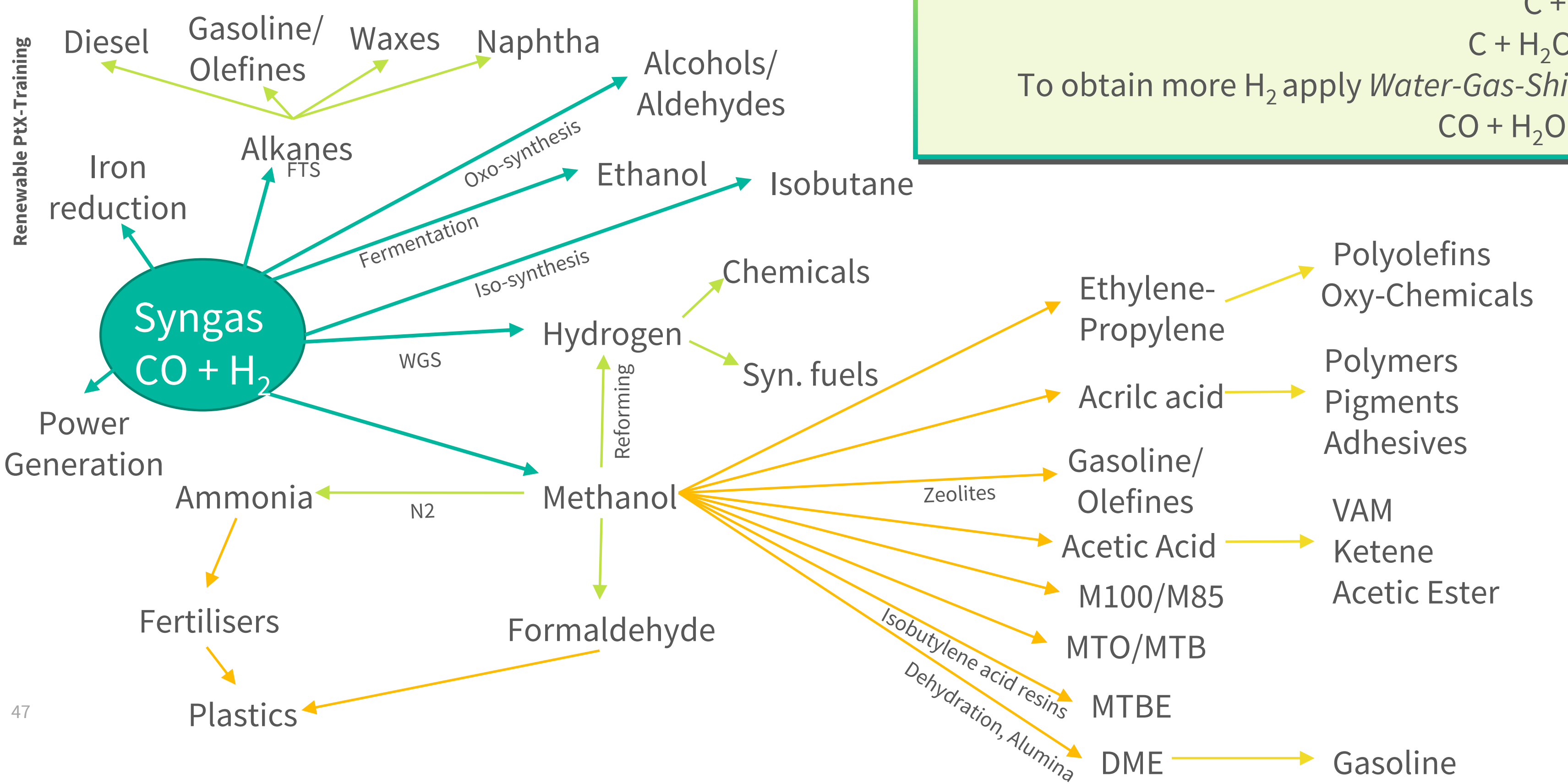
Syngas can be obtained via Methanation or FTS:

$C + ½ O_2 \rightarrow CO$

$C + H_2O \rightarrow CO + H_2$

To obtain more H_2 apply *Water-Gas-Shift-Reaction*:

$CO + H_2O \rightarrow CO_2 + H_2$



Different processes to produce different PtX products

1. Methanation Process

- Production of synthetic "natural gas" – CH_4
- Process: Sabatier Process, mature, commercially available, complex
- Other process in lab scale/pilot stage
- Overall efficiency around 50%
- Currently very high costs for synthetic CH_4 when using H_2

2. Fischer-Tropsch Synthesis

- Production of synthetic crude (C_XH_Y) that is then refined to different synthetic fuels
- Gasoline, diesel, kerosene through hydro cracking, isomerisation and distillation
- Fischer-Tropsch Synthesis process is mature, commercially available for large volumes
- Overall efficiency is low (below 50%)
- Requires CO and H_2 => requires additional process RWGS
- Smaller processes with DAC in development/pilot stage
- Very high costs for synthetic fuels when using hydrogen

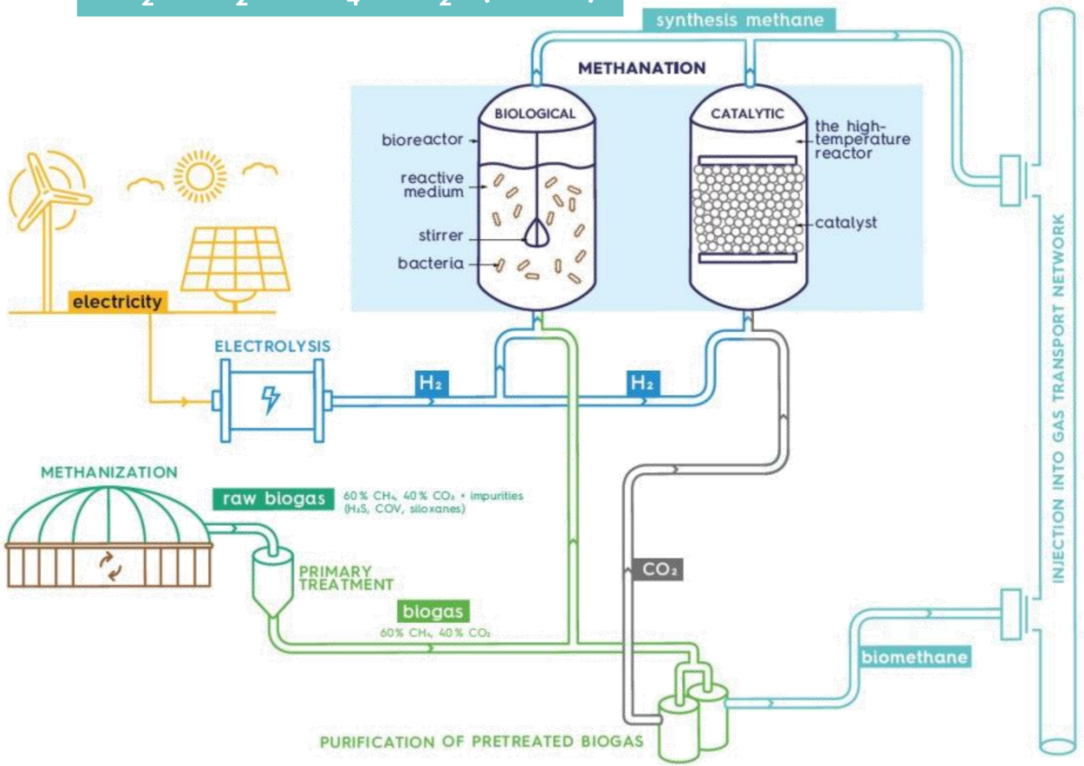
3. Methanol Process

- Process to produce olefins for plastics, OME (oxymethylene ether), DME (dimethyl ether)
- Can use CO_2 and H_2 directly to produce Methanol

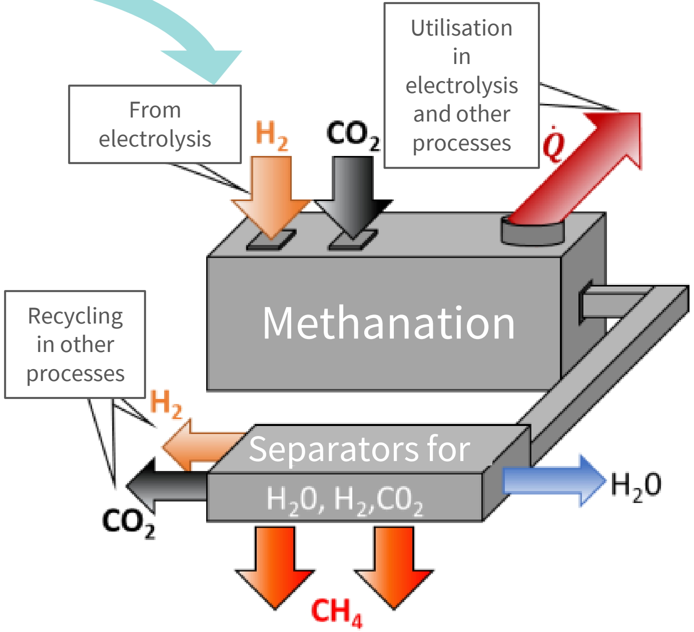
4. Green Ammonia

3.1. Methanation: Production of syn. gas via Sabatier Process

$4H_2 + CO_2 \rightarrow CH_4 + 2H_20$ (+heat)



Source: Terega, Synthetic Methane: Teréga working today for the future of gas, 2022.



Producing green methane (CH_4) with Sabatier Process at 300–400 °C and 30 bar in the presence of a nickel catalyst.

Conversion efficiency approx. 50%

Source: Technische Universität Berlin, Technischer Stand und Flexibilität des Power-to-Gas-Verfahrens, 2018, p.4.

3.2. Fischer-Tropsch Synthesis: Production of synthetic liquid (I)

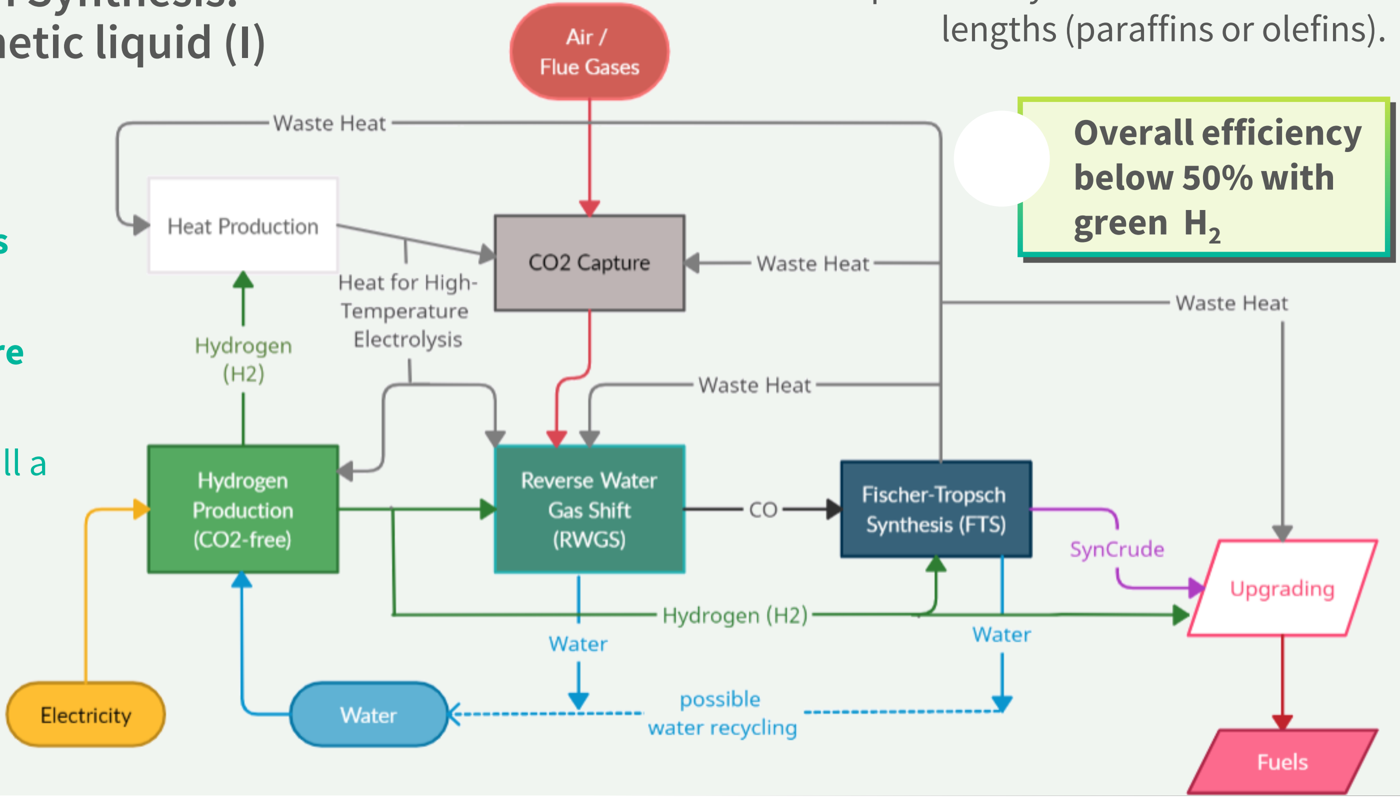
FTS reaction is one of the reactions for growing carbon chains (–CH_2–) to produce hydrocarbons of various lengths (paraffins or olefins).

FTS to produce syn. fuels exists on large scale and is mature.

Further cost reductions are not expected.

But commercial RWGS is still a technological challange!

Overall efficiency below 50% with green H_2



Output of FTS depends on final product (conversion efficiency from CO + H_2 to final product)

- **Diesel fuel:** 230°C, 40 bar, 60 – 90%
- **Gasoline:** 340°C, 25 bar 85%

Source: Adaption: Öko-Institut e.V.: Wasserstoff und wasserstoffbasierte Energieträger bzw. Rohstoffe, 2020, p.63/Abb.2-16.

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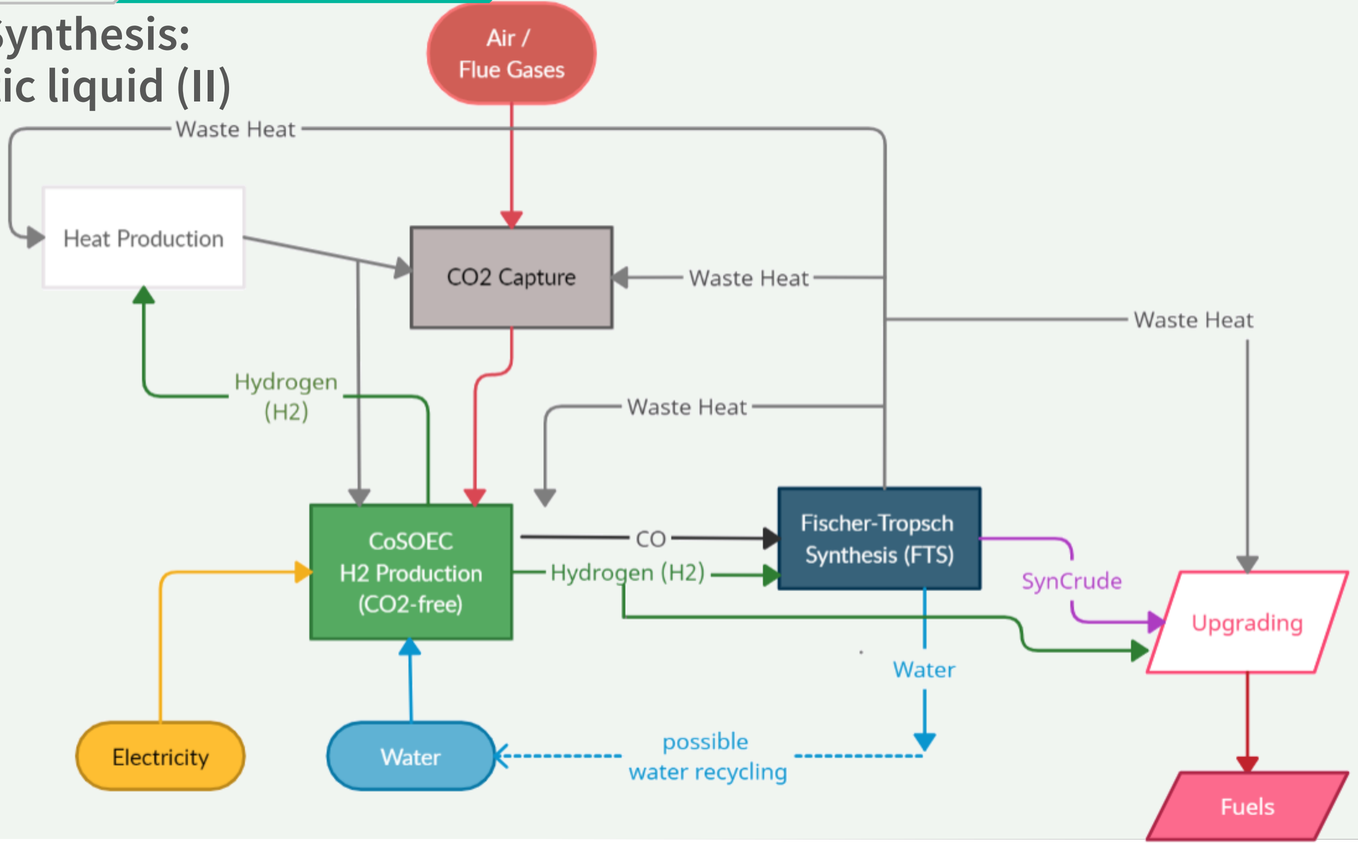
3.2. Fischer-Tropsch Synthesis: Production of synthetic liquid (II)

FTS to produce synthetic fuels exists on large scale.

When coupled with CoSOEC, this process can be scaled to commercial level.

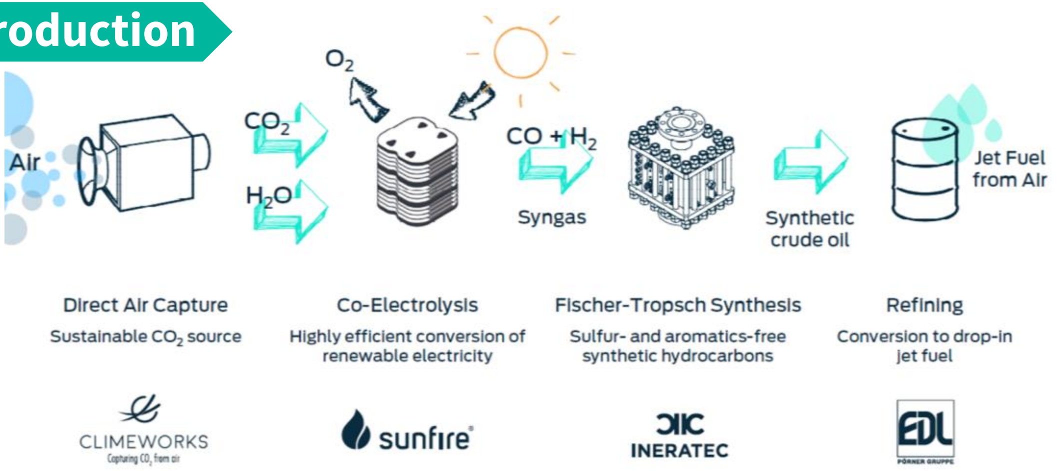


3.2. FTS: Decentralised PtX production with DAC (pilot stage)

Kopernikus-Project P2X

Phases in the scale-up of DAC technology

- Pilot plant currently produces **10l fuel** per day
- **200l/d plant in planning** within the Kopernikus project
- Demonstration plant in megawatt range with **1500-2000l/d production capacity**



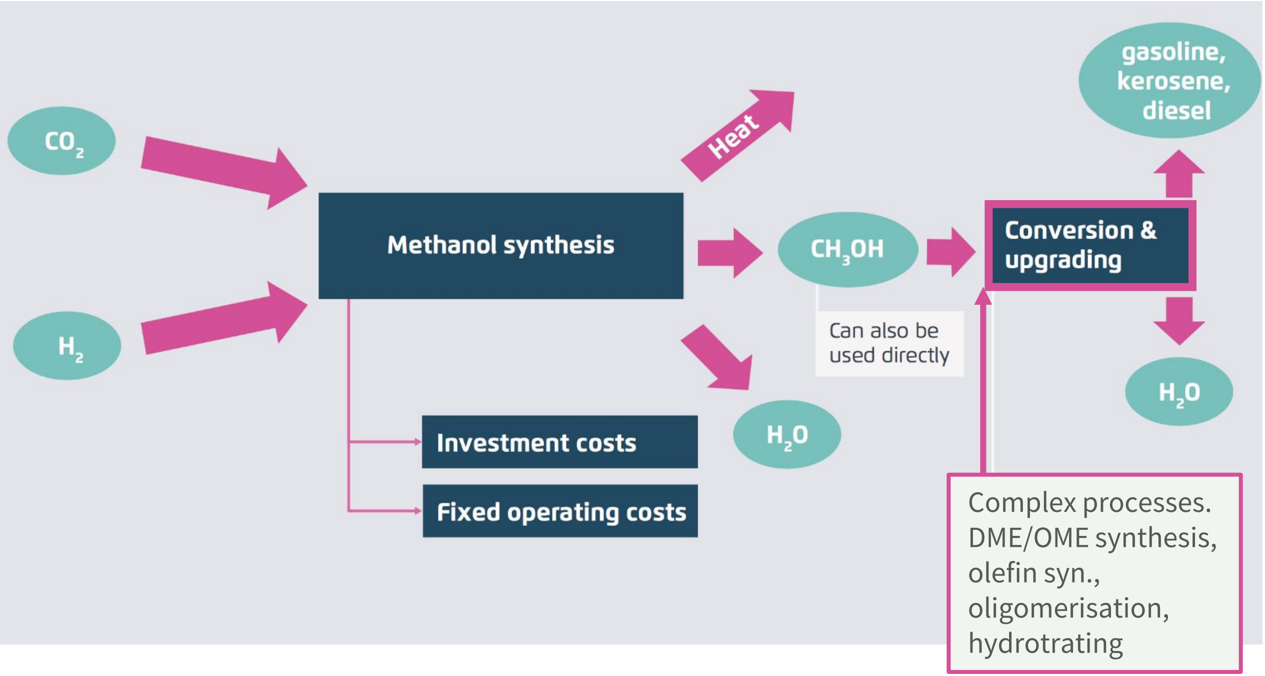
Source: KIT, Kohlendioxidneutrale Kraftstoffe aus Luft und Strom, 2019; Zenid, Jet Fuel from Air, 2020; Climeworks, 2020.

3.3. Methanol (CH_3OH) synthesis: Liquid fuel production

Future cost reductions are linked to electrolysis development and not to the synthesis process itself.

Methanol synthesis is a mature process. Further cost reductions are not expected in large scale.

Methanol process at 250°C, 75 bar, efficiency 80%.
If one uses DAC and RE power costs are 5-times more higher than from fossil fuel 100$/t to 200$/t.



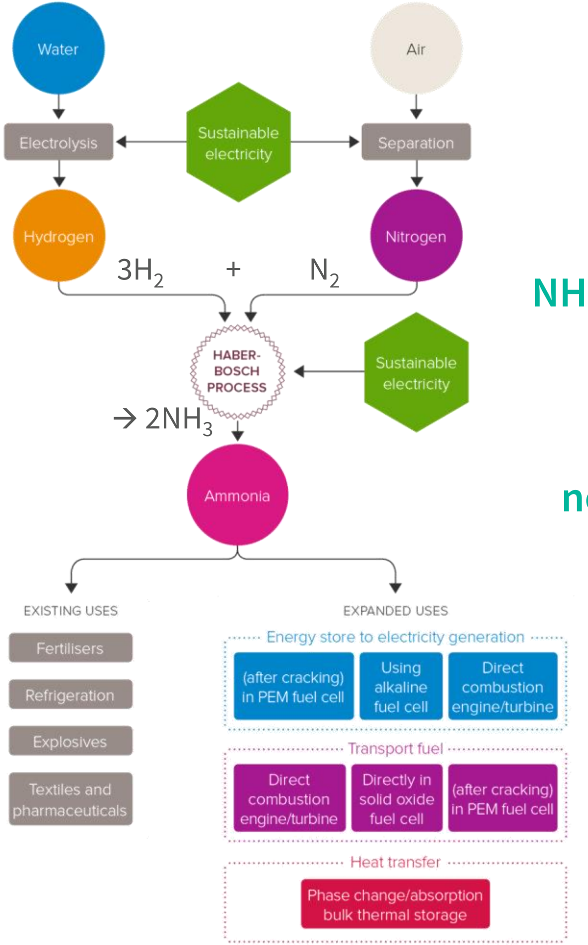
Source: Adapted from: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels, p.69/figure 14.

3.4. Green ammonia

- **Extraction of N_2** from air with a **cryogenic air separation unit (ASU) and electric power**
- Green NH_3 is produced from green hydrogen (H_2) and nitrogen (N_2) via the industrial **Haber-Bosch process** (high technology maturity)

How can green NH_3 be used?

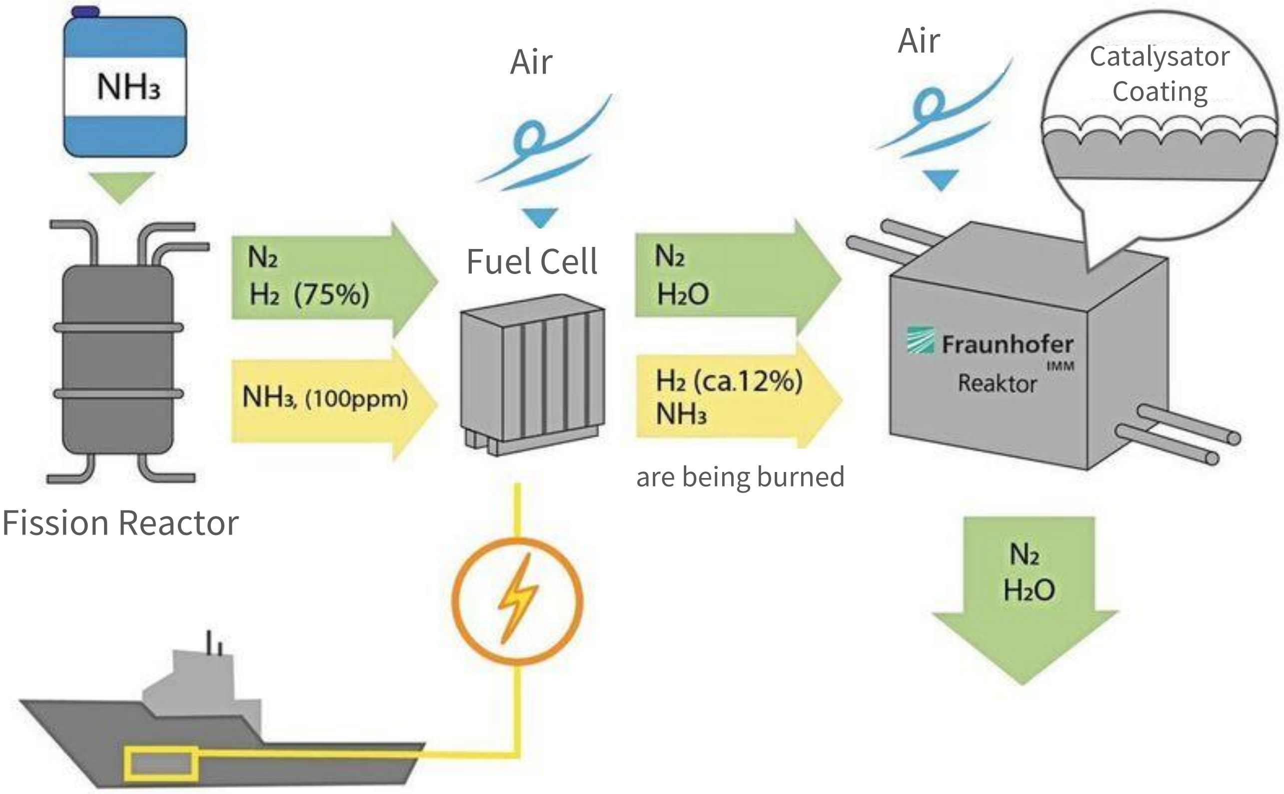
- As **energy carrier** of H_2 to enable transportation (higher energy density compared to H_2)
- As **fuel in fuel cells**
- or **directly in combustion engines**
- And to **decarbonise the fertiliser production**



Big advantage: NH_3 provides a pathway to fully CO_2 neutral electricity generation + storage; not limited by scarcity of materials or storage space.

Source: The Royal Society, Ammonia: zero-carbon fertiliser, fuel and energy store, 2020

Ammonia splitting in a fuel cell to produce power – if catalysator used is only water and N_2 as exhaust possible



Source: Campfire, NH3 (teil 2): Grüner Ammoniak – Energieträger der Zukunft (mehr), n.d.

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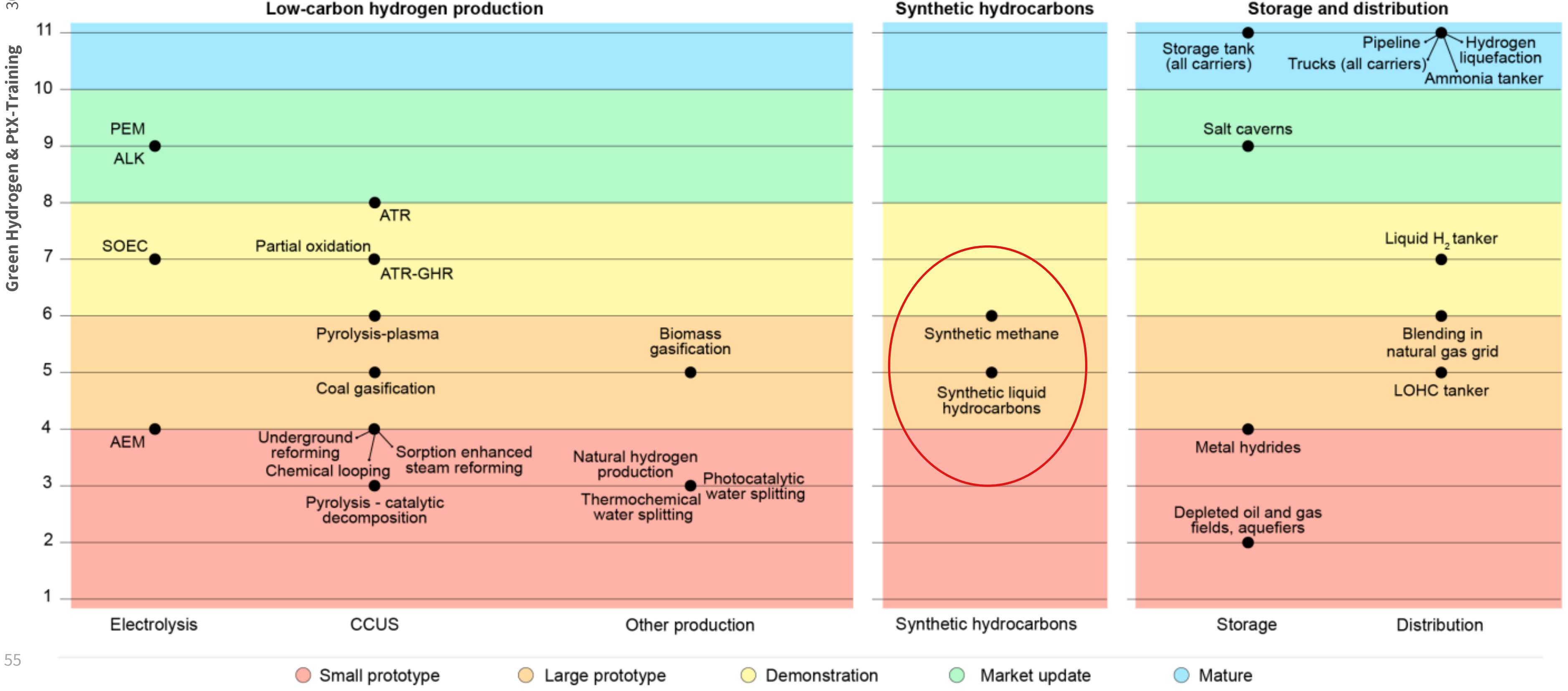
30.06.2022

Technology readiness levels of key PtX production, storage and distribution technologies



Source: IEA, Global Hydrogen Review 2021, 2021, p.170.

MODULE 2: Key messages – 1/2

Hydrogen Production

- There are **various ways of producing H_2,** designated in colors
- **H_2 is the core of PtX,** converting electric power to other forms of energy carriers. Diverse H_2 production pathways that can **replace fossil fuels across many sectors**
- **Emissions for blue H2 can be higher than those from natural gas**, methane leakage must be considered!

Electrolysis

- (Green) Hydrogen and oxygen are derived from the **electrolysis** of water using (renewable) energy. **Water electrolysis is therefore the base technology** for the PtX process

Carbon Capture

- If you have CO2 and water you can convert power to nearly everything. However, **green CO_2 is crucial** to decarbonize synthetic fuels production. In the long run, **CO_2 has to come from DAC or biomass**
- **Cost reduction is needed**

MODULE 2: Key messages – 2/2

PtX product sourcing, production of:

- H_2 is used as product and energy input in chemical industry, as substitute in energy applications and as material input for further refining, **mainly PtX (e-fuels and methanol) or ammonia**
- There are **different processes to produce different PtX products**
- **E-fuels** like Kerosine, Diesel, gasoline are **produced via Fischer Tropsch Synthesis process**, which requires a syngas (CO and H_2)
- An electrolyiser produces H_2 and if you aquire CO2 from DAC or Biomass you need an additional RWGS process to produce the syngas (CO and H_2), which can go into FT.
- **Co-Electrolyzes produces CO and H_2 and offers a direct way to produce PtX** via Fischer Tropsch Synthesis.
- If you want to **produce ammonia in a Haber Bosch process**, you need H2 and N2 from the air. **No CO_2 is required**.


Q
A

Break out group discussion

"What could be possible PtX applications for your country in the future?"

"Which PtX processes do you consider for your country?"

"What seems the biggest challenge to establishing PtX plants in your country?"

Module 3

Renewable PtX Economics

Production Cost of Green Hydrogen

- Country-specific developments (RE cost, regulations)
- Green vs. blue hydrogen

Renewable Energy Generation Cost Development

- RE costs worldwide (wind, PV) vs.
- Traditional energy sources cost development
- RE potential worldwide

Electrolyser Cost Development

- Alkaline and PEM
- Dependencies

Scale-Up and Outlook for Hydrogen and PtX Production

- Green hydrogen
- Green ammonia
- Synthetic fuels etc.

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Test your knowledge

"What are the biggest challenges to reduce production costs of green H_2?"

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1. Production Cost of Green Hydrogen

It depends on some key factors

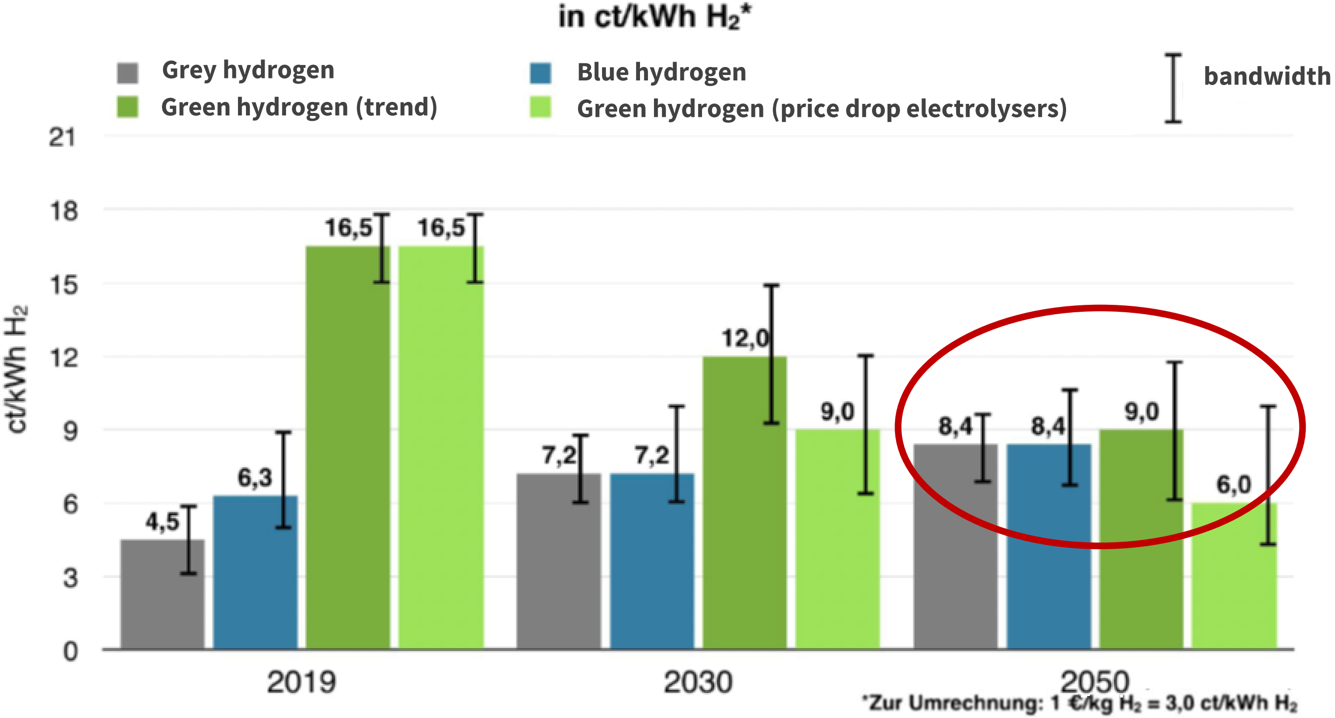
1. Green Hydrogen Production Cost

Hydrogen production costs: now and in 2050 in Germany

Key figures and trends showing the challenge we face!

Assumption for CO_2 price in Germany:
2030: 100 Euro/t
2050: 100 Euro/t
+ Carbon Import tax 100 Euro/t

6 ct/kWh H_2 = 2 Euro/kg H_2



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Source: Dr. Steffen Bukold (Greenpeace Energy), Blauer Wasserstoff, 2020, p.8.

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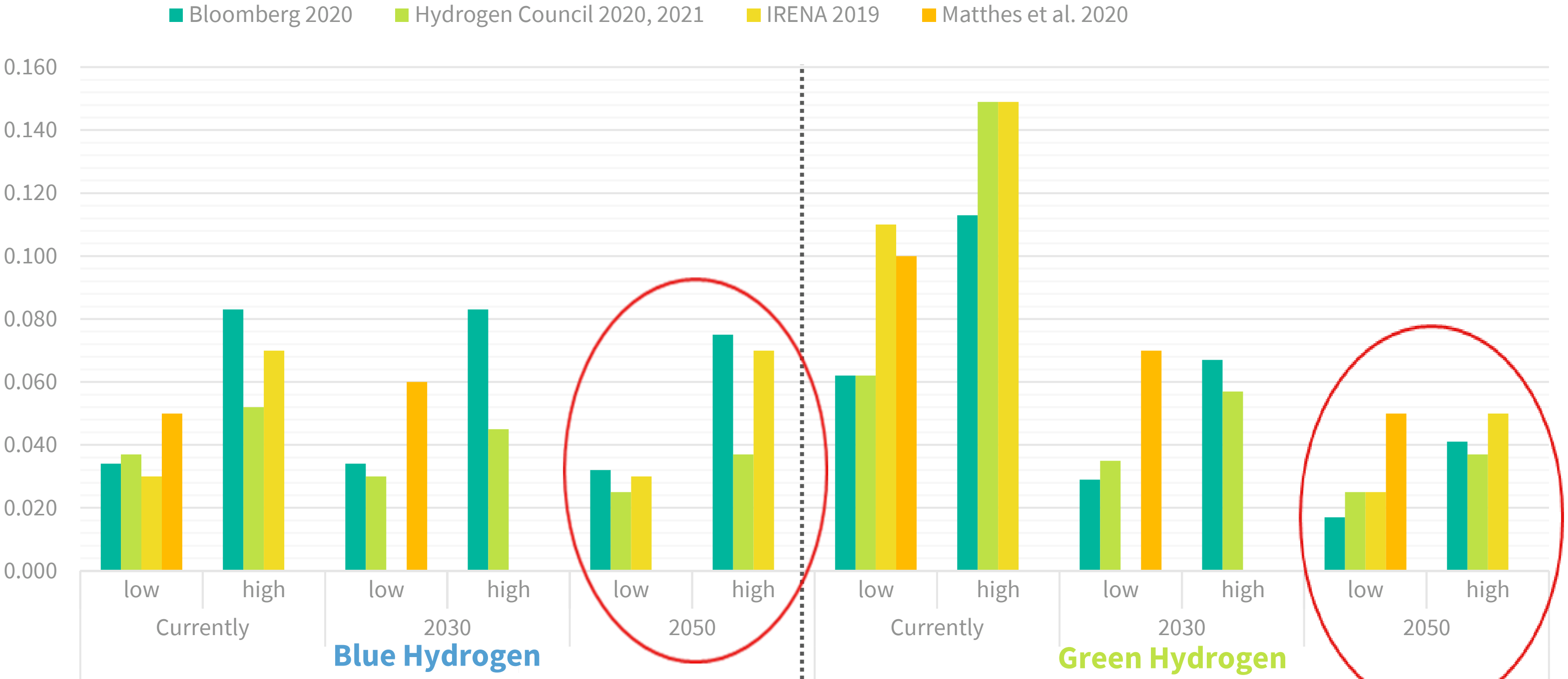
1. Green Hydrogen Production Cost

Production costs for green and blue hydrogen (in € /KWh$_2$)

0.02 €/kWh = 0.66 €/kg



	Blue Hydrogen						Green Hydrogen					
	Currently		2030		2050		Currently		2030		2050	
	low	high	low	high	low	high	low	high	low	high	low	high
Bloomberg 2020	0.034	0.083	0.034	0.083	0.032	0.075	0.062	0.113	0.029	0.067	0.017	0.041
Hydrogen Council 2020, 2021	0.037	0.052	0.030	0.045	0.025	0.037	0.062	0.149	0.035	0.057	0.025	0.037
IRENA 2019	0.030	0.070			0.030	0.070	0.110	0.149			0.025	0.050
Matthes et al. 2020	0.050		0.060				0.100		0.070		0.050	0.000

Source: Sachverständigenrat für Umweltfragen, Wasserstoff im Klimaschutz: Klasse statt Masse, June 2021, p.22/fig.5.

1. Green Hydrogen Production Cost

How to reduce production costs? Key elements and their trends

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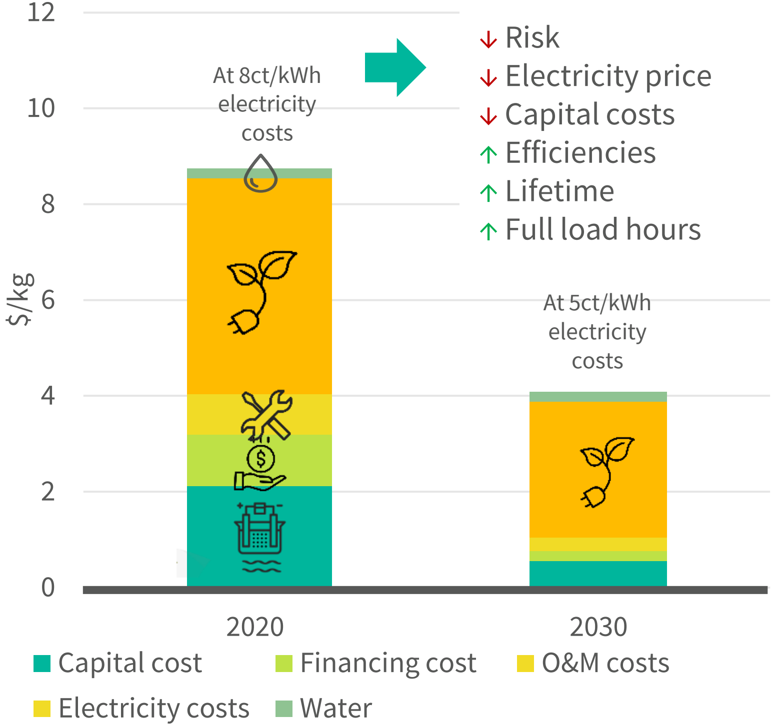
Green hydrogen production costs $/kg



CAPEX: capital expense for the electrolyser (including the balance of plant)

Finance & risk: Interest rates depend on financing mechanism and perceived risk of project

Operation and Maintenance (O&M): Often paid as Service-Level Agreement (SLA) or warranties → deferred capex costs for replacements of stacks or other parts (1-3% of capex annually)

Electricity costs (either as part of project (CAPEX) or as purchase agreement (OPEX; incl. taxes, levies, surcharges...))

Water costs negligible

Efficiency = Output GH_2 per input electricity
The higher the efficiency, the lower the costs per kg GH_2.

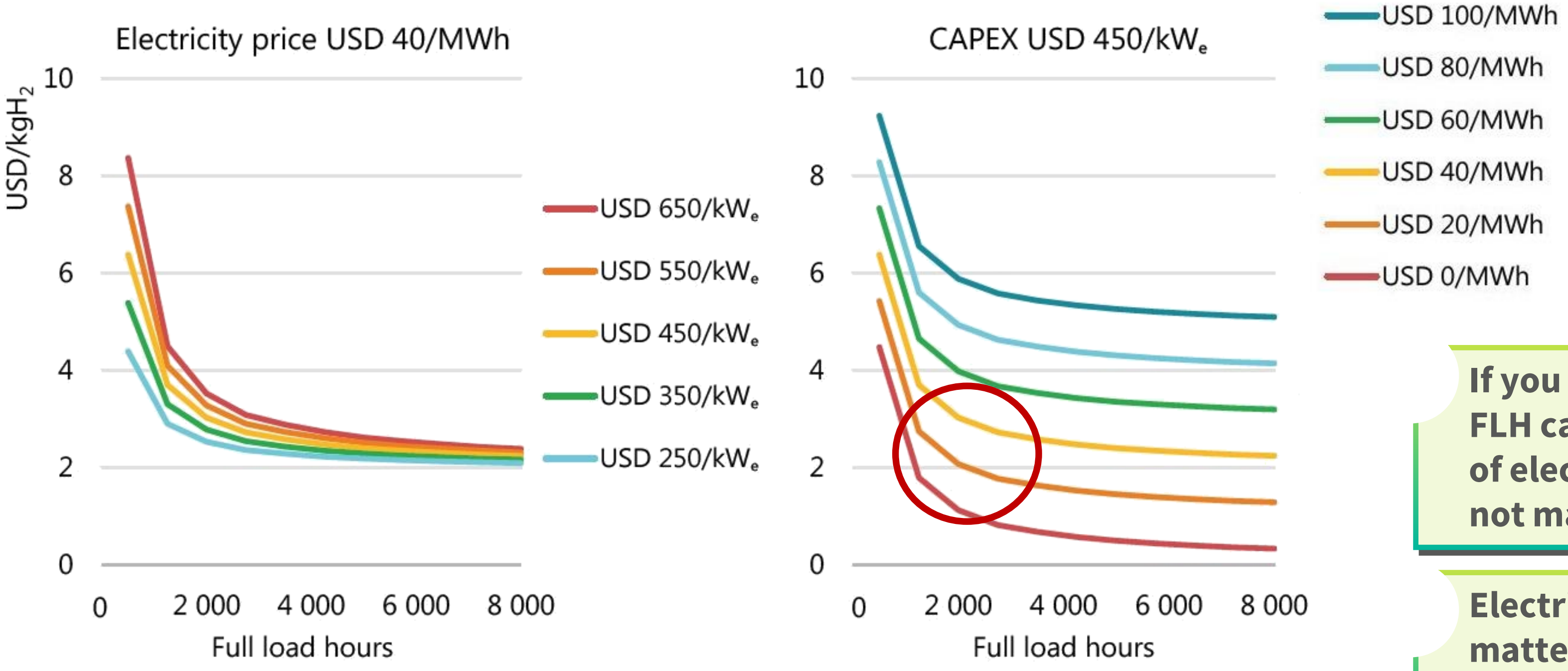
Lifetime: Capital costs can be spread over the GH_2 produced over lifetime

Full load hours (availability of renewable electricity) define the utilisation of the plant

Source: Roland Berger & FCH, Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities, 2017.

1. Green Hydrogen Production Cost

Impact of CAPEX, Full load hours (FLH) and electricity cost



If you have high FLH capital costs of electrolyser do not matter

Electricity costs matter always and a lot

*Numbers based on an electrolyser efficiency of 69% (LHV), discount rate of 8% and stack lifetime of 95.000 hours.

Source: IEA, The Future of Hydrogen – Seizing today's opportunities, 2019, p.47/fig.12.

1. Green Hydrogen Production Cost

Renewable hydrogen production costs depending on operating hours

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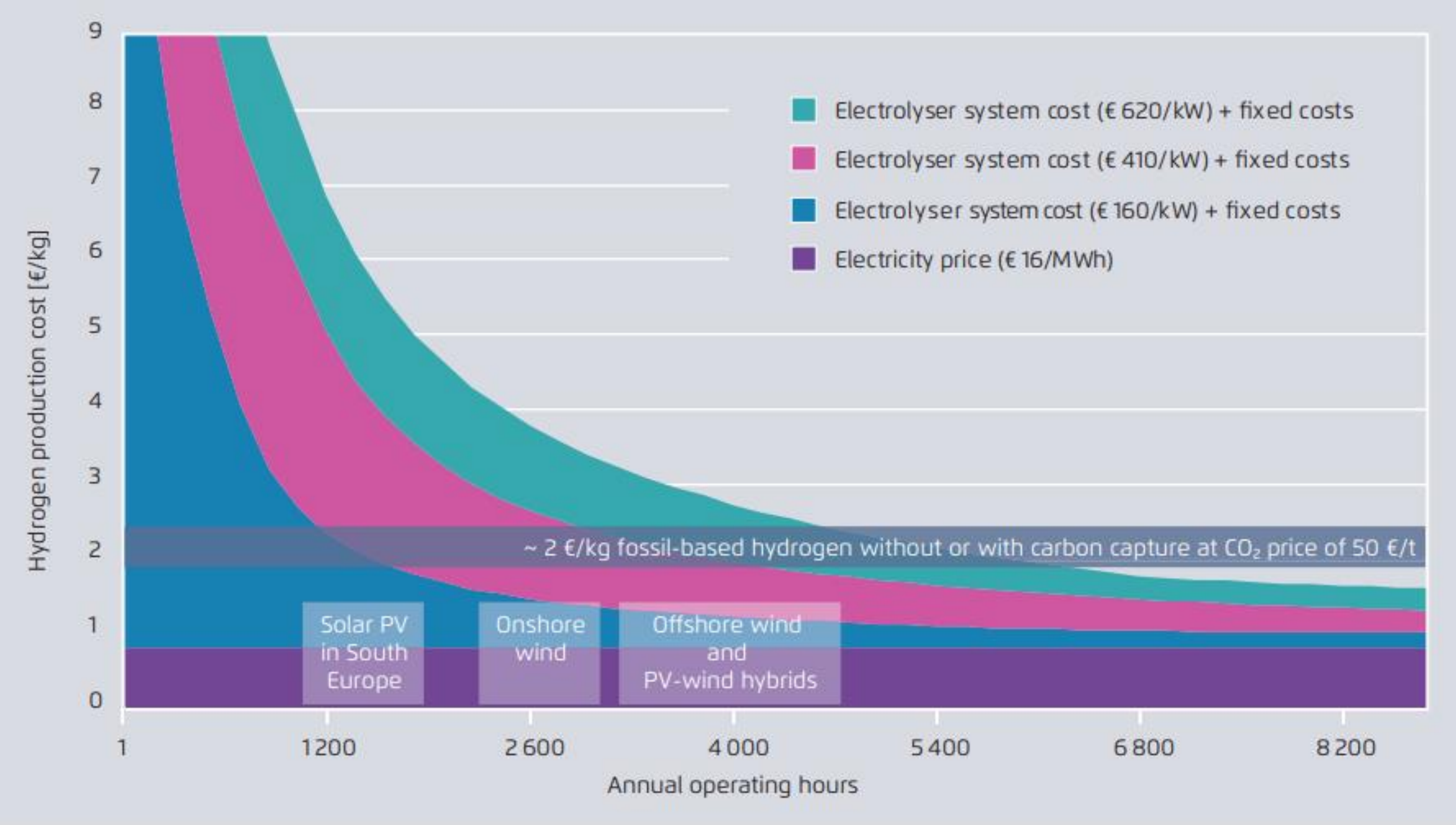
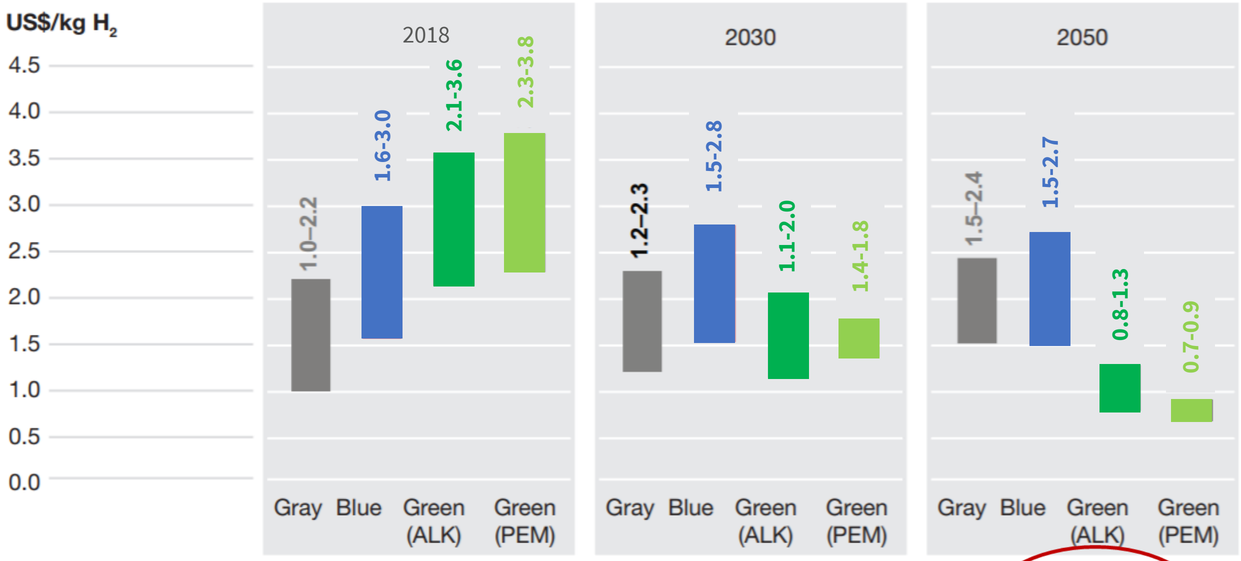


Source: Agora Energiewende, Making renewable hydrogen cost-competitive, 2021, p.12/fig.2.

1. Green Hydrogen Production Cost
Worldwide expectations look much better

Hydrogen cost development by production type



	2018	2030	2050
Renewable LCOE (US$/MWh)	**30—45**	**18—26**	**14—18**

Green H_2 will become cost competitive compared to grey and blue H_2!

It depends mainly on LCOE of renewable power

1 US$/ kg in 2050 or much earlier is achievable.

Notes:
- ALK: alkaline water
- LCOE: levelised cost of energy
- MWh: megawatt hour
- PEM: polymer electrolyte membrane

1 Cost assumptions based on greenfield projects, excl. cost for buildings and building cooling requirements.

Source: adapted: Dr. Raed Kombargi, Dr. Shihab Elborai, Dr. Yahya Anouti, and Ramzi Hage, “The dawn of green hydrogen: Maintaining the GCC’s edge in a decarbonized world", Strategy&, 2020, p.5/ exhib.3.https://www.strategyand.pwc.com/m1/en/reports/2020/the-dawn-of-green-hydrogen.html

1. Green Hydrogen Production Cost

What makes up costs of green hydrogen?

Four main parameters are critical for economic viability of H_2 production from renewables

→ **Country specific evaluation required**

1. **Cost of renewable electricity** used in the process (levelised cost of electricity: LCOE),
2. **Electrolyser capital expenditure**,
3. **Number of operating hours** (load factor) on a yearly basis (IRENA 2019),
4. **Transport and storage** considerations.

- **Full load hours (FLH): higher → more economic/ high load factors**
- **CAPEX:** decrease with scale + time
- **OPEX: constant**
- **WACC: lower perceived risk → lower WACC**
- **Electrolyser efficiency:** increase with scale + time
- **Desalination (cost negligible)**

→ We need cheap and plenty of dedicated RE power!

2. Renewable Energy Generation Cost Development

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Test your knowledge

"What are current lowest power purchase cost/agreements for large scale PV power worldwide *in USc/kWh* ?"

"What are the expected future LCOE for PV power in 2030 in your country *in USc/kWh?*"

"What are expected future LCOE for wind power in your country for 2030 *in USc/kWh?*"

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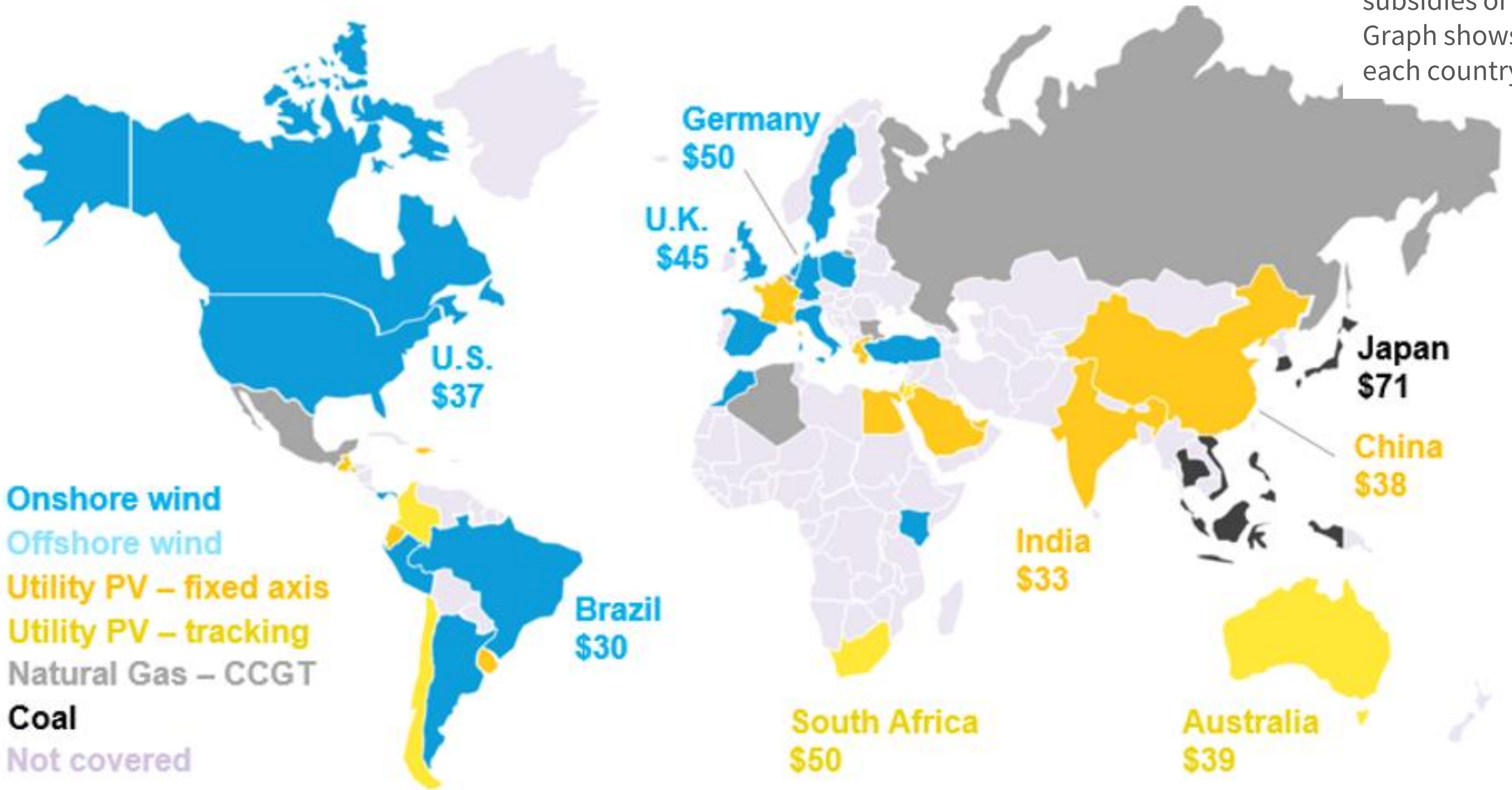
2. RE Cost Development

Cheapest source of new bulk electricity generation by country, in early 2020

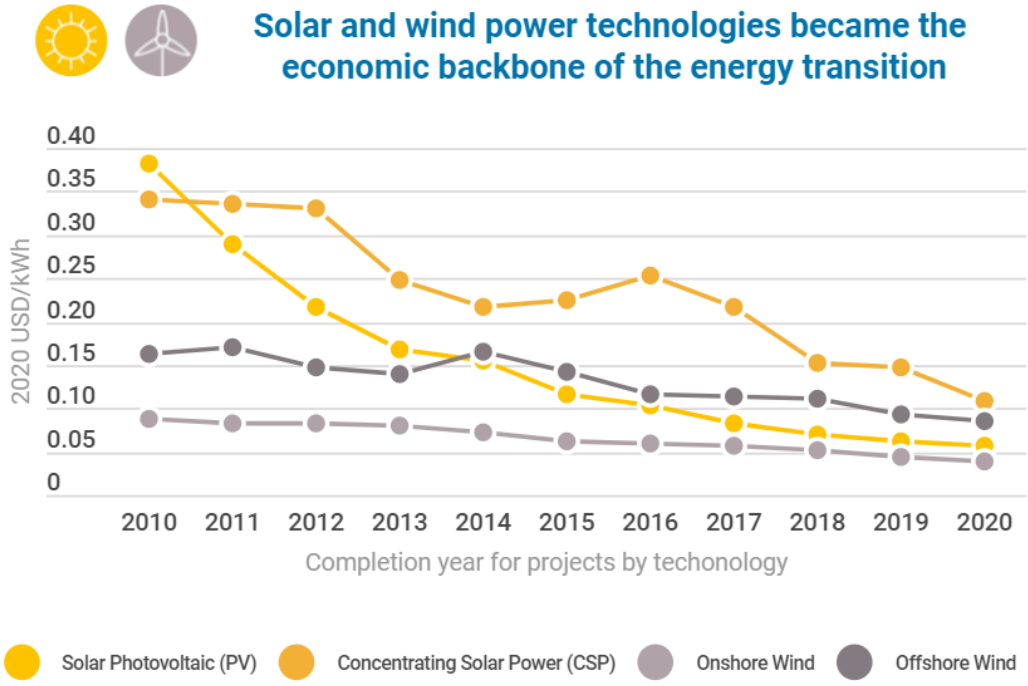
Note: LCOE calculations exclude subsidies or tax-credits.
Graph shows benchmark LCOE for each country in USD per MWh.



Source: BloombergNEF, Scale-up of Solar and Wind Puts Existing Coal, Gas at Risk, 2020.

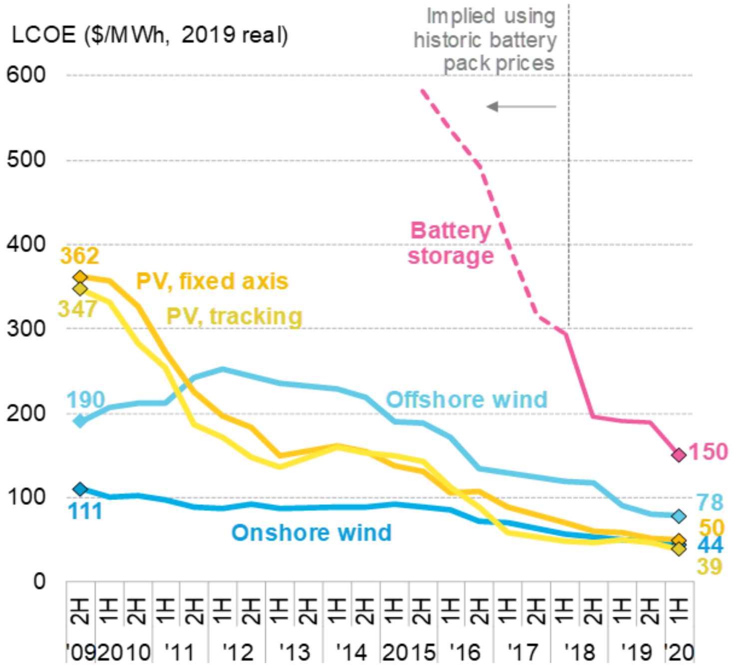
2. RE Cost Development
Cost development of solar and wind

Solar and wind power technologies became the economic backbone of the energy transition



Source: Renewable Market Watch, Renewable Power Generation Costs Reduction - 2020 Overview in the Recent Study of IRENA Released in 2021 with LCOE of Renewable Energy Technologies, 2020.

Global LCOE benchmarks of PV, wind and batteries



Source: BloombergNEF, Scale-up of Solar and Wind Puts Existing Coal, Gas at Risk, 2020.

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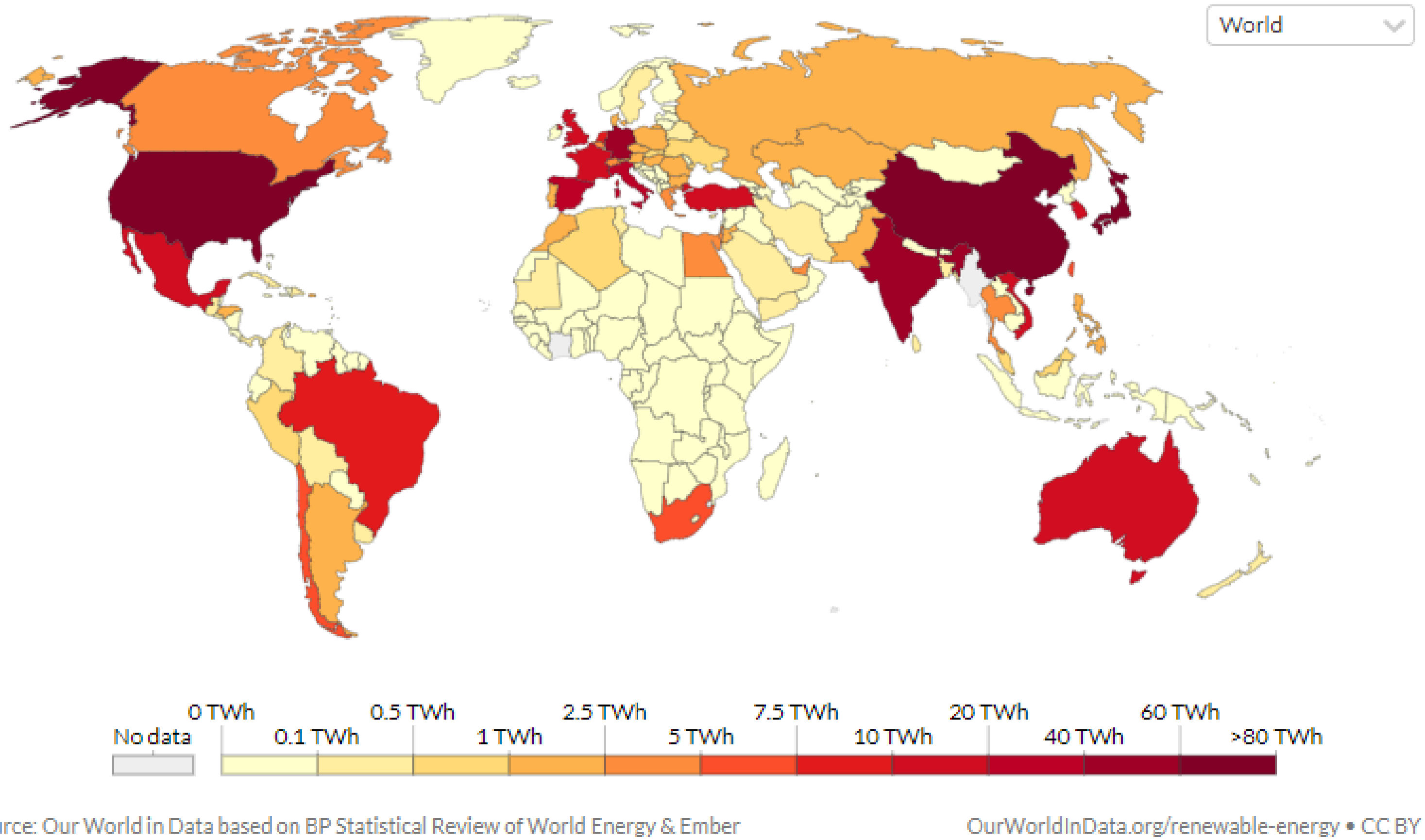
2. RE Development

Solar power generation, 2020 (in TWh/year)



Source: Hannah Richie/Max Roser (Our World in Data), Renewable Energy - Solar energy generation, 2020.

2. RE Development

Wind energy generation, 2020 (in TWh/year)

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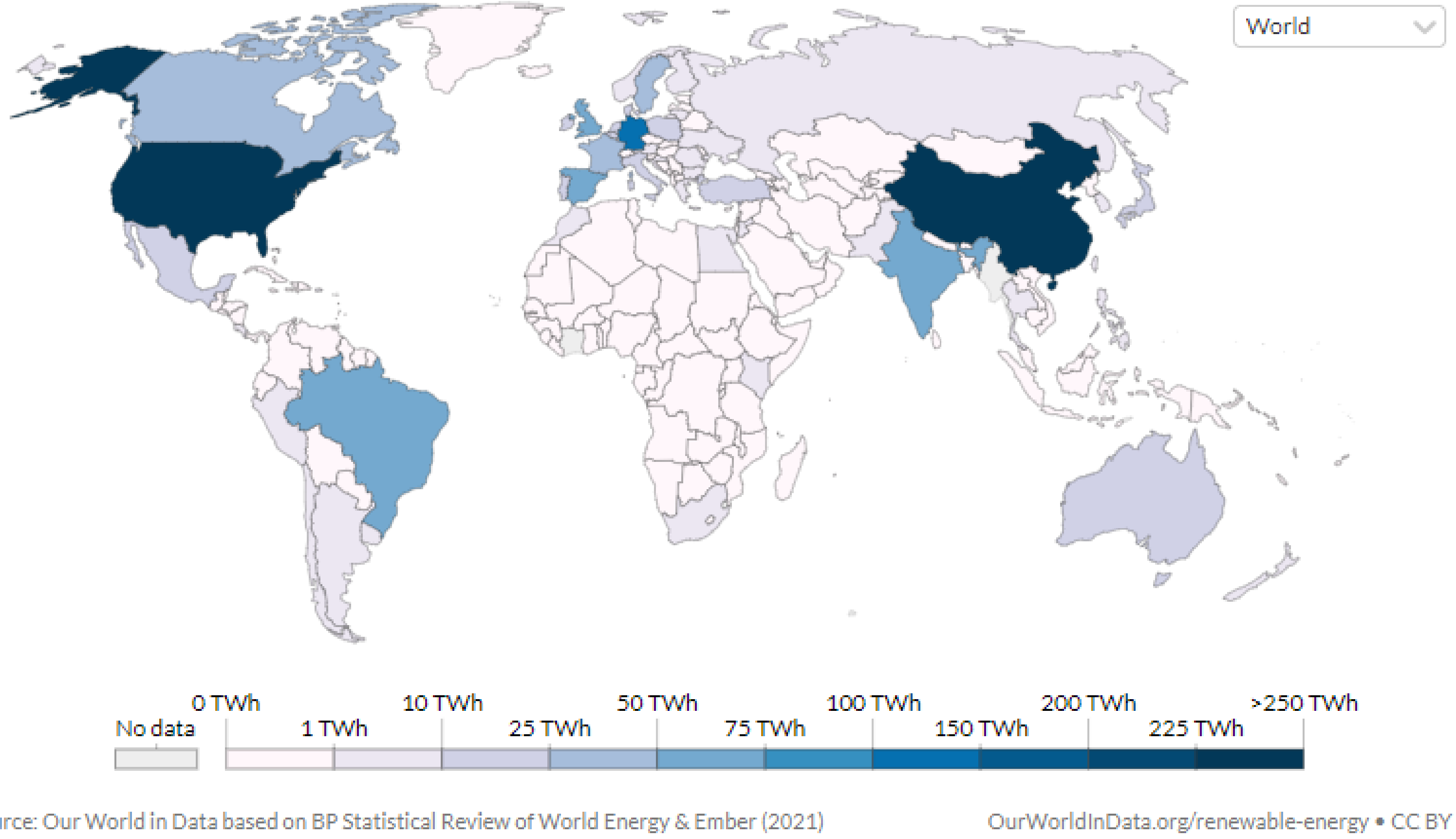

Source: Hannah Richie/Max Roser (Our World in Data), Renewable Energy - Wind energy generation, 2020.

2. RE Cost Development
→ Full load hours matter

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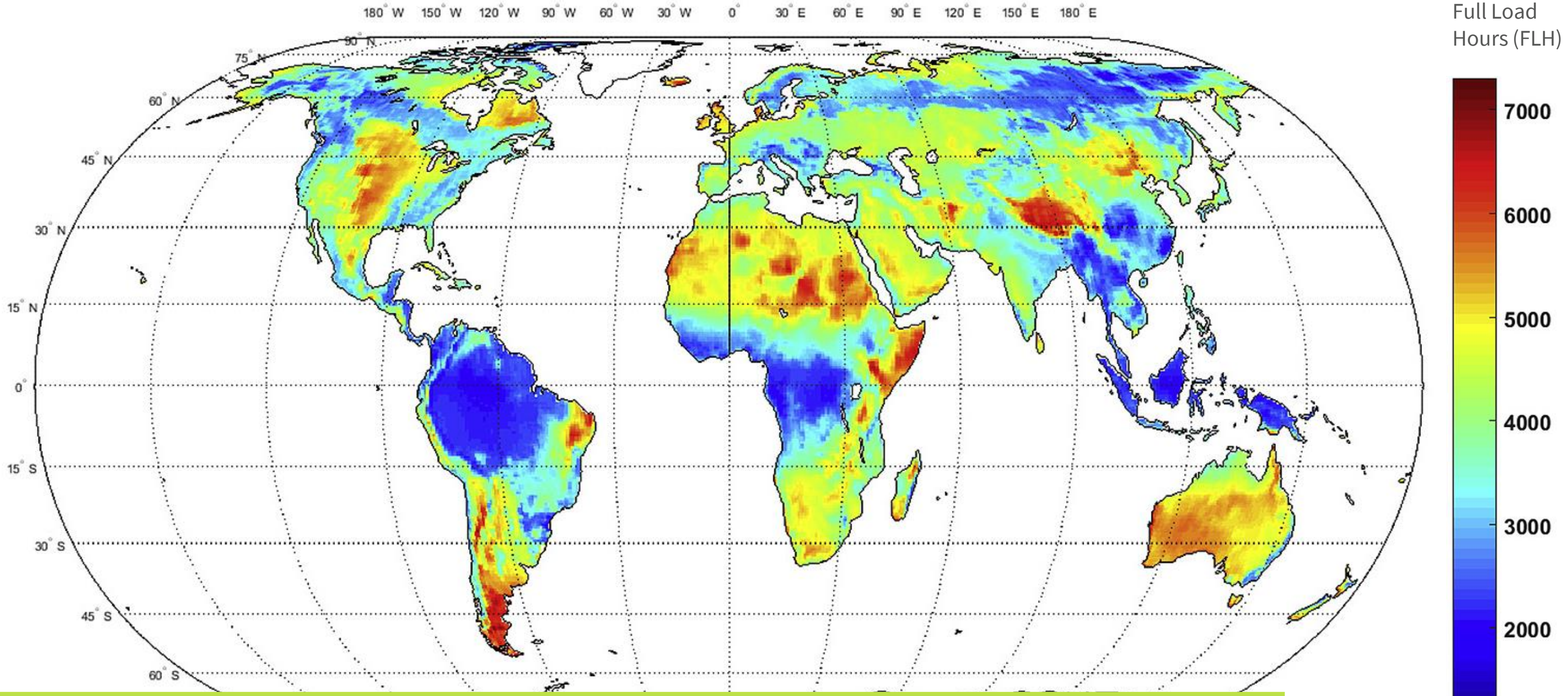

High FLH needed → Locations with PV and wind as hybrid systems are best locations!
Also: locations with large hydropower and geothermal potential

Source: Fasihi Mahdi & Breyer Christian (Journal of Cleaner Production), Baseload electricity and hydrogen supply based on hybrid PV-wind power plants, 2020, p.9/fig.8.

2. RE Cost Development

Each GW electrolysis must come with 1-4 GW of additional renewables power!

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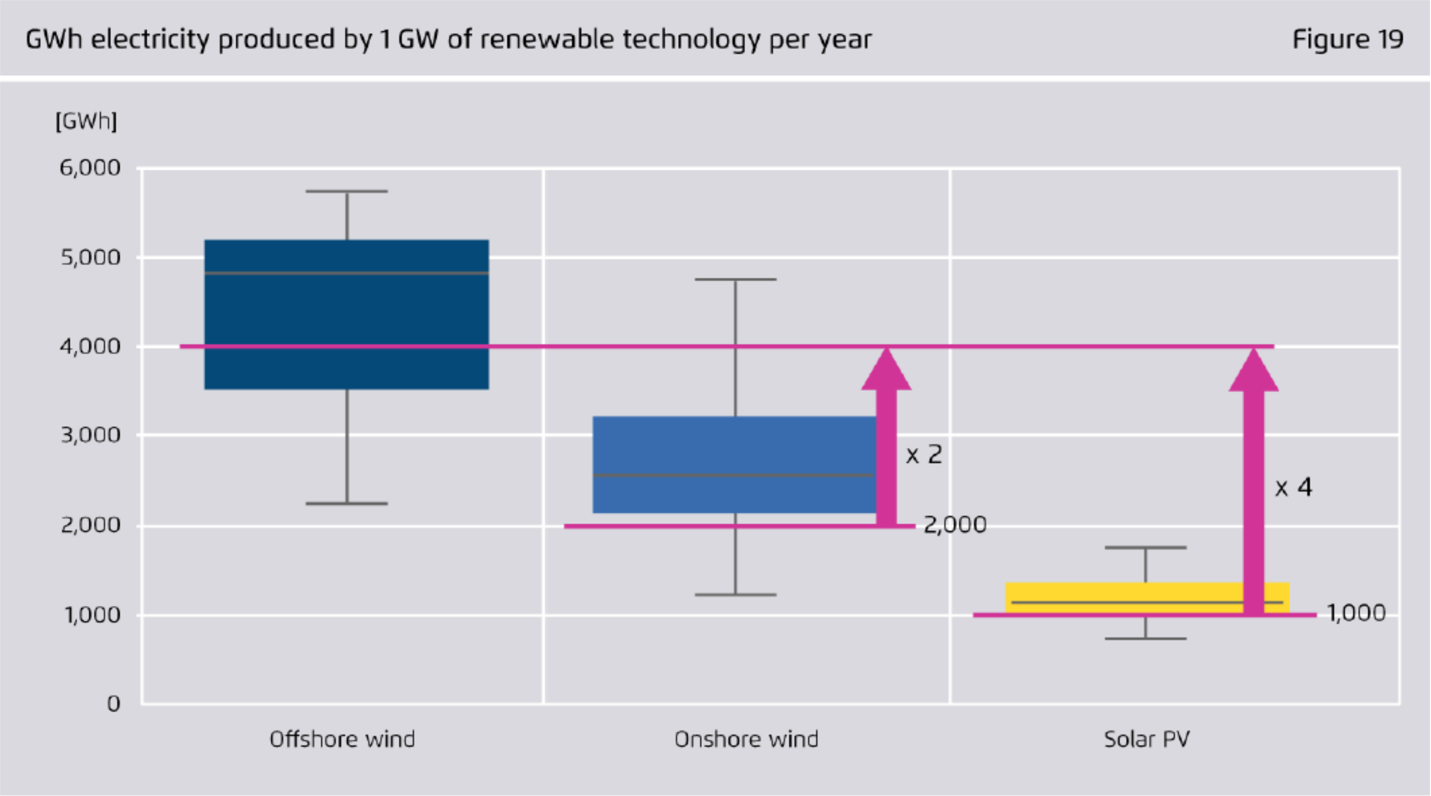
→ We need massive deployment of renewables!



Source: Agora Energiewende, Agora Industry (2021): 12 Insights on Hydrogen , p. 32

2. RE Cost Development

Cost development of power sources in Germany

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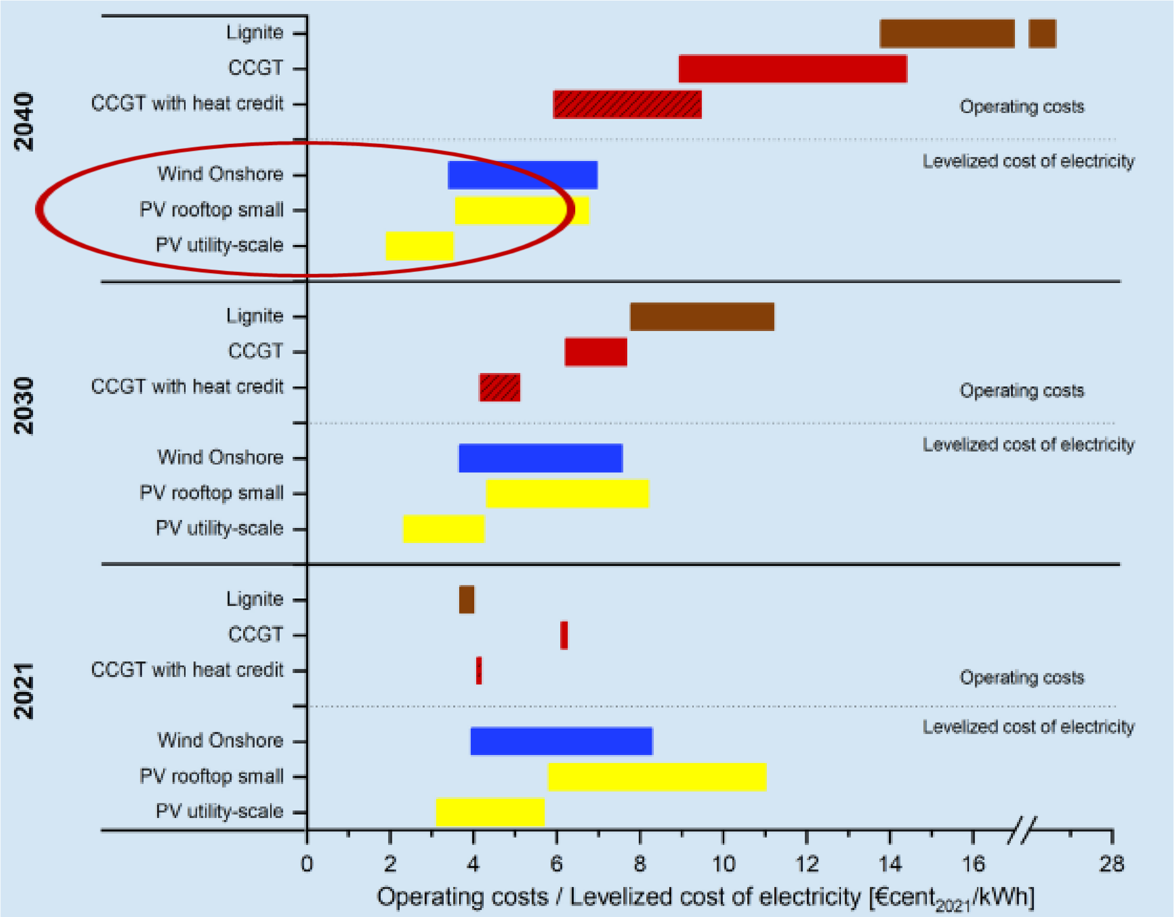

Source: Fraunhofer ISE, Levelized Cost of Electricity Renewable Energy Technologies, 2021, p.5.

Comparison of **LCOE of newly installed** PV and onshore wind power plants with **operating costs of existing** lignite-fired and CCGT power plants (in Germany).

Note: Cost of lignite and gas power increase due to carbon pricing

$$\text{LCOE} = \frac{\text{Sum of costs over lifetime (CAPEX + OPEX)}}{\text{sum of electricity produced over lifetime}}$$

Open discussion/ Break out groups

"What are the biggest challenges to reduce RE power costs in your country?"
What shall be done?

3. Electrolyser Cost Development

Test your knowledge

"What do you think will drive the reduction of electrolyser cost in future?"

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3. Electrolyser Cost Development

Cost breakdown for alkaline electrolysers (current costs)

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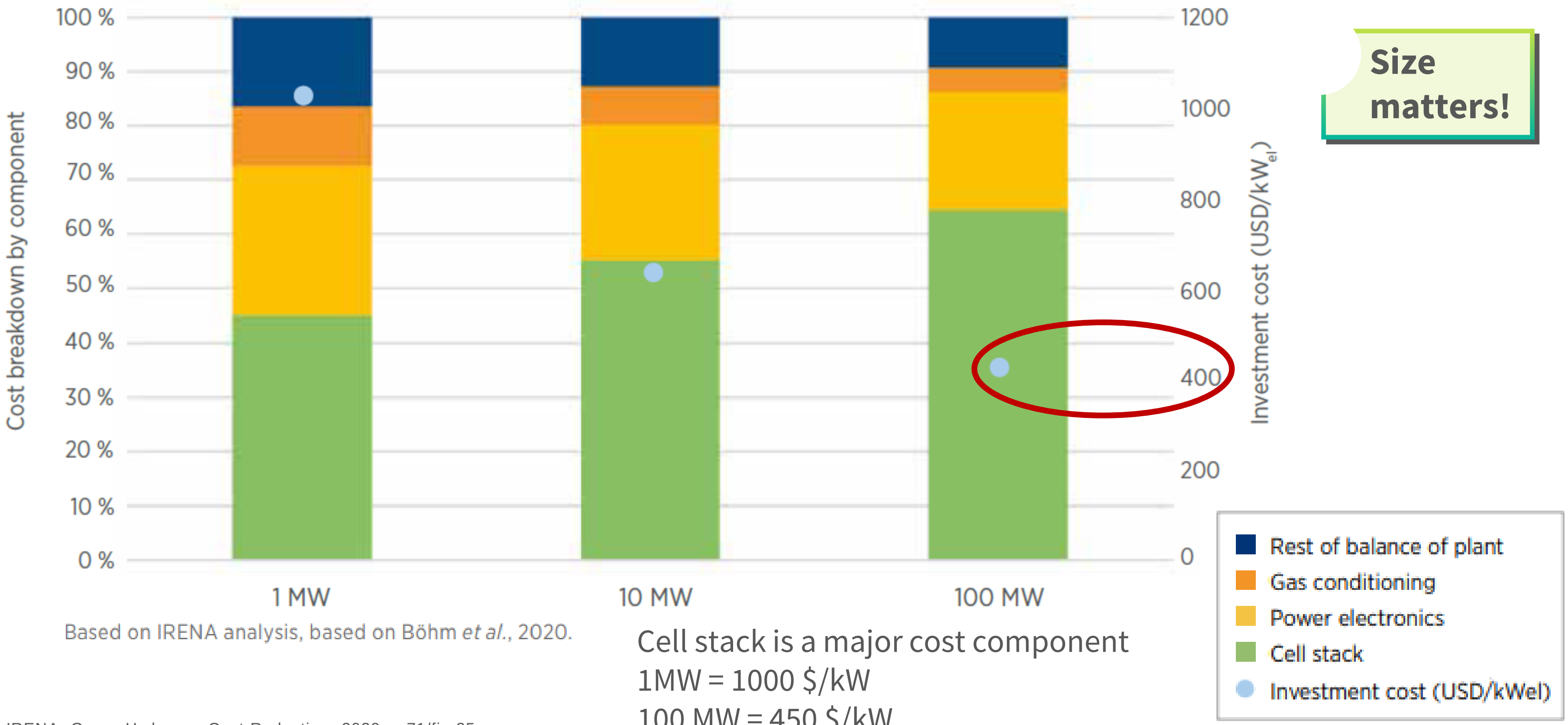


Based on IRENA analysis, based on Böhm *et al.*, 2020.

Size matters!

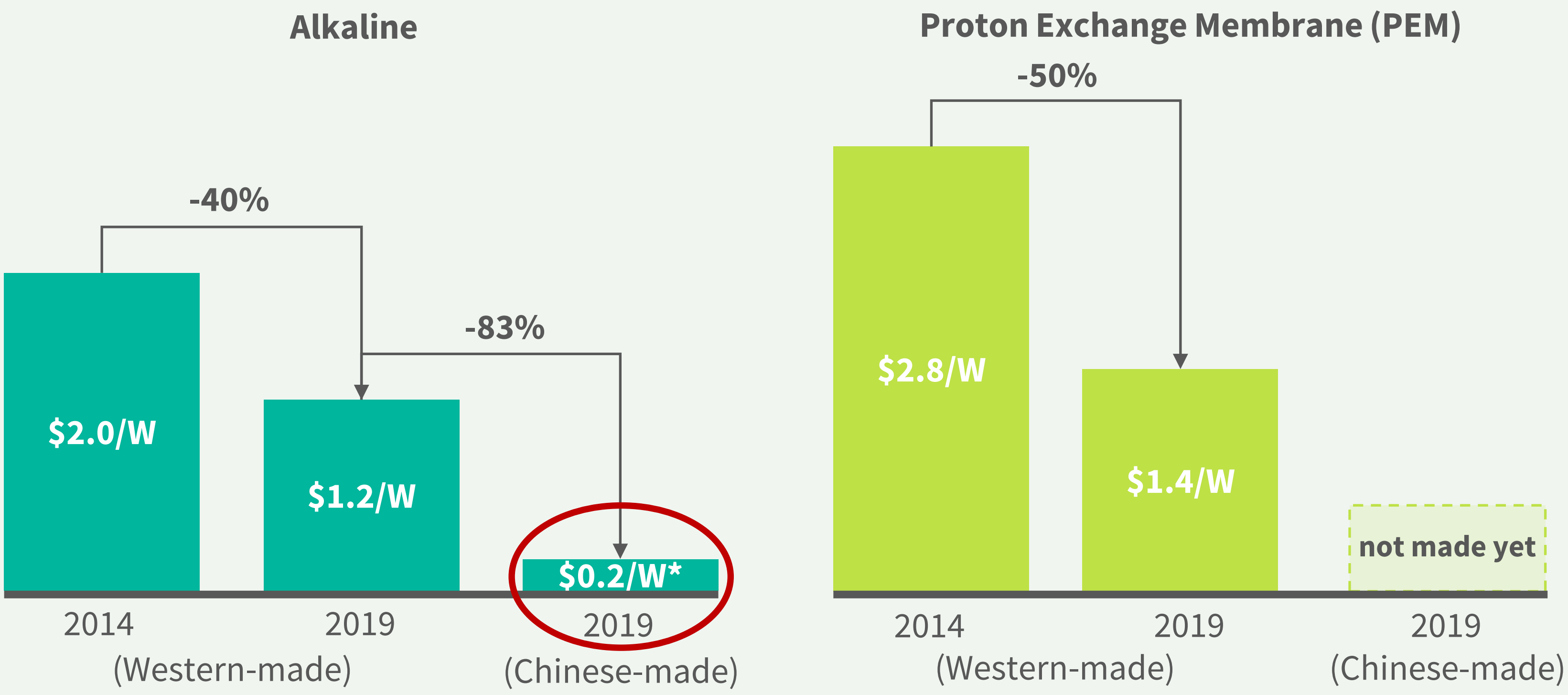
Cell stack is a major cost component
1MW = 1000 $/kW
100 MW = 450 $/kW

Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.71/fig.25.

3. Electrolyser Cost Development

Cost development of electrolysers in last years

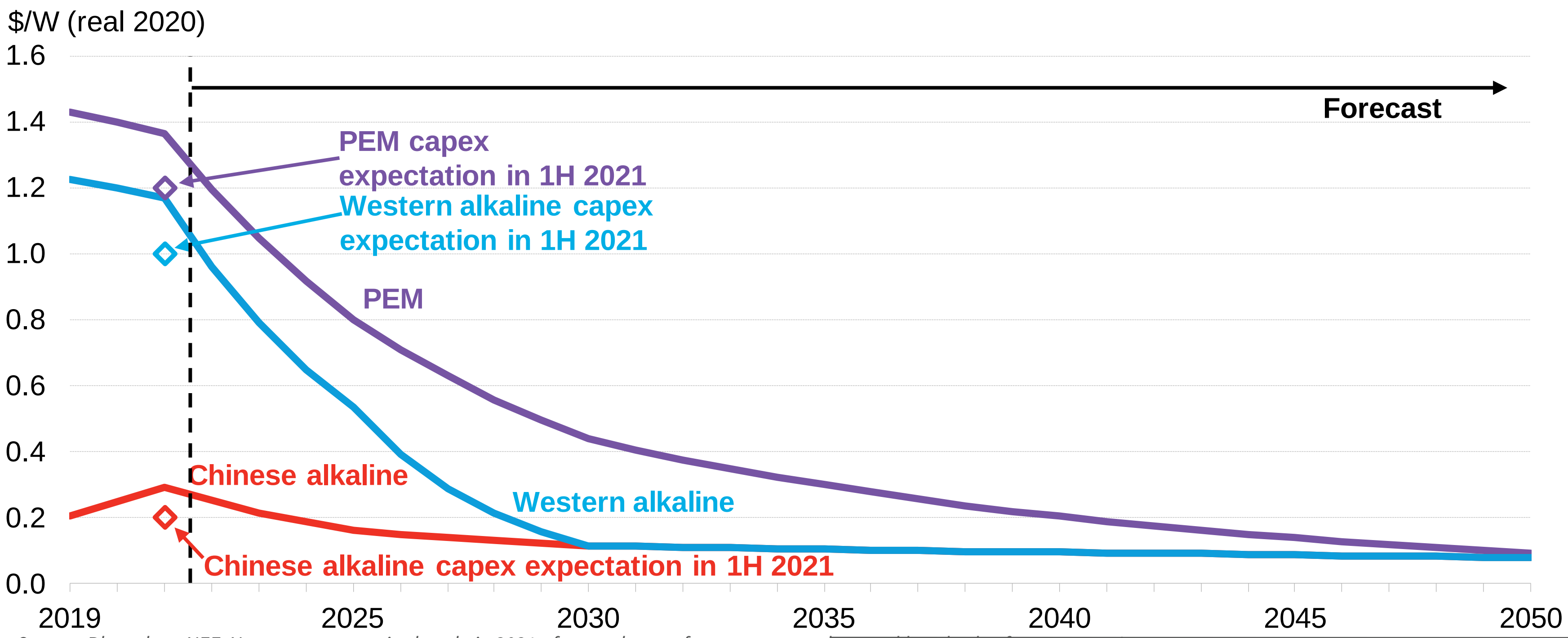
Costs have been falling



*approximate values and subject to change according to technological improvements and material costs.

Source: Own illustration based on: BloombergNEF, Hydrogen Economy Outlook, 2020.

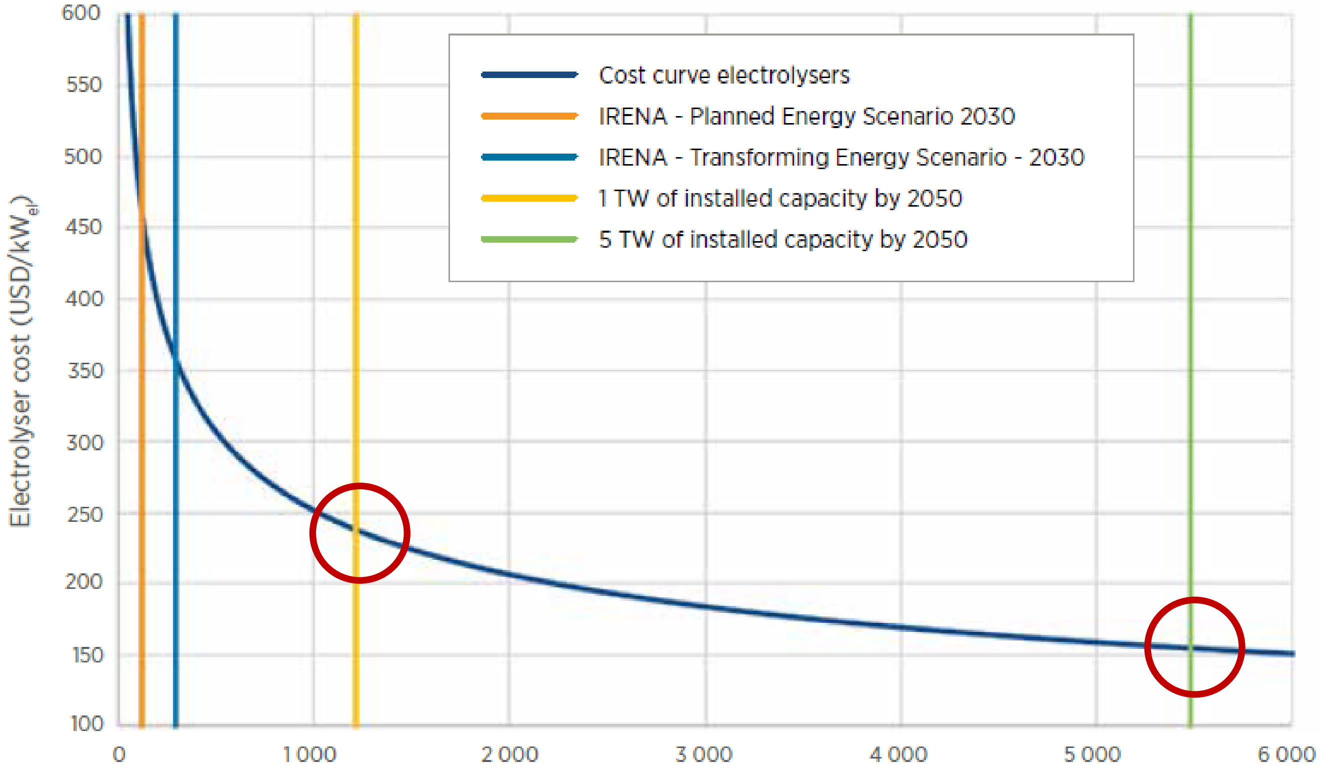
Benchmark electrolysis system capex



Source: BloombergNEF. Note: assumes a single sale in 2021 of several tens of megawatts and several hundreds of megawatts in 2025.

3. Electrolyser Cost Development

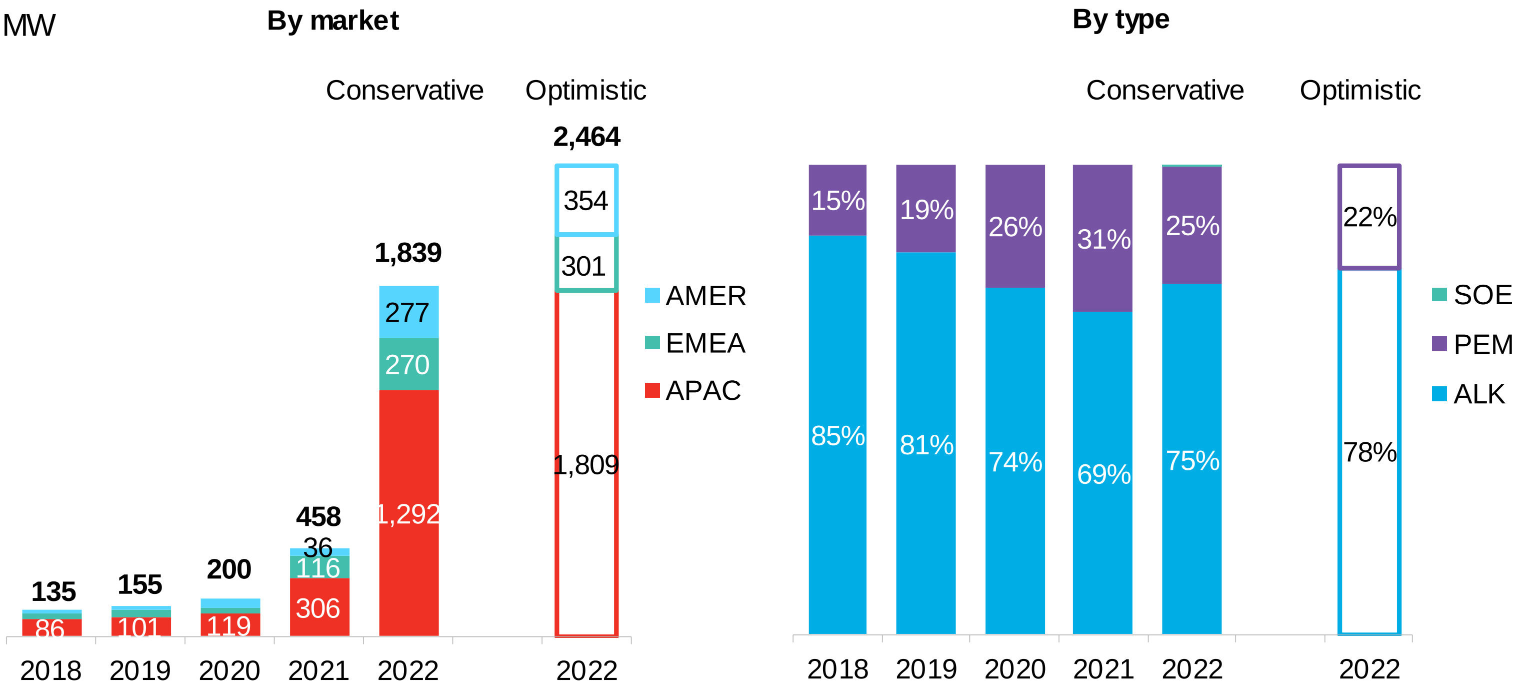
Future cost development of electrolysers as function of installed capacity (expected learning curve)



Notes:
1 TW of installed capacity by 2050 is about 1.2 TW of cumulative capacity due to lifetime and replacement. Similarly, 5 TW by 2050 is equivalent to 5.48 TW of cumulative capacity deployed.
(Based on IRENA analysis).

Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.79/fig.29.

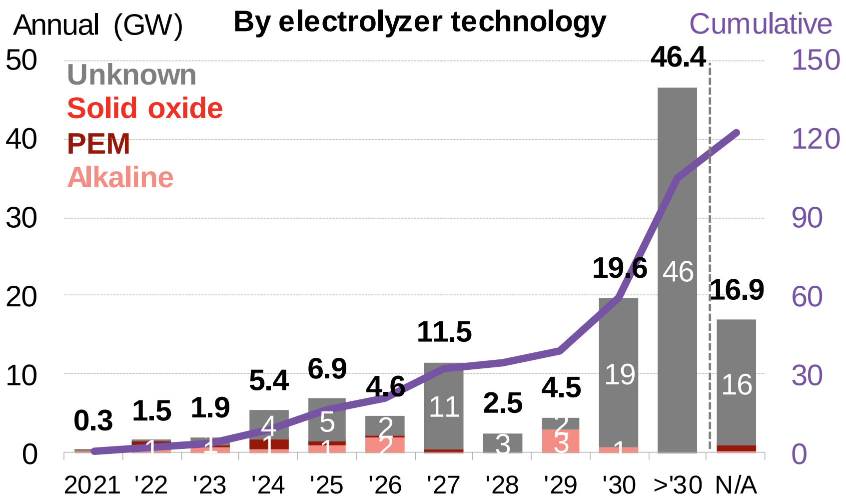
Estimate and forecast of annual electrolyzer shipment, 2018-22



Source: *BloombergNEF*

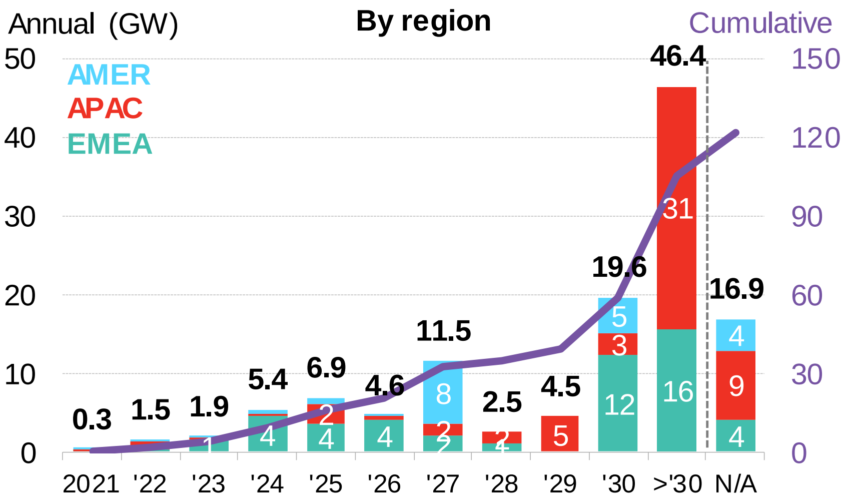
Announced electrolysis pipeline

By electrolyzer technology



Source: BloombergNEF

By region



Source: BloombergNEF

4. Scale-Up and Outlook for Hydrogen and PtX Production

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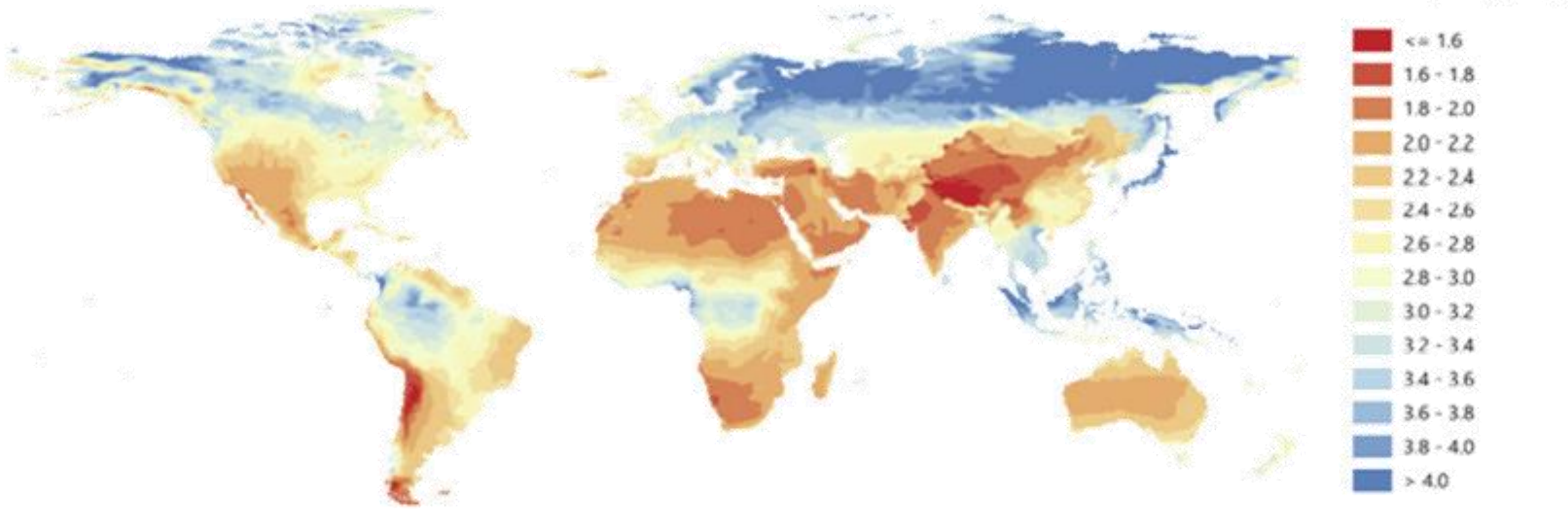
4. Scale-up and Outlook for H2 and PtX Production

Current Production costs of green hydrogen depends on combination of Wind and PV resources

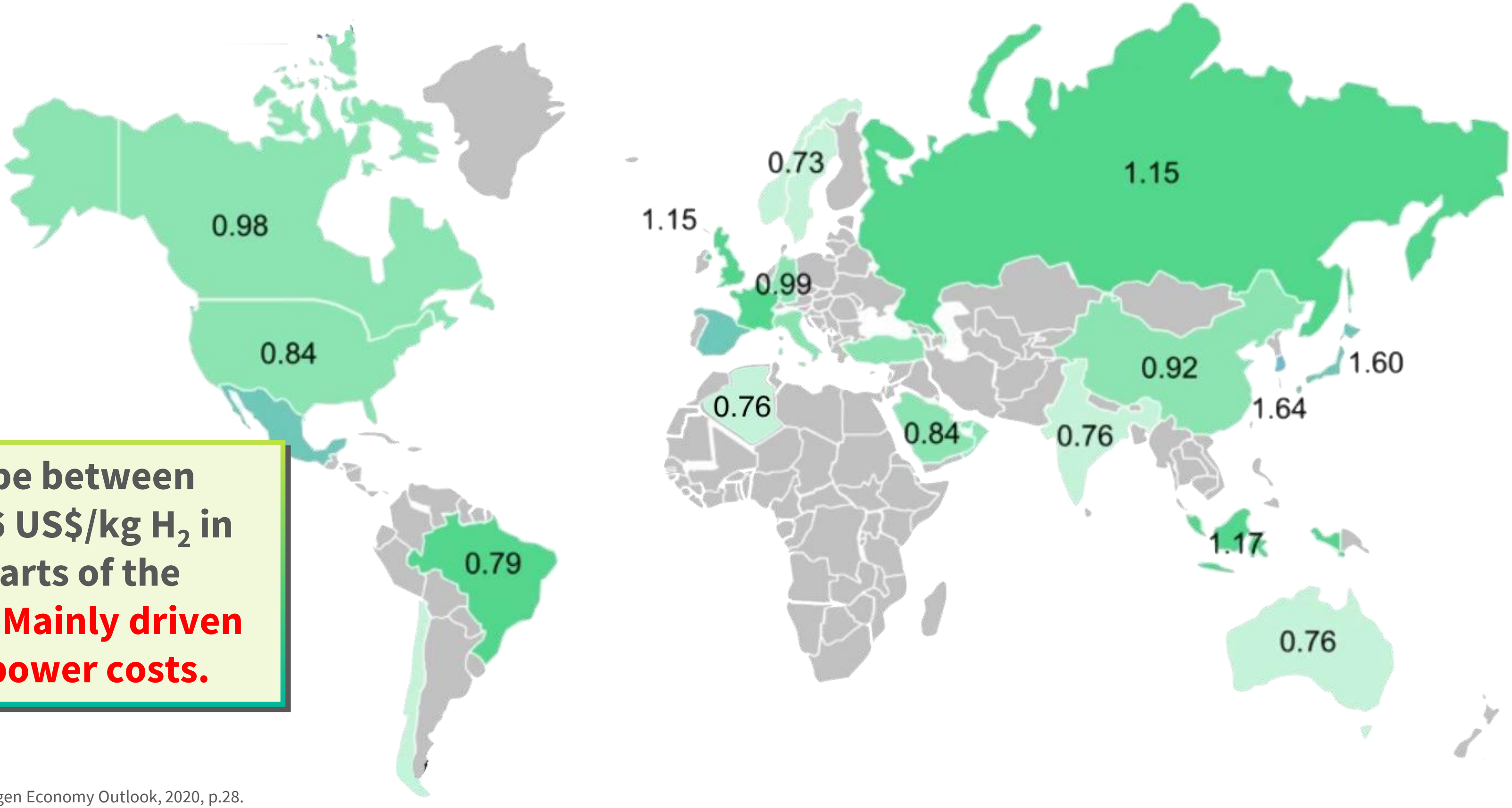


Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Electrolyser CAPEX = USD 450/kWe, efficiency (LHV) = 74 %; solar PV CAPEX and onshore wind CAPEX = between USD 400–1 000/kW and USD 900–2 500/kW depending on the region; discount rate = 8 %.

Source: Sachverständigenrat für Umweltfragen, Wasserstoff im Klimaschutz: Klasse statt Masse, June 2021, p.48/fig.8.

4. Scale-up and Outlook for H2 and PtX Production

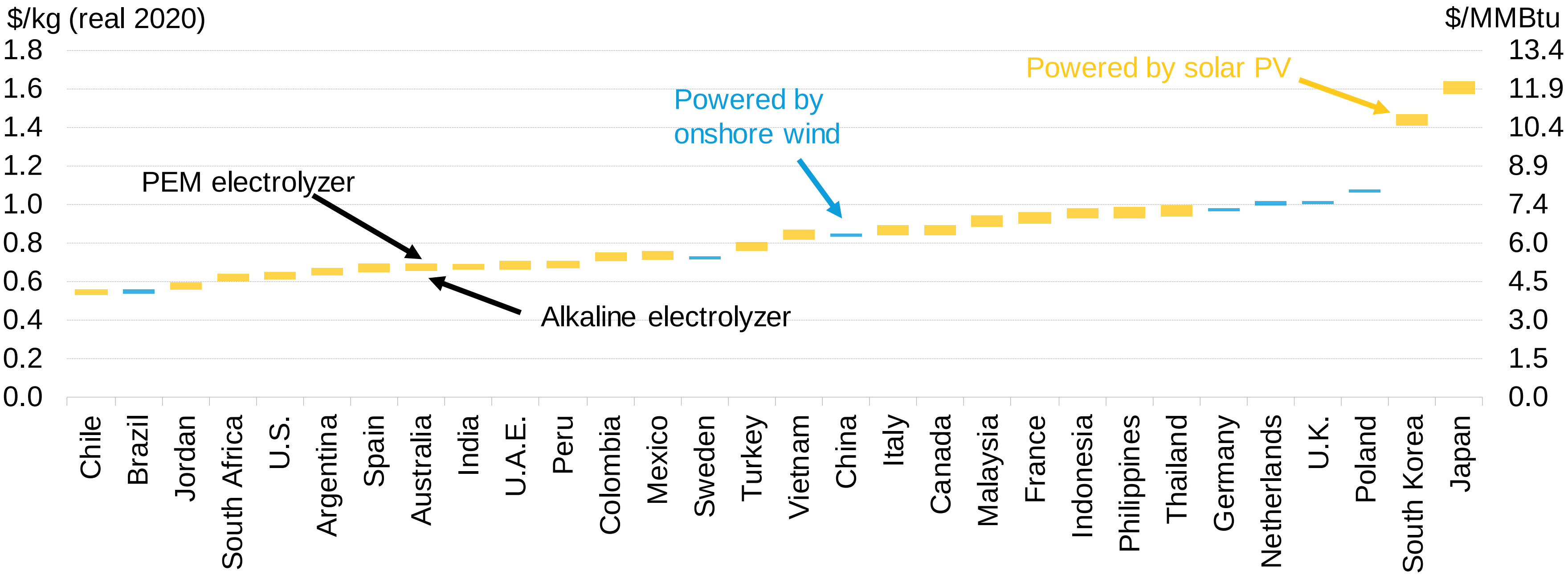
For latest 2050 according to BNEF: Levelised cost of green hydrogen production in $/kg H2



Could be between 0.8–1.6 US$/kg H_2 in most parts of the world; **Mainly driven by RE power costs.**

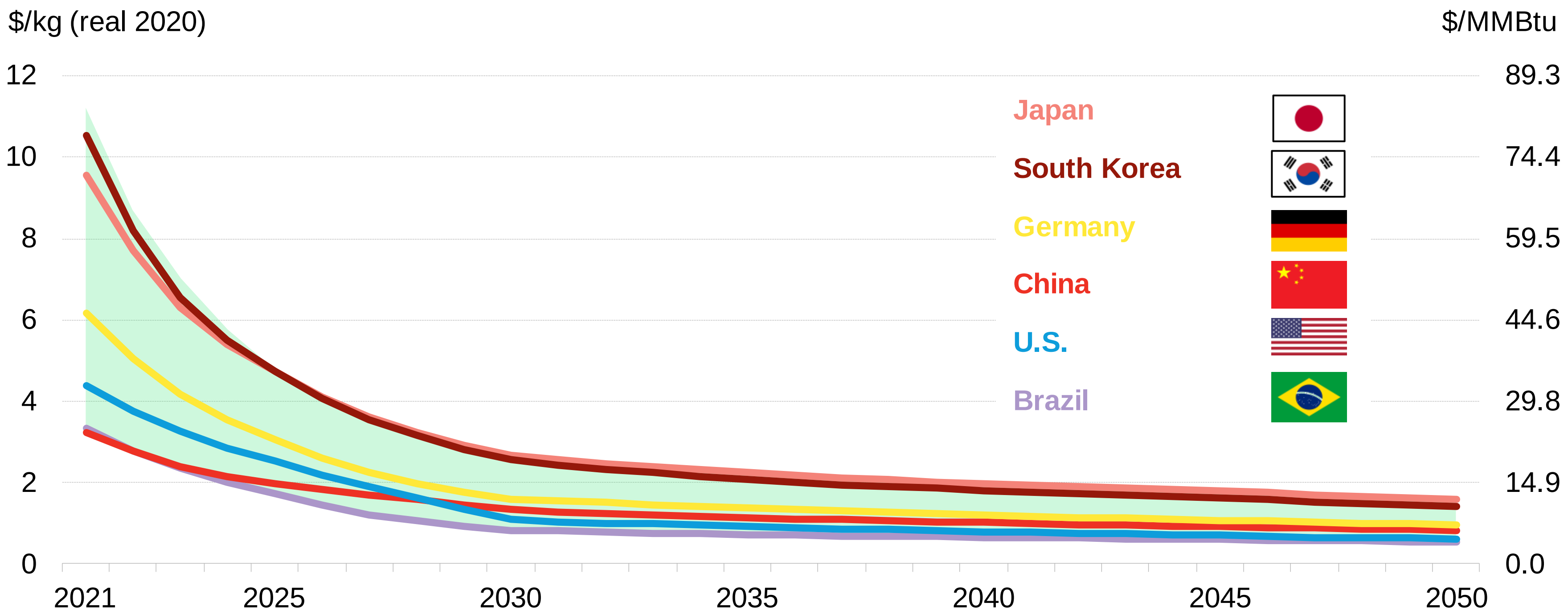
Source: BloombergNEF, Hydrogen Economy Outlook, 2020, p.28.

$LCOH_2$ from renewable electricity, 2050



Source: BloombergNEF. Assumes electrolyzer costs converge to those in Hydrogen: The Economics of Production From Renewables (web | terminal). Electricity costs derived from BNEF's 1H 2021 LCOE Update (web | terminal), mid scenario. These electricity costs were further discounted by 25% (wind) and 26% (PV) to account for savings from co-locating H_2 production with renewables and faster renewable energy cost reduction caused by extra H_2 demand.

Levelized cost of hydrogen production from renewable electricity, 2021-2050



Source: BloombergNEF. Note: assumes our optimistic alkaline electrolyzer costs (Chinese in China, western elsewhere). See rest of report for data on all 30 markets.

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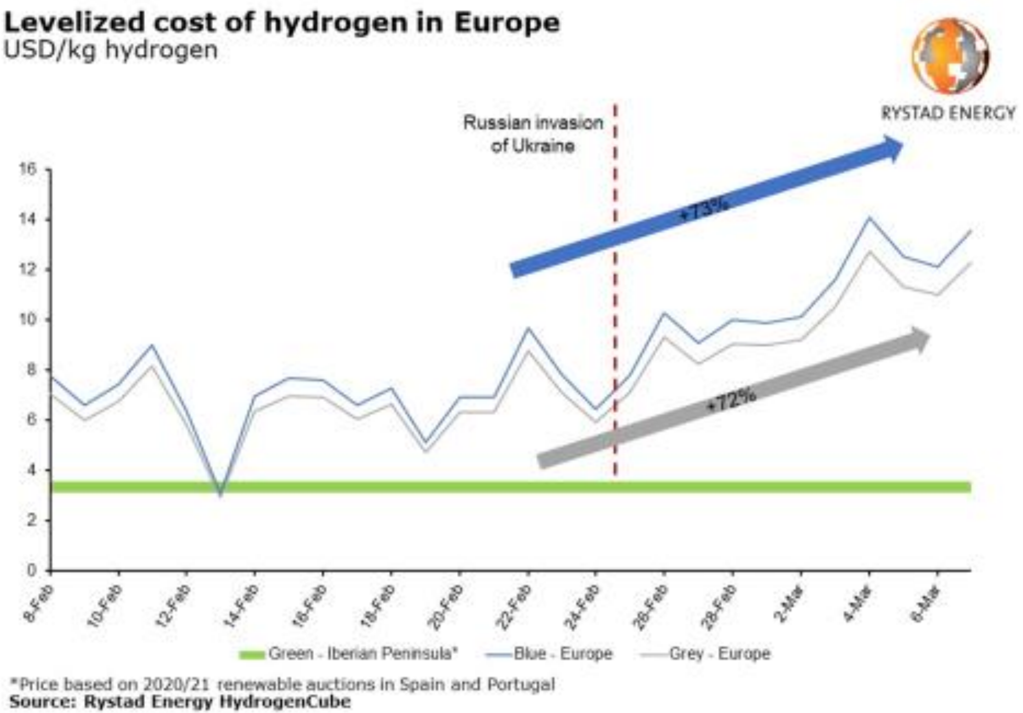
1. Green Hydrogen Production Cost

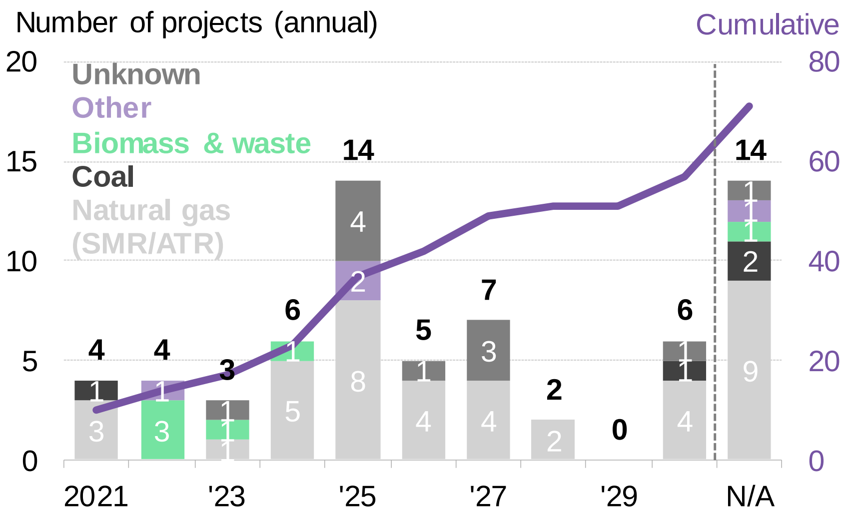
Impact of Russian war on blue hydrogen costs in Europe



Source: PV Magazine, Invasion of Ukraine an inadvertent boost for green hydrogen, 03/2022.

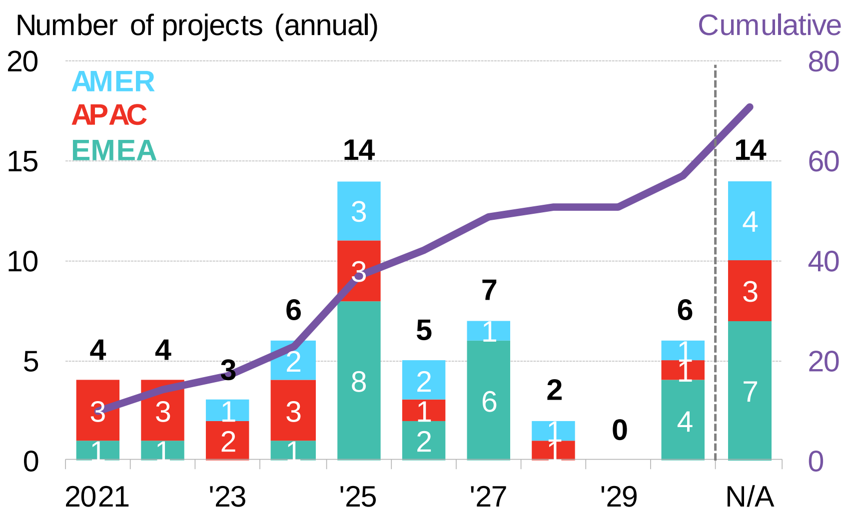
Announced pipeline of H_2 production projects with CCS

By fuel source



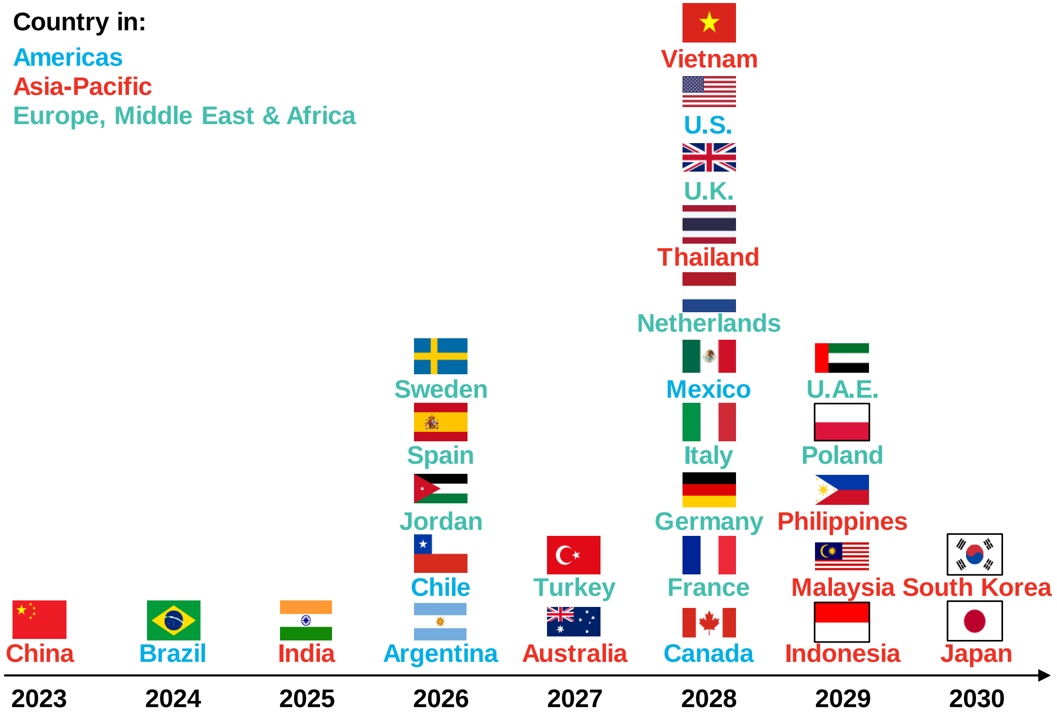
Source: BloombergNEF

By region



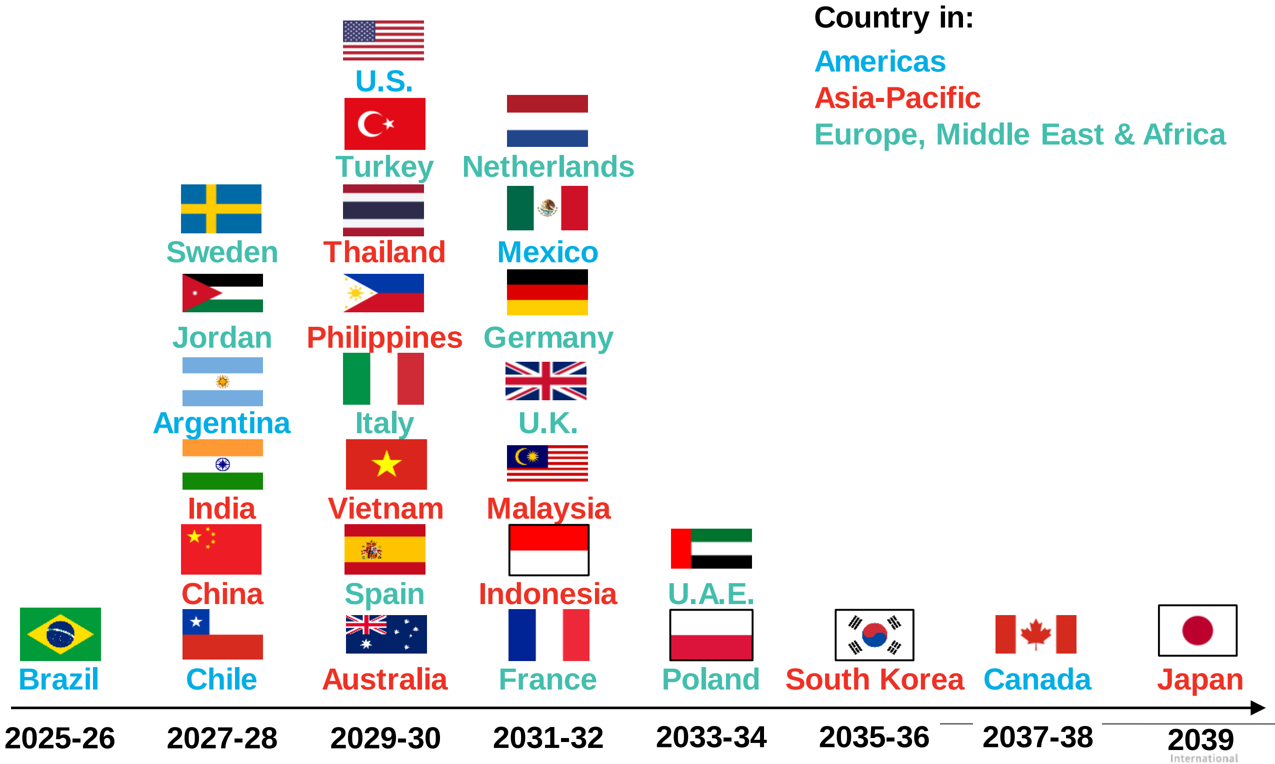
Source: BloombergNEF

Year when ‘green’ H_2 outcompetes ‘blue’ H_2



Source: BloombergNEF

Year when new 'green' H_2 outcompetes new 'gray' H_2

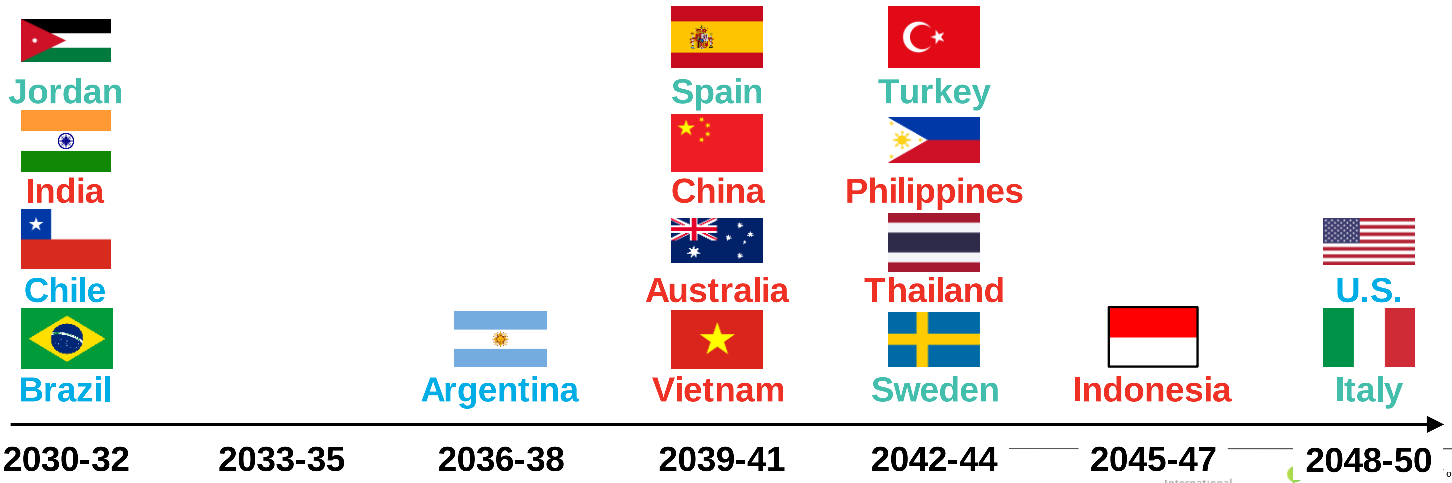


Source: BloombergNEF. Flags: Wikimedia. Note: assumes our optimistic alkaline electrolyzer cost scenario (Chinese for China, otherwise western) and 20-year gas price outlook averages. Argentina gas price assumed same as Brazil. Jordan gas prices based on average of oil-indexed LNG, Henry Hub-indexed LNG and spot LNG. Actual prices could differ from this assumption. Columns in ascending alphabetical order from bottom to top for each year. For example, this means that Chile, China and India reach the tipping point in in 2027, while Argentina, Jordan and Sweden reach it in 2028.

Year when new ‘green’ H_2 outcompetes natural gas

Country in:

Americas
Asia-Pacific
Europe, Middle East & Africa



Source: BloombergNEF. Flags: Wikimedia. Assumes our optimistic alkaline electrolyzer cost scenario and 20-year gas price outlook averages. Note: Argentina gas price assumed same as Brazil. Jordan gas prices based on average of oil-indexed LNG, Henry Hub-indexed LNG and spot LNG. Actual prices could differ from this assumption

Test your knowledge

"What are the main drivers for future cost reductions for green hydrogen?"

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4. Scale-up and Outlook for H2 and PtX Production

How to achieve 85% reduction of green hydrogen production costs in the future?

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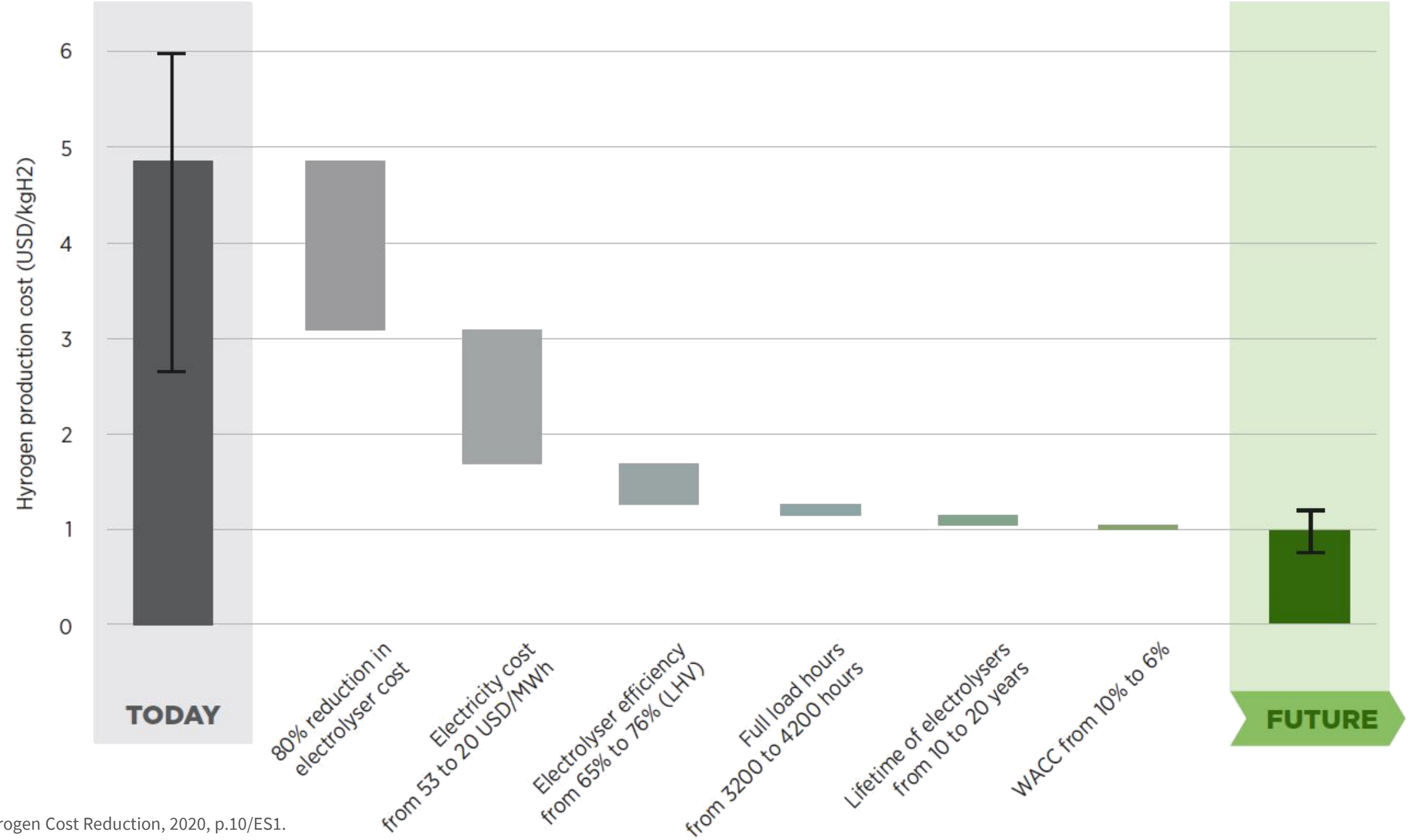
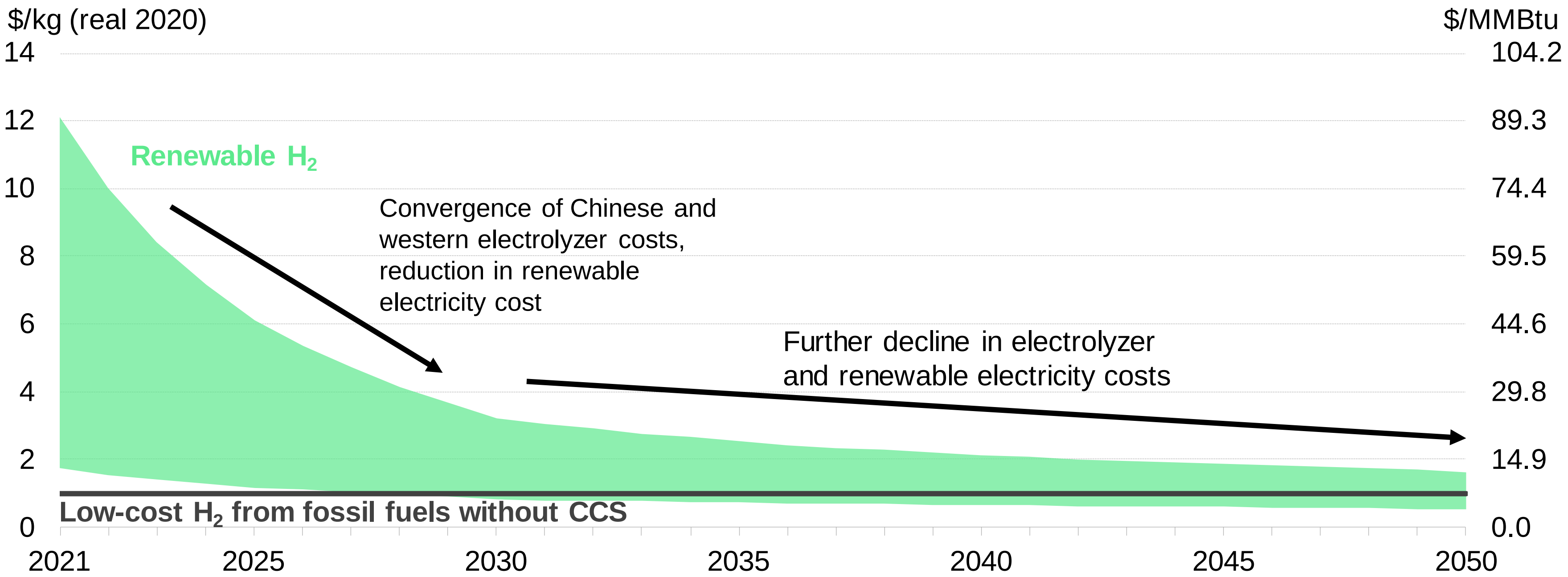


Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.10/ES1.

$LCOH_2$ from cheapest available renewable power in 30 countries

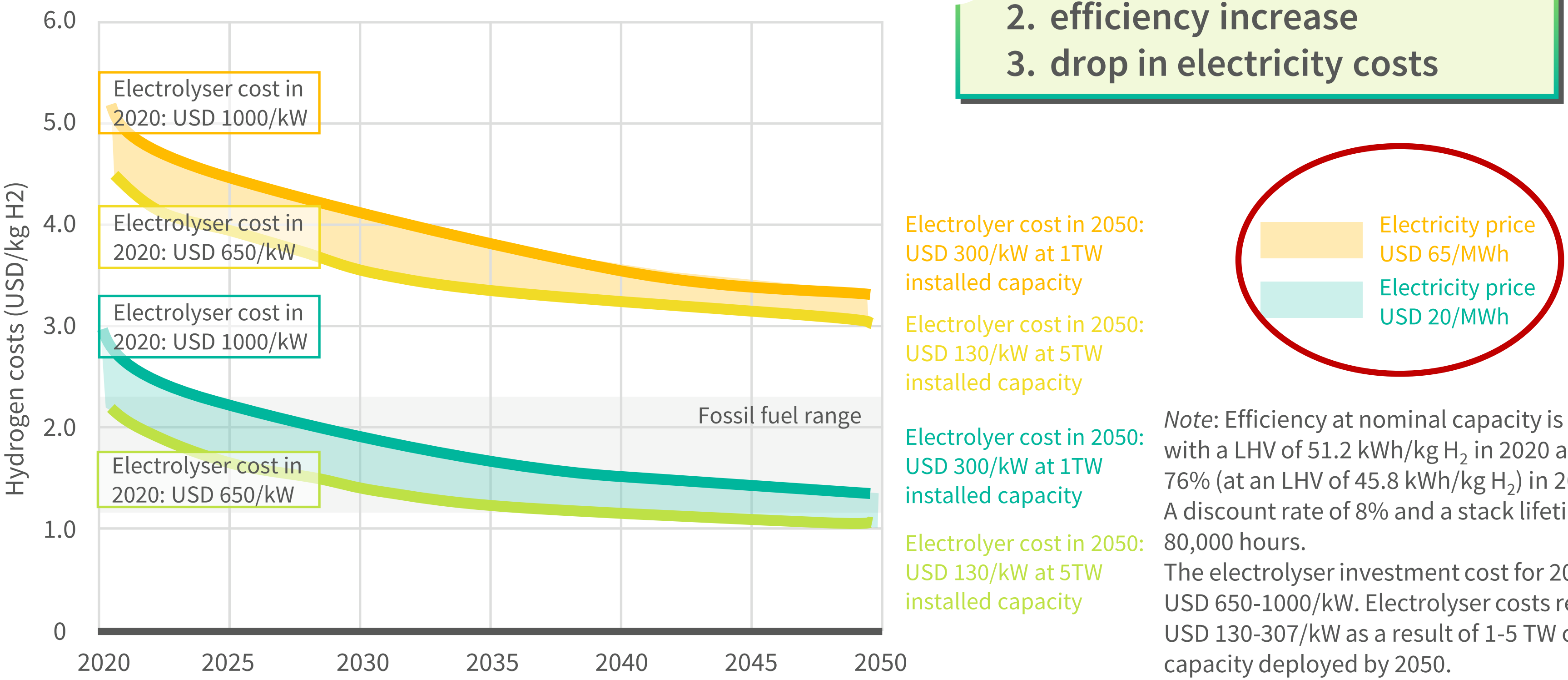


Source: BloombergNEF. Assumes 2021 Chinese alkaline electrolyzer costs of $0.3/W, western alkaline electrolyzer costs of $1.2/W and PEM electrolyzer costs of $1.4/W (see Appendix). By 2030, costs are assumed to converge to those listed in Hydrogen: The Economics of Production From Renewables (web | terminal). Electricity costs derived from BNEF's 1H 2021 LCOE Update (web | terminal), mid scenario.

4. Scale-up and Outlook for H2 and PtX Production

Green hydrogen costs will decrease based on:

1. electrolyser cost reduction
2. efficiency increase
3. drop in electricity costs

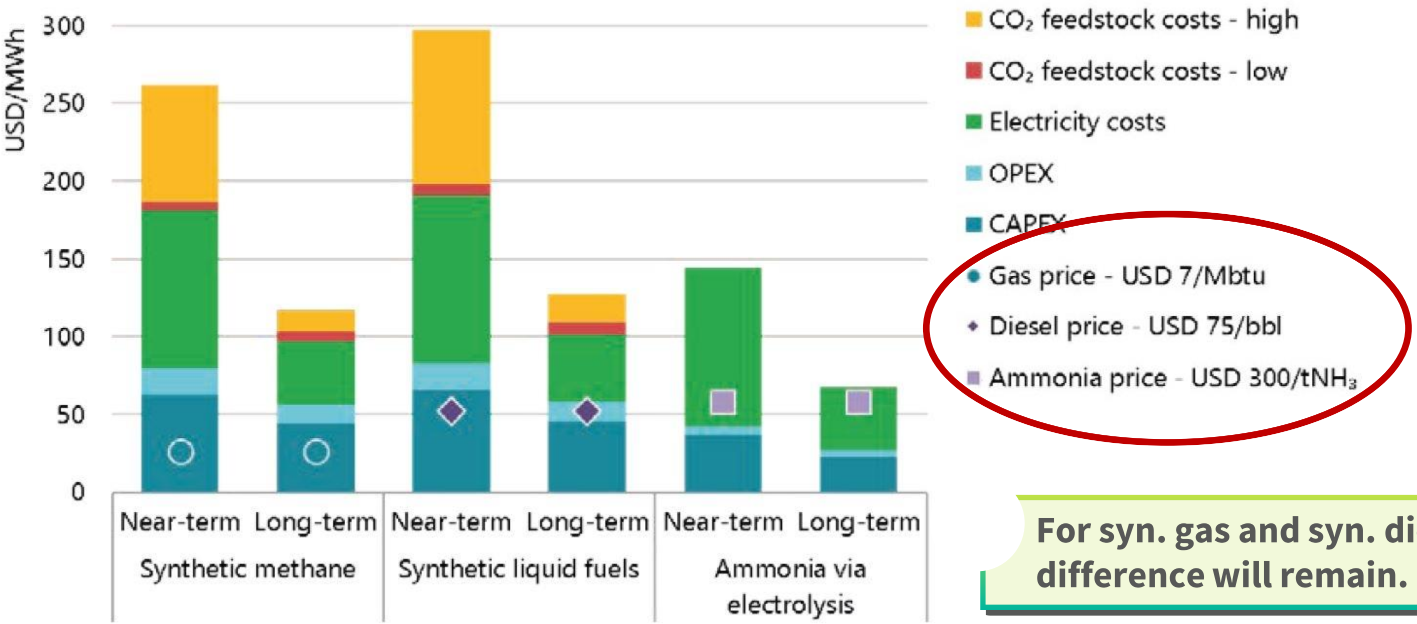


Note: Efficiency at nominal capacity is 65% with a LHV of 51.2 kWh/kg H_2 in 2020 and 76% (at an LHV of 45.8 kWh/kg H_2) in 2050. A discount rate of 8% and a stack lifetime of 80,000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.11/ES2.

Competitiveness of future production costs for PtX products

Update End of March 2022:
Gas up to 4 x higher (EU nat. gas import: 30 \$/MMbtu = 100 \$/MWh)
Diesel: Oil EU Brent up by 60% (EU Brent 120 \$/bbl)
Ammonia up to 3,5 x higher (Ammonia price 1100\$/t NH3)



High feedstock CO_2 costs:
DAC = 400 US\$/t short term - 100 \$/t long term

Low feedstock CO_2 costs:
Bio CO_2 = 30 US\$/t

Assumption: Ammonia price at electricity price of USD 50/MWh at 3.000 FLH near term &
USD 25/MWh in long-term

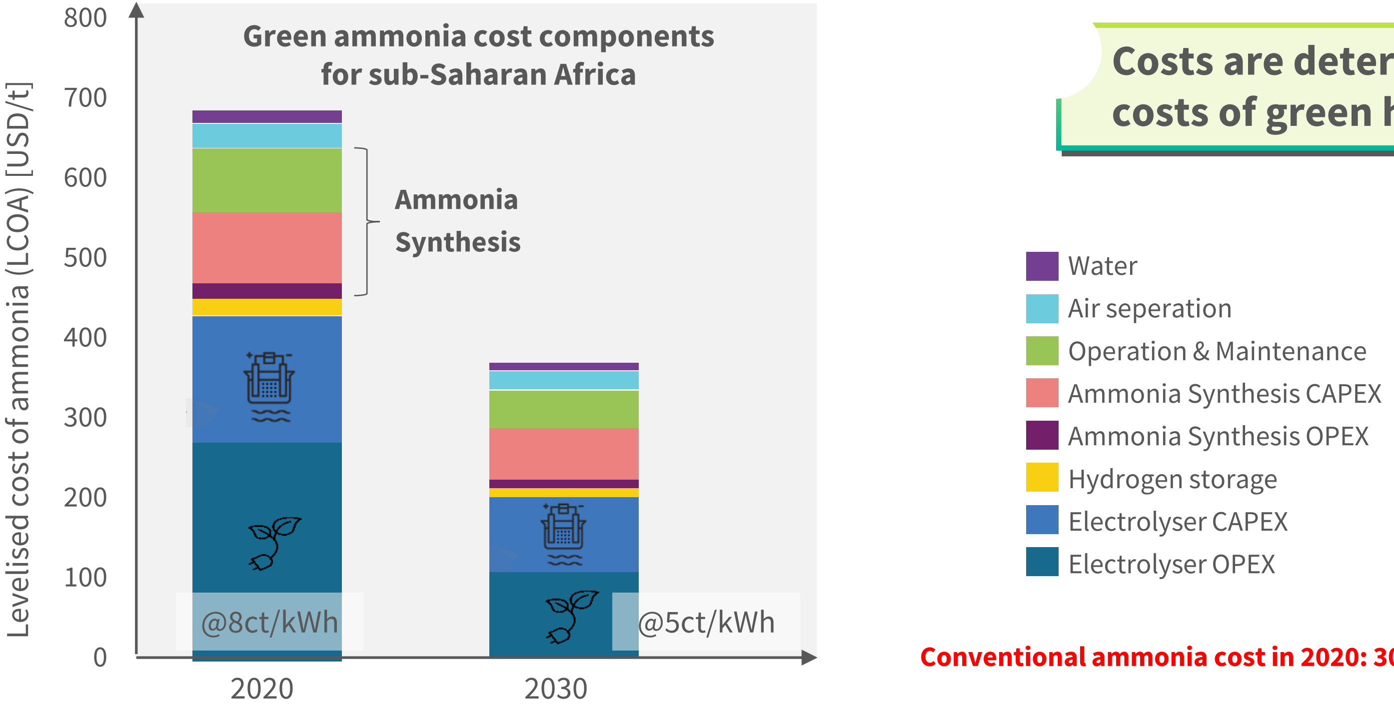
For syn. gas and syn. diesel a large price difference will remain.

For ammonia the near future looks brighter.

Source: IEA, The Future of Hydrogen, 2019, p.60/fig.22.

4. Scale-up and Outlook for H2 and PtX Production

Cost development of green ammonia prodution



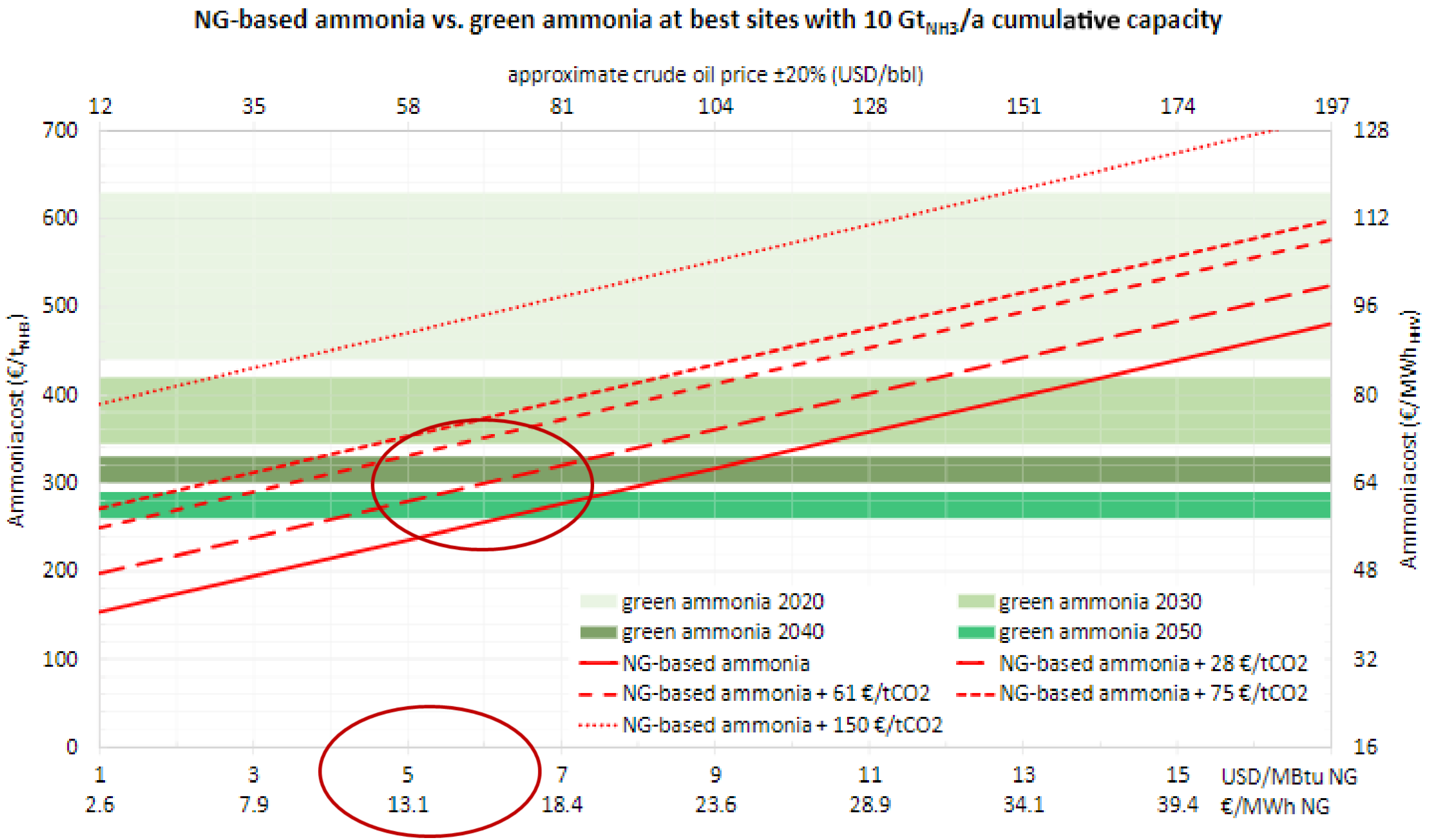
Costs are determined by costs of green hydrogen

Conventional ammonia cost in 2020: 300 US$/t, now up to 650 US$/t

Source: Richard Michael Nayak-Luke & René Bañares-Alcántara Royal society of chemistry, Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production, 2020.

4. Scale-up and Outlook for H2 and PtX Production

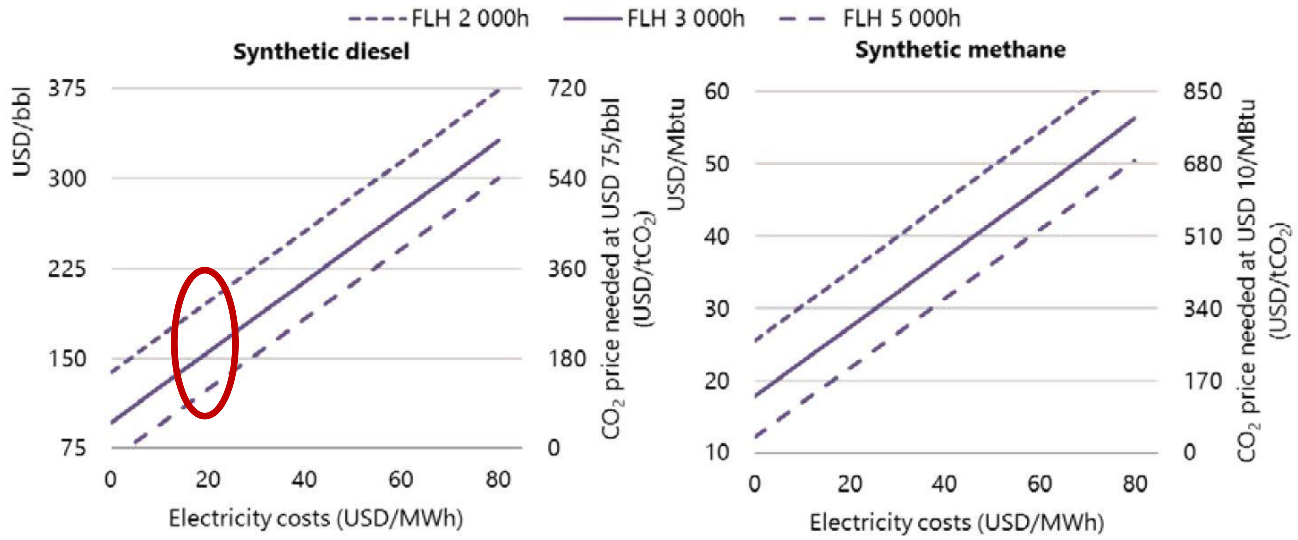
Cost development of green ammonia prodution



Source: Mahdi Fasihiet al., Global potential of green ammonia based on hybrid PV-wind power plants, Applied Energy 294, 2021, p.13/fig.14.

4. Scale-up and Outlook for H2 and PtX Production

Required CO_2 price to make syn. shipping fuel and syn. gas competitive



For syn. fuels to be competitive to fossil fuels **low electricity costs and high CO_2 prices needed!**

Higher FLH compensate electricity costs!

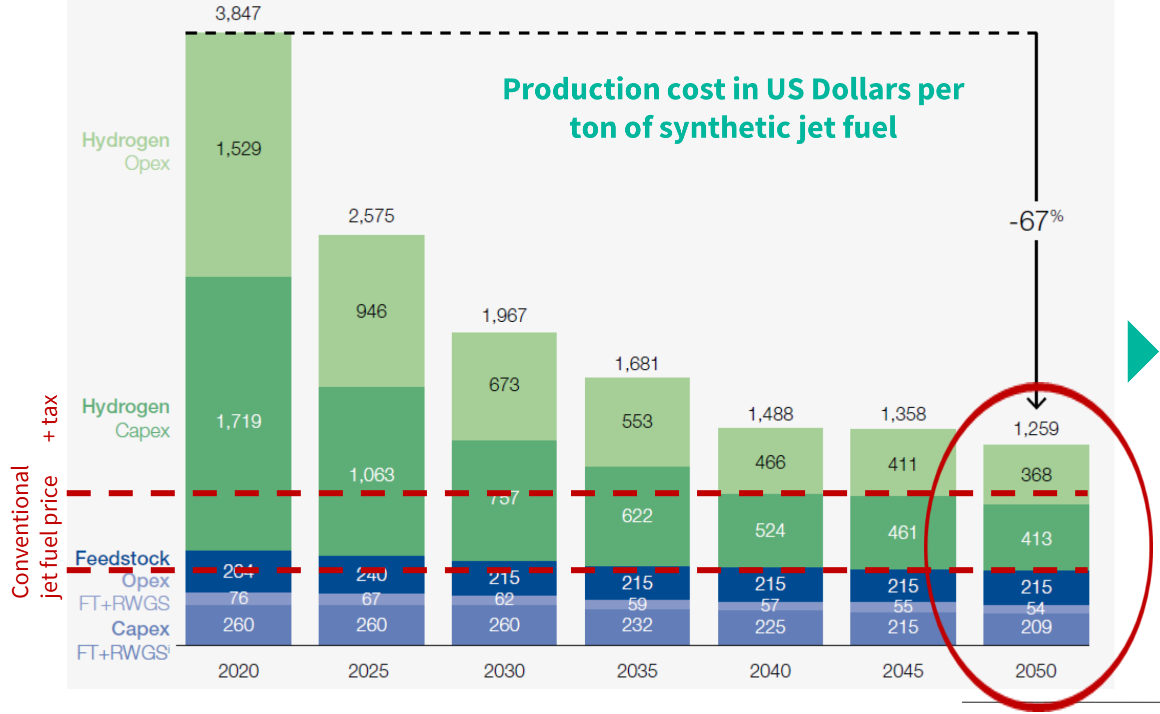
Production cost for synthetic shipping fuel and methane.

CO_2 price needed to reach competitiveness with fossil fuel at USD 75/bbl and with natural gas at USD 10/Mbtu.

Source: IEA, The Future of Hydrogen, 2019, p.62/fig.23.

4. Scale-up and Outlook for H2 and PtX Production

Synthetic jet fuel costs are driven by H_2 cost with potential to decline by 70% in 2050… But under which assumptions?



Water electrolysis + RWGS

- H_2 costs can vary greatly by power source and region
- shown for solar power-based H_2 at
  - 7.3 USD/kg H_2 in 2020
  - 3.2 USD/kg H_2 in 2030
  - 1.7 USD/kg H_2 in 2050

CO_2 feedstock

- Industrial CO_2 (shown in graph)
  - 81 USD/t in 2020
  - 66 USD/t by 2030
- Direct air capture *(not in graph)*
  - 600-800 USD/t in 2020
  - 100 USD/t by 2030

Source: World Economic Forum, Clean skies for tomorrow –sustainable aviation fuels as a pathway to net-zero aviation, 2020, p.39/fig.20.

MODULE 3: Key messages – 1/2

Production Cost of Green Hydrogen

- As the **major cost component for green H2 is the electricity supply**, cost decline is already underway through the competitive deployment of renewables. **By 2050 latest, green H2 is competitive**. The Ukraine war has made blue and grey hydrogen **uneconomical in Europe much earlier than expected**
- **Cost declines is expected for electrolysers** due to massive increase of production in scale and size in addition to increasing performance and durability.
- The **minimum of operating hours** per year for the electrolyzer are required beside the low cost of electricity to produce cost effective hydrogen → **Electricity cost matters**

Renewable Energy Generation Cost Development

- Overview RE costs worldwide showing that **LCOE of PV, wind etc. has come down by 80-90%** in last decade. It is expected that **further cost reduction will happen** especially for PV
- Many countries and regions in the world have good wind and good solar conditions to achieve sufficient FLH **through a combination of PV and Wind.**
- However, **massive RE deployment necessary** since 1 GW electrolysis comes with 1-4 GW of additional renewables

Electrolyser Cost Development

- In last years, **costs have come down** by expected learning curve due to number and size of projects (importance of **economies of scale,** like for PV modules

MODULE 3: Key messages -2/2

Scale-Up and Outlook for Hydrogen and PtX Production

- Many countries **will** be able to **produce green hydrogen for around 1 $/kg or lower in the longer future**, depending largely on RE power costs
- Up to 85% of green H2 **production costs can be reduced** in the long-term by a combination of cheaper electricity and electrolyser costs, in addition, to increased efficiency and optimized operation of the electrolyser

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Open discussion

"What are your findings and observations from the economics module?"

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Modules prepared by the
International PtX Hub Berlin

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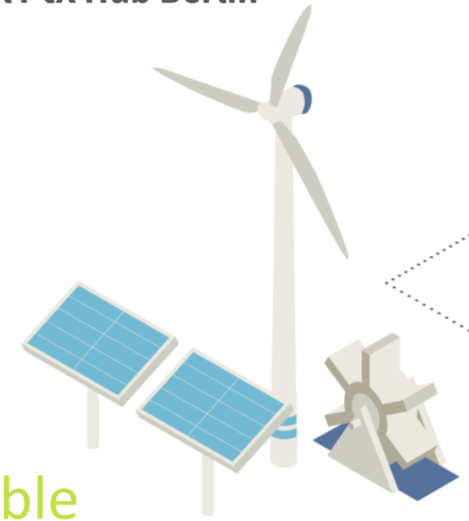

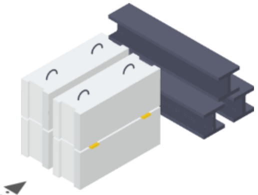

Renewable
POWER TO X

Presented by Prof. Dr. – Ing. Christoph Menke
Professor for Energy Systems, Technology and Economics
Trier University of Applied Sciences, Germany
Senior Energy Consultant

Agenda

1

Introduction to Renewable PtX
Why are we talking about renewable PtX now?

2

Production of Renewable PtX
What is needed to produce green hydrogen and PtX?

3

Renewable PtX Economics
How will the cost of renewable PtX and RE develop? What are the parameters to lower it?

4

PtX Infrastructure
How to transport and store hydrogen best?

5

Markets for Renewable PtX
How to determine where to start a PtX market in your country?

6

Sustainability Criteria for Renewable PtX
Which sustainability criteria will be applied for renewable PtX? Why are they so important?

7

Support Policies and Regulations for Renewable PtX
What policies and regulations are useful and necessary to start your national strategy? How to ramp up the market and business?

Module 4

Renewable PtX Infrastructure

Transport Options
- Long vs. shorter distances
- Different PtX products (H_2 derivatives)

Storage Options
- Physical storage places
- Storage stages of the product (liquid, gaseous)

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Test your knowledge

“What is the best option to transport hydrogen over a distance of up to 5,000 km?”

“What is the most expensive option of H_2 transport?”

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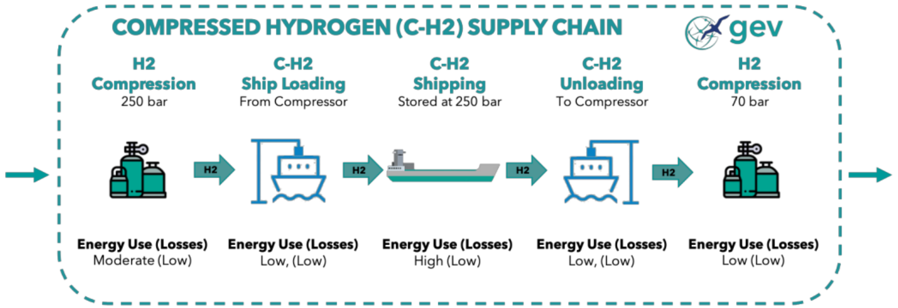
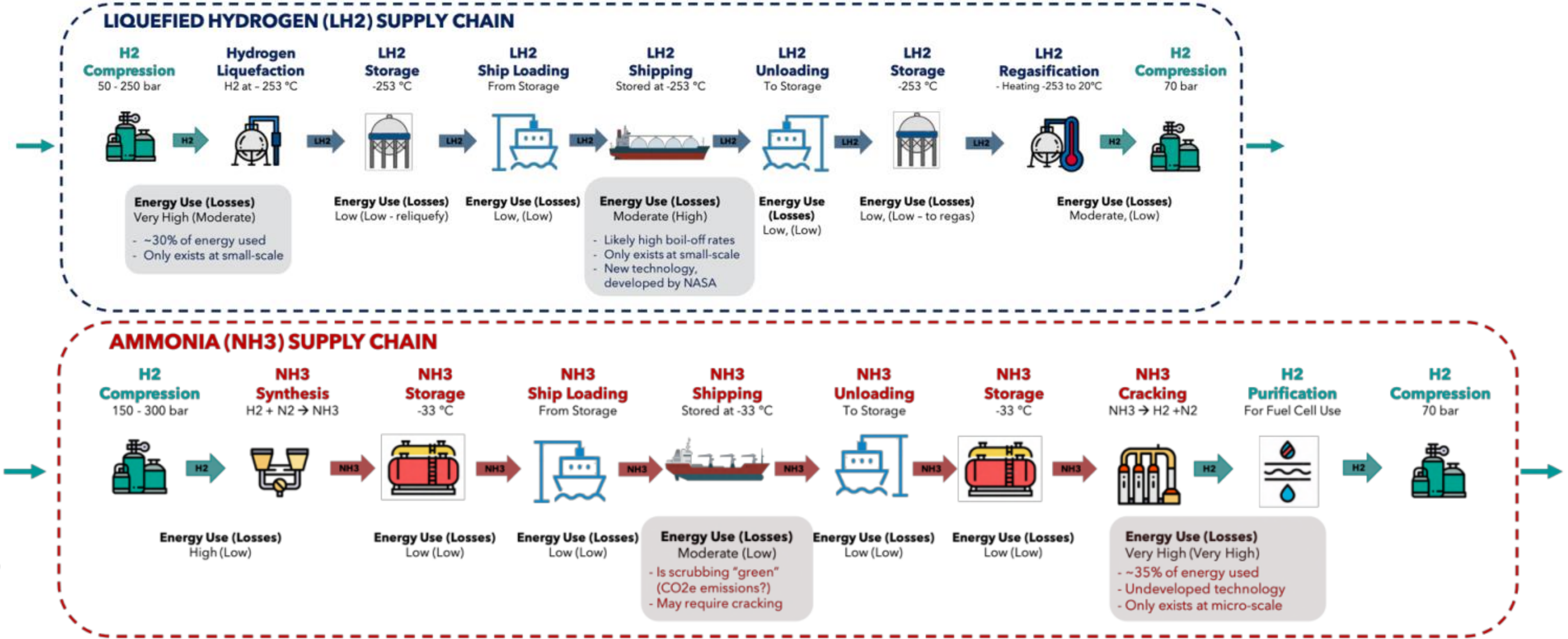
4.1. Transport

Comparison of C-H2 supply chain with liquification (LH2) and ammonia (NH3) – Western Australia





Source: Global Energy Ventures, GEV SCOPING STUDY DELIVERS ZERO EMISSION SUPPLY CHAIN FOR GREEN HYDROGEN, 03/2021.

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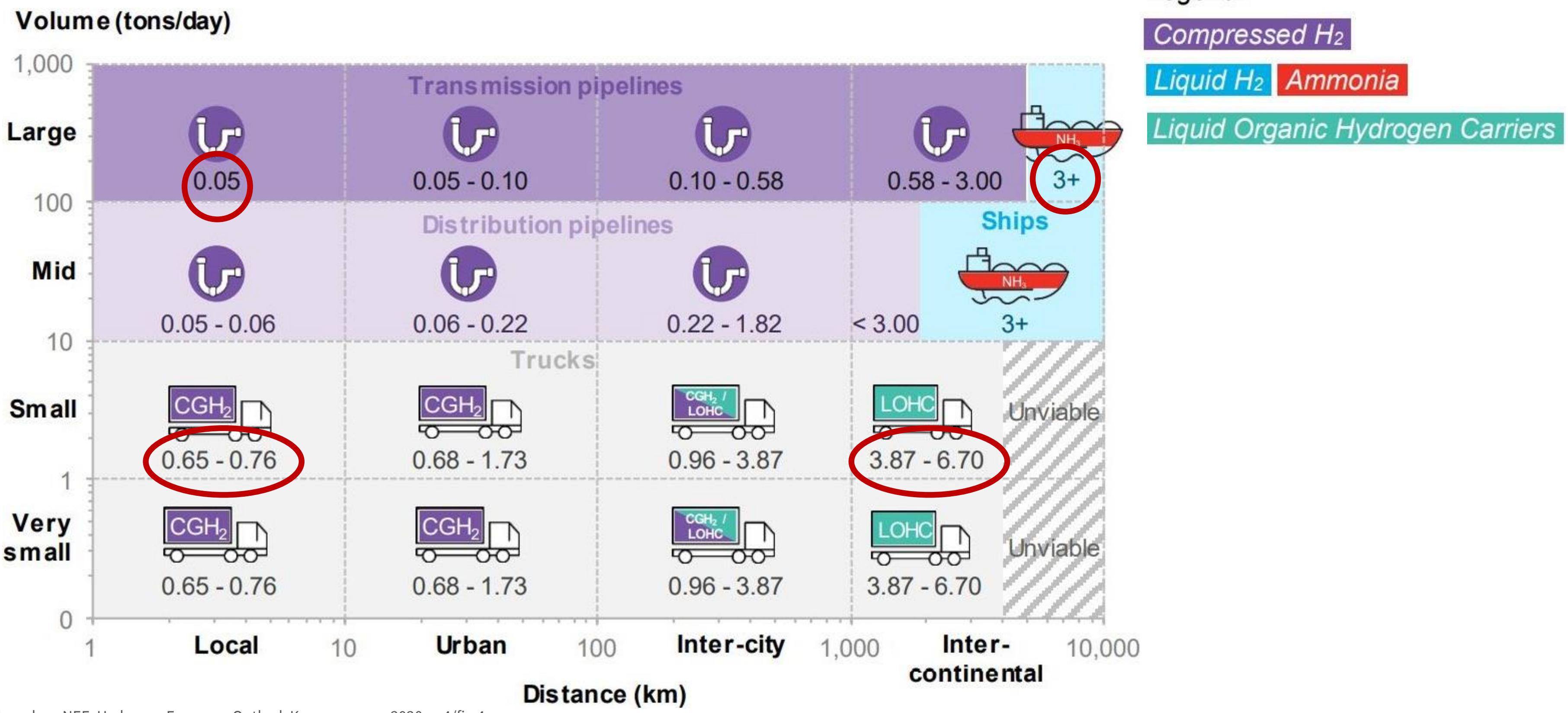
4.1. Transport

H_2 transport costs based on distance and volume, in \$/kg H_2 in 2019



Source: BloombergNEF, Hydrogen Economy Outlook Key messages, 2020, p.4/fig.4.

4.1. Transport

Costs of different options for the long-distance transport of hydrogen depending on transport distance

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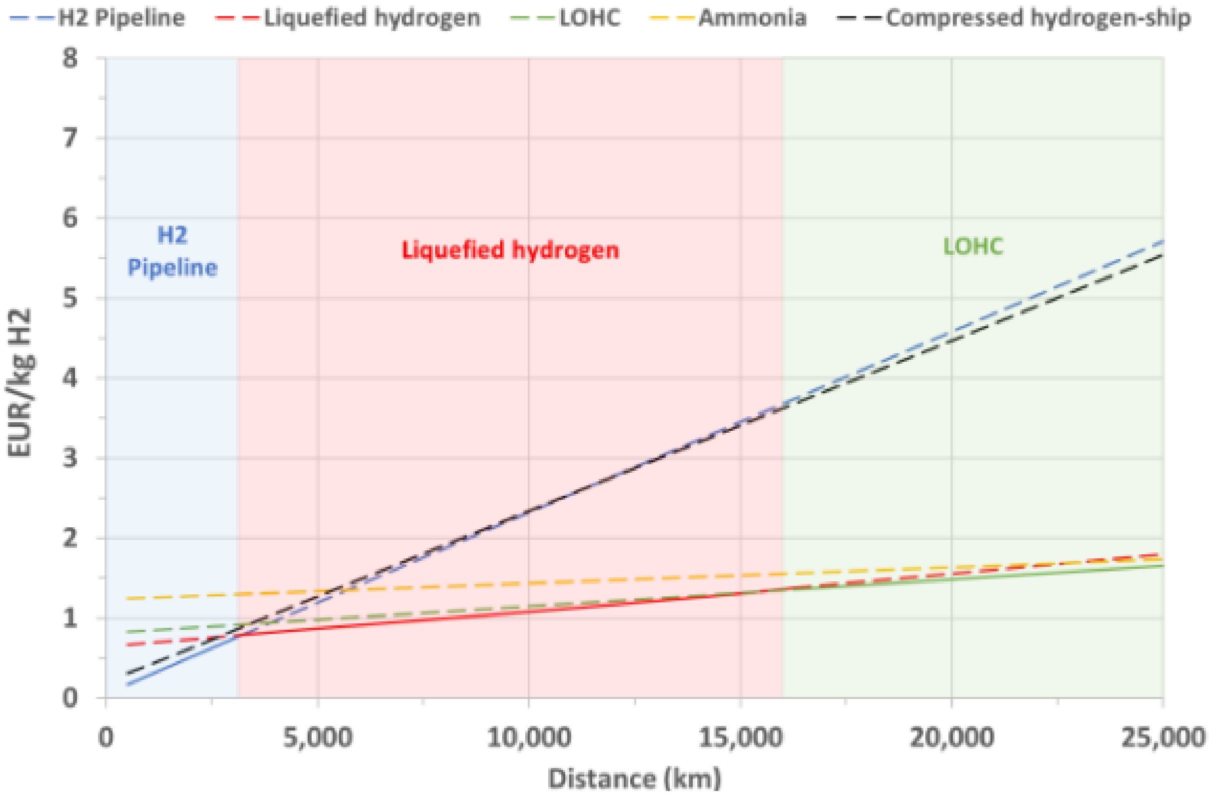


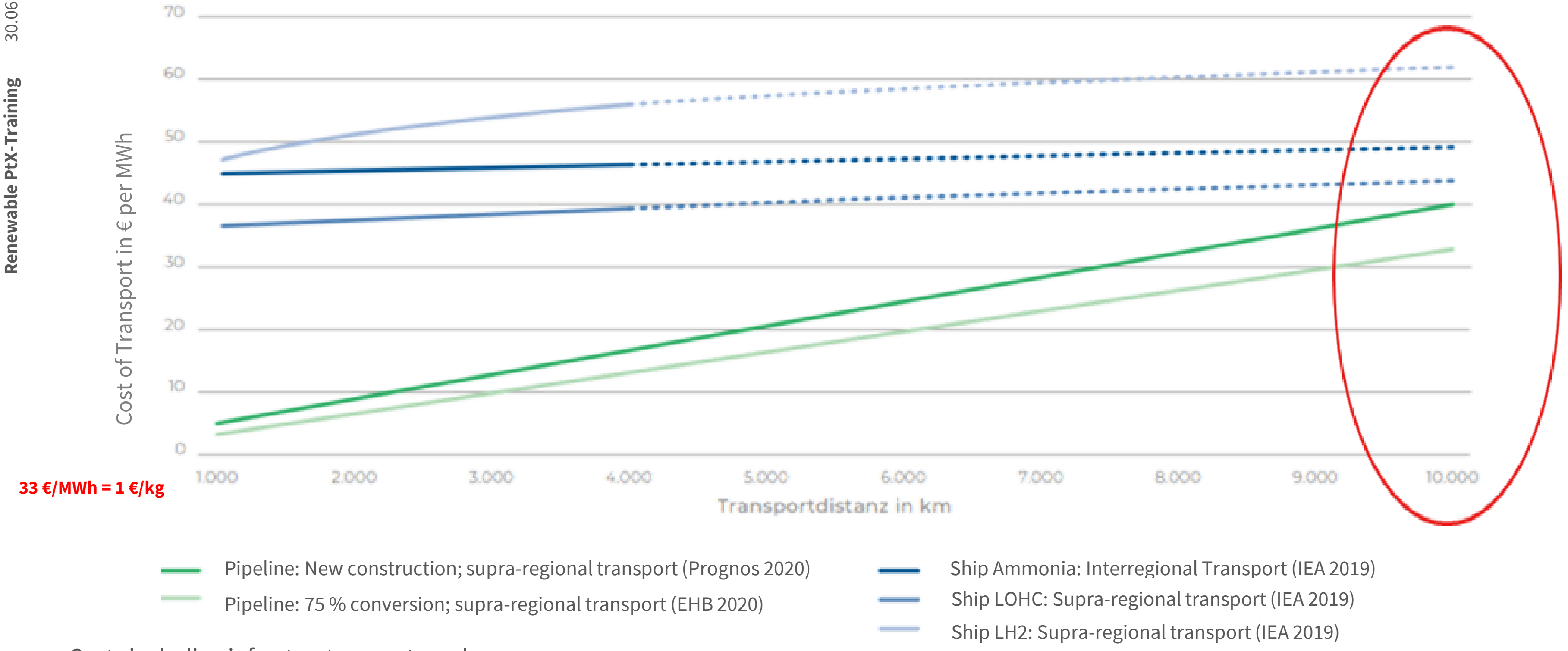
Distance up to ~2,600 km: H_2 pipeline and compressed H_2 shipping are the cheapest options. Other sources assume up to 5,000 – 8,000 km if existing pipelines can be converted!

Distances from 2,600-16,000 km should be covered with liquified H_2, ammonia or PtLs

Source: European Union, Assessment of Hydrogen Delivery Options, 2021 – JRC124206, p.3.

4.1. Transport

Comparison of selected hydrogen total transport costs options



Costs including infrastructure costs and costs for conversion and reconversion of Hydrogen into Ammonia, LH2, LOHC

Source: Nationaler Wasserstoffrat, Wasserstofftransport, July 2021, p.4.

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4.1. Transport

Key question: Transport electricity or hydrogen? It depends!

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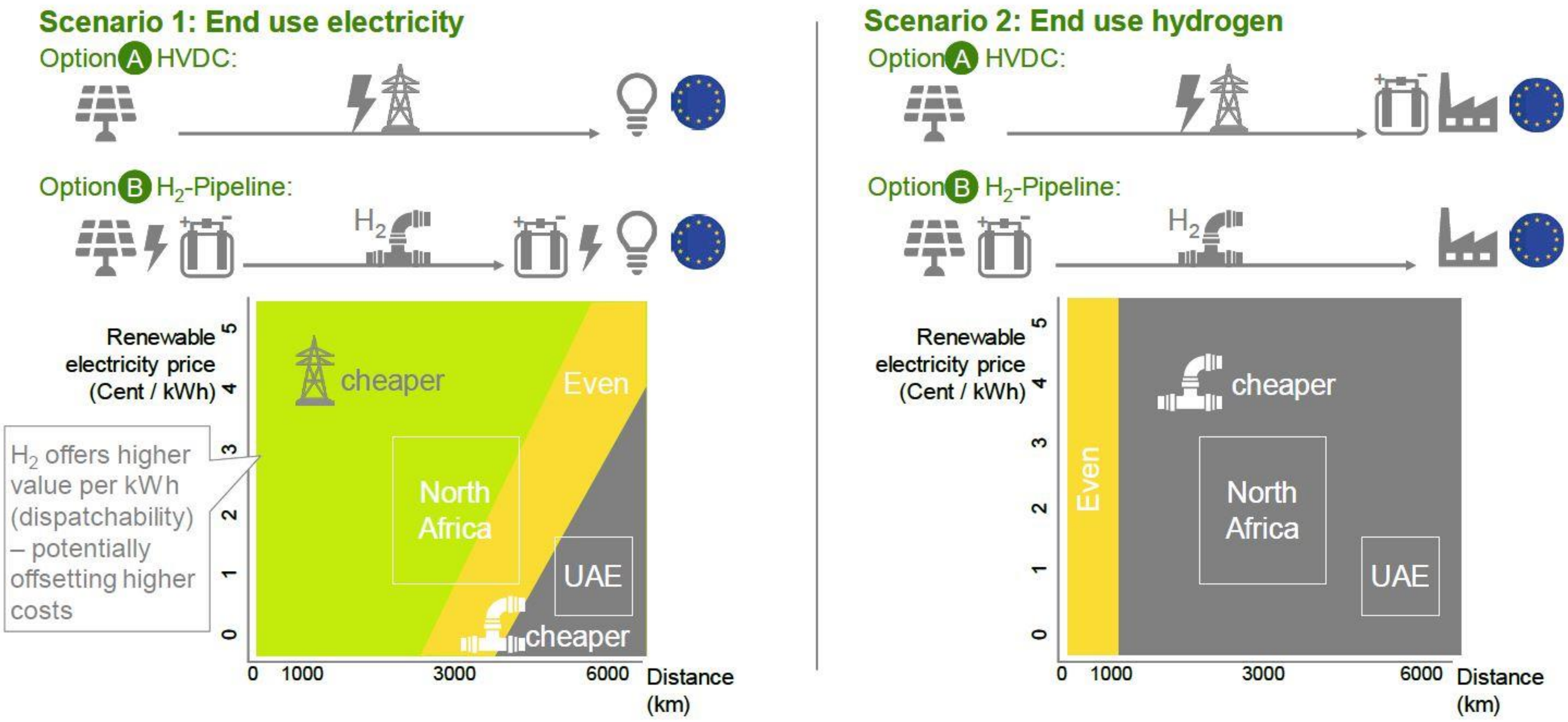
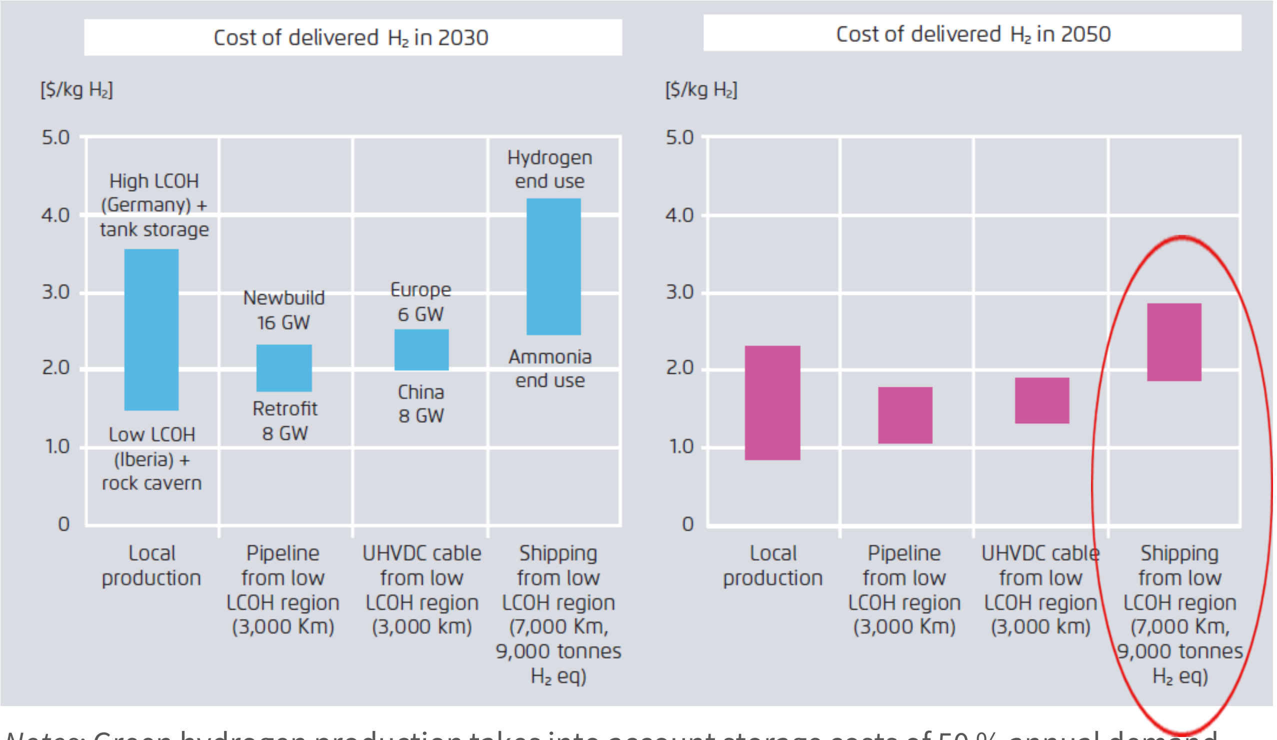
Example for cost of importing electricity or hydrogen from MENA region to Germany, 2030.



Source: Guidehouse, Electrons or molecules: Comparing electricity and hydrogen imports from the MENA region to Europe, 2020, p.7.

4.1. Transport

Economics of delivered hydrogen for 2030 and 2050



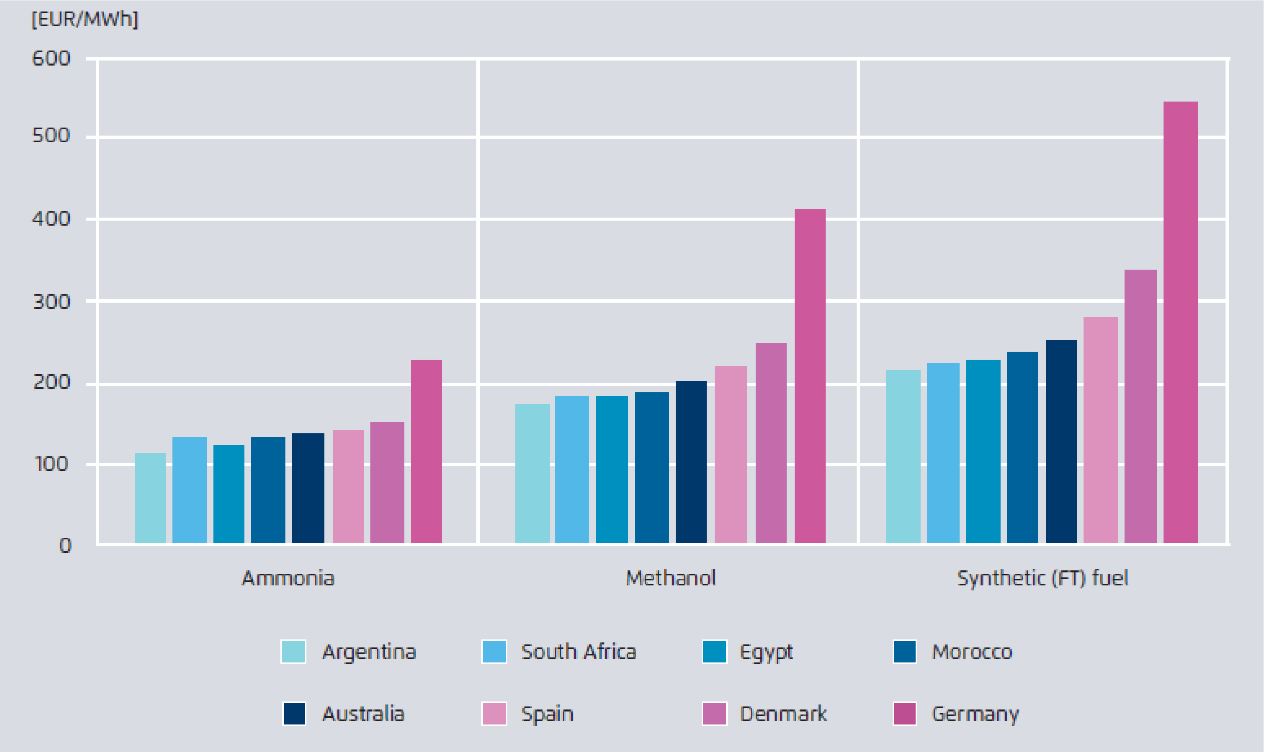
Notes: Green hydrogen production takes into account storage costs of 50 % annual demand. This is the lowest-cost retrofitted gas pipeline according to the European Hydrogen backbone report.

- Retrofitted pipelines (if available) are cheapest
- Ship-based trade lends itself better to hydrogen-based products or where pipelines are not feasible
- Long distance transport can be more expansive than local production in Europe in the long run, but Europe will most likely need to import in addition to own production!

Source: Agora Energiewende/Agora Industry, 12 Insights on Hydrogen, p. 33/fig.20.

4.1. Transport

From a European perspective for 2030



Hydrogen pipelines will keep European industry in business and ensure a firm power market.

The **EU** should **foster international power-to-X markets** for sustainable chemicals and for sustainable maritime and aviation fuels.

Importing sustainable methanol or synthetic fuels from places with cheap renewables is more cost-effective than producing them in Germany.

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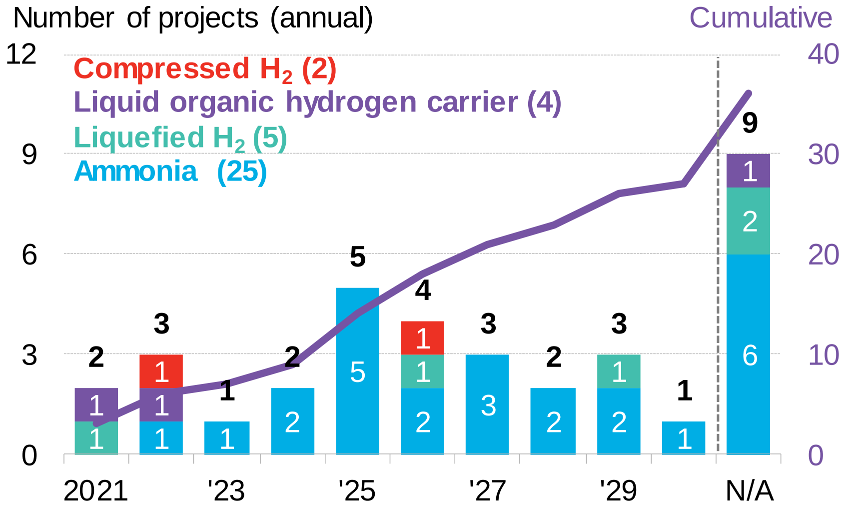
Source: Agora Energiewende, Agora Industry, 12 Insights on Hydrogen, 2021, p. 41/fig.25.

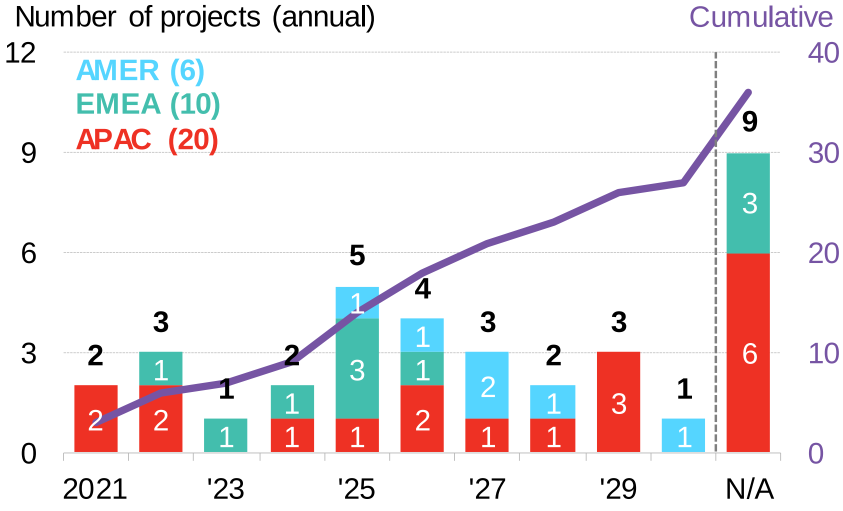
Announced pipeline of H_2 shipping projects

By segment



Source: BloombergNEF

By region



Source: BloombergNEF

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Test your knowledge

“What is the best option to store large quantities of H_2?”

“What is the biggest challenge to store H_2?”

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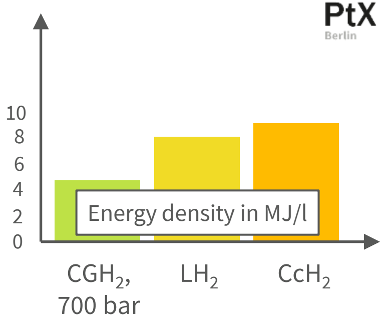
4.2. Storage
Hydrogen storage options

H_2-Storage

- **Physical**
  - Pressure storage (CGH_2) up to 700 bar
  - Liquid Storage (LH_2) at -253°C
  - Cryo-Compressed (CcH_2) at 300 bar, -235°C
- **Material**
  - Adsorption
    - ex. Zelithen, Carbon nanotubes
  - Hybrid Storage
    1. Loading: Hydrogenation
    2. Unloading: Dehydration
  - Liquid Organic Hydrogen Carriers
    1. Adsorption on metal surface
    2. Binding into metal lattice under heat release



Bildquelle: EWE Gasspeicher

Source: DLR, Wasserstoff als ein Fundament der Energiewende Teil 1: Technologien und Perspektiven für eine nachhaltige und ökonomische Wasserstoffversorgung, 09/2020, p.27/fig.22.

Note: Schematic illustration of an existing cavern in northern Germany. Several caverns are brought together at a cavern head from where the stored gas is distributed to the grid and, if necessary, cleaned and dried beforehand.

Source: Prof. Dr.-Ing. B. Epple Innovative Energieumwandlungsprozesse – Energy Systems and Technology TU Darmstadt, Stoffliche Nutzung von Synthesegas.

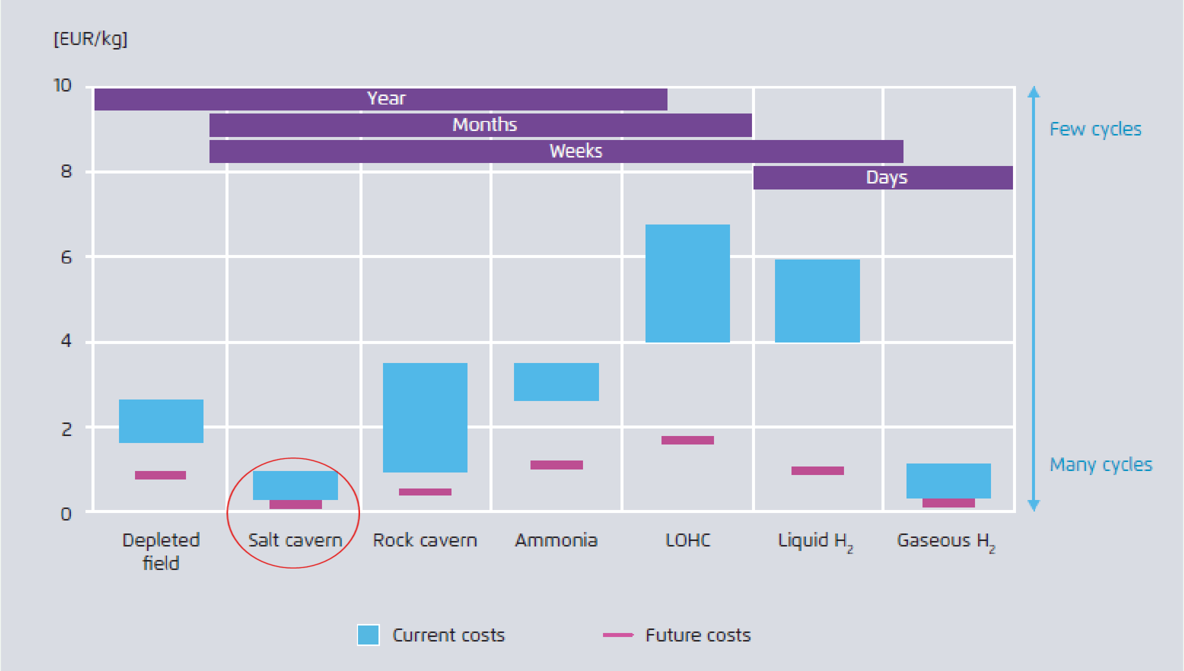
4.2. Storage

Levelised cost of hydrogen storage

Geological storage is the **cheapest** form of **large-scale** hydrogen storage

BUT: Low cost, large-scale options like salt caverns are geographically limited

Cost of using alternative liquid storage technologies often greater than cost of producing H_2 in the first place



Source: Agora Energiewende, Agora Industry, 12 Insights on Hydrogen, 2021, p. 18/fig.9.

4.2. Storage

Comparision of hydrogen storage options

	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Delivered cost of green H_2 of around $2/kg ($15/MMBtu*) in 2030 and $1/kg ($7.4/MMBtu*) in 2050 in China, India and Western Europe achievable.

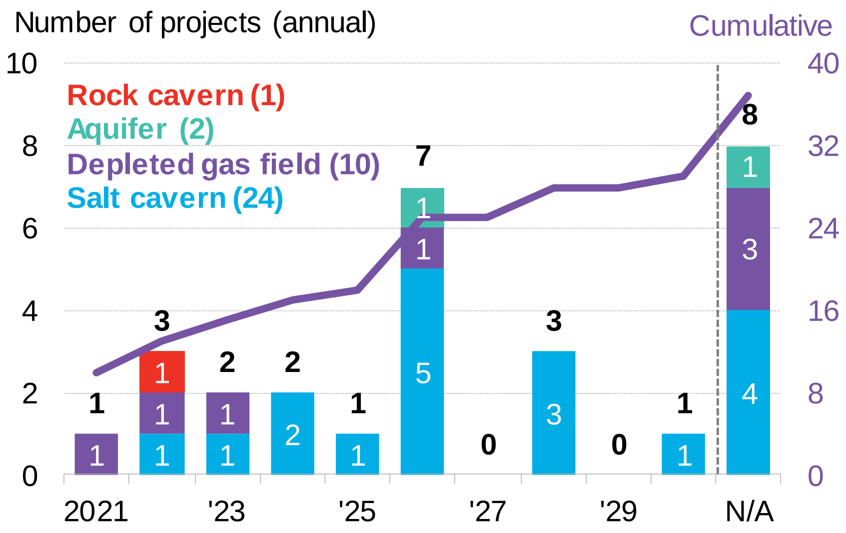
***1 MWh H_2 = 3.4 MMBtu H_2**

Costs could be 20-25% lower in countries with best renewable and hydrogen storage resources, i.e. *USA, Brazil, Australia, Scandinavia and Middle East*

Source: BloombergNEF, Hydrogen Economy Outlook, 2020, p.3/table1.

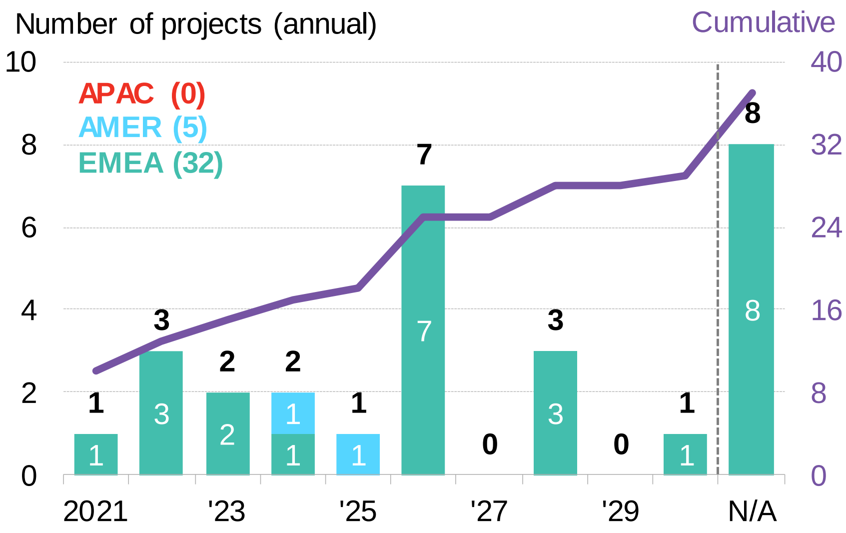
Announced pipeline of underground H_2 storage projects

By segment



Source: BloombergNEF

By region



Source: BloombergNEF

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MODULE 4: Key messages

Transport Options

- Overview **three main H2 supply chains**
- **Transport costs** of H2 are based on distance and volume, H2 pipelines and compressed H2 for smaller quantities and distances cheaper than liquid organic H2 carriers. **Transportation options of electricity or H2 depends on end-use, renewable electricity price and distance**
- **Import** of ammonia, methanol or synthetic fuel **will most likely always be cheaper than production** in Germany and even in most other European countries

Storage Options

- **Storing H2 in large quantities** will be one of the most **significant challenges** for a future H2 economy **especially for countries and regions that need to store it, e.g. for heating purposes in winter times**.. At the same time, the complex storage and distribution (expensive, energy-intensive) of H2 is one of the biggest disadvantages of the technology as direct energy storage
- **Storage costs depend on kind of storage and number of cycles** for its use, further **cost reduction** is expected

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Open discussion

"What are the best transport and storage options for your country?"

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Module 5

Markets for Renewable PtX

PtX's Way

- Hydrogen value chain
- Importance of electrification first

Marginal Abatement Cost Curve

Classification of the Transition Need

- Classification: No regret options

Example Sector Cases

- Steel industry
- PtL for aviation

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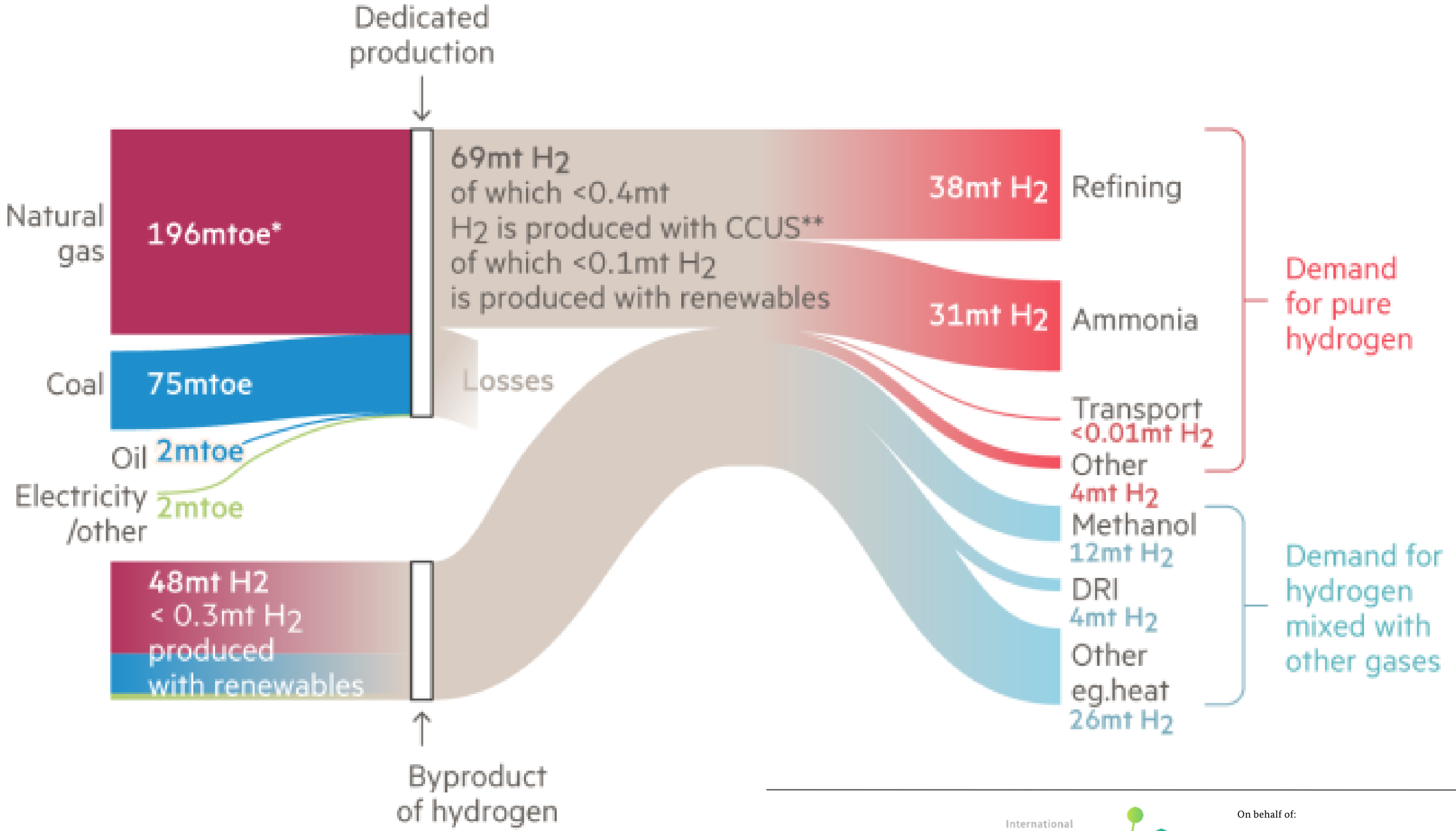
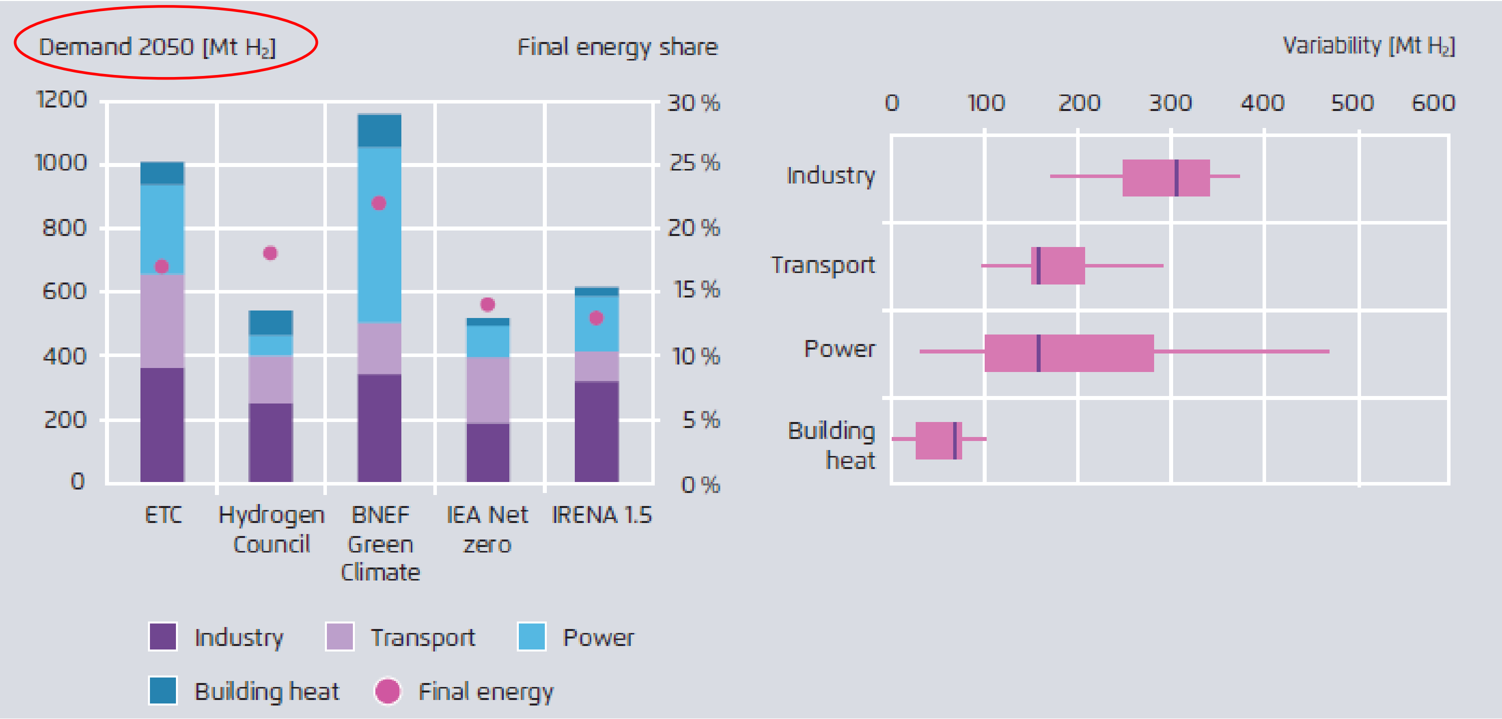
Today's hydrogen value chains



Source: Financial Times, The race to scale up green hydrogen, 2021.

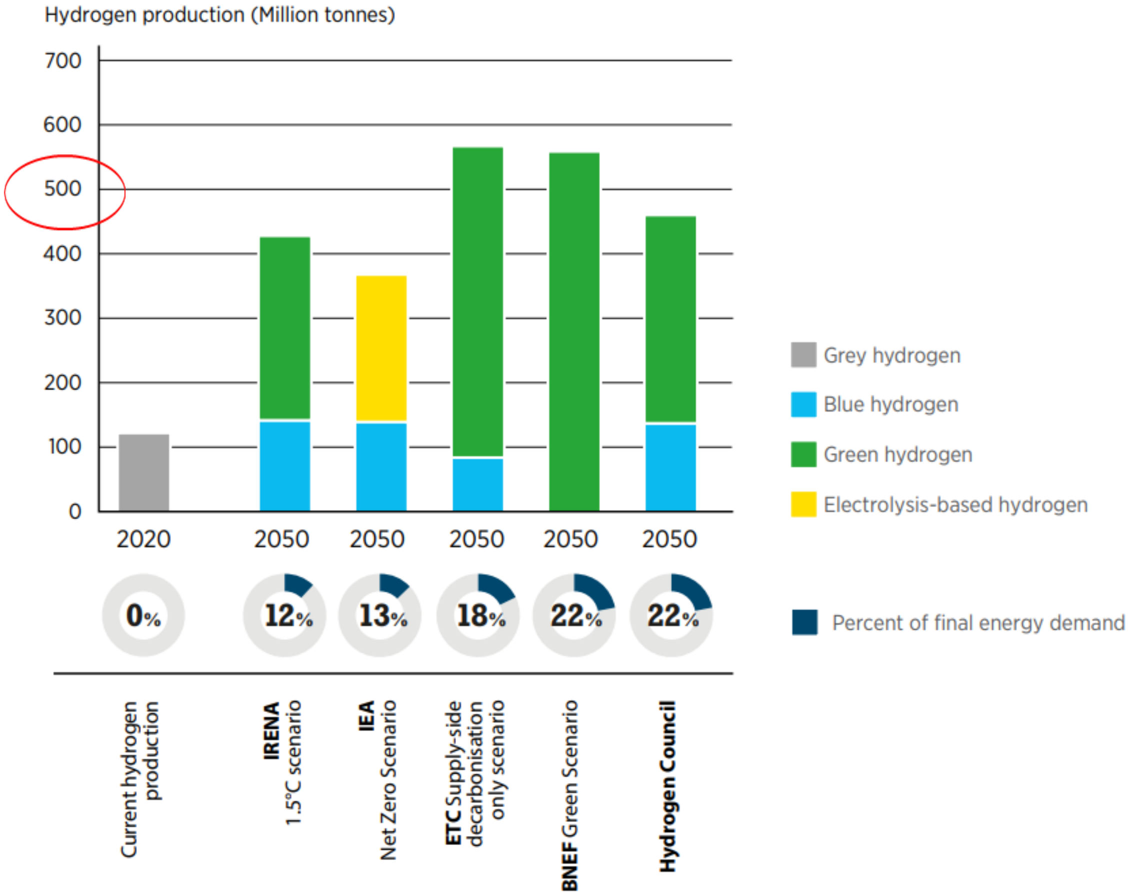
Everyone agrees that hydrogen is key to industrial decarbonisation



Note: Final energy does not include feedstocks and other non-energy use.

Source: Agora Energiewende, Agora Industry, 12 Insights on Hydrogen, 2021, p. 14/fig.6.

Estimates of global H2 demand for 2050 converge to 500 Mio t H2/a



Source: IRENA, Geopolitics of the Energy Transformation The Hydrogen Factor, p.20/fig.1.1., 2022

Test your knowledge

"Which sectors have the *largest potential* for renewable PtX in your country in the long run?"

"In which sectors would you use renewable PtX products *FIRST* in your country?"

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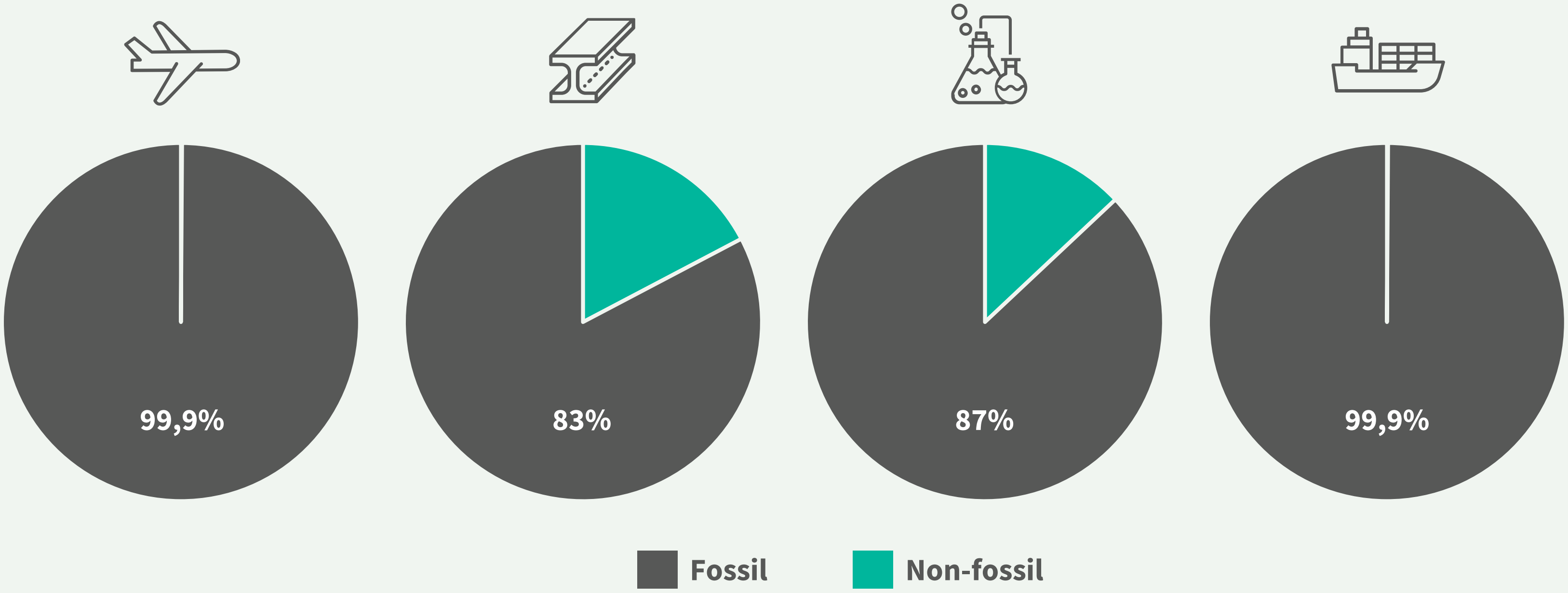
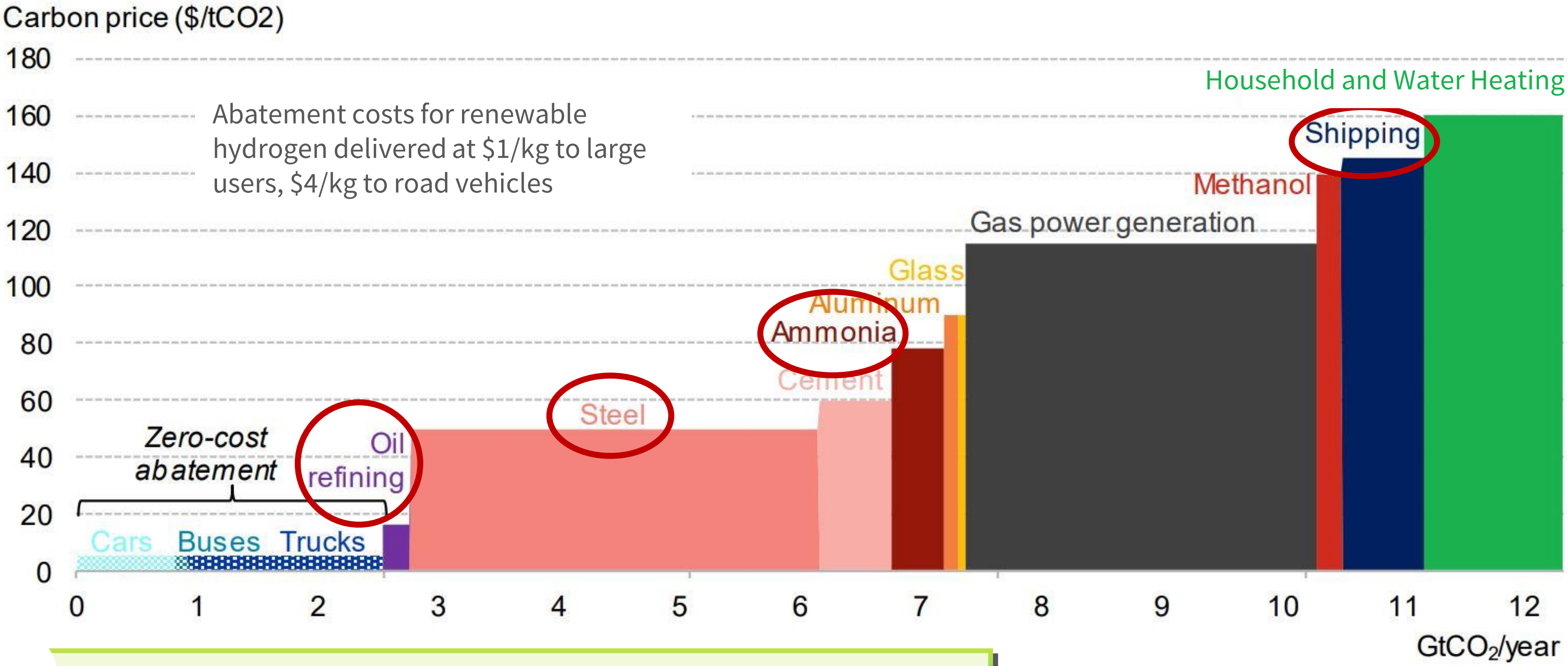
Industrial sectors still use fossil sources - But where to start?



Source: own illustration based on: IEA, Iron & Steel, 2020; IEA, International Shipping, 2020; dena, Feedstocks for the chemical industry, 2019.

1. Step: Create a country-specific marginal abatement cost curve to determine your priorities

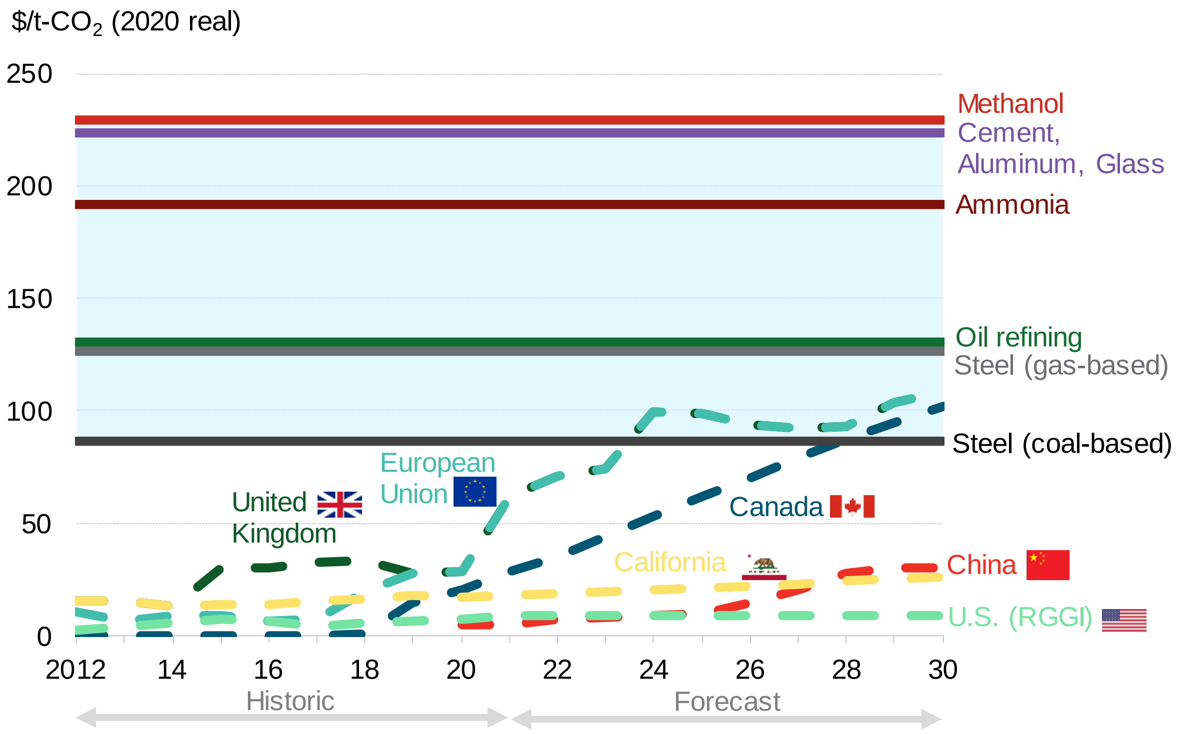
Global marginal abatement cost curve for CO_2 assuming \$1/kg for H_2 in 2050



With your country specific curve you can see potential CO_2 savings and required CO_2 price in the sectors of your country.

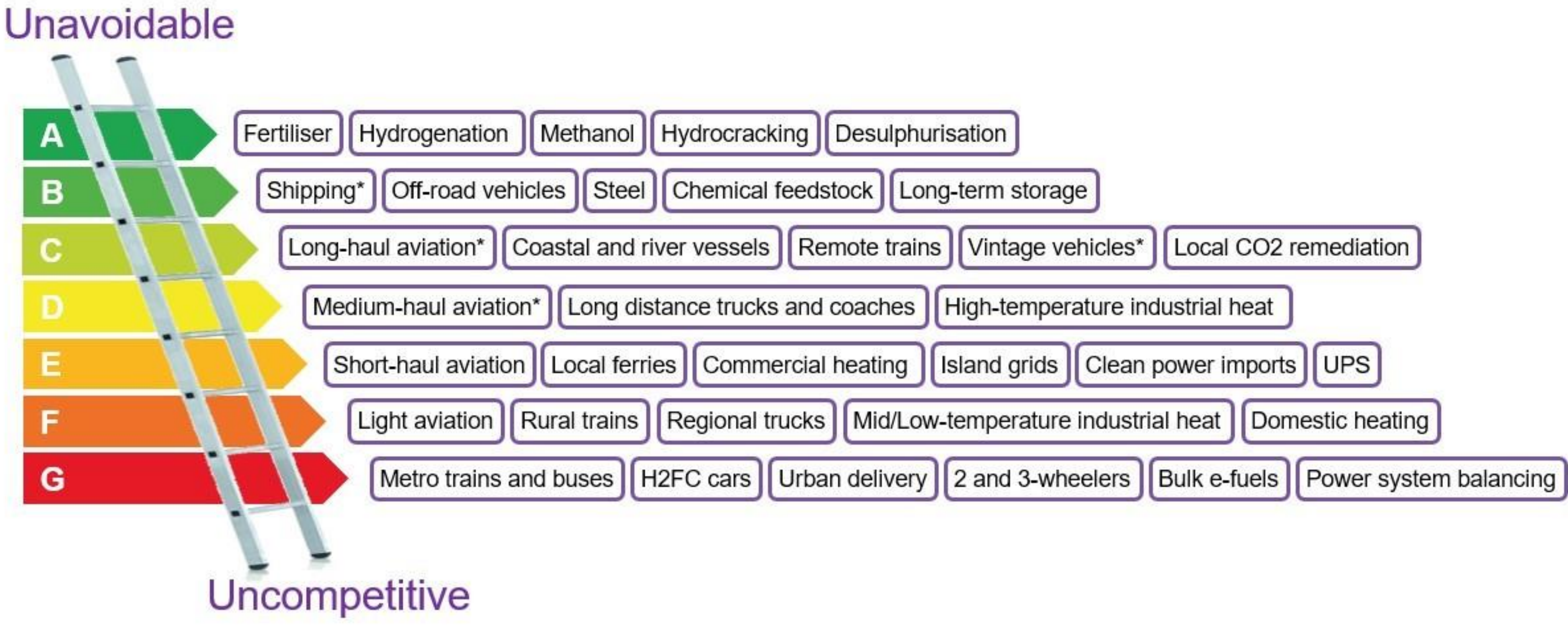
Source: BloombergNEF, Hydrogen Economy Outlook, 2020, p.6/fig.7.

Carbon prices around the world



Source: BloombergNEF

2. Step: Check the clean hydrogen ladder



** Via ammonia or e-fuel rather than H2 gas or liquid*

Source: Liebreich Associates (concept credit: Adrian Hiel/Energy Cities)

Source: Recharge, Liebreich: 'Oil sector is lobbying for inefficient hydrogen cars because it wants to delay electrification', 06/2021.

3. Step: Start with the no regret options first!
→ They may be different for each country!

Green molecules needed?	Industry	Transport	Power sector	Buildings
No-regret	· Reaction agents (DRI steel) · Feedstock (ammonia, chemicals)	· Long-haul aviation · Maritime shipping	· Renewable energy back-up depending on wind and solar share and seasonal demand structure	· Heating grids (residual heat load *)
Controversial	· High-temperature heat	· Trucks and buses ** · Short-haul aviation and shipping · Trains ***	· Absolute size of need given other flexibility and storage options	
Bad Idea	· Low-temperature heat	· Cars · Light-duty vehicles		· Building-level heating

* 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 to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.

** Series production currently more advanced on electric than on hydrogen for heavy duty vehicles and buses. Hydrogen heavy duty to be deployed at this point in time only in locations with synergies (ports, industry clusters).

*** Depending on distance, frequency and energy supply options

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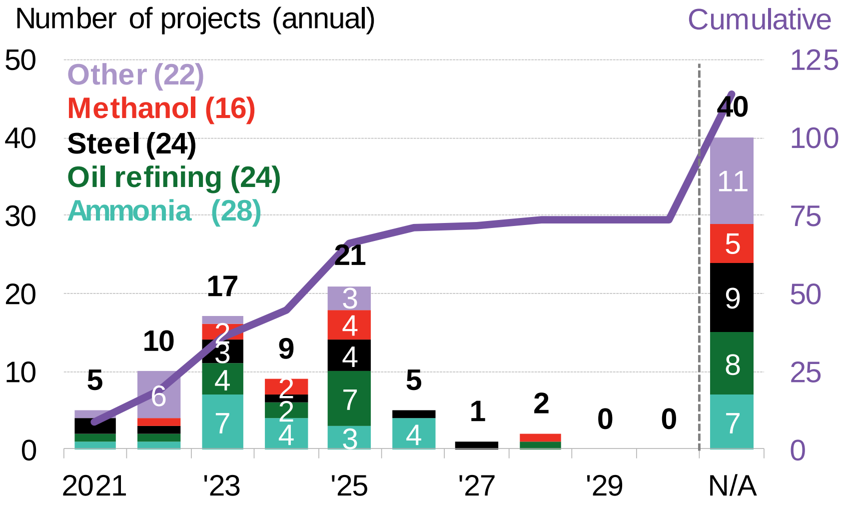
Source: Agora Energiewende, Agora Industry, 12 Insights on Hydrogen, 2021, p. 12/fig.4.

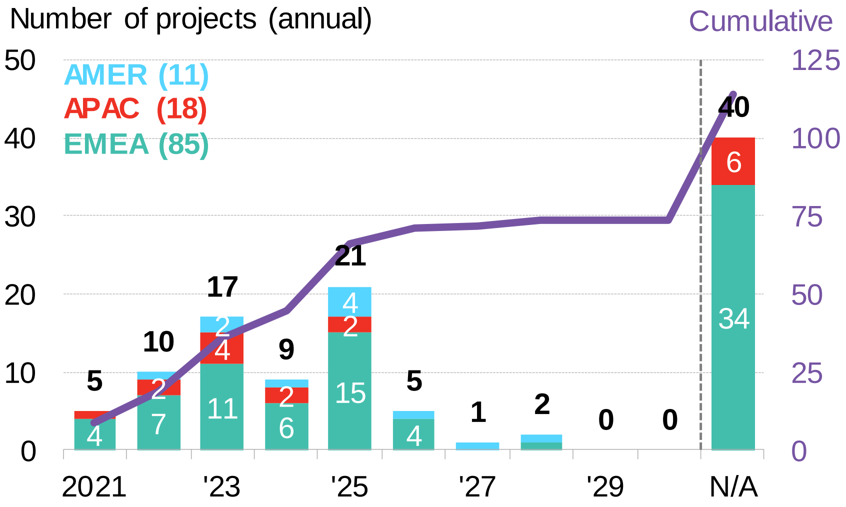
Announced pipeline of industrial hydrogen projects

By segment



Source: BloombergNEF

By region



Source: BloombergNEF

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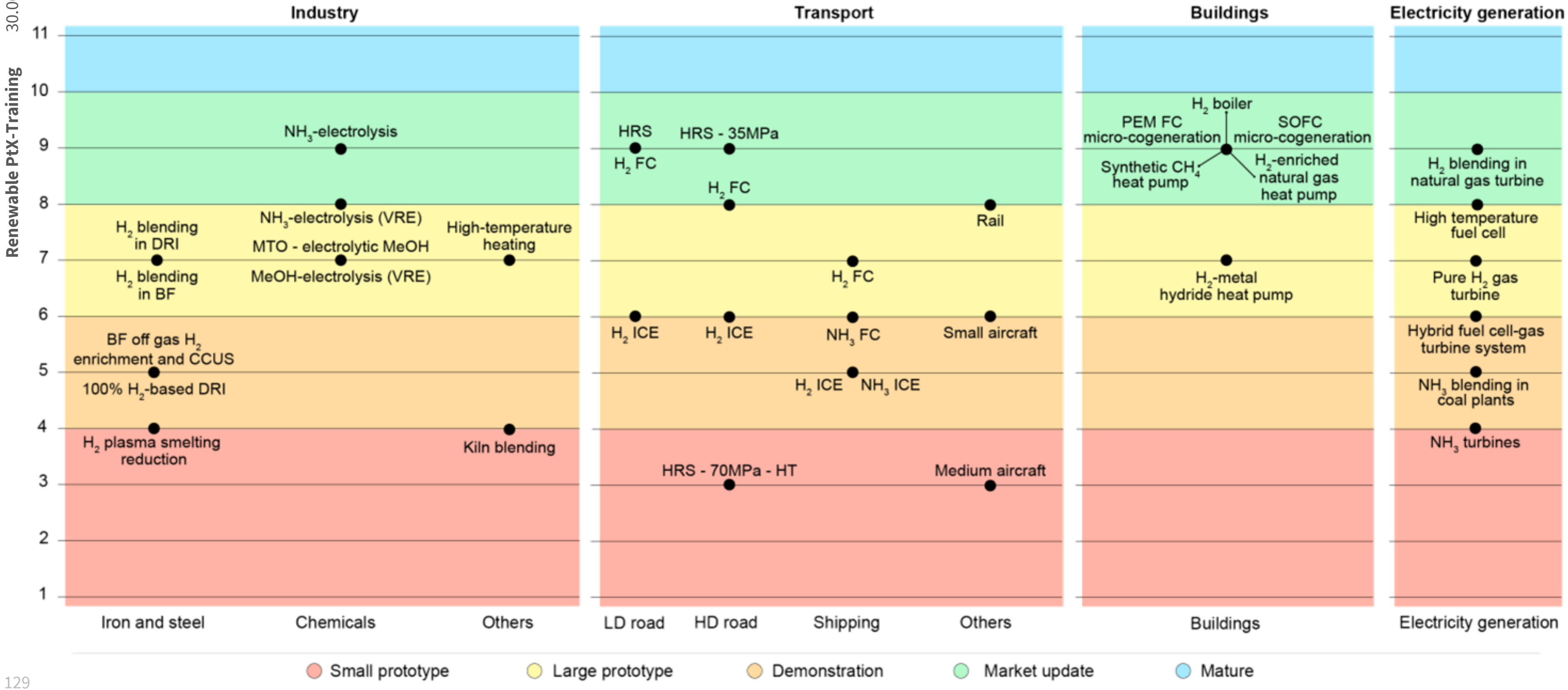
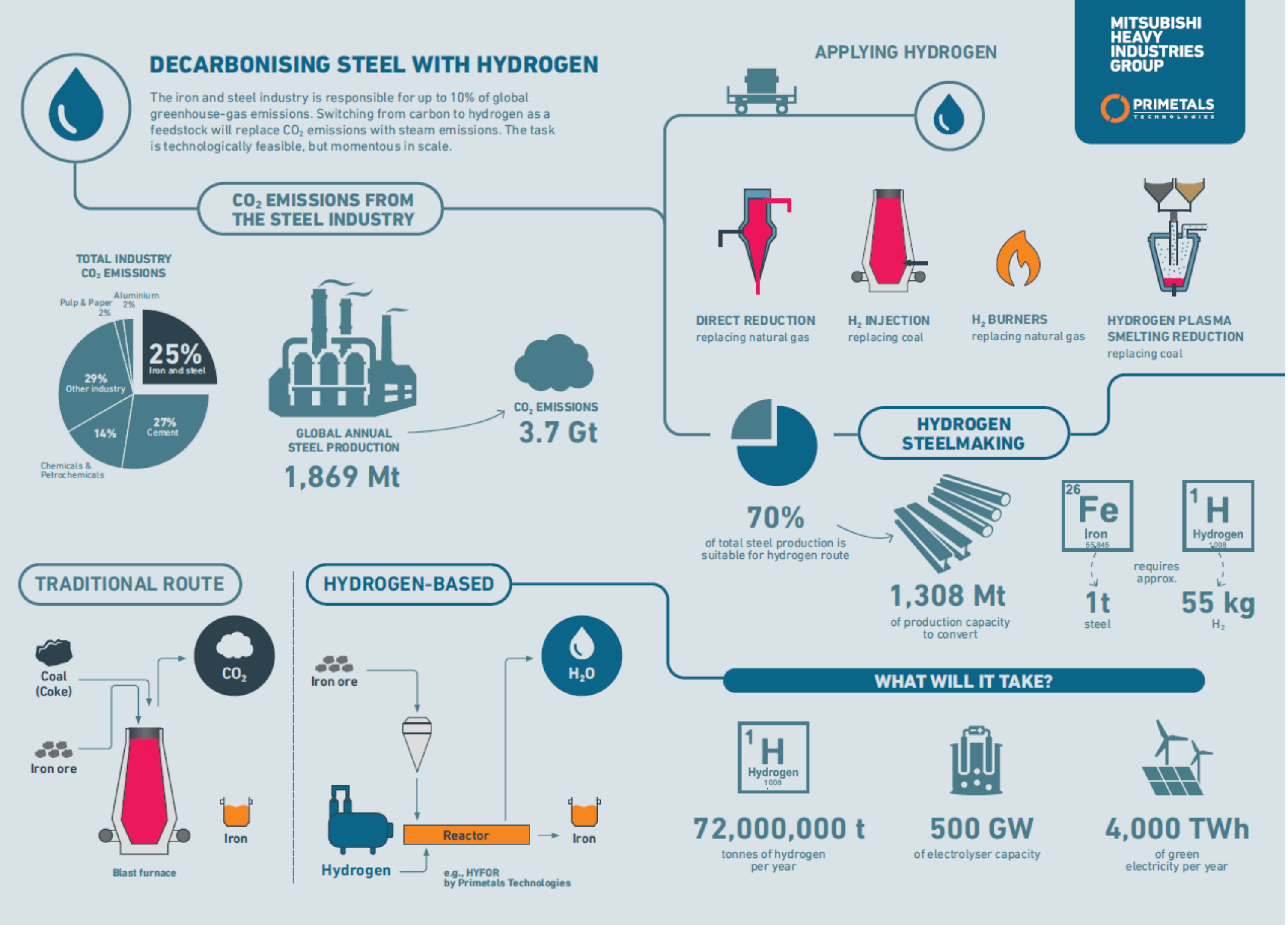
6. Step: Consider technology readiness levels of key PtX production, storage and distribution technologies

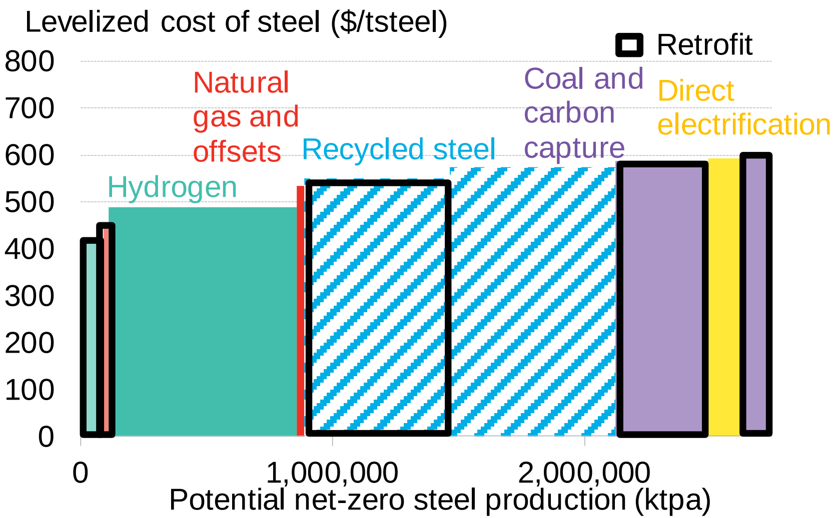


Source: IEA, Global Hydrogen Review 2021, 2021, p.171.


DECARBONISING STEEL WITH HYDROGEN
The iron and steel industry is responsible for up to 10% of global greenhouse-gas emissions. Switching from carbon to hydrogen as a feedstock will replace CO_2 emissions with steam emissions. The task is technologically feasible, but momentous in scale.
CO_2 EMISSIONS FROM THE STEEL INDUSTRY
TOTAL INDUSTRY CO_2 EMISSIONS
Pulp & Paper 2%
Aluminium 2%
25% Iron and steel
29% Other industry
14%
27% Cement
Chemicals & Petrochemicals
GLOBAL ANNUAL STEEL PRODUCTION
1,869 Mt
CO_2 EMISSIONS
3.7 Gt
APPLYING HYDROGEN
MITSUBISHI HEAVY INDUSTRIES GROUP
PRIMETALS TECHNOLOGIES
DIRECT REDUCTION
replacing natural gas
H_2 INJECTION
replacing coal
H_2 BURNERS
replacing natural gas
HYDROGEN PLASMA SMELTING REDUCTION
replacing coal
HYDROGEN STEELMAKING
70%
of total steel production is suitable for hydrogen route
1,308 Mt
of production capacity to convert
26 Fe Iron 55.845
1 H Hydrogen 1.008
1t
steel
requires approx.
55 kg
H_2
TRADITIONAL ROUTE
Coal (Coke)
Iron ore
CO_2
Blast furnace
Iron
HYDROGEN-BASED
Iron ore
H_2O
Reactor
Iron
Hydrogen
e.g., HYFOR by Primetals Technologies
WHAT WILL IT TAKE?
1 H Hydrogen 1.008
72,000,000 t
tonnes of hydrogen per year
500 GW
of electrolyser capacity
4,000 TWh
of green electricity per year

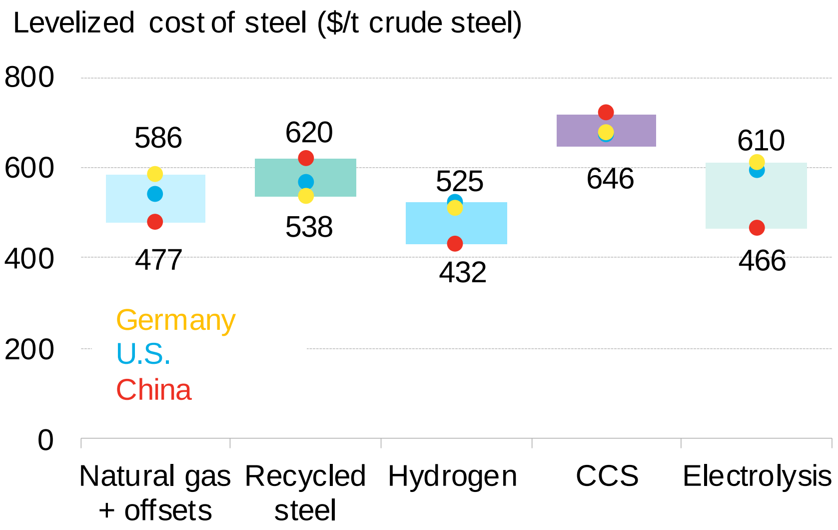
Net-zero steel, 2050

Potential supply curve for net-zero steel



Source: BloombergNEF. Note: This analysis assumes a least-cost scenario with a mandate for near net-zero steel.

Cost of net-zero steelmaking routes



Source: BloombergNEF. Note: CCS is carbon capture and storage.

7. Step: Analyse market in your country! Example from marginal cost curve: Green steel in Germany

Maximum CO_2 reduction in Germany

2030	2050
14 Mio. t CO_2/a	**50** Mio. t CO_2/a

2030: Direct reduction with natural gas and 7,5% blend of green hydrogen

CO_2 avoidance costs in Germany

2030	2050
60–99 €/t CO_2	**85–144** €/t CO_2

2030: 60 €/t CO_2 at 100% natural gas-based direct reduction
99 €/t CO_2 for direct reduction with hydrogen

- **Cost of t crude steel: 659 \$/t (20.12.2019) = 557,15 €/t**
- Additional costs for a car from low-carbon steel **~ 500 €/car**
- Is that too much for a car that costs 50 000 €?

Source: Agora Energiewende und Wuppertal Institut (2019): Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin, November 2019, p.167.
HySteel / DWV, Grüner Stahl - Die Wasserstoffrevolution der Stahlindustrie, Juni 2021.

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Green steel production

[Fossil free steel production: This is HYBRIT - YouTube]

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Climate friendly steel in Sweden

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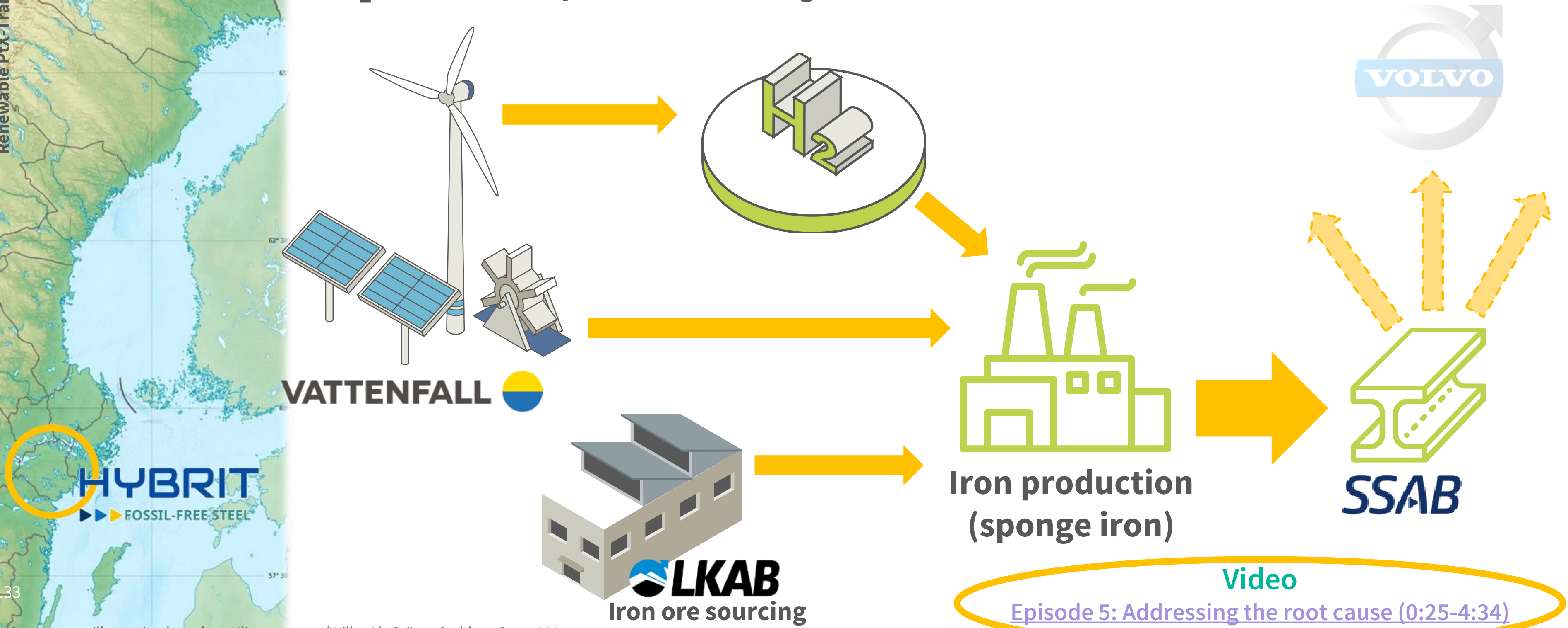
Goal: Production of green steel on an industrial scale from 2026 and capacity of **2.7 million tons of steel raw material by 2030** + **reduction** of Sweden's **CO_2 emissions by min. 10%** (long-term)



Video

Episode 5: Addressing the root cause (0:25-4:34)

Source: own illustration based on: Klimareporter (Wille, J.), Grüner Stahl am Start, 2021.

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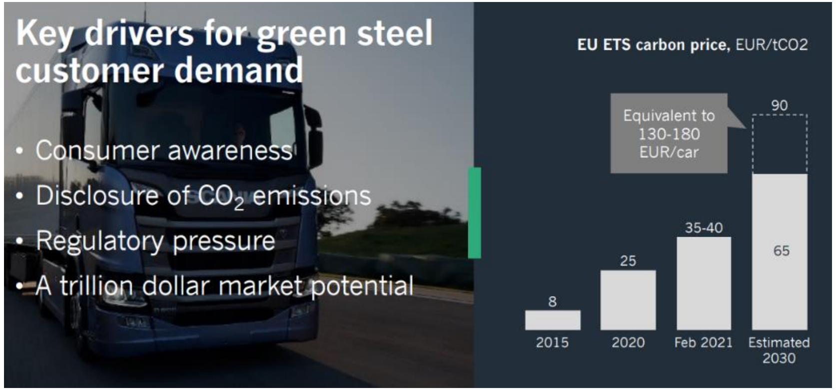
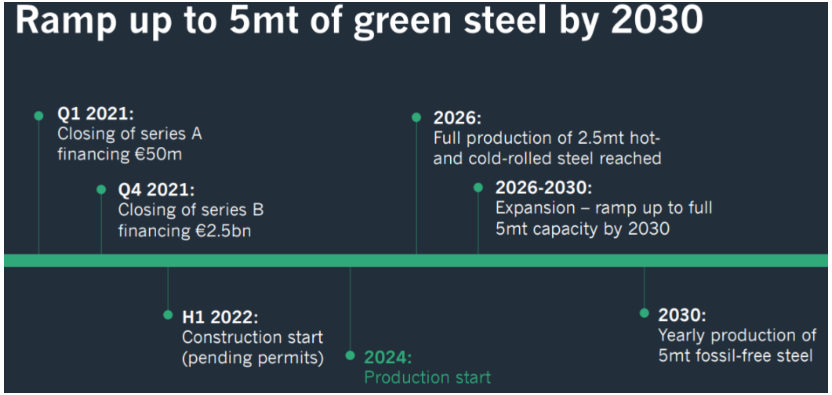
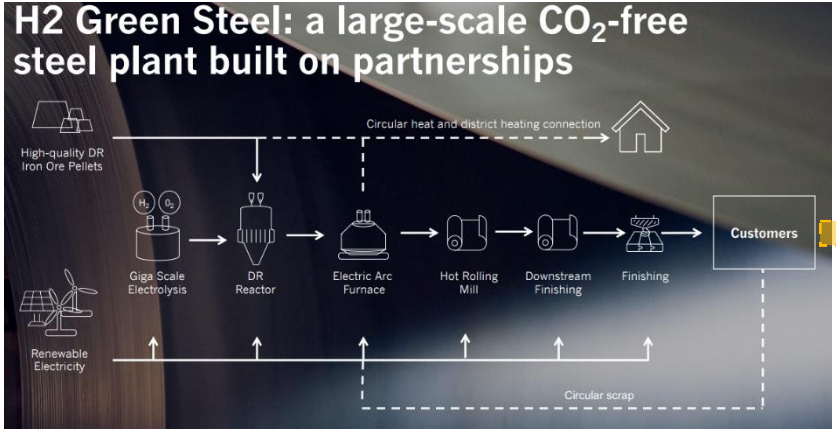
Premium Markets for Green Steel
H2 Green Steel Initiative







Source: www.h2greensteel.com; https://media.daimler.com/ 28.09.2021.

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Example: Decarbonising the German steel industry

Impact on power and product costs

Increase in electricity demand?

Production cost of **1kg H_2**:
3.6-5.3 €/kg, using **50-55 kWh**

→ **50 kg** of H_2 required to produce **1 t of steel**

Germany (EU's largest steel producer):
100 TWh of RE needed to fully decarbonise annual production of **42 Mt of steel**

→ This **100 TWh** of additional RE demand
→ **20 % increase in total electricity demand in Germany!**

To compare: Solar park Benban (Egypt): 3800 GWh/ year; land use 37.2 km² → that is 3.8% of electricity needed to decarbonise German steel industry

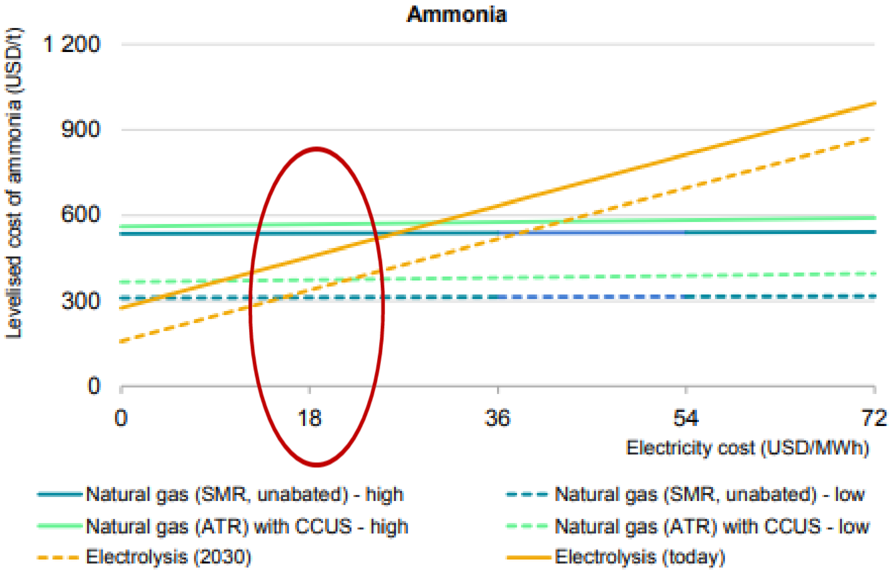
Increase in steel production costs?

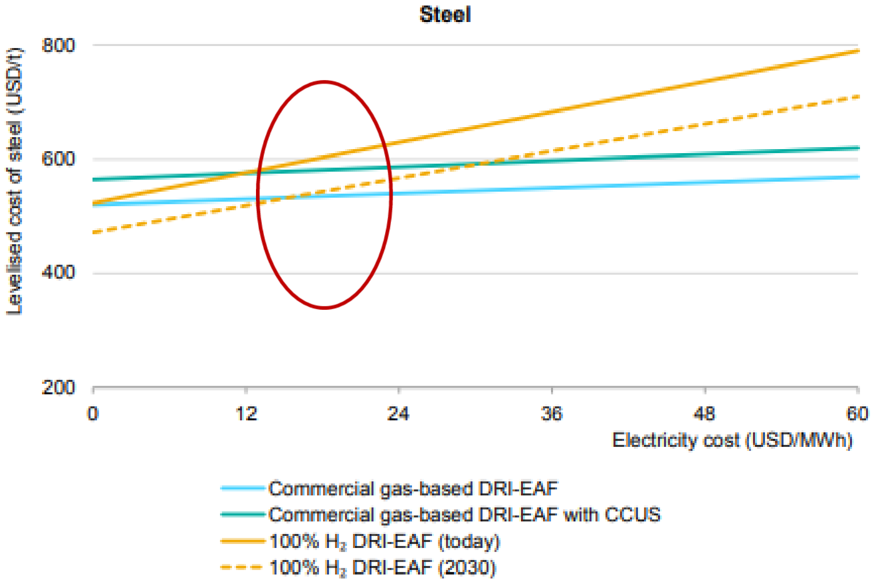
Price of 1t steel: around €400, incl. €50 required for the coal used

@ 3.6 €/kg H_2:
Replacing coal with H_2 costs extra 180 €/t steel
→ **1/3 increase of total price**

@ 1.80 €/kg H_2 (2030):
Price difference would drop approx. 10%

Cost sensitivities for ammonia and steel production

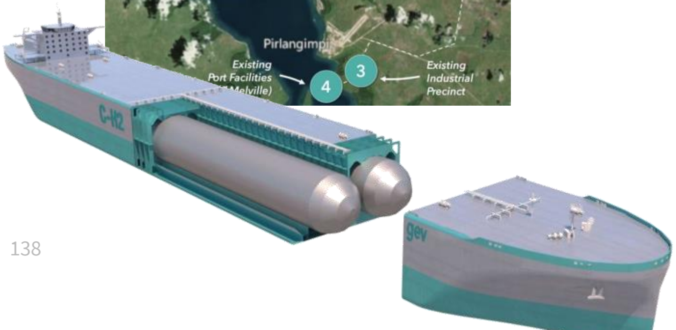




Notes: SMR = steam methane reforming. ATR = autothermal reforming. DRI-EAF = direct reduced iron - electric arc furnace. CCUS = carbon capture, utilisation and storage.

Source: IEA, Global Hydrogen Review 2021, Nov. 2021, p.66.

Australian H_2 ship maker to develop 2.8 GW green facility



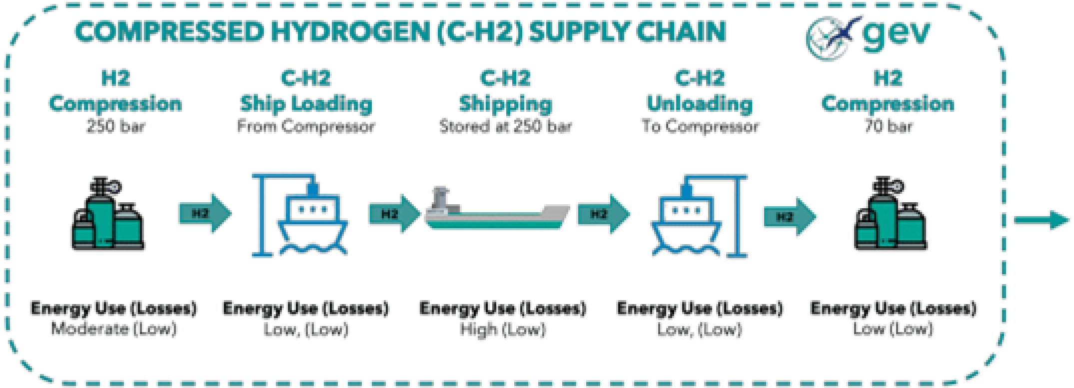
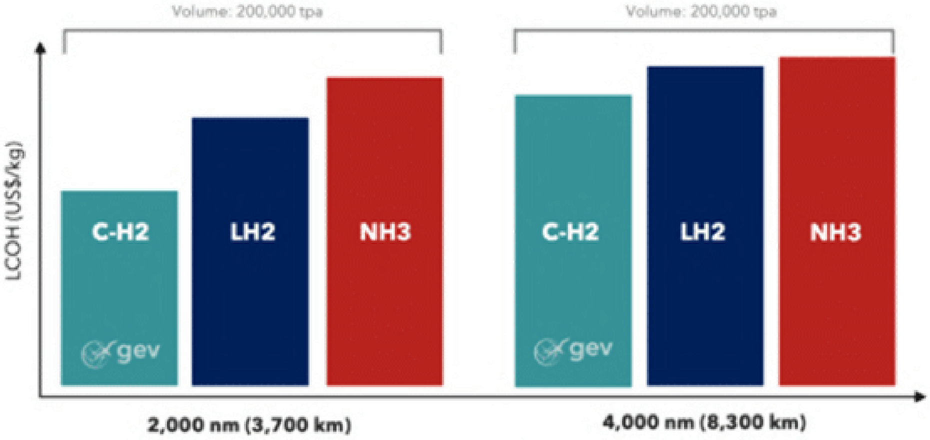


Figure 1: Levelised Cost of Hydrogen (LCOH)



Source: (1) PV Magazine, Australian hydrogen ship maker to develop 2.8 GW green facility, 10/2021.
(2) PV Magazine, Compressed green hydrogen ship for Aussie exports deemed 'highly competitive', 03/2021.

Renewable PtX-Training 30.06.2022

Remote base load Power Plant using Hydrogen

CEOG in French Guiana

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French Guiana:

CEOG Renewable Power Plant

Centrale Electrique de l'Ouest Guyanais (CEOG) is an optimised combination of a **solar park**, a **hydrogen long-term energy storage** and a **battery (short-term energy storage)** to produce **24/7 baseload power**

- **55 MW PV** solar farm
- **16 MW alkaline electrolyser,** 16 bar
- hydrogen storage unit to store 128MWh
- produce approximately 860t/a
- **fuel cells generate 3 MW** of electricity during night
- The project will also include a battery storage system.

The integrated solar and green hydrogen power plant will deliver

- a fixed electrical output of 10MW from 8am to 8pm
- and 3MW from 8pm to 8am
- Supposed to have lower costs than a diesel power plant

139.6

Source: ESI Africa (2021) https://www.esi-africa.com/industry-sectors/smart-technologies/worlds-largest-green-hydrogen-power-project-to-begin-construction/ -

MODULE 5: Key messages

PtX's Way

- Overview of **industrial sectors energy sources**
- **Today limited demand and use of hydrogen**. Hydrogen is mainly used in oil refining and for production of ammonia. In future, **demand will be rising up to an estimate of around 500 Mio. tH2/a** with industry as main user of hydrogen

Marginal Abatement Cost Curve & Classification of the Transition Need

- There are **some sectors** and applications **where hydrogen will be unavoidable, in others, hydrogen will be not competitive** and hence not suitable to start hydrogen economy **– start with no regret options** and always remember that direct use of electricity comes first

Example Sector Cases

- Steel industry
- PtL for aviation: ProQR Brazil
- Remote Power Plant using Hydrogen

Q

A

Check out this video in your break:
https://www.youtube.com/watch?v=ywHJt88H5YQ

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Break out group discussion

“What could be the role of hydrogen and PtX in your country?”

“Where do you see market opportunities?”

Grab a coffee & discuss among your group

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Module 6

Sustainability Criteria for Renewable PtX

EESG Framework, dimensions:

- Environmental
- Economic
- Social
- Governance

Sustainability Criteria

… along the PtX Value Chain

- Energy
- Sustainable carbon
- Land use
- Water use
- Recycling + critical raw materials

Certification Schemes

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The Paris Agreement

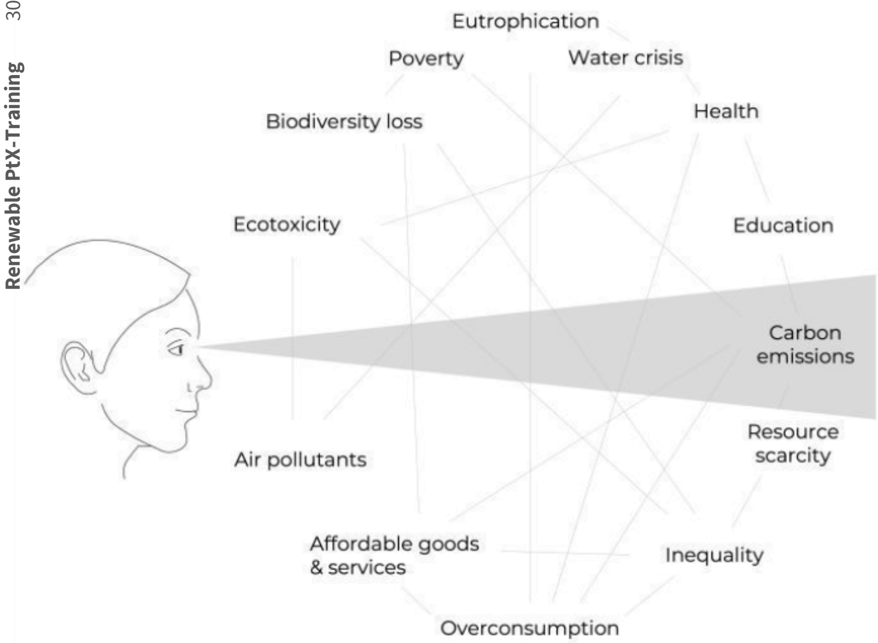
PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Limit temperature increase
to **1.5° Celsius**

Reduce GHG Emissions
to **Net-Zero**

→ *the 1.5° challenge*

How to get to Paris?
- A broader perspective



A Carbon Tunnel Vision is not enough!

Graphic by Jan Konietzko

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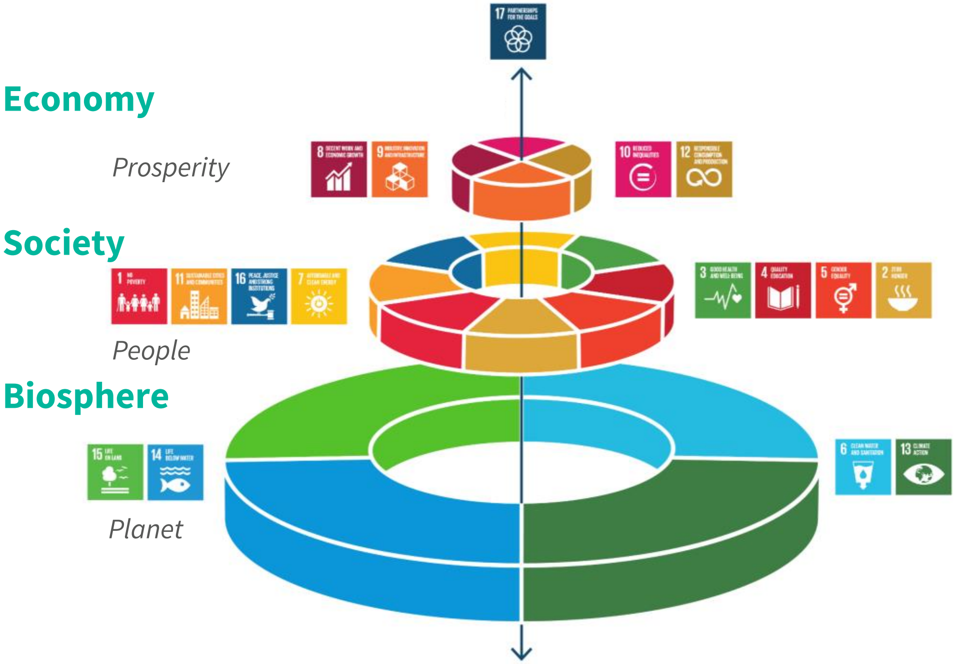
How to get to Paris?
- A broader perspective

17 SDGs for Planet, People and Prosperity



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PtX sustainability dimensions

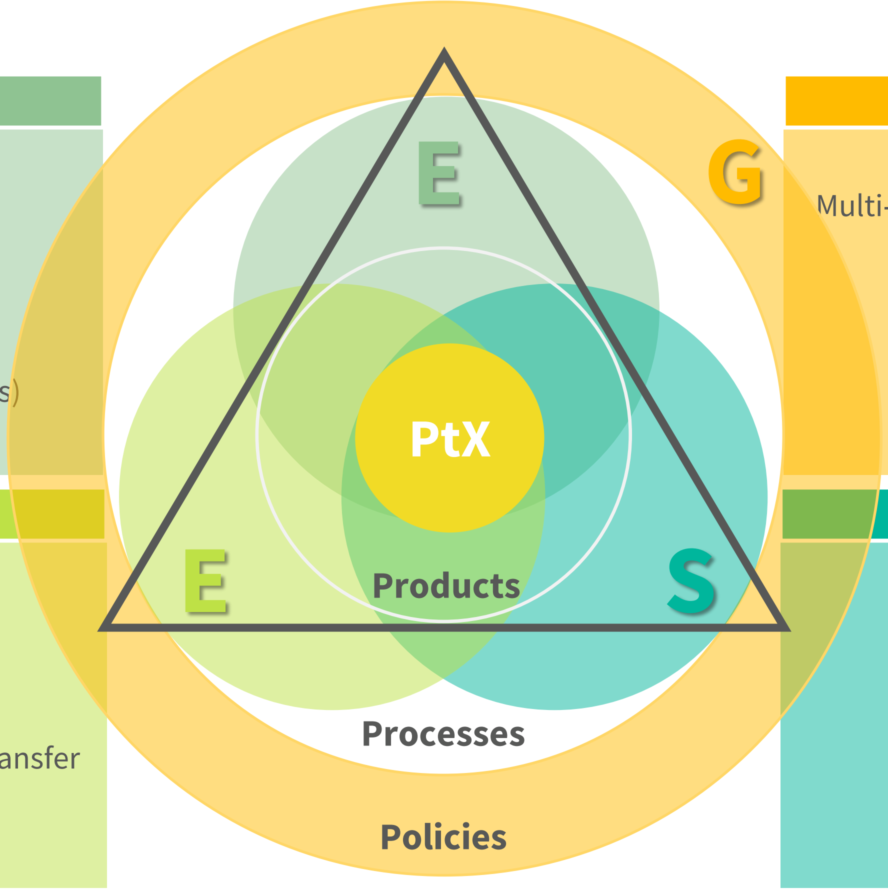
EESG: key for production and use renewable PtX

ENVIRONMENTAL

- Energy
- Carbon
- Water
- Land use
- Biodiversity
- Resources (Critical Raw Materials)

GOVERNANCE

- Political situation
- Multi-sector + multi-level cooperation
- Transparency + Rule of Law
- Business environment
- Ownership
- Stakeholder Participation



ECONOMIC

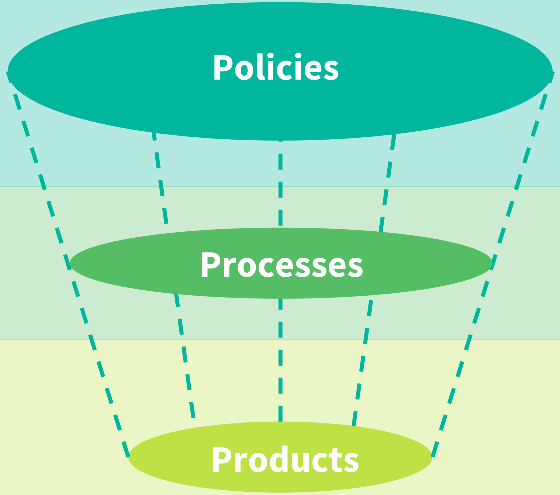
- Decoupled growth
- Local value added
- Employment
- Energy mix
- Innovation, R&D, Technology Transfer
- Infrastructure
- Circular economy

SOCIAL

- Energy Poverty + Access
- Human rights
- Labour standards
- Jobs, skills and training
- Health and safety
- Just Transition

Sustainability concerns must be considered at different assessment levels

Intervention Levels		Territorial Levels
Policies and Programmes	Institutions Instruments Incentives	**International** **EU/supranational**
Production Processes	Value Chains	**National** **Regional**
Products **Plants/Places**	Operations Investments	**Local**



Tools

Measuring/Monitoring

Valuing/Evaluation

Standards

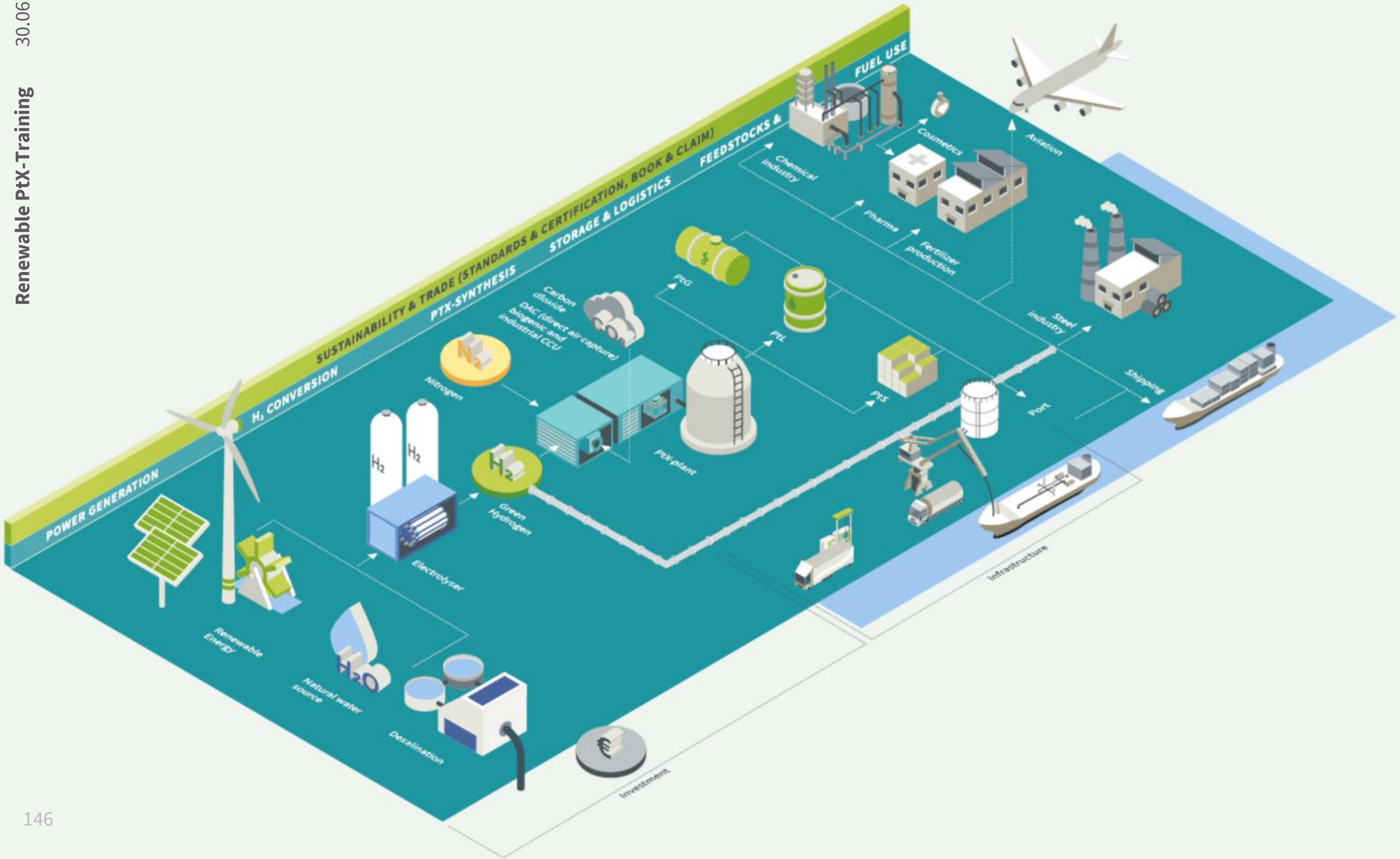
Certification

Due Diligence

Indicators
- *data*
- *thresholds*
- *timelines*

Challenge: Application of sustainability standards

Towards a comprehensive assessment concept



Sustainability standards

must ensure

- ecosystem integrity
- economic value added
- social inclusion
- decent work and human rights
- transparency
- public acceptance
- financial support

at **different levels and**

at **every step of the value chain**

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RISKS

- Prolongation of **fossil structures** and power plants
- **Water** scarcity
- Impairment of **ecosystems**
- **Land use conflicts**
- **Corruption**
- **Debt**
- **Energy poverty**
- Declining local **acceptance** for RE
- Lack of concepts for **recycling** + sustainable use of RE plants

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Embedding PtX strategy in SDGs and NDCs

- Good governance
- Participation
- Systemic approach
- Local value
- Existing electricity mix
- Public debt

Source: UNESCO, 2021.

CHANCES

+ **Local value creation** and **jobs**
+ **Competence** gains
+ **FDI**
+ Acceleration of **RE development**
+ Improved **energy access**
+ **Infrastructure** development and reconstruction
+ **Meeting local** syn. hydrocarbon **demand**
+ Building **long-term partnerships**

Source: Nationaler Wasserstoffrat, Nachhaltigkeitskriterien für Importe von erneuerbarem Wasserstoff und PtX-Produkten, 06/2021.

Break out group discussion

"Which sustainability challenges need to be addressed in PtX projects in your country?"

"… and how could this be done?"

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Environmental Dimensions

PtX production requires different inputs, from electricity to material inputs. How these are sourced and managed is extremely important in determining the environmental sustainability of the final product.

Energy + Carbon	PtX electricity supply should always be **RENEWABLE + ADDITIONAL and correlated.** Prioritising carbon sources that guarantee a closed CO_2 cycle. Limitation and phase out of use of industrial point sources.
Water, Land + Biodiversity	Use of water resources should not aggravate regional water risk. Desalination plants should respect strict standards for brine management and electricity supply. Even though PtX technologies require significantly less land than comparable technologies, the deployment should avoid areas with high carbon stocks or biodiversity potential.
Resources + Recycling	CRM: Reduction of demand of scarce raw materials via prevention, lifetime extension and recycling strategies
Pollution Risks + Safety	PtX production, transport and storage must respect strict anti-pollution and safety standards based on EIA. Emissions linked to transport and storage must be included when assessing PtX carbon intensity.

Environmental Dimension
ENERGY

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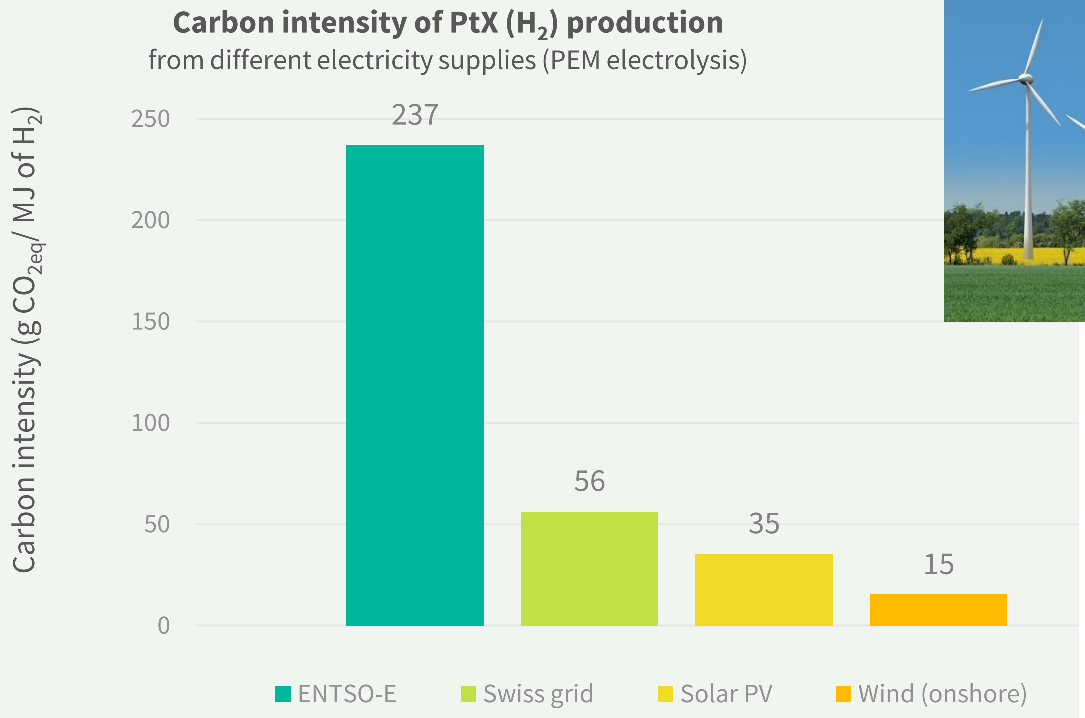
ELECTRICITY

Renewability



ENTSO-E
European Network of Transmission System Operators for Electricity (approx. 41% fossil, 36% RE)

Swiss grid
represents an electricity mix with a high share of RE (predom. hydropower)

Environmental Dimension
ENERGY

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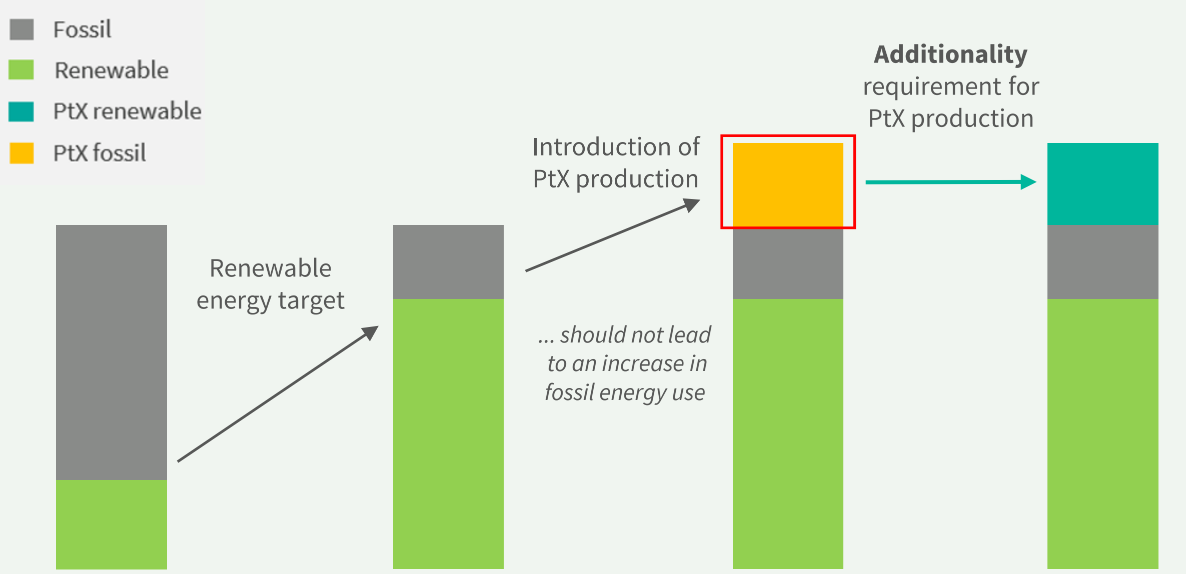
ELECTRICITY

Additionality



Additional RE demand for PtX should be integrated in energy and climate strategies (NDCs) → prepare a national plan!

Source: adapted: Öko-Institut e.V., Not to be taken for granted: climate protection and sustainability through PtX, 2019, p.12.

Environmental Dimension

ENERGY

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ELECTRICITY

SUMMARY

Carbon footprint of PtX production: **to achieve a 70% emission reduction, approx. 90% of electricity used must be carbon-free**

Renewability

Additionality

Geographical Correlation

Temporal Correlation

Geographical **proximity** between electricity production unit and PtX production unit

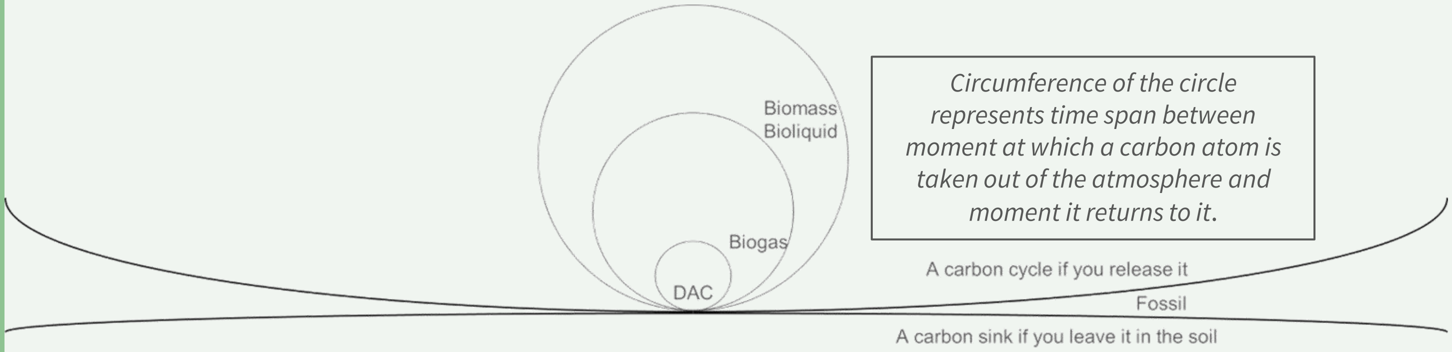
PtX products are produced **when contracted RE generation unit is generating electricity**

Environmental Dimension
CARBON: renewable carbon

CARBON

Carbon Cycle

- Needed for the production of **hydrocarbons**
- Can be obtained from **various sources:**
  - **ambient air**
  - **biomass sources**
  - **industrial/geological point sources**
- For PtX products to be **carbon neutral**, a **closed carbon cycle** must be in place
- **The shorter the cycle, the better** → less carbon atoms stay in the atmosphere



Circumference of the circle represents time span between moment at which a carbon atom is taken out of the atmosphere and moment it returns to it.

Environmental Dimension
CARBON

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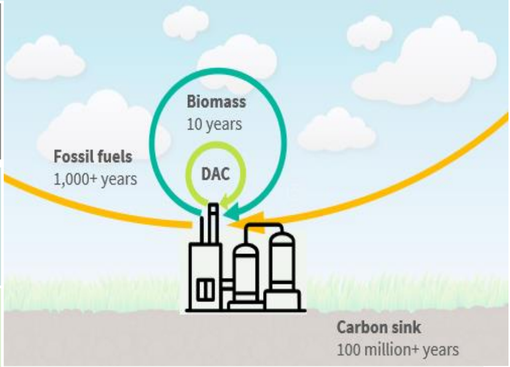
CARBON

Carbon Cycle

Sources	Closed carbon cycle	Costs	Technology maturity	Scalability	Sustainability issues
Ambient air (DAC)	✓	**High** (currently)	**Low**	**High**	• **Upscaling needs energy requirements** (Costs) • **Land use management**
Biogenic sources	✓	**Low,** but depend on **regional availability**	**High**	**Depends**	• **Land use risk** (ILUC) **Biodiversity risk** • **Efficient allocation** (e.g. biofuels)
Industrial point sources (CCU)	X	**Low**	**Medium -high**	Reduces over time	• **Lock-in risks** (for fossil technologies) • **Phase-out trajectories** • **Contracts only with** highly efficient **hard to electrify industries**



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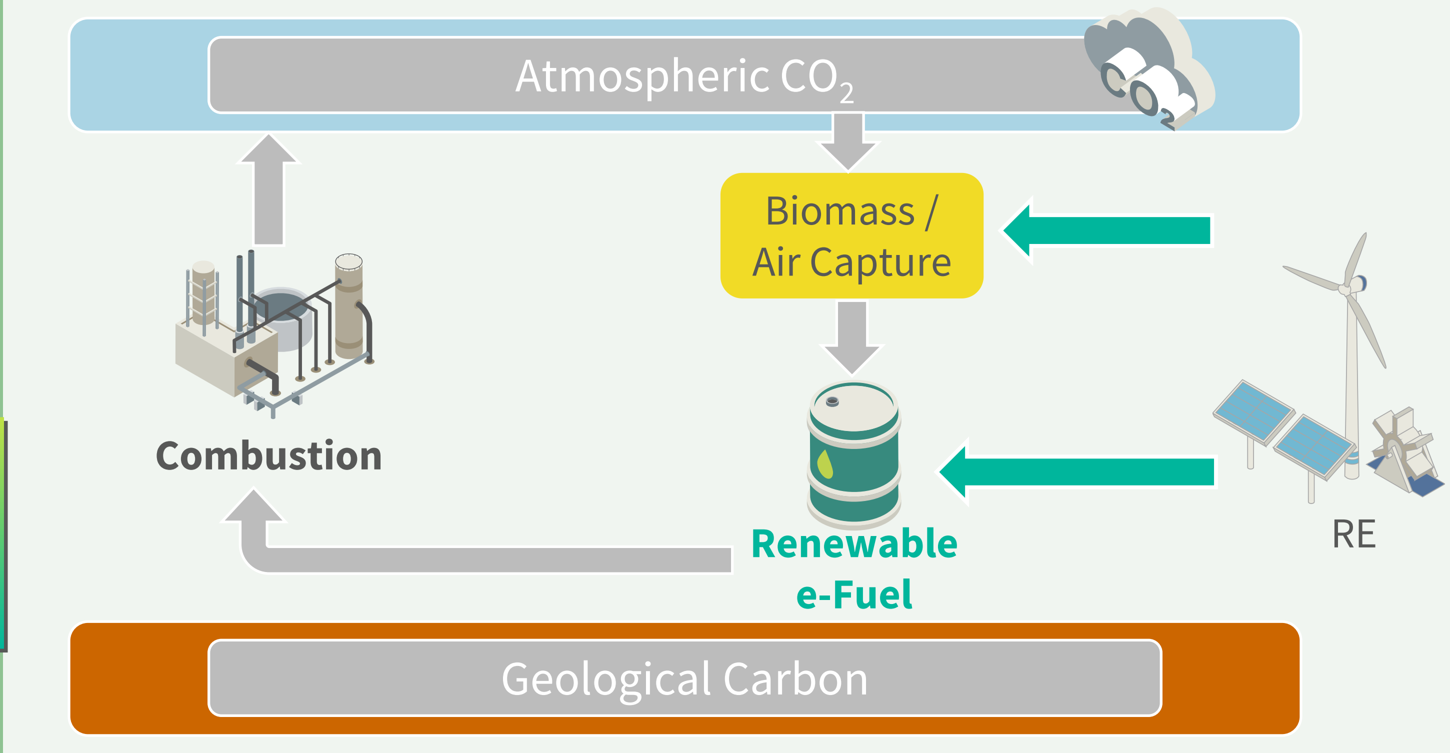
Environmental Dimension

CARBON: renewable carbon

CARBON

RENEWABLE Carbon Cycle

Cycle with renewable carbon sources is best option



Environmental Dimension

CARBON: renewable carbon

CARBON

RENEWABLE

Carbon Cycle

Direct Air Capture (DAC)

DAC is best option for **long-term perspective:**

- **Closed, immediate carbon cycle**
- Available in **sufficient amounts** and at every potential production site
- But: efficiency is low and costs increase

Requirements:

- Same energy requirements as electrolysers
- Land use management

Criticalities:

- **Energy intensive** process
- Reduces **efficiency** of production process by **about 10%**
- Increases total **cost of fuel production by 30%**
- **No implementations at scale** yet
- Limited land use risk

Table 3-1: Synthetic fuel production efficiencies (fuel output vs. electricity input)

Pathway*	Production efficiency today		
	Air	Exhaust gas (e.g. wood burner)	Fermentation (e.g. biogas upgrading)
Low-temperature electrolysis	38%	47%	48%
High-temperature electrolysis	45%	60%	62%

*Differences between the Fischer-Tropsch and the methanol pathway are negligible

Source: German Environment Agency 2016

Source: Öko-Institut, Outline of sustainability criteria for synthetic fuels used in transport, 2017, p.12/table3-1.

Environmental Dimension
CARBON: renewable carbon

CARBON

Carbon Cycle

Biomass sources

Biomass can be a critical carbon source on the way to reducing GHG emissions
→ should be part of the portfolio to produce PtL paraffin and other PtL products

- Can come from **biogenic residues**
- **Closed carbon loop = renewable**

Requirements:

- **Only use residues**
- **At least same criteria as for biofuels,** especially for **biodiversity** and **land use** (international frameworks)
- Prefer the most resource efficient process!

Criticalities:

- **Availability** of biomass is **limited** → might **not be available at potential locations** of syn. fuel production sites (e.g. Middle East)
- **Land use and biodiversity risk**
- **Efficient allocation** in a PtX world: **biomass is a carbon source, not an energy carrier**

Environmental Dimension
CARBON: industrial point sources

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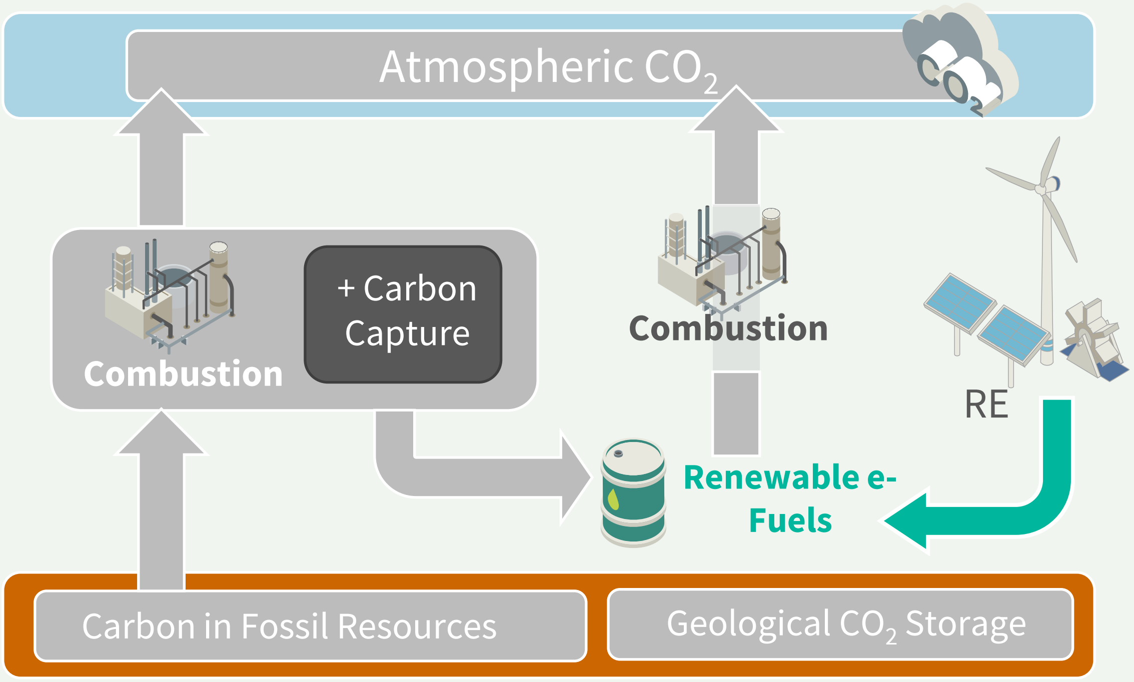
CARBON

Carbon Cycle

Industrial point source carbon is not sustainable: it is still released into the atmosphere

Significant risk of **lock-in effect** for CO_2-intensive technologies and industrial processes



Potential for **recycling:** large amounts of fossil carbons can be captured and reused via **Carbon Capture and Usage (CCU).**

Environmental Dimension
Water

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WATER

Water footprint per litre SAF

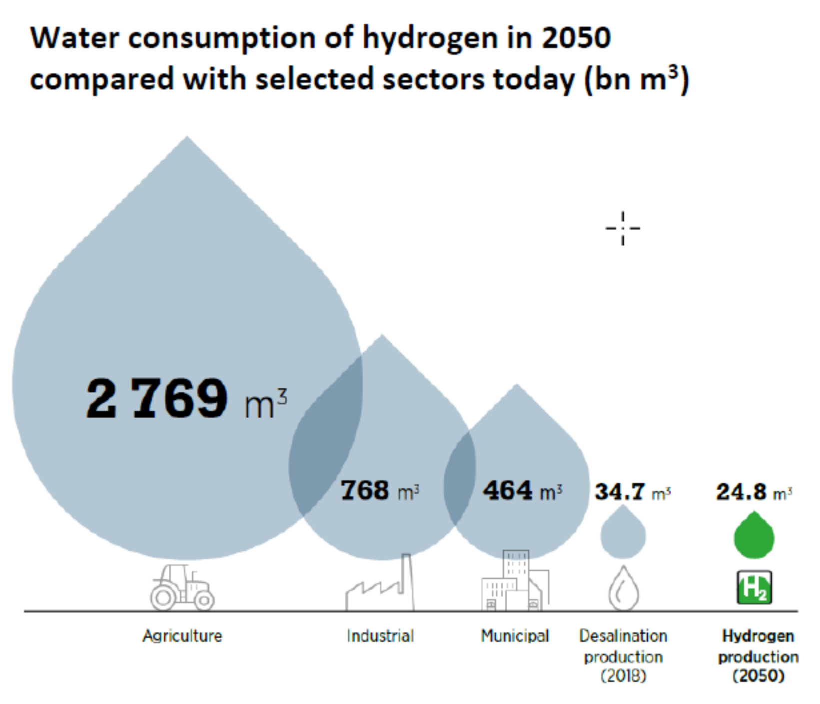
Water Use for Sustainable Aviation Fuels - (litre H_2O / litre SAF)

Source: UBA (2016). Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. German Environmental Agency.

Environmental Dimension
Water (land and biodiversity)

WATER

Water Footprint



Source: IRENA, The Geopolitics of the Energy Transformation: The Hydrogen Factor, 01/2022, p.9.

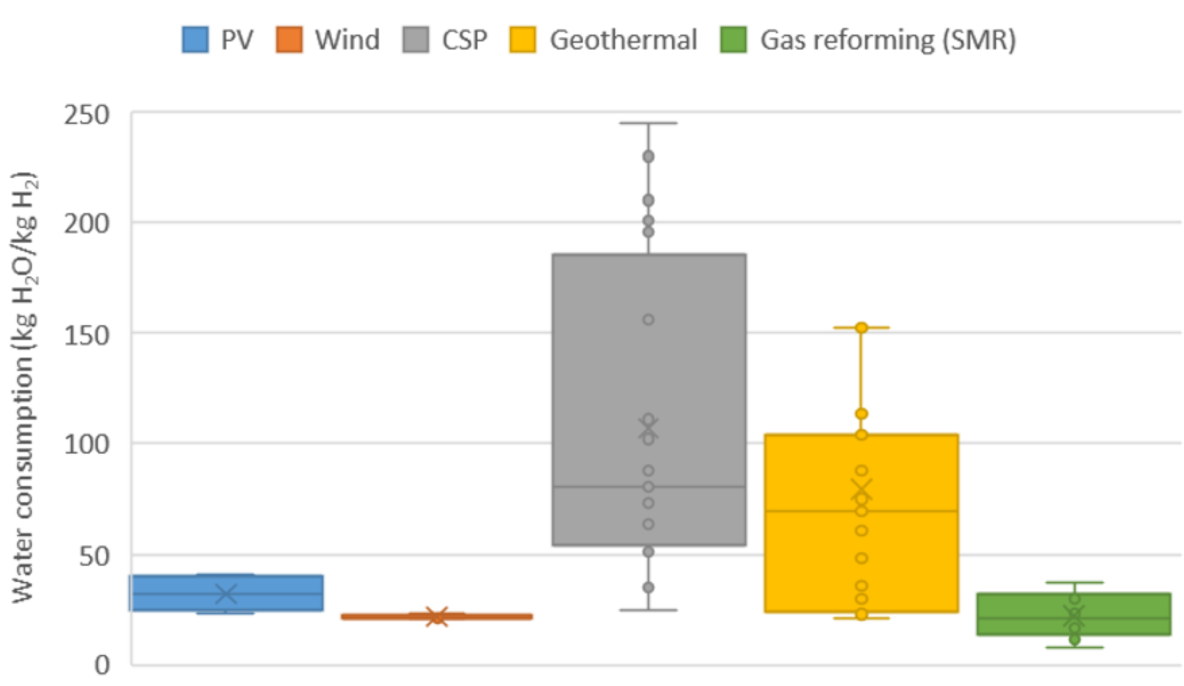
Environmental Dimension
Water

Water footprint can be low when using some RE!

WATER

Water Footprint

Lifecycle water consumption for various hydrogen production pathways



Source: Energypost.eu, Hydrogen production in 2050: how much water will 74EJ need?, 2021.

Environmental Dimension
Water (land and biodiversity)

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WATER

Water Stress

PtX production **could compete with other water uses.**

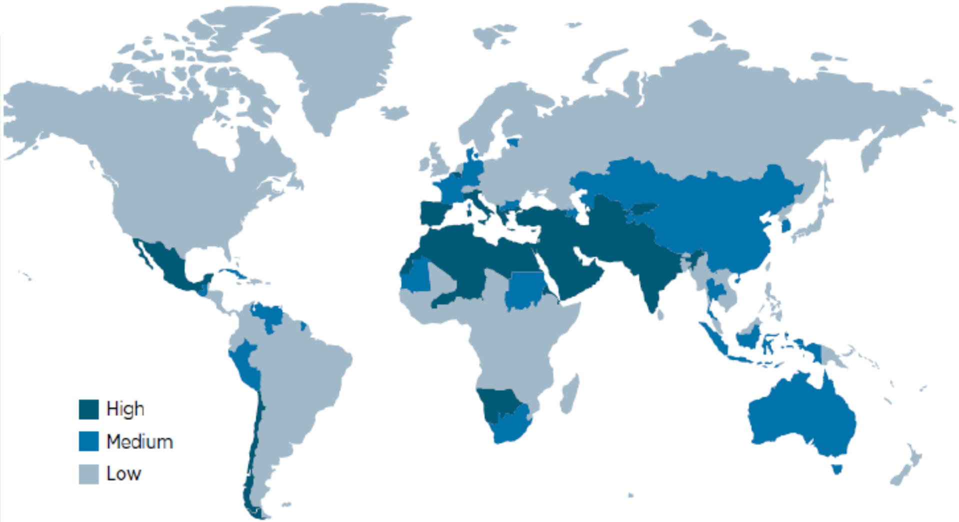
1. **Asses sustainability** upfront, consider regional data for water stress level
2. **If water stress** is *significant:* solution could be **water desalination**

Pros ✓

- **Costs** 0.6-1.6 €/m^3 in 2030 (**< 2%** of total H_2 production costs)
- Potentially **creates local added value**

Risks X

- **Very energy intensive** process: **electricity** must meet the **same requirements as PtX plants**
- **Brine disposal: mandatory independent ecological assessment based on local indicators** and legislation to **minimise** negative externalities



Picture Source: Indiatimes, Solar Desalination Device Will Turn Sea Water Into Fresh Water For 400,000 People, 10/2021.

Source: IRENA, The Geopolitics of the Energy Transformation: The Hydrogen Factor, 01/2022, p.9.

Environmental Dimension
Land

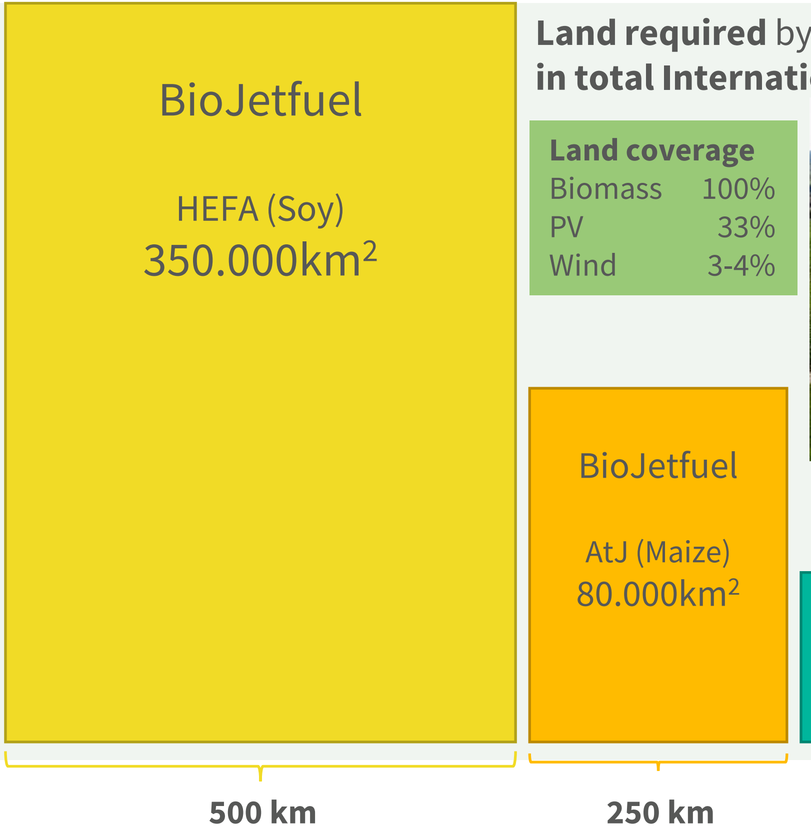
LAND

Land Use

Land required by different SAF types for a **5% blend in total International Jet Fuel** (17 mil tonnes PtL).

Land coverage

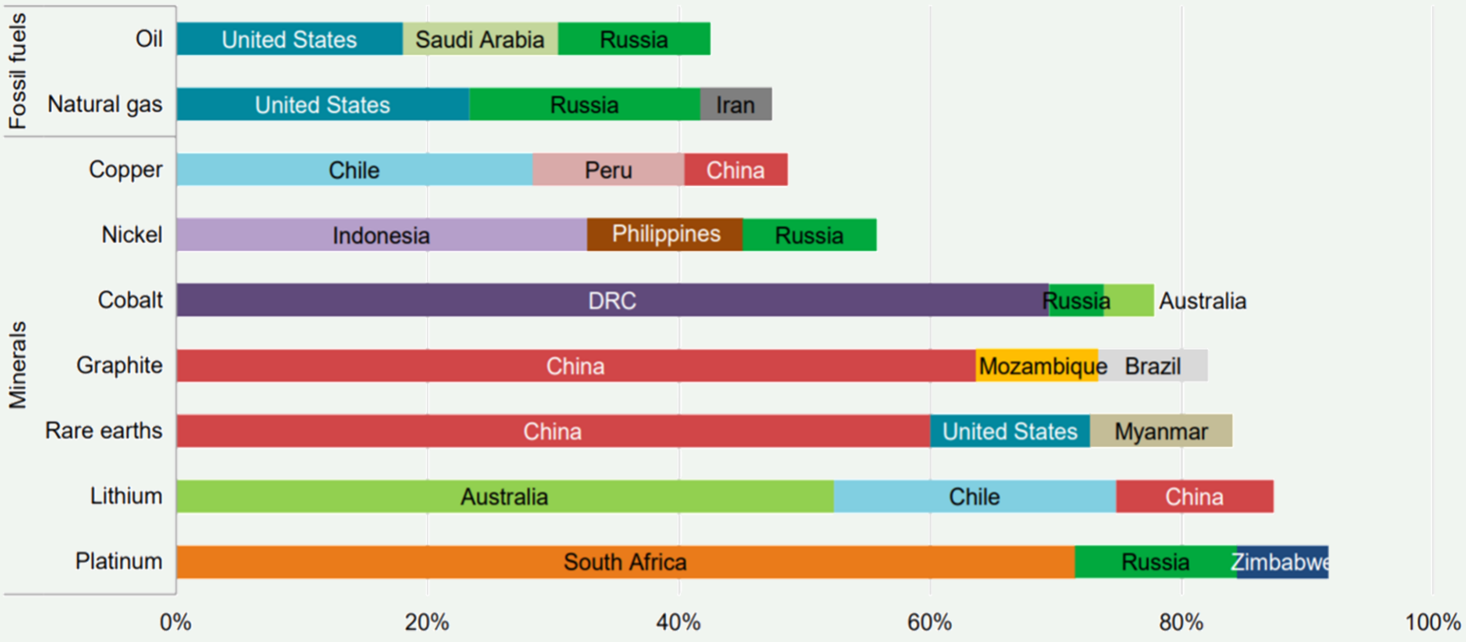
Biomass	100%
PV	33%
Wind	3-4%



Environmental Dimension
Resources and Recycling

CRITICAL RAW MATERIALS (CRM)

- Iridium for PEM
- Tantalum for PEM
- Platinum for AEL
- …



Source: IEA, TheRoleofCriticalMineralsinCleanEnergyTransitions.

Environmental Dimension
Resources and Recycling

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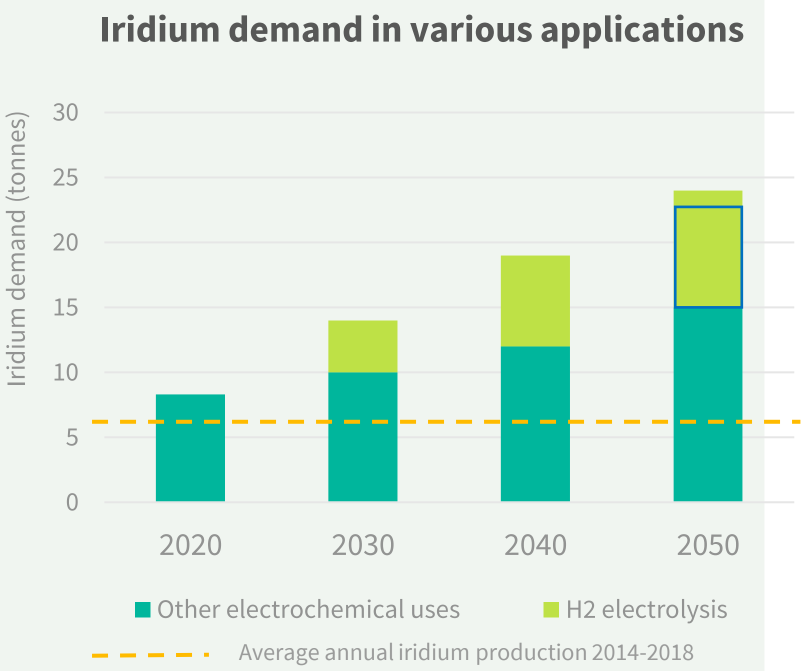
CRITICAL RAW MATERIALS (CRM)

- Iridium for PEM
- Tantalum for PEM
- Platinum for AEL
- …

CRM needed to produce EU 2050 Green H2 target (2,250TWh with 50% AEL, 50% PEM)	
CRM	**% global CRM production p.a.**
Iridium	122%
Tantalum	33%
Platinum	25%
Raney-Ni	0.4%
Nickel (class 1)	2%
Cobalt	0.1%

CRM as defined by the EU Commission 2020 list of Critical Raw Materials

2050 target: European Hydrogen Roadmap



Environmental Dimension
Resources and Recycling

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CRITICAL RAW MATERIALS (CRM)

Savings strategies

- prevention
- extention
- recycling

Type	Strategy	Short description	PEM	AEL
Prevention	Reduction	Reduction of the amount of CRM used	Ir, Ta, Pt	Pt, Ni
	Substitution	Replacement of CRM by other material	-	Pt, Co
	Technology mix	Balance between AEL, PEM, and (later) SOEC	Ir, Ta, Pt	Pt, Co, Ni
Extension	Higher productivity	Higher productivity of electrolyser stack	Ir, Ta, Pt	Pt, Co, Ni
	Extended lifetime	Extended lifetime of the stack	Ir, Ta, Pt	Pt, Co, Ni
Recycling	Hydrometallurgical treatment		Pt	-
	Transient dissolution		Pt	-
	Acid process		Pt	-
	Selective electrochemical dissolution		Pt	-

With these strategies it is possible to **save up to 95% of CRM usage.**

Social Dimensions

The transformation of energy systems and introduction of new technologies like PtX always have major social implications.
This is not just a transition. It must become a "Just transition"

Access to Energy + Resources	PtX should not conflict with peoples' access to essential resources, which must be guaranteed and monitored along the whole value chain.
Human Rights + Labour Standards	Human rights and basic labour standards must be respected along the entire value chain. Sustainability assessments must include social concerns. Communities and workers should have access to remedy.
Health + Safety	PtX safety standards must follow strict technical guidelines, with constant audits and updates.
Jobs + Skills	The potential for local and regional employment creation should be taped and where necessary, the transition from fossil to RE industries should be facilitated. This implies e.g. re-training of the labour force.

Social Dimension
Access to Energy and Resources

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On behalf of: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of the Federal Republic of Germany

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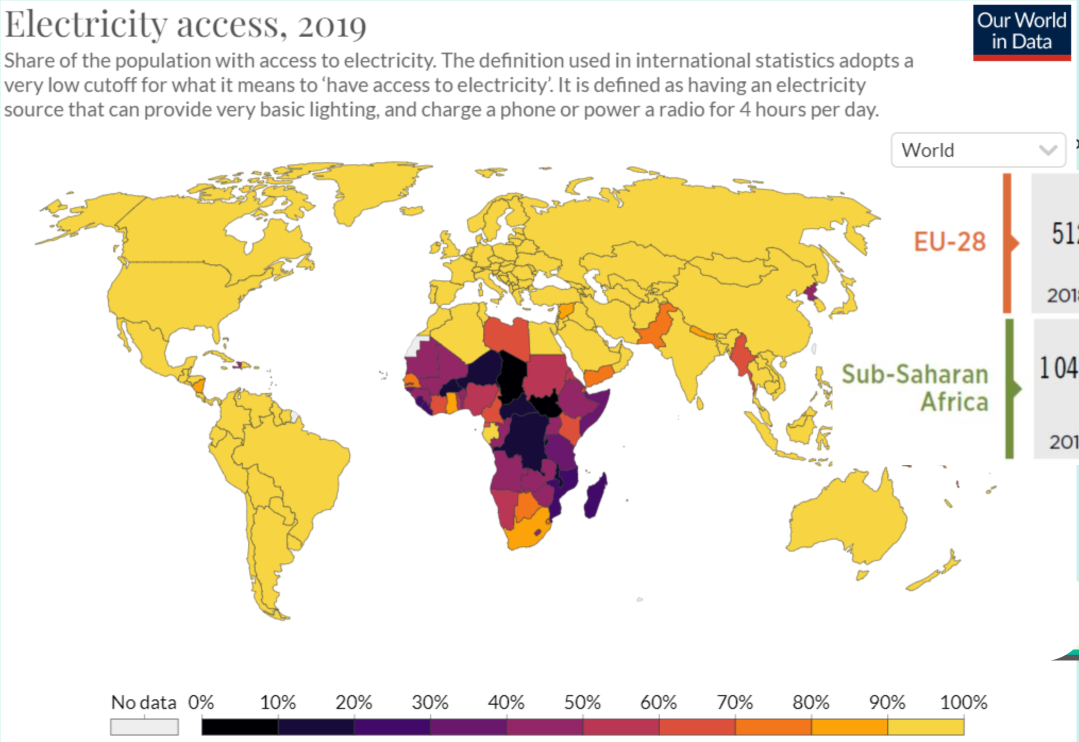
ACCESS TO:

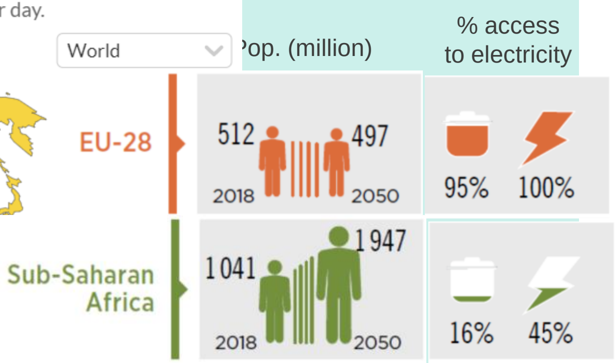
1. Energy: connection to electricity (SDG7)

2. Water:

- water stress
- clean dringing water (SDG6)
- irrigation
- desalinisation (opportunities and risks) for H2/Ptx and local needs

3. Land: land use conflicts





IRENA 2020

ADDITIONALITY

SDG7 (energy) does not sufficiently promote a holistic transformation. Part of the problem: neither the goal nor its targets and indicators specify who is responsible for which action.

Source: Our World in Data, Access to Electrictiy, 2021.

Social Dimension
Human Rights and Labour Standards

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LABOUR STANDARDS

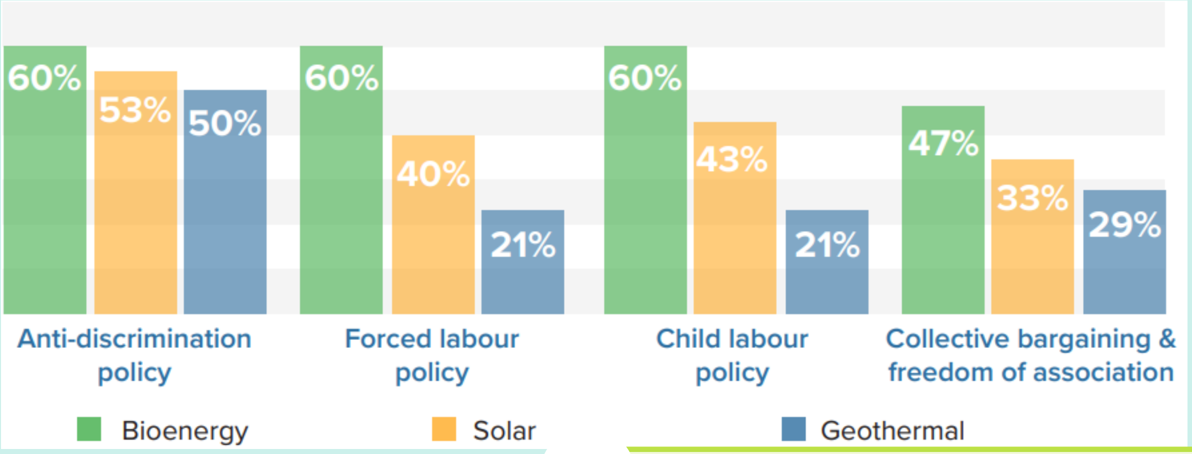
International Labour Organization

Core Labour Standards

- **Freedom of association** and right to **collective bargaining**
- **Elimination of** all forms of **forced** or compulsory labour
- Effective **abolition of child labour**
- **Elimination of discrimination** in respect of employment and occupation

Since 2010: **197 allegations** of human rights abuses across all 5 sub-sectors of RE *(wind, solar, bioenergy, geothermal, hydropower),* incl.:
killings, threats, and intimidation; land grabs; dangerous working conditions and poverty wages; and harm to indigenous peoples' lives and livelihoods.

Percentage of solar, bioenergy and geothermal companies with labour rights policies.



Nexus between human rights, climate change and energy remains underdeveloped in international law and practice.

Source: Business & Human Rights Resource Centre, Renewable Energy & Human Rights Benchmark, 06/2020.
Business & Human Rights Resource Centre , RENEWABLE ENERGY RISKING RIGHTS & RETURNS, 09/2018, p.16/fig.2.

Social Dimension
Human Rights and Labour Standards

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LABOUR STANDARDS AND HUMAN RIGHTS

How to include principles to respect human and labour rights into my business?

1. **Identify, prevent and monitor risks** related to human (HR) and labor rights (LR) that are salient in sector of activity.
2. **Recognise stakeholders**: workers and their families, local communities, any other person/group of people whose lives and environment may be influenced by your activities, incl. legitimate representatives, labour unions, social or environmental organisations.
3. **Engage with stakeholders**, especially those affected by activities, incorporating their views and concerns in business decisions and development of its approach to HR and LR.
4. **Implement a reporting system**, with a guarantee of confidentiality and non-retaliation.
5. **Transparency** reg. HR and LR: identify risks and impacts, mitigation, compensation and remediation measures taken and results of such actions.
6. **Extend commitments to business partnerships and suppliers**, working towards the extension of commitments to entire supply chains and partnerships.
7. **Work with partners and suppliers** to mitigate adverse impacts that are directly linked to operations, products or services through own mechanisms or cooperation in development of third-party non-judicial solutions.

Source: EDP, Human and Labor Rights Policy.

Social Dimension
Jobs and Skills

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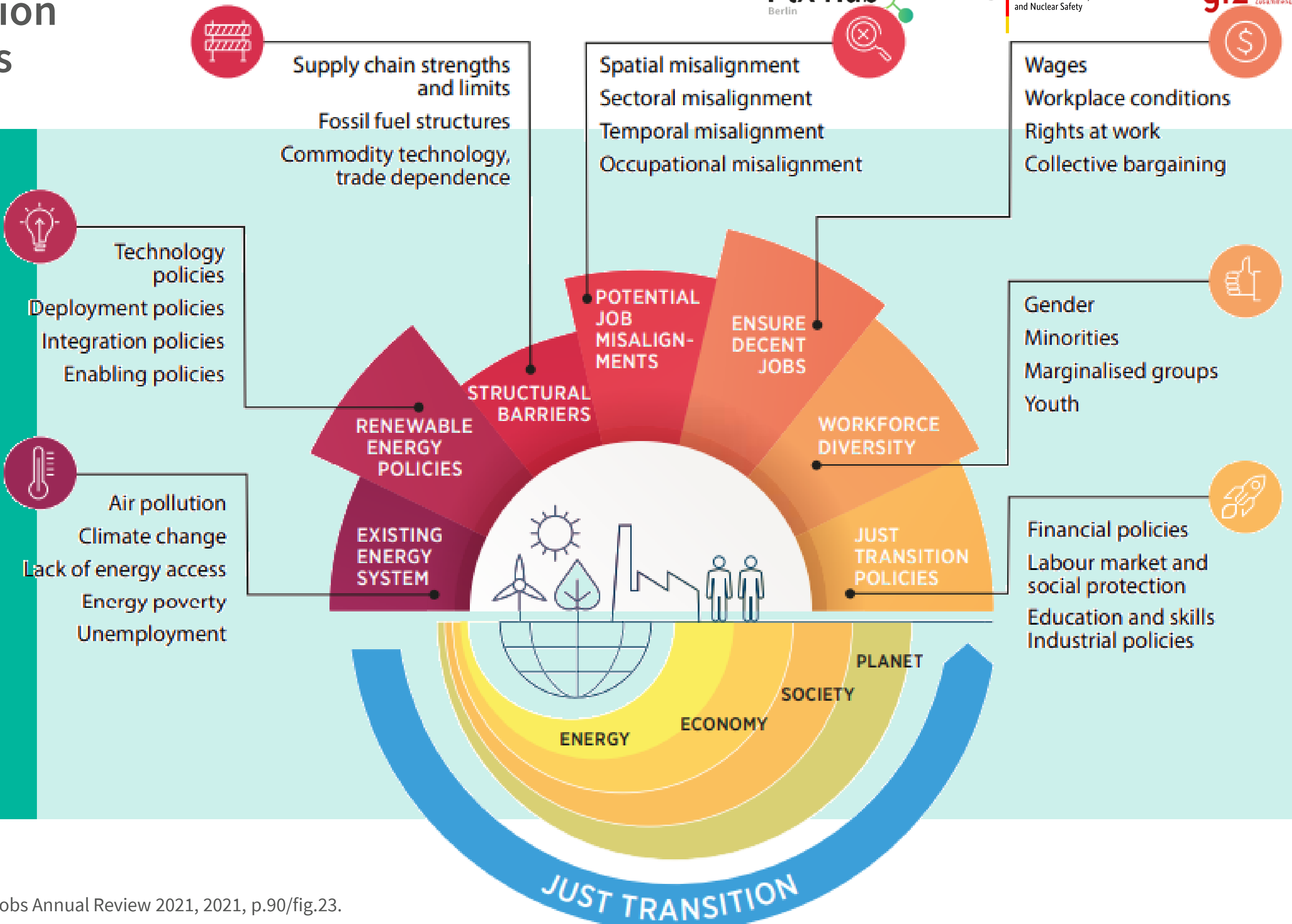
On behalf of: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Implemented by giz

JUST TRANSITION

Jobs in the Just Energy Transition: Challenges and policies



Source: IRENA / ILO: Renewable Energy and Jobs Annual Review 2021, 2021, p.90/fig.23.

Social Dimension
Jobs and Skills

JOBS AND SKILLS

Jobs

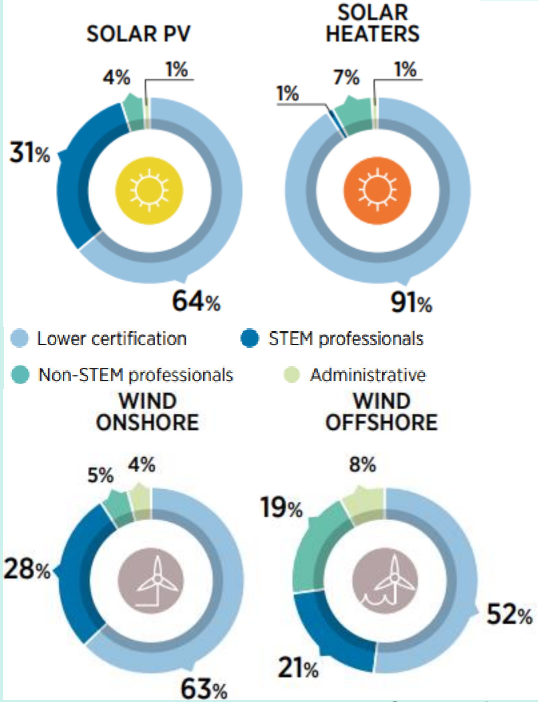
- ***Gains*** in Renewables
- ***Losses*** in Fossils

Jobs and Just Transition

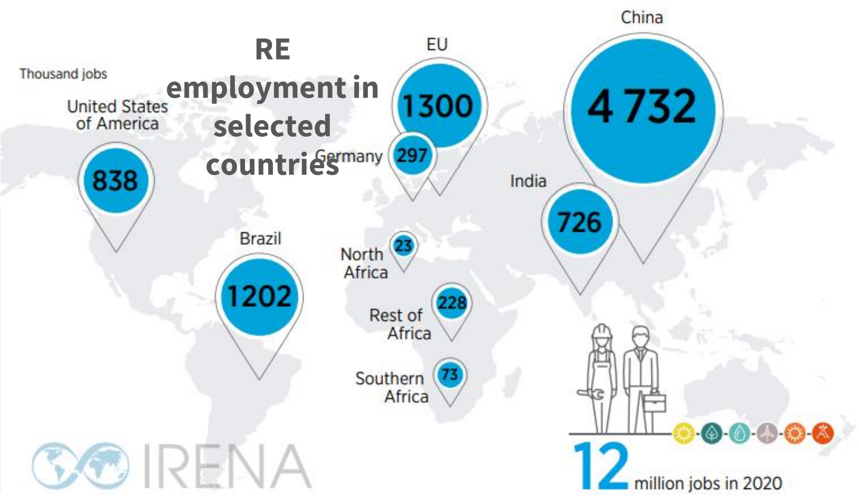
- ***Regional disparities / diversity***

Skills and Training

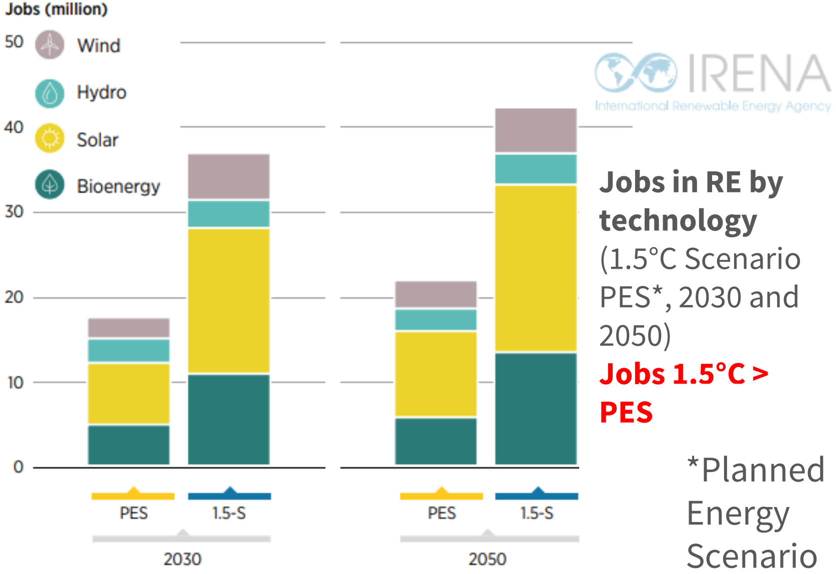
- ***Qualifications*** and skills profile



Human resource requirements for workers in solar PV, wind energy (onshore and offshore), and solar water heaters.



RE employment in selected countries



Jobs in RE by technology
(1.5°C Scenario PES*, 2030 and 2050)
Jobs 1.5°C > PES

*Planned Energy Scenario

Source: IRENA / ILO, Renewable Energy and Jobs Annual Review 2021, 10/2021, fig. 9,11,15.

Test your knowledge

"Which socio-economic and governance issues are important when developing renewable PtX in your country?"

Economic Dimensions

PtX production and trade should contribute to improving economic prosperity and well-being. Leap-frogging potentials should be taped.

Value Added + Decoupled Growth	PtX can offer opportunities for **leapfrogging over fossil dependency**. Production should also be integrated into local productive networks, leveraging their potential.
Energy Mix + Transformation	PtX should be an integral part of the energy transition. Stability of a region’s power grid should be considered when assessing PtX sustainability. Options for off-grid solutions should be considered.
Trade + Tech. Transfer	For some countries and regions PtX offers new export opportunities; yet this should not go at the expense of domestic development priorities. Technology transfer, promotion of innovation and the development of local knowledge are key.
Infrastructure + Public Finance	PtX should be included in public and private investment and funding schemes. Infrastructures such as pipelines and ports will have to be PtX compatible.

Economic Dimension
Value Added and Decoupled Growth

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VALUE ADDED AND DECOUPLED GROWTH

Value Added

Value Added
- per capita
- overall growth
- sectoral mix

GDP
- *local*
- *regional*
- *national*

Value Added and employment
local /regional
(regional disparities)

GHG/GDP
- carbon intensity
- *level & trend*

New projects: ensure **economic profitability + contribute to the local development**

- **Equitable profit sharing** between owners, employees and local community
  → assess compliance with national labour rules, e.g. minimum wages
  → inspect labour contracts + wages of employees
- Local economic conditions should improve on time
  → assess (macro)-economic indicators in statistical document

→ Improvements in human well-being and welfare go far beyond gains in GDP
Doubling share of RE by 2030 raises global welfare by 2.7 % while GDP by 0.6%

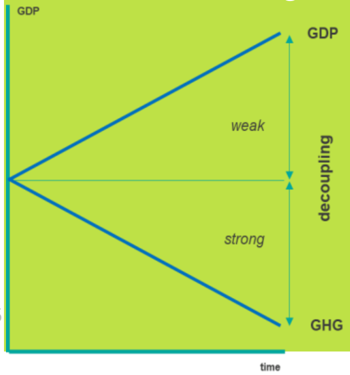
Source: IRENA, Renewable Energy Benefits: Measuring the economics, 2016, p.33.

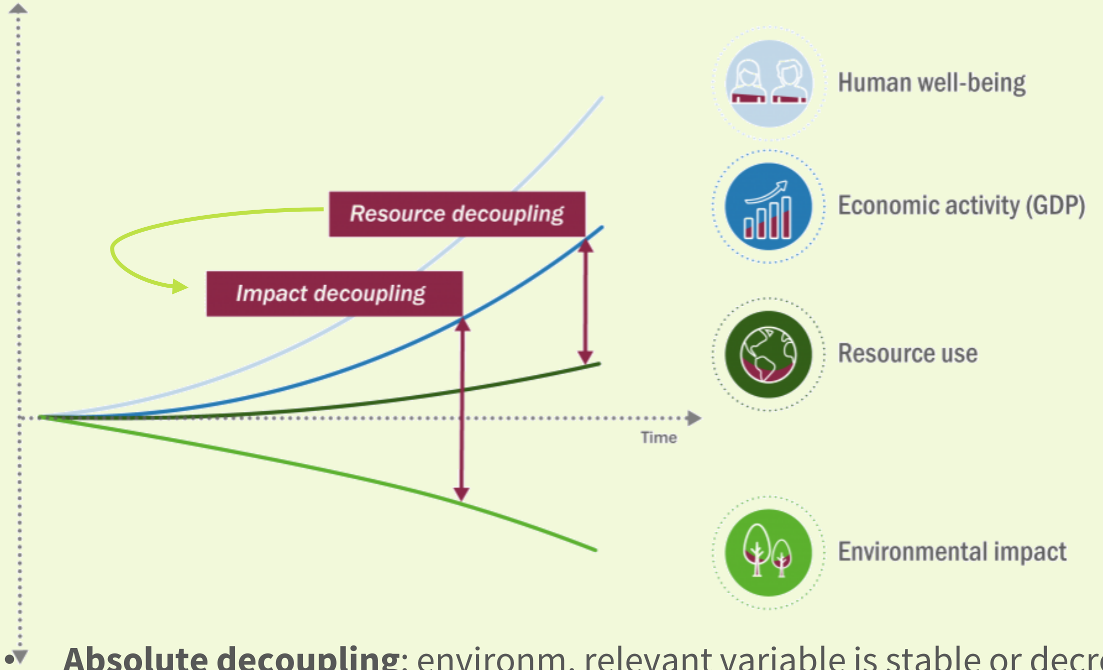
Economic Dimension
Value Added and Decoupled Growth

VALUE ADDED AND DECOUPLED GROWTH

Decoupled Growth

→refers to breaking the link between environmental bads and economic goods





- **Absolute decoupling**: environm. relevant variable is stable or decreasing while econom. driving force is growing
- **Relative decoupling**: environm. relevant variable is positive, but less than growth rate of econom. variable

Source: UNIDO, The Circular Economy: A driver of inclusive and sustainable industrial development, 04/2021.

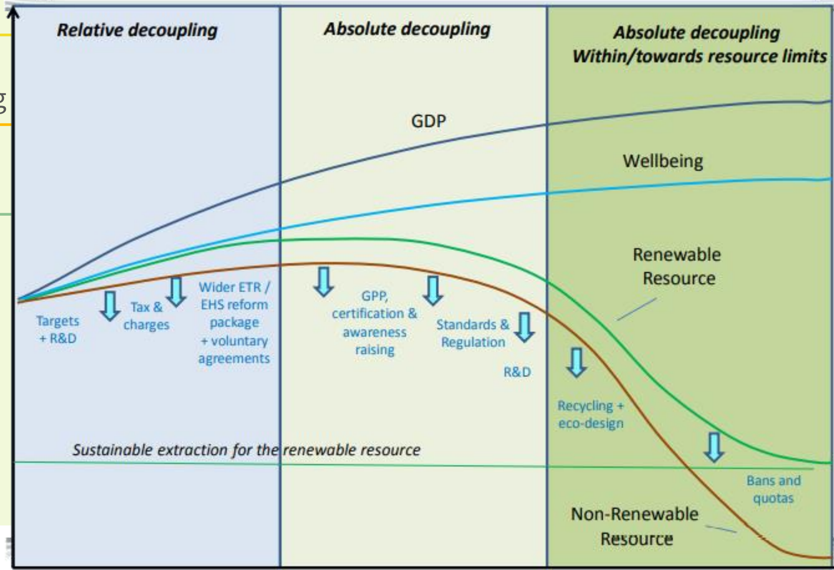
Economic Dimension
Value Added and Decoupled Growth

VALUE ADDED AND DECOUPLED GROWTH

Decoupled Growth

→refers to breaking the link between environ-mental bads and economic goods

Regulatory instruments	Regulation, bans, standards, limits
Planning instruments	Regional planning, land-use, urban planning
Market-based instruments or economic instruments	Revenue-generating instruments (taxes, charges) Subsidies (direct payments, tax allowances) Property rights (licenses, tradable permits) Others (user benefits, environmental liability, payments for ecosystem services)
Public investments	Infrastructure investments, procurement, R&D spending
Cooperation-based instruments	Voluntary commitments, negotiations, networks
Information-based instruments	Info campaigns, education, advisory services + capacity building, labelling, environ. reporting + monitoring, access to information + justice rights



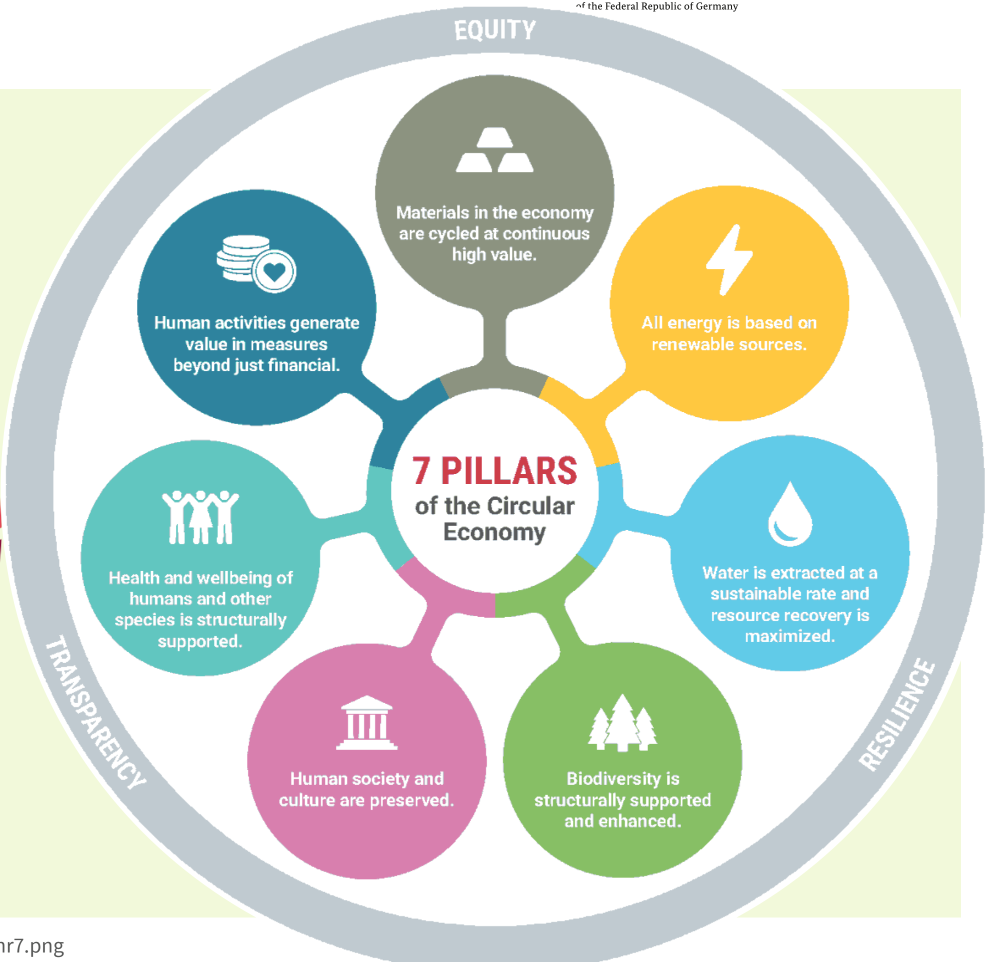
Source: DYNAMIX, How will we know if absolute decoupling has been achieved? And will it be enough?, 10/2015, p.19ff.

Economic Dimension
Value Added and Decoupled Growth

VALUE ADDED AND DECOUPLED GROWTH

Circular Economy

Refuse
Rethink
Reduce
Re-use
Repair
Refurbish
Remanufacture
Repurpose
Recycle
Recover



Source: SRIP – Circular Economy. Source II: https://pbs.twimg.com/media/ETzOWQpXgAQYnr7.png

Economic Dimension
Energy Mix and Transformation

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ENERGY MIX AND TRANSFORMATION

Energy Mix

-- fossil

-- renewables

Energy trends and scenarios

H2 and PtX

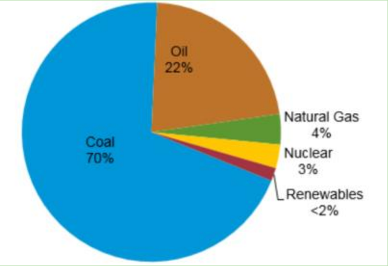
-- potentials

-- actual

Market Design (ETS, CDM etc)

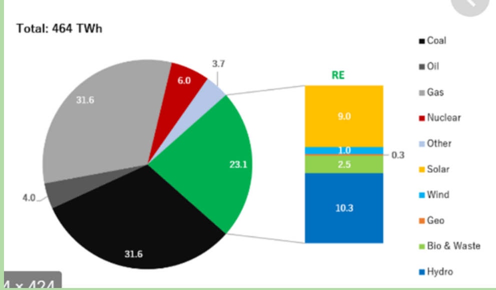
...

Energy mix



South Africa

Costa Rica



Open discussion

"What are potential positive socio-economic impacts of your projects?"

"How could potential negative impacts be avoided or mitigated?"

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Governance Dimensions

	National + international standards and certification schemes must provide proper regulatory frameworks for ramping-up PtX markets and trade. Essential: clear policy commitments, empowerment and participation of stakeholders.
Standards + Certifications	Renewable PtX standards will play a key role in kickstarting the market and should cover the entire value chain. Certification schemes should be transparent about assessment procedures and criteria.
Transparency + Participation	PtX councils and roundtables should be established, and stakeholder trainings should take place. Moreover, bottom-up approaches such as surveys and free, prior and informed consent (FPIC) should be adopted, with audits and access to complaint procedures.
Policy Commitment + Coherence	Renewable PtX should be part of energy and climate strategies and included in NDCs.
Stability + Rule of Law	Political stability and respect for the rule of law are important considerations when setting-up bi- or multilateral partnerships.

Governance Dimension
Standards and Certifications

STANDARDS AND CERTIFICATIONS

Requirements for PtX Certification

- Simplicity
- Transparency
- Coherence with existing regulation
- Stakeholder inclusion

- PtX products need rigorous **SUSTAINABILITY STANDARDS** → don't sacrifice for quick market run-up (*see biofuels*):
  market run-up and sustainability standards have to go hand in hand!
- Standards must be developed via **comprehensive and harmonised legislation; CERTIFICATIONS must be in place**

- **Sustainability requirements** along the **whole supply chain** and for each relevant element
- Ensuring a **level playing field across different sectors** through certifications principles that apply to all markets and products

  → consider costs involved!
- Attention to **human and labour rights**, including socio-economic aspects in the assessment, especially when operating in areas with high social risk

Governance Dimension
Standards and Certifications

STANDARDS AND CERTIFICATIONS

Different certification institutions / schemes

Notes: IPHE: International Partnership for Hydrogen and Fuel Cells in the Economy

Governance Dimension
Standards and Certifications

STANDARDS AND CERTIFICATIONS

Several green hydrogen standards are in place or under development

Status	Country	Name	Body	Legal Status
✓	EU	**RED II Delegated Acts**	European Commission	**Binding** for RFNBO used in transport sector*
dvlpm.	EU	Taxonomy	European Commission	Binding for "sustainable investment"
✓	EU	**CertifHy**	FCH JU	**Voluntary** certification
✓	Germany	CMS 70	TÜV SÜD	Voluntary certification
dvlpm.	Germany	EEG Ordinance	German government	Binding to be exempt from the EEG levy
✓	Netherlands	SDE++ criteria	Dutch government	Binding to be eligible for gov. funding
✓	France	AFHYPAC standard	AFHYPAC	
✓	California	Low carbon fuels standard	State of California	Binding for fuel suppliers' emission targets
trial	Australia	*'GO Hydrogen Certification Scheme'*	Australian govern.	?

Consolidation into EU-wide single standard?

Source: Guidehouse, EU certification frameworks Sustainability criteria for green hydrogen, Knowledge Session Certification of Green Hydrogen, 24.11.2021.

Notes: *RFNBO: renewable fuels of non-biological origin. REDII revision proposed to expand this to all end use sectors.

Governance Dimension
Standards and Certifications

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STANDARDS AND CERTIFICATIONS

Guarantee of Origin (GO) Schemes

BODY	REFERENCE	THRESHOLD	QUALIFIED PROCESSES
AFHYPAC	None	100% renewable	All renewable-based solutions
Low Carbon Fuel Standard	Well-to-wheel emissions from new gasoline vehicles	30% lower GHG, 50% lower NO_x	Green hydrogen, catalytic cracking of biomethane or thermochemical conversion of biomass, including waste
CertifHy	Grey hydrogen	60% lower GHG than reference (36.4 gCO_2/MJ)	Two labels: • "Green hydrogen" if the hydrogen is made from renewable energy • "Low carbon hydrogen" otherwise Hydrogen must meet the threshold with 99.5% purity
TÜV SÜD	Grey hydrogen	35-75% lower than reference depending on process	Renewable electrolysis; biomethane steam methane reforming; pyro-reforming of glycerine
Clean Energy Partnership	Grey hydrogen	100% renewable	Renewable electrolysis; biomass
REDII[12]	Transport fuels	70% reduction	Renewable transport fuels of non-biological origin
Technical Expert Group on Sustainable Finance	None	5.8 tCO_2/tH_2 or 100 gCO_2/kWh used as input	Water electrolysis

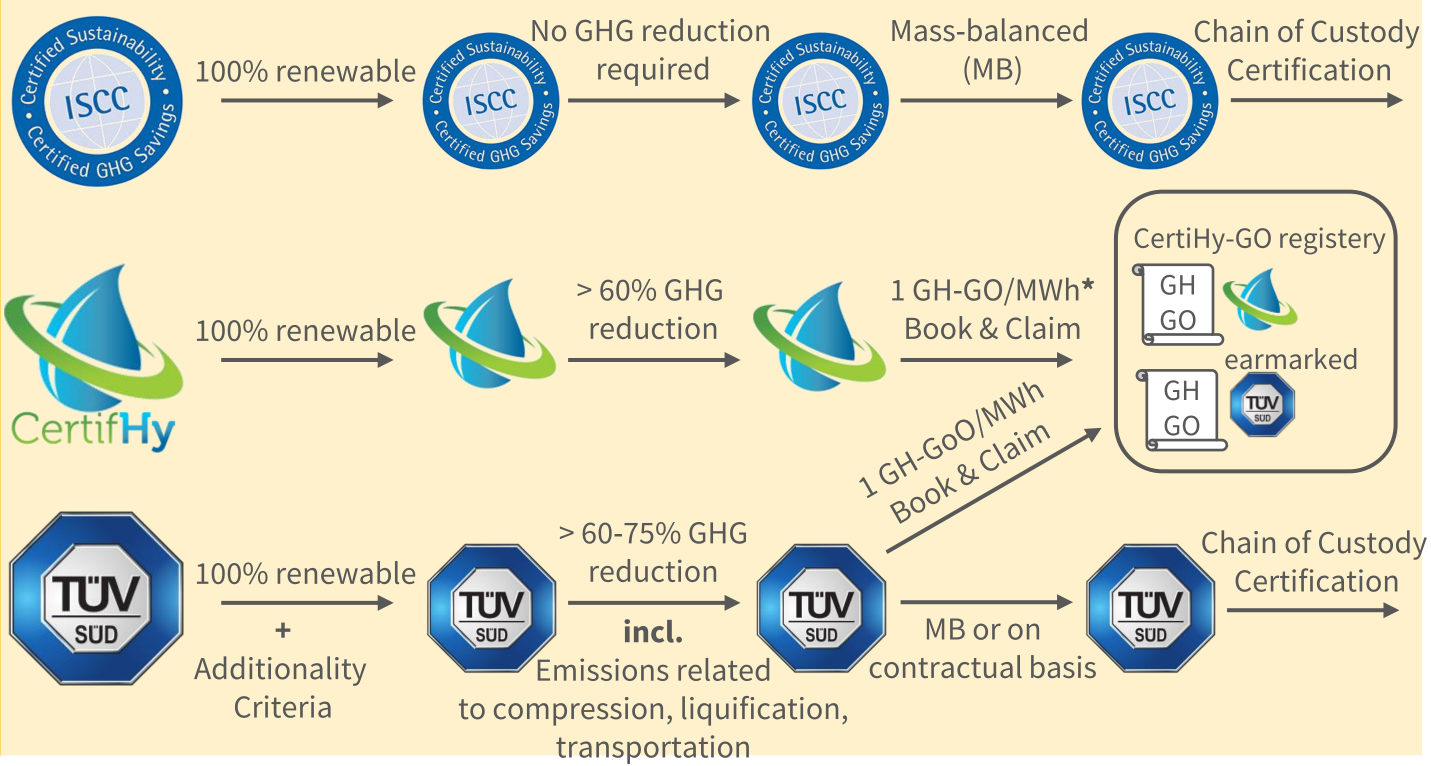
Source: IRENA, Green Hydrogen A Guide To Policy Making, 2020, p.29/fig.2-1.

Governance Dimension
Standards and Certification

STANDARDS AND CERTIFICATIONS

Existing certification systems:

- Hydrogen from renewable energy resources ISCC
- CertifHy (only EU)
- TÜV SÜD Green Hydrogen



*Trading unit: 1 Green Hydrogen (GH) – Guarantee of Origin (GO) in unit of 1 MWh (based on lower heating value)

Source: (adapted) TÜV SÜD, Certification systems on Hydrogen and its relevance for a sustainable future, Knowledge Session Certification of Green Hydrogen, 24.11.2021.

Standards and Certifications
Book and Claim(BC) procedure for Guarantee of Origin (GO)

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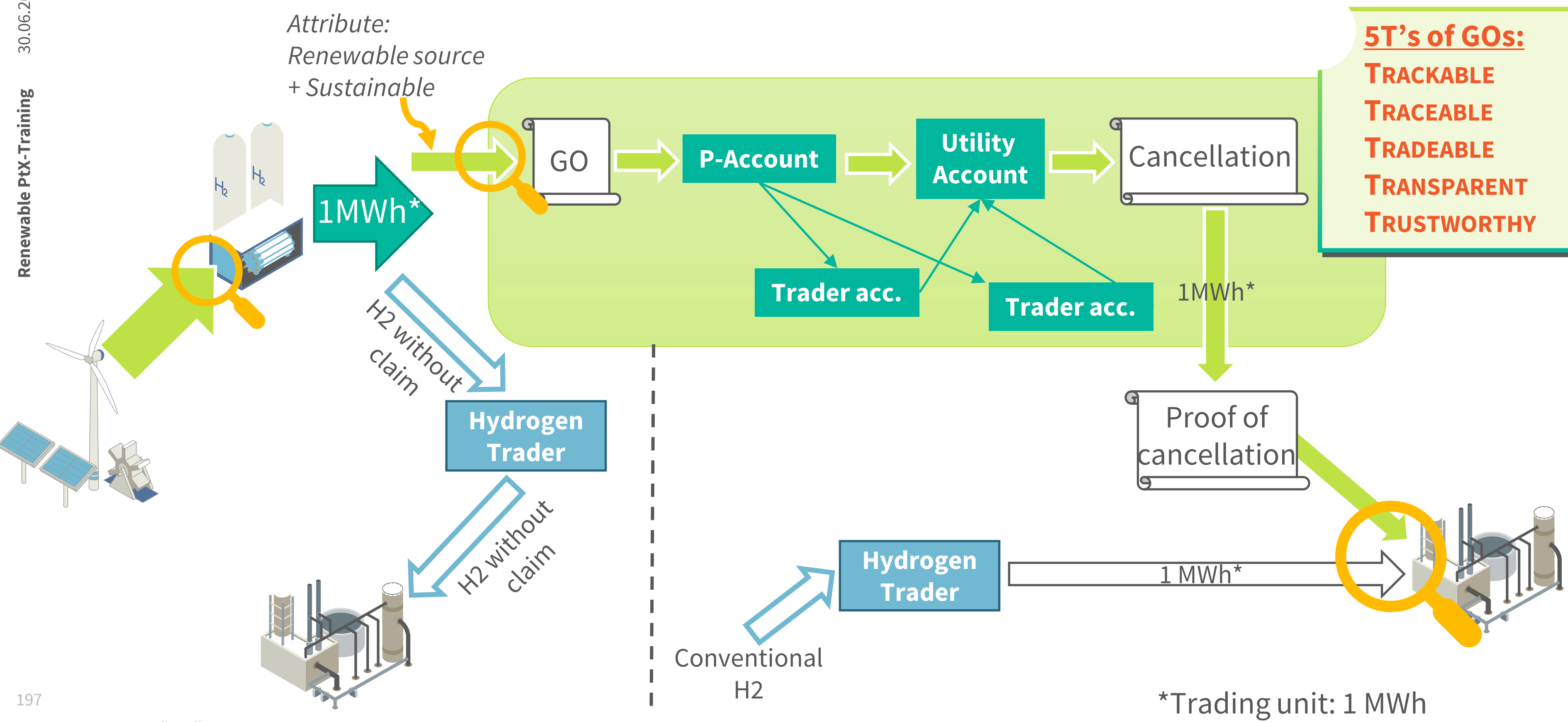
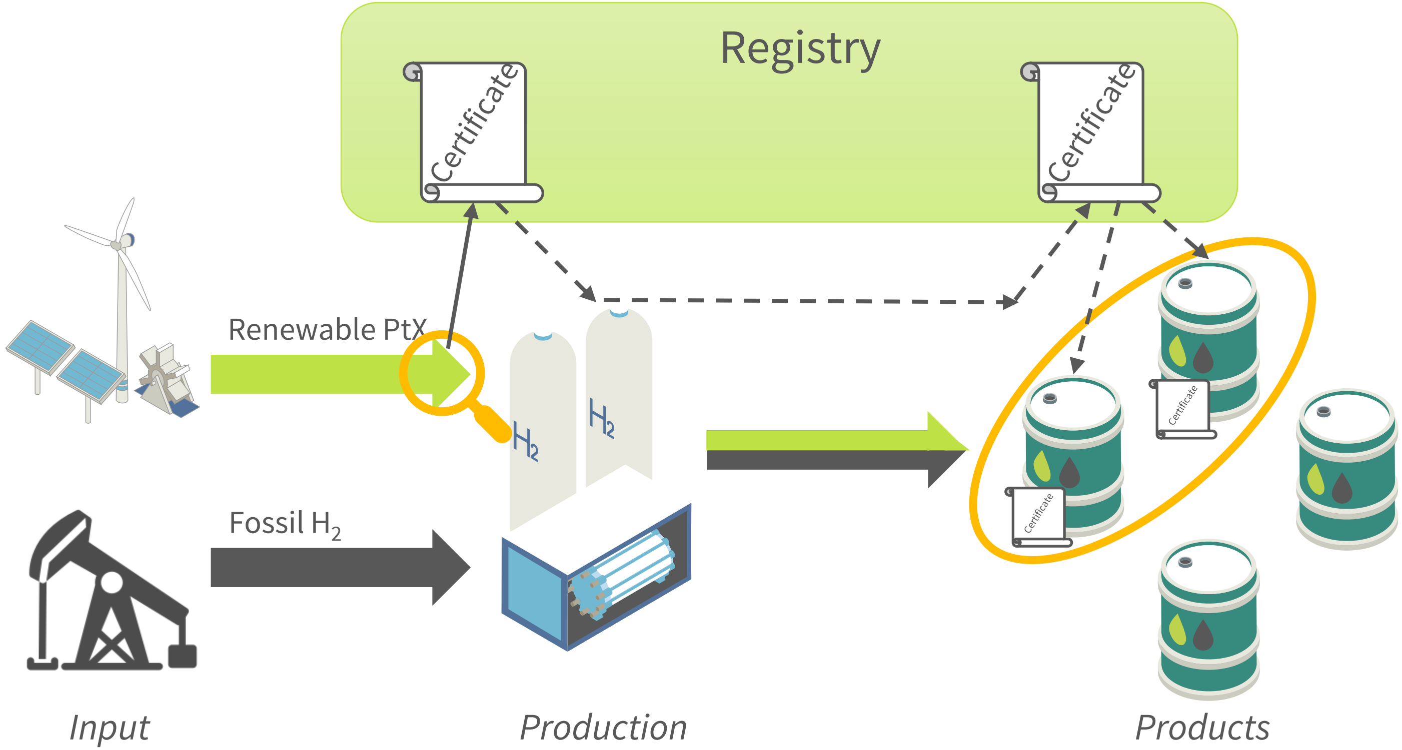


5T's of GOs:
- TRACKABLE
- TRACEABLE
- TRADEABLE
- TRANSPARENT
- TRUSTWORTHY

*Trading unit: 1 MWh
(based on lower heating value)

Source: (adapted) TÜV SÜD, Certification systems on Hydrogen and its relevance for a sustainable future, Knowledge Session Certification of Green Hydrogen, 24.11.2021.

Standardards and Certifications
Mass Balance (MB) approach

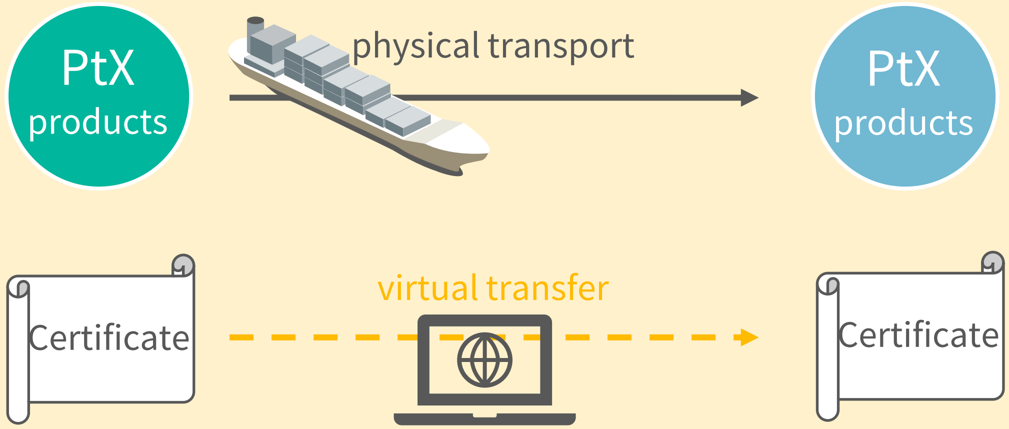


Governance Dimension
Standards and Certification

STANDARDS AND CERTIFICATIONS

Trading products or properties ?

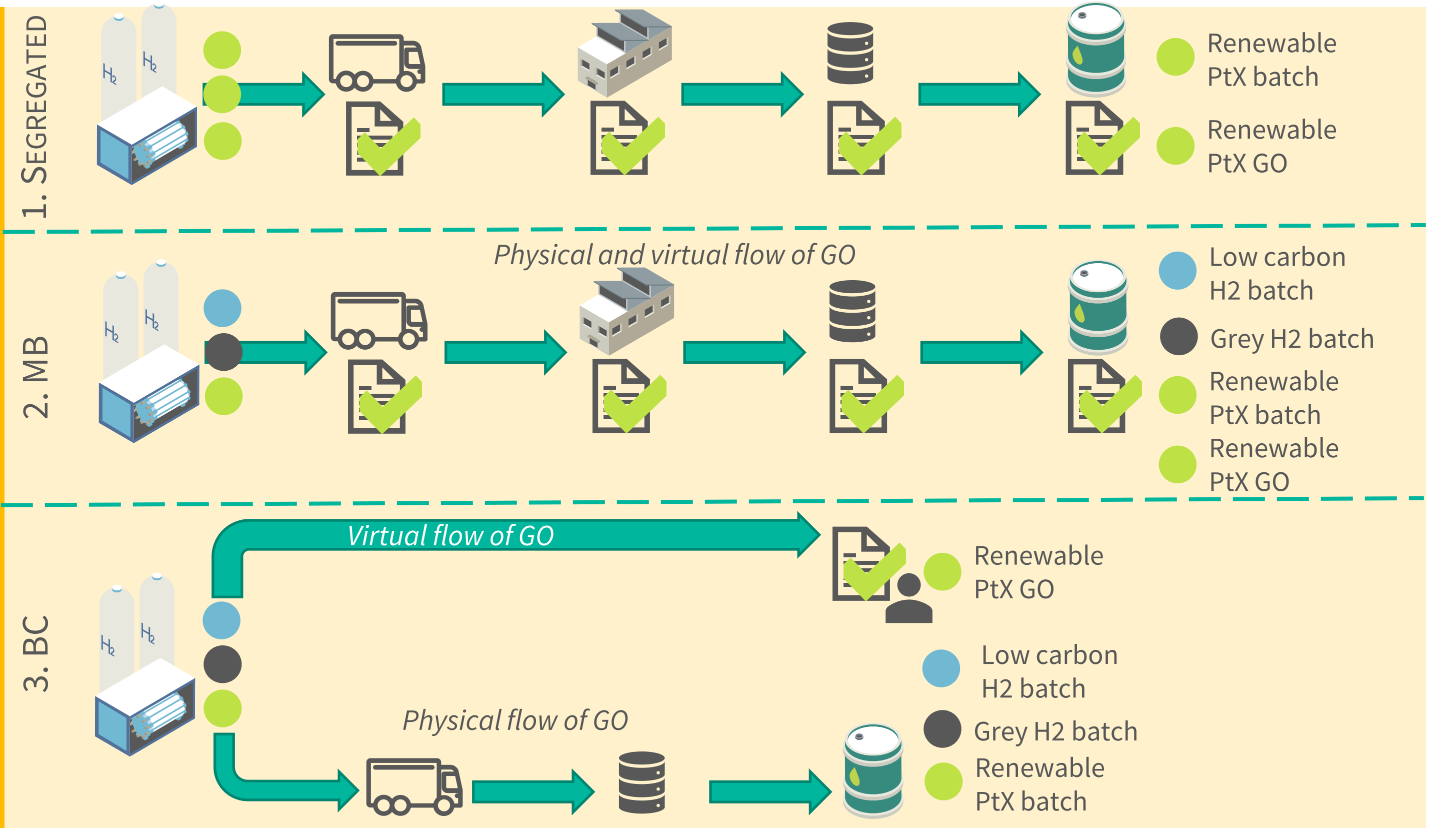
Production **Trading (ex- / import)** **Consumption**



Governance Dimension
Standards and Certification

STANDARDS AND CERTIFICATIONS

Types of certification approaches



Source: (adapted) https://ars.els-cdn.com/content/image/1-s2.0-S0301421520300586-gr2.jpg

Open discussion

"How important do you think a certification scheme is, and do you agree with the EU approach?"

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Sustainability Indicators to consider according to Fraunhofer‘s PtX Atlas

Economics

- Energy imports
- Development of RE in the country
- Investment risk
- Economic dynamics
- Gross domestic product
- Import and export of goods and services
- Investment climate
- Global Resilience Index
- Electricity price

Technology

- RE infrastructure (PV/wind)
- Energy supply in the country
- Innovation
- Expenditure on education & research

Politics

- Corruption
- Political risk
- Political stability and absence of violence
- Rule of law
- Legislation in the country to reduce emissions
- Sustainable policy-making in line with Agenda 2030
- Freedom
- Country Regime

Society

- Satisfaction and peace
- Health system
- Energy demand
- Absence of repressive state violence or acts of war

Nature Conditions

- PV/wind potential
- Size of the country
- RE Capacity
- Water Stress
- Oil and coal reserves
- Oil production and coal mining

Proximity to Germany

- Logistics infrastructure
- Distance (km)
- Economic relations
- Cultural proximity

MODULE 6: Key messages

EESG Framework

- To achieve Paris Agreement, **defossilization of the economy is needed**, for the economy and biosphere
- **PtX sustainability dimensions need to address the entire value chain** and specifically analyse the environmental, economic, social and governance dimension
- Sustainability concerns must be considered at **different assessment levels**

Sustainability Criteria

- The **various environmental dimensions** of PtX production are **essential to determine the level of sustainability**
- The **transformation of energy systems** and introduction of new technologies like PtX **always have major social implications**. This is not just a transition. It must become a **"Just transition"**
- PtX production and trade should **contribute to improving economic prosperity and well-being** as well as environmental wellbeing **(decoupled growth).** Leap-frogging potentials should be taped
- **Additionality for the production of additional renewable power is a must**. The use to renewable power for hydrogen production **does not reduce the overall energy transition** and especially the decarbonization of the power sector.

Certification Schemes

- National + international standards and certification schemes must provide **proper regulatory frameworks** for ramping-up PtX markets and trade

Open discussion

“How critical do you see the compliance to sustainability criteria in your country?”

looking at:
energy (renewable and additional), carbon sources, land use issues, water availability

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Module 7

Support Policies and Regulations for Renewable PtX

Summary of EU Policy Developments (2020-2021), e.g.

- Climate Law
- RED and RED II
- RefuelEU Aviation
- FuelEU Maritime

Regulatory Architecture and Policy Recommendations

- Supply-side measures
- Demand-side measures

Market Ramp-up

- Roadmaps
- Country examples

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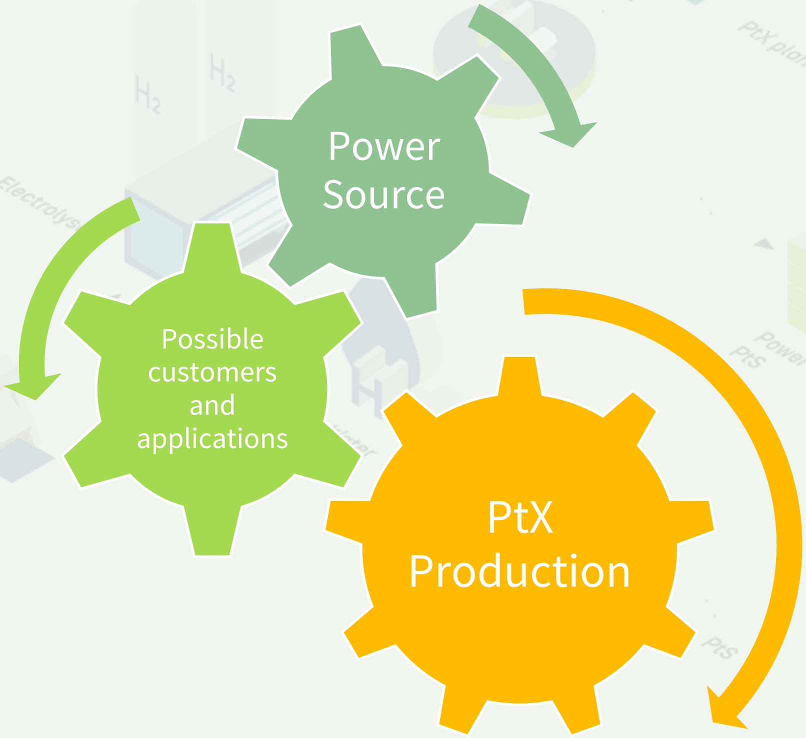
Setting up a green hydrogen project → Holistic approach needed!



- Formulate **clear goals** and intermediate steps
- Be aware that the project might be economically challenging

  → look for partners, build alliances

  → look for funding, subsidies etc.
- Find your story/narrative and inspire creditors and/or political initiatives
- Think from a customer's point of view
- Stay open to opportunities, be flexible

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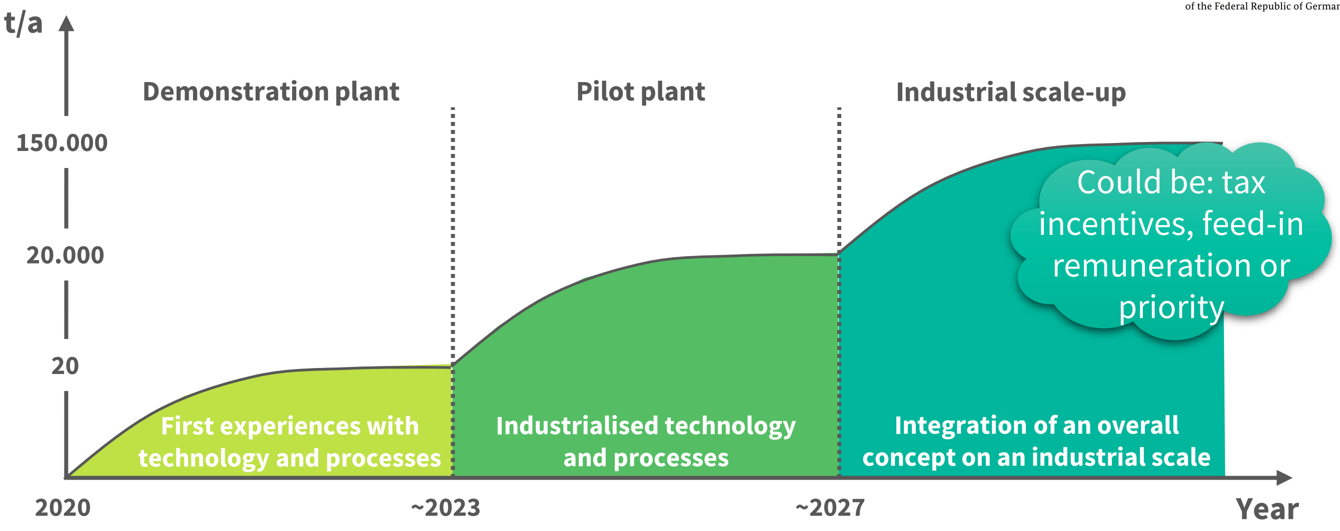
Steps of scaling-up a market



- **PtX faces the typical hen-egg-dilemma: technologically** ready for take-off, but **economically** the rocket is not yet flying
- **Supply side: investors** claim there is not yet sufficient solvent demand
- **Demand side: potential customers** (e.g. airlines) complain that there is not yet sufficient stable supply (e.g. of synthetic e-Kerosene) at affordable prices
- For a **breakthrough** and effective transformation **market mechanisms** alone will not be sufficient
- **Policy intervention** providing regulatory frameworks, R&D and financial support, **on both sides of the market** (supply & demand) will be required!

Test your knowledge

"What are typical policy instruments to ramp-up a market in your country ?"

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Policy Instruments for Market Ramp-Up

1 Long- term policy signals

- **PtX roadmaps**
- **Targets**
- **Industrial strategies**
- **International agreements and commitments**

NDCs Paris Agreement; EU Green Deal; Germany's National Hydrogen Strategy; Japan's Basic Hydrogen Strategy; China's Ecological Civilisation commitment; Make in India […]

2 Demand creation

- **CO_2 and pollution pricing**
- **Mandates and bans**
- **Performance standards**
- **Tax credits**
- **Reverse auctions**

RED II, Canadian Clean Fuel Standard; **EU Emissions Trading System**, Dutch public procurement provisions for low carbon materials; UK Renewable Transport Fuel Obligation (RTFO); US 45Q tax credit for CCUS […]

3 Investment risk mitigation

- **Loans + export credits**
- **Risk guarantees**
- **Trading of "guarantees of origin"**
- **Risk mitigation: CCfDs**
- **Tax breaks**

Chinese policy bank loans; Australia's Clean Energy Finance Corporation; EU projects of common European interest; EIB Energy Lending Policy; multilateral bank financing; EU Connecting Europe Facility […]

4 Removing barriers

- **Safety + sustainability standards**
- **Avoiding double taxation of energy**
- **Certification of CO_2 intensity and provenance**
- **Benchmarks for processes**
- **International frameworks**

International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE); **International Organisation for Standardisation (ISO); HySafe; EU CertifHy** […], **RED II Delegated Acts**

5 R&D + knowledge sharing

- **Direct project funding**
- **Concessional loans**
- **Multilateral collaboration initiatives**
- **Communication campaigns**
- **Prizes**

Japanese NEDO Roadmap for fuel cells and hydrogen; EU Horizon 2020; Germany National Innovation Program for Hydrogen and Fuel Cell Technology; US Department of Energy Hydrogen and Fuel Cells Program and H2@Scale […]

Source: Own illustration based on: IEA, The future of Hydrogen, 2019, p.175/table 12 ff..

EU example: Policy targets to increase demand and supply for green H_2 and minimise commercial off-taker risk!

Social **C**limate **F**und

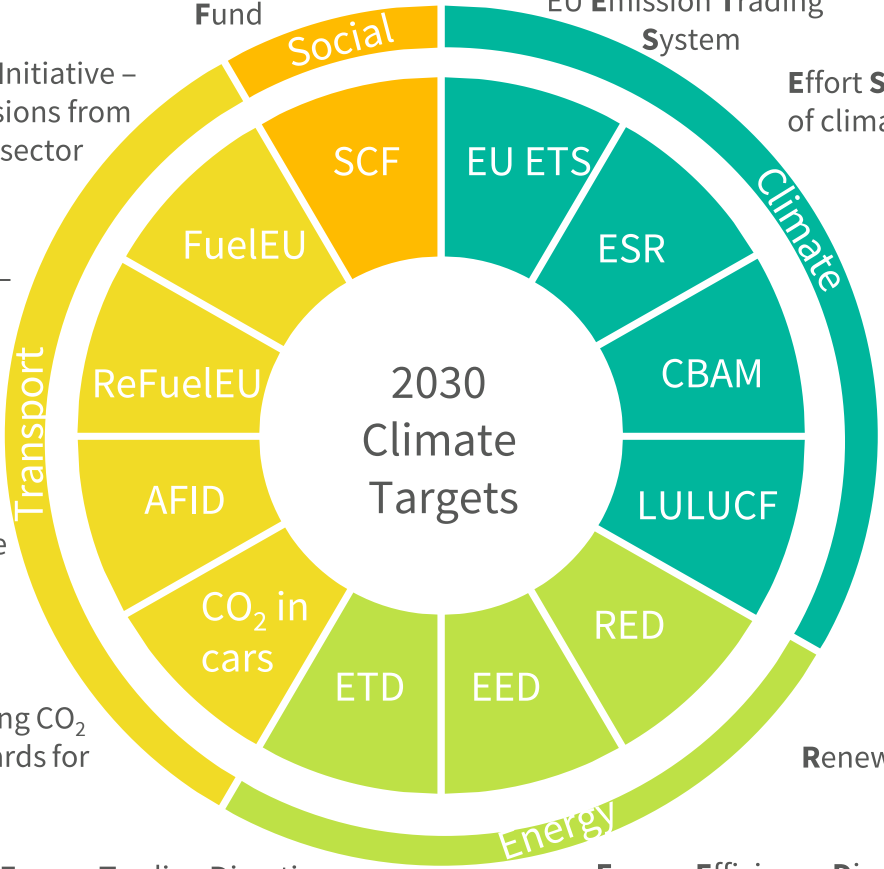
Revision of the EU **E**mission **T**rading **S**ystem

Maritime Initiative – CO_2 emissions from maritime sector

Effort **S**haring **R**egulation of climate action regulation

Aviation Initiative – sustainable aviation fuels

Carbon **B**order **A**djustment **M**echanism



Alternative **F**uels **I**nfrastructure **D**irective

Regulation of the inclusion of GHG and removals from **L**and **U**se, **L**and-**U**se **C**hange, and **F**orestry

Regulation setting CO_2 emission standards for cars and vans

Renewable **E**nergy **D**irective

Energy **T**rading **D**irective

Energy **E**fficiency **D**irective

Policy Developments IV – EU Hydrogen Backbone

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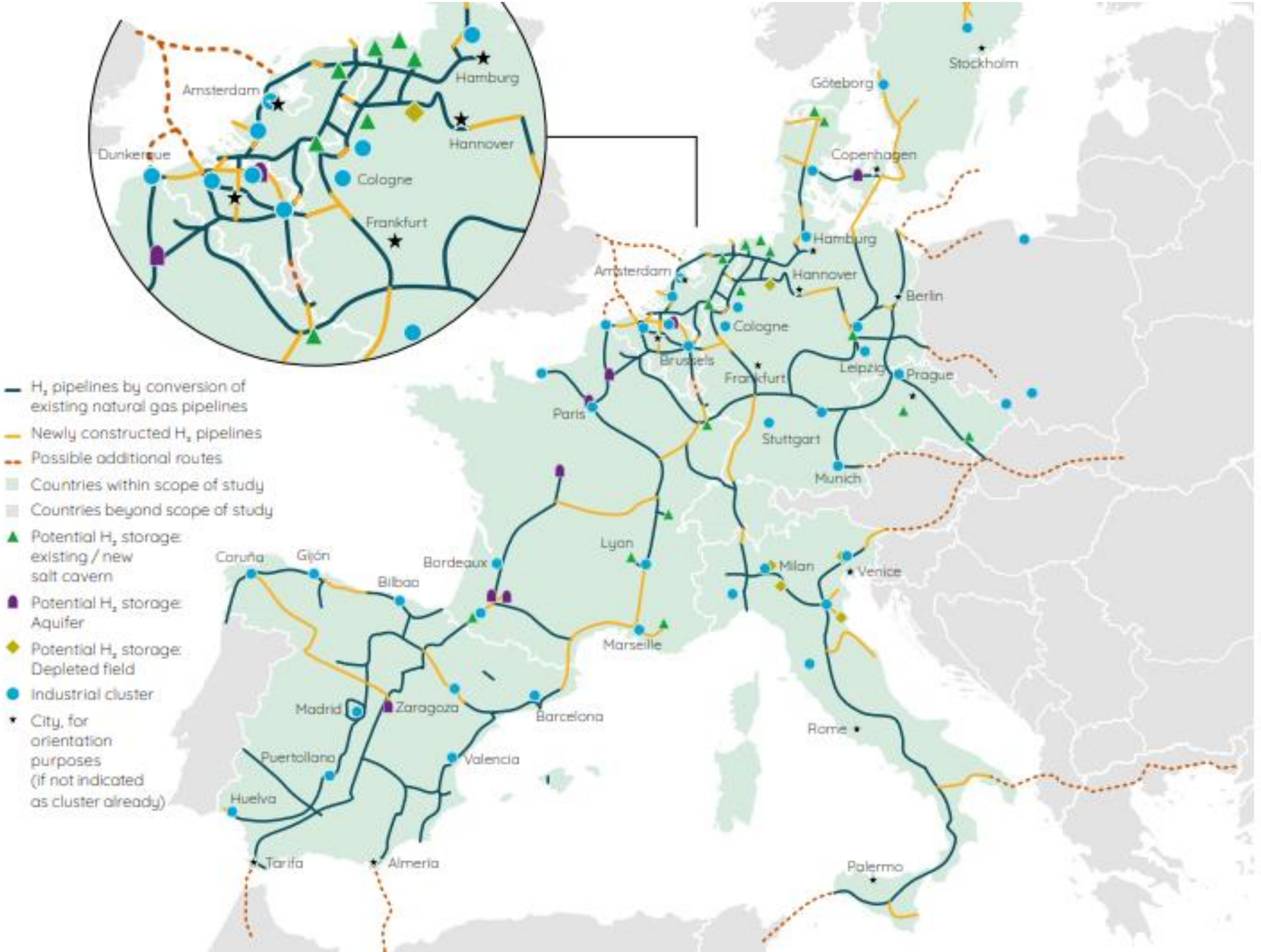
Mature Hydrogen Backbone can be created by 2040



Source: European Hydrogen Backbone, How a dedicated hydrogen infrastructure can be created, 2020 p.8/fig.5.

Regulatory architecture – Building blocks of an adequate policy framework for the H_2 economy

Besides *policy instruments*, adequate *support architecture* is needed to ramp up supply and demand for GH_2

Sustainability

System integration

Supply

- De-risking
- H_2 supply contracts (operating support)
- Investment support
- Exemption taxes & levies

Demand

- Carbon CfD
- Quotas
- H_2 in CHP*
- CO_2 pricing (ETS/BEHG**)
- Public procurement

Infrastructure and markets

*CHP: Central Heating Plant/ Co-generation Heat and Power Plant

**BEHG: *Brennstoffemissionshandelsgesetz*. The German Fuel Emissions Trading Act creates the basis for trading in certificates for emissions from fuels and ensures that these emissions are priced insofar as they are not covered by EU emissions trading.

Source: illustration adapted: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive *Policy instruments for supporting green H2,* ONLINE EVENT, 08 JULY2021, p.16-21.

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Policy Recommendations: Supply Side Measures

- **Investment aid** could finance **CAPEX** for electrolysers
  At EU level, the Innovation Fund supports innovative low-carbon technologies (such as electrolysers) with revenues from the EU ETS

- **Exemption** of electrolysers **from taxes and levies:** decreases cost of electricity, which is largest component of **OPEX**

- **De-risking instruments** to reduce financing costs: significantly lowers necessary investment outlays

- **H_2 supply contracts**: provide support for both production and demand → could be harnessed to address remaining cost discrepancy

Source: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive Policy instruments for supporting green H2, 2021, p.46ff.

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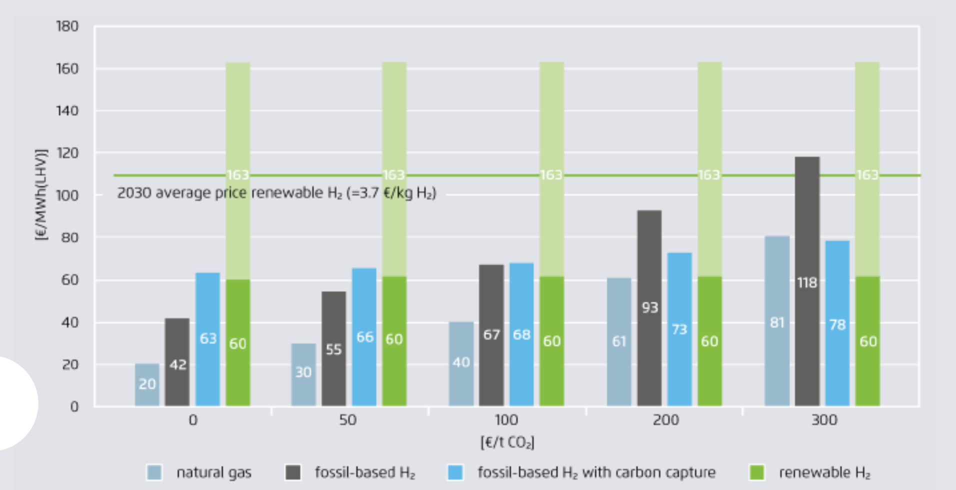
Policy Recommendations: Demand Side Measures

- **Carbon Pricing** triggers cost-efficient GHG abatement measures
- **Carbon Contracts for Difference (CCfDs)**: facilitate investment, de-risk long-term investment
- **PtL quota** in aviation would create investment security
- **Fixed feed-in premium for new renewable H_2-fuelled CHP plants** → support per unit of energy generated, covering incremental CAPEX + OPEX cost difference between renewable H_2 and natural gas
- **Green Public Procurement**

CO_2 prices in 2020s won't be high enough to ensure stable demand for green H_2
→ need for H_2 policy framework!

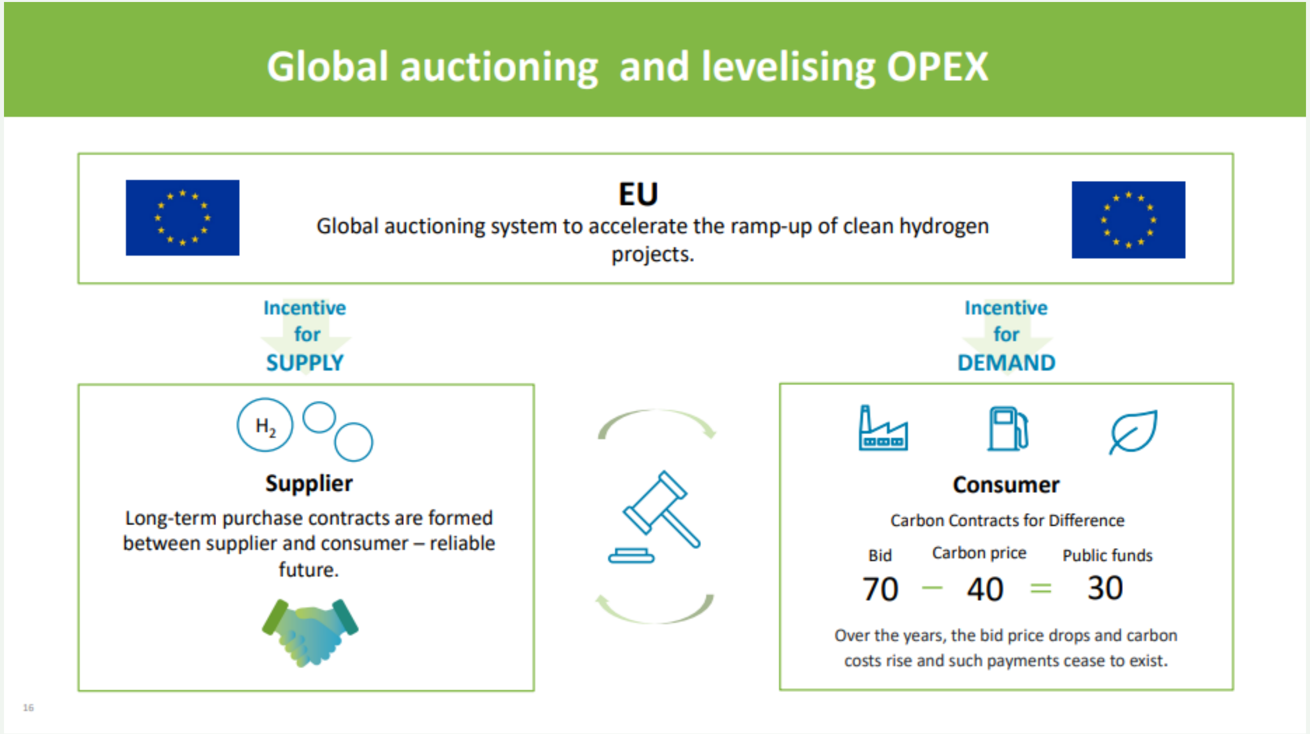
Impact of **carbon pricing** on hydrogen production costs in 2030



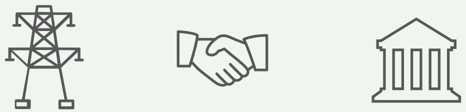
For natural gas, a price of €20/MWh is assumed. The capture rate for fossil-based H_2 with carbon capture is assumed to be around 75%

Source: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive *Policy instruments for supporting green H2,* 2021, p.47.

Policy Recommendations
Connection of Supply and Demand Side



Policy Instrument: Carbon Contract for Difference (CCfD)



Electricity Generator

Low Carbon Contracts Company (LCCC)

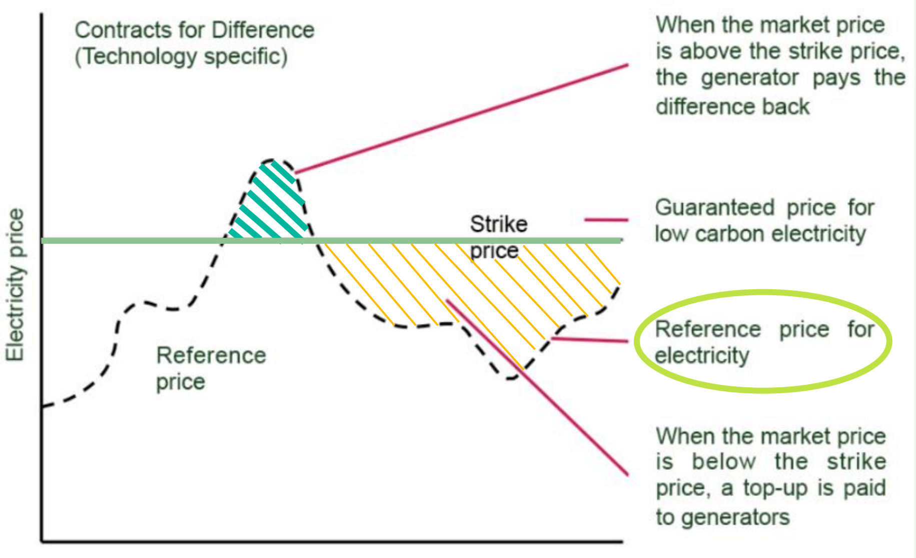
Generator can stabilise its revenues at a pre-agreed level (**strike price**) via long-term contract with LCCC.

a) **Market price < Strike price**
→ **LCCC pays** difference to generator

b) **Market price > Strike price**
→ **Generator pays** difference to LCCC

Can also be applied to steel, cement and fertiliser

Goal: **facilitate industry investment in breakthrough abatement technologies** by **offsetting their additional OPEX** while **de-risking long-term investments** and laying foundation for green lead markets.



Source: Renewable UK, Rebecca Explains It All: The CfD, Sep 17, 2019.

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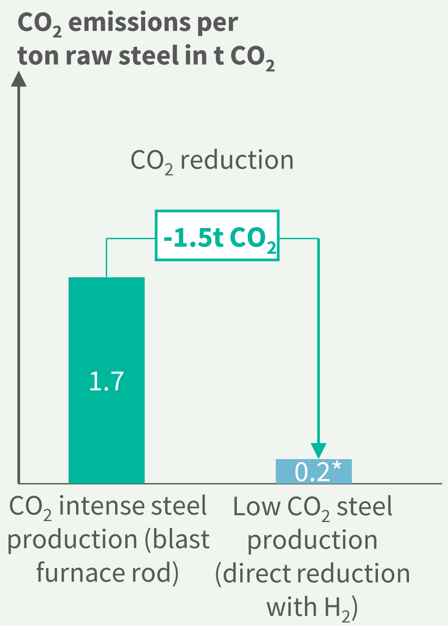
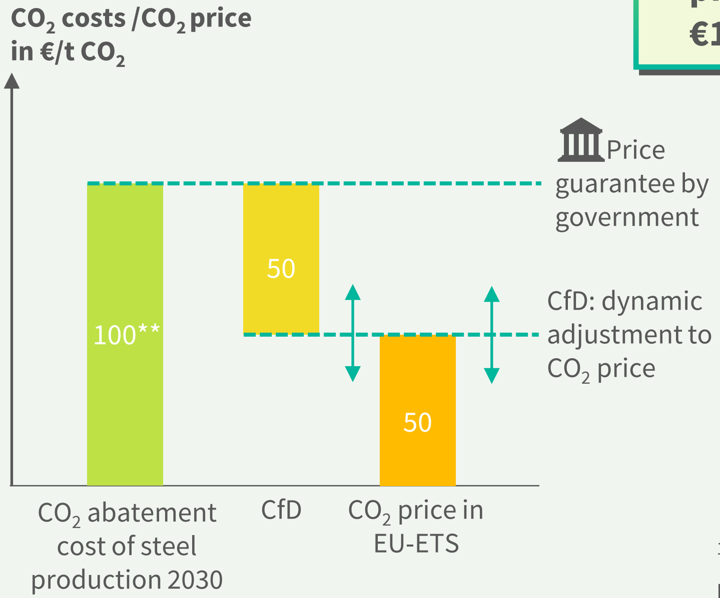
Example: German Steel Production

How a Carbon Contract for Difference (CCfD) works

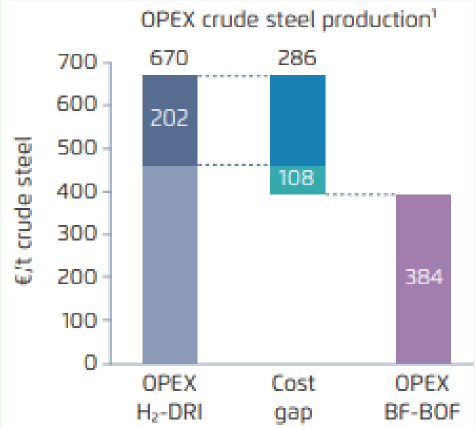


Assumption: Reducing agent use of 65% green % fossil natural gas in direct reduction.



*** Assumption: 150€ additional costs per t of crude steel / 1.52t CO2 saved per t of crude steel.*

Funding requirements for CCfDs can be very large: estimates place **funding required to convert 1/3 of German primary steel** production to H_2 at **€1.1–€2.7 billion per annum** (Agora, p.48).



[1] Under the current free allocation regime. **Carbon price increase** from €50/tCO_2 (2021) to €90/tCO_2 in 2040 would **decrease the cost gap due to higher OPEX for BF-BOF** *(Blast Furnace Basic Oxygen Furnace)*; costs of CO_2 are included in OPEX.

Sources:
1) Agora Energiewende, 2019, Fig. D.7.
2) Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive - *Policy instruments for supporting green H2*, 2021, p.77.

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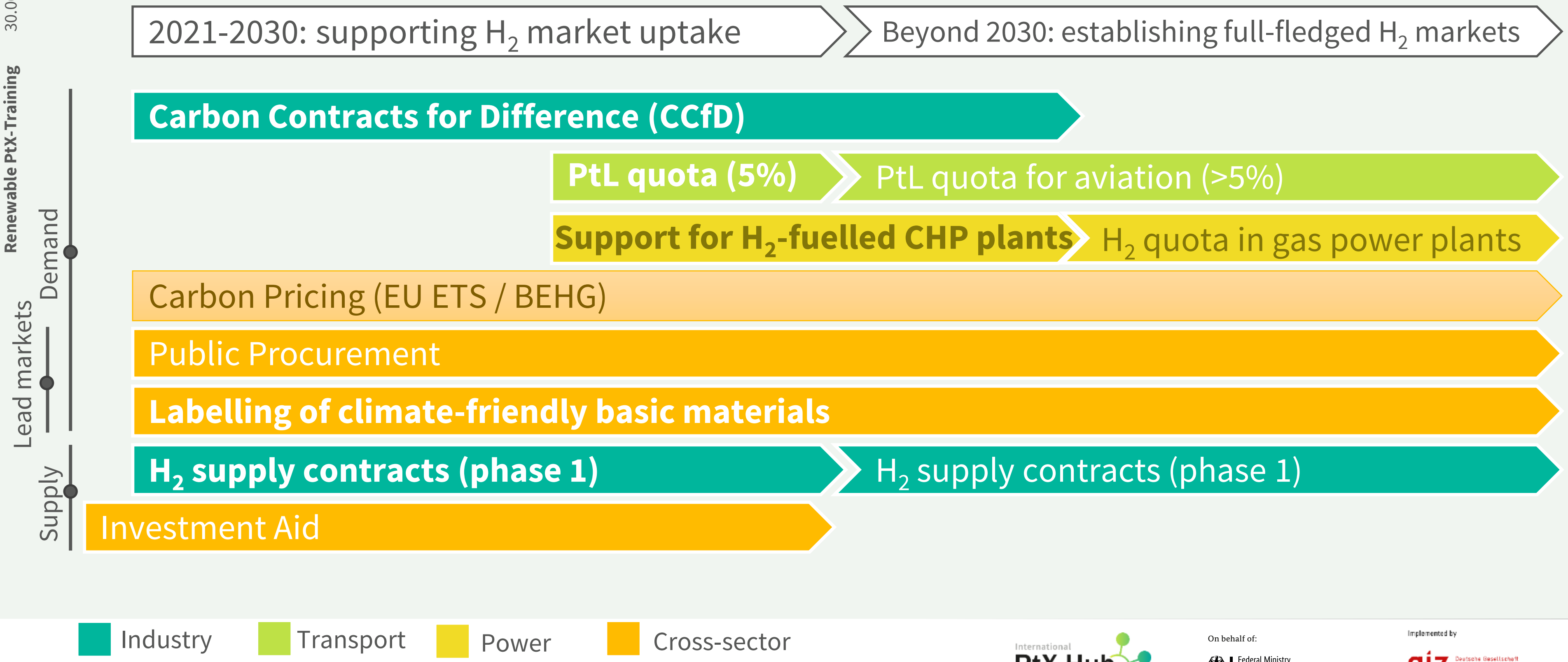
Roadmap of Policy Recommendation Integration (suggestion)



Source: (Adapted) Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive - *Policy instruments for supporting green H2*, 2021, p.32.

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Policy Recommendations: Summary

- Policy framework should **initially target applications where PtX is CLEARLY NEEDED NO-REGRET OPTION** → *general* quota is too imprecise and fails to future-proof our infrastructure

- **Scalable GREEN LEAD MARKETS** could help to create a business case for renewable H_2

  Short run: **CO_2 performance labelling + public procurement** can help to create lead markets

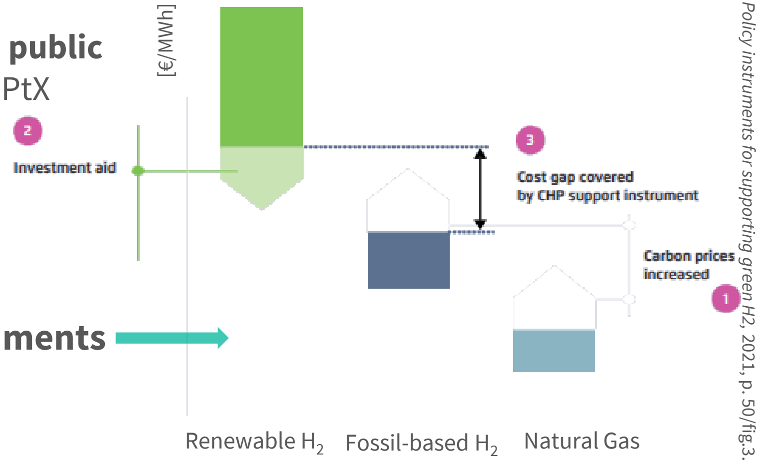
  (1) **Labels:** communicate necessity of a price premium for recouping investment in new production processes (e.g. based on renewable H_2)

  (2) **Standards** to determine rules for accounting of embedded emission intensities, e.g. for PtX used during production of basic materials

  (3) Demand creation by government by setting **minimum green public procurement requirements** for basic materials likely to use PtX as an input (such as steel or plastics for construction)

- **Supply contracts** can enable competition between production in EU and abroad

- Creating **interaction between demand and supply side instruments** →



Source: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive *Policy instruments for supporting green H2*, 2021, p. 50/fig.3.

Important policy instruments: Development and international cooperation

To get access to premium markets, EU standards have to be met on an EU and international level

Creating standards + removing barriers
international standardisation crucial across entire value chain, incl. “guarantees of origin”

R&D, strategic demo. projects + knowledge sharing
improving the access to essential technological knowledge will be fundamental to ensure a fair international market

Co-financing (e.g. for pilot projects)
between countries re-distribute access to financial resources

International stakeholder dialogues
involvement of different stakeholders facilitates internat. trade + creates inclusive internat. framework

International agreements
setting up international trade routes

Strict regulations
sustainability and respect of human + social rights crucial to guarantee *just* internat. cooperation

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How to tackle policy making?
(1) Set up a National Strategy first!

R&D program is important but it may be adopted to needs and capability of each country!

Source: (adapted) IRENA, Green Hydrogen – A Guide to Policy Making, 2020, p.20/fi.2.2.

How to tackle policy making?
(2) Establish Policy Priorities

Acceleration of manufacturing capacity and **tackling high investment costs** of electrolysers + enabling infrastructure

- Grants
- Loans
- Tax Credits

Reduction of costs of **renewable electricity** for green H_2 production

- Changes to electricity taxes + grid fees
- CCfDs
- Auctions
- Feed-in tariffs/ premiums

Addressing **sustainability**

- Certification schemes
- Eco-labels
- Additionality measures/ mandates

Enablement of **demand and market entry** for green H_2

- Electrolyser capacity targets
- Green H_2 mix targets
- Green product mandates
- Public procurement schemes
- Carbon taxes
- Quotas

Policies

Where to start? No regret options first!

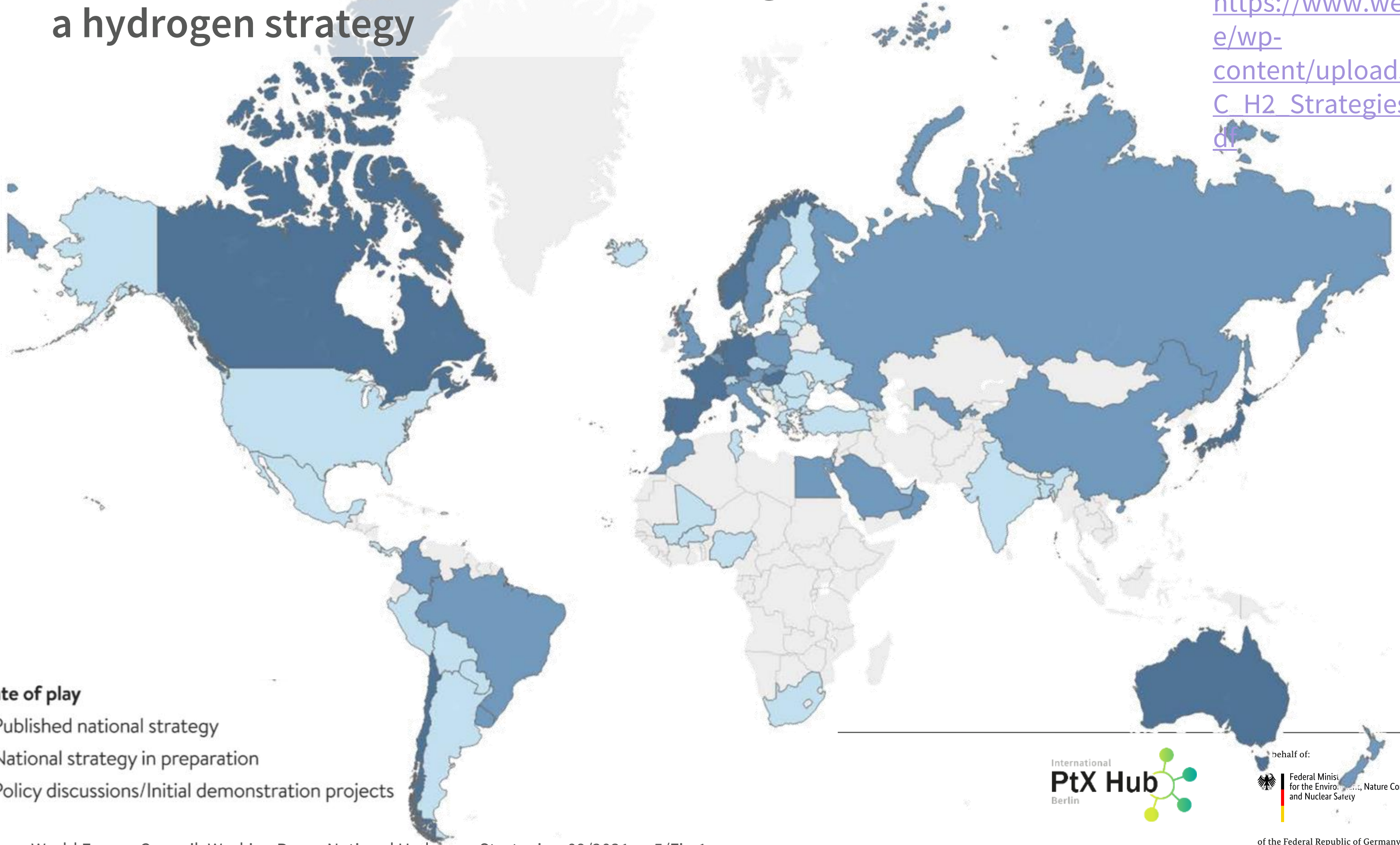
The deployment of green H_2 faces some sector specific **barriers**, some universal (main barrier being **cost**).

Political commitment + obligations (→ sales guarantees) ensure investment security and can be a backbone of a market run-up

Source: adapted from: IRENA Coalition for Action, Decarbonising end-use sectors: Practical insights on green hydrogen, 2021, p.13/fig.3.

Overview: Activities towards developing a hydrogen strategy

CHECK OUT THIS REPORT:
https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf



Source: World Energy Council, Working Paper National Hydrogen Strategies, 09/2021, p.5/Fig.1.

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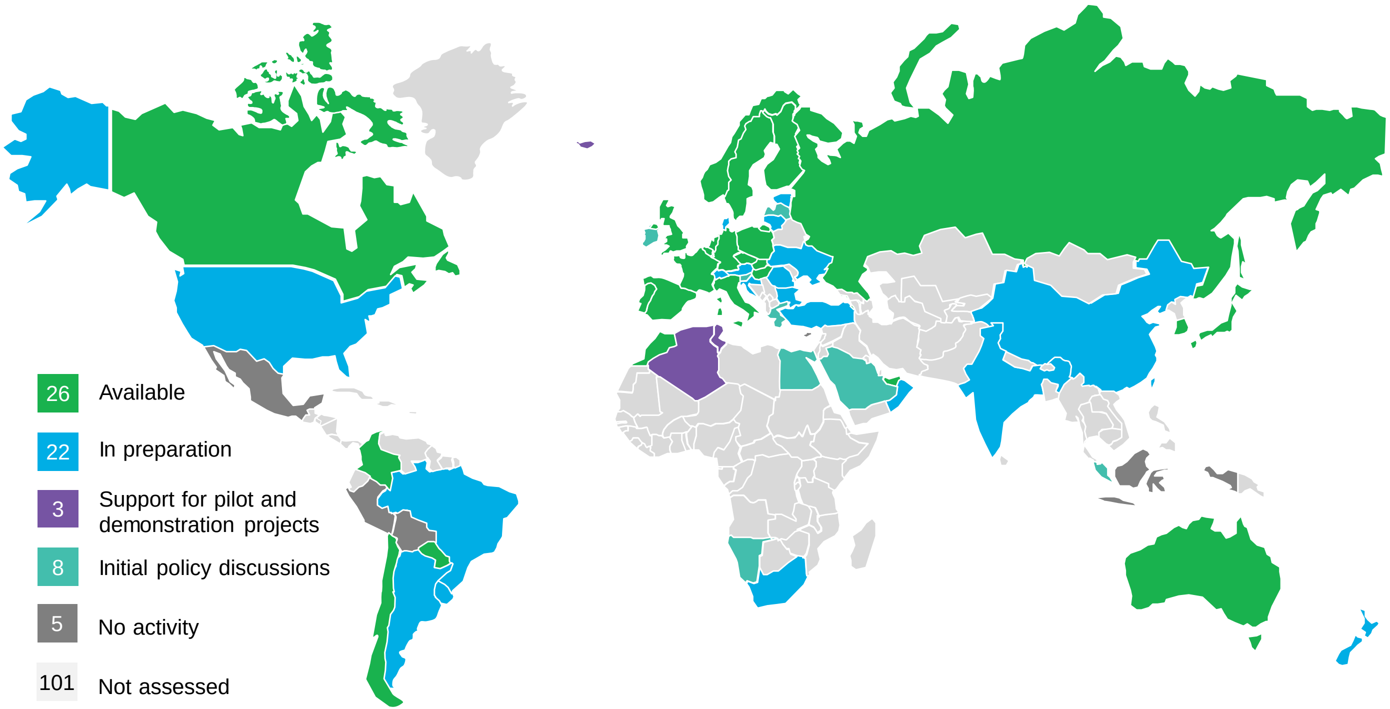
National hydrogen strategies as of January 6, 2022



Source: BloombergNEF

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MODULE 7: Key messages

Summary of EU Policy Developments (2020-2021)

- When you design a hydrogen project **think from a customer perspective**, the approach must be **holistic**
- PtX faces **the typical hen-egg-dilemma**: technologically ready for take-off, but economically the rocket is not yet flying. **The market alone will not overcome this challenge**
- **To over come this challenge interventions by governments are required on both side, demand and supply side.**
- There are **five different areas for policy interventions**

Regulatory Architecture and Policy Recommendations

- Besides policy instruments, adequate support architecture is needed to ramp up supply and demand for GH2
- To get access to premium markets, **EU standards have to be met** on an EU and international level
- **Set up a national strategy first**

Market Ramp-up

- **Political commitment + obligations** ensure investment security and can be a backbone of a market run-up

Final recommendations

- To be **sustainable, hydrogen (H_2) must come from additional renewable energy.**

  → If not it undermines the overall **powershift towards renewables** (→ additionality).
- By going **the extra mile beyond H_2 towards PtX, use options and added value creation rise significantly.**
- Necessary carbon sources should come from **Direct Air Capture (DAC).**
- PtX can provide **carbon-neutral feedstocks and fuels for industry: chemicals and fertilisers, steel, cement or glass; as well as aviation, maritime shipping or long-haul heavy transport**.
- **Countries should** identify their respective PtX profiles and PtX solution that fit their needs and long-term ambitions.
  - **(1) undertake a SWOT analysis**
  - **(2) develop a national H_2/PtX strategy**
  - **(3) design a PtX Road Map** with measurable targets and clear timelines
- Measures should be aligned with country's **SDG Agenda and Paris Agreement NDCs**.
- **National PtX policy** should be driven by **national opportunities, priorities and needs**.
- **International co-operation** and partnerships **help speeding-up knowledge and technology transfer**, generating mutual benefits, trade and much needed revenue.

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Is the renewable PtX really kicking off now? Hype or Reality?

Seven signposts of scale-up towards a renewable PtX economy (BNEF)

1 Net-zero climate targets are legislated

Necessity to decarbonise hard-to-abate sectors

2 Harmonising of standards + Removing regulatory barriers

Clears or minimises obstructions to PtX projects

3 Targets with investment mechanism

Provides a revenue stream for producers, increases competition, builds capacity + experience

4 Stringent heavy transport emissions standards

Incentive for *manufactures to produce*, and *users to buy*, fuel cell trucks and NH_3-powered ships

5 Mandates and markets for low-emission products

Incentive for manufacturers to produce low-emission goods (e.g. steel, cement, fertilisers, plastics)

6 Industrial decarbonisation policies and incentives

Helps to coordinate infrastructure investment, scale efficient use of and provides incentives for PtX use

7 PtX-ready equipment becomes commonplace

Enables and reduces the cost of fuel switching to PtX products

Source: (adapted) BNEF, Hydrogen Economy Outlook, 2020.

Open discussion

“How do you want to start the development of H_2 and PtX in your country?”

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Your opinion is important to us!

Please go to menti.com one last time and provide us your opinion!

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Thank you for your kind attention!

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Selection of Resources

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